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POSTCLOSURE SAFETY ASSESSMENT - NPD CLOSURE PROJECT REV 0

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Nuclear Power Demonstration Closure Project

Postclosure Safety Assessment Technical Supporting Document 4th Iteration

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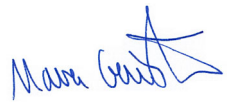
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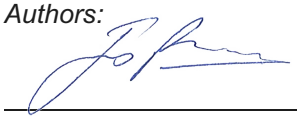
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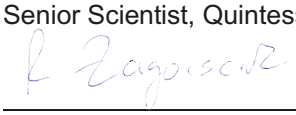


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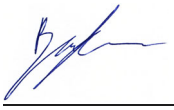
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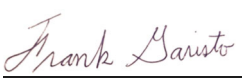


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POSTCLOSURE SAFETY ASSESSMENT

Technical Supporting Document

Postclosure Safety Assessment of the In-situ Disposal of the NPD 4th Iteration

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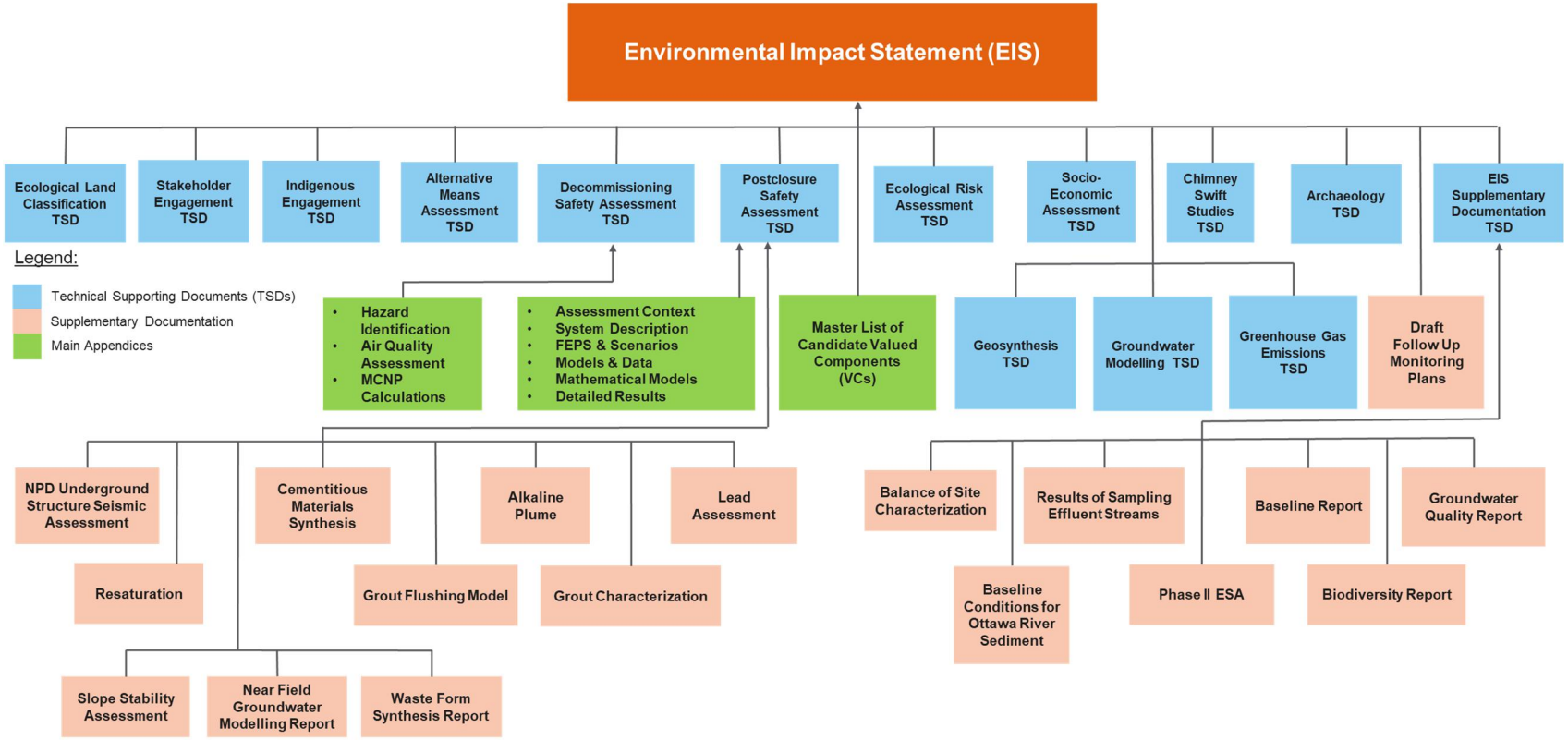
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CNL – Postclosure Safety Assessment

This Technical Supporting Document (TSD) has been prepared in support of the Nuclear Power Demonstration (NPD) Closure Project. The project qualifies as a Designated Project under the *Canadian Environmental Assessment Act (2012),* and therefore, an Environmental Impact Statement (EIS) is being prepared as part of the Environmental Assessment process.

The findings of this TSD have been summarized in the NPD Closure Project EIS (CNL Doc #64-509200-ENA-004). The following figure shows the various documents associated with the EIS, and their relationships.



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ACRONYMS AND ABBREVIATIONS

AECL	Atomic Energy of Canada Limited
ALARA	As Low as Reasonably Achievable
AOPFN	Algonquins of Pikwàkanagàn First Nation
BAF	Bioaccumulation Factor
BDBE	Beyond Design Basis Earthquake
BFS	Blast Furnace Slag
BRA	Background Reference Area
CANDU	CANada Deuterium Uranium
CEAA	*Canadian Environmental Assessment Act*
CMT	Continuous Multi-Channel Tubing
CNL	Canadian Nuclear Laboratories
CNSC	Canadian Nuclear Safety Commission
CRL	Chalk River Laboratories
CSA	Canadian Standards Association
CSH	Calcium-Silica-Hydrate
DBE	Design Basis Earthquake
DBF	Design Basis Flood
DCF	Dose Conversion Factor
DE	Disruptive Event
DRL	Derived Release Limit
EA	Environmental Assessment
ECCC	Environment and Climate Change Canada
EIS	Environmental Impact Statement
EPM	Equivalent Porous Medium
ET	Evapotranspiration
EQS	Environmental Quality Standard
FEPs	Features, Events and Processes
GRS	Ground Response Spectra
HC	Health Canada
HER	Hydrologically Effective Rainfall
HLW	High Level Waste
HTSCh	Heat Transport System Charging
HTSCo	Heat Transport System Collection
HTSD	Heat Transport System Demineraliser
HTSEI	Heat Transport System Emergency Injection
HTSSC	Heat Transport System Standby Cooling
IAEA	International Atomic Energy Agency
IC	Institutional Control
ICRP	International Commission on Radiological Protection
IPCC	Intergovernmental Panel on Climate Change
ISAM	Improvement of Safety Assessment Methodologies for Near Surface Disposal Facilities

ISD	In-situ Disposal
LLWR	Low-Level Waste Repository
mASL	Meters Above Sea Level
MD	Moderator Demineraliser
MHS	Moderator Helium System
MOD	Moderator System
MOE	Ontario Ministry of Environment
MOECC	Ontario Ministry of Environment and Climate Change
MOECP	Ontario Ministry of Environment, Conservation and Parks
NEA	Nuclear Energy Agency (of the Organization for Economic Cooperation and Development)
NES	Normal Evolution Scenario
NHB	Non-Human Biota
NMNTI	New Millennium Nuclear Technologies Incorporated
NPD	Nuclear Power Demonstration
NPDDF	Nuclear Power Demonstration Disposal Facility
NPDNGS	Nuclear Power Demonstration Nuclear Generating Station
NPDWF	Nuclear Power Demonstration Waste Facility
OBT	Organically Bound Tritium
OGS	Ontario Geological Survey
ORRPB	Ottawa River Regulation Planning Board
PC	Portland Cement
PCB	Polychlorinated Biphenyl
PGA	Peak Ground Acceleration
PHTS	Primary Heat Transport System
PMF	Probable Maximum Flood
PMP	Probable Maximum Precipitation
PPE	Personal Protective Equipment
PostSA	Postclosure Safety Assessment
PSAG	Probabilistic System Assessment Group
PWQO	Provincial Water Quality Objective
QA	Quality Assurance
RC	Reflector Circuit
RCP	Representative Concentration Pathways
REE	Rare Earth Element
REGDOC	Regulatory Document
RVCS	Reactor Vault Ventilation Cooling System
SWS	Storage with Surveillance
TDS	Total Dissolved Solids
TSD	Technical Supporting Document
UCL	Upper Confidence Limit
UV	Ultraviolet
WI	What-If

EXECUTIVE SUMMARY

Background and Objectives

After being in a safe shutdown state for more than 30 years, CNL is proposing the final decommissioning of the Nuclear Power Demonstration Waste Facility (NPDWF). After decommissioning, the facility is referred to as the Nuclear Power Demonstration Disposal Facility (NPDDF). As part of the Environmental Impact Statement for the decommissioning of the facility, a Postclosure Safety Assessment (PostSA) has been conducted to assess the long-term safety of the NPDDF. This PostSA assesses the long-term impacts of both radiological and chemical contaminants on the public and the environment.

The objective of CNL's project is to safely carry out the decommissioning of the NPDWF using the in-situ disposal (ISD) approach to isolate and contain the contaminated systems and components inside the below-grade structure. All above-grade structures will be demolished, size reduced and placed into the below-grade structure as backfill prior to final grouting. All below-grade areas will be filled with grout from an on-site batch mixing plant. The footprint above the reactor vault and other portions over the nuclear area will be capped with reinforced concrete and the entire NPDWF covered with an engineered cover. The ventilation stack will be retained for chimney swifts, which are a species at risk. The NPD site will then be restored and prepared for long-term care and maintenance activities, carried out under an amendment to the current decommissioning licence.

Assessment Context

The PostSA was prepared for the NPDDF following the International Atomic Energy Agency's (IAEA's) ISAM approach (Improvement of Safety Assessment Methodologies). It was developed using an iterative approach. This report documents the 4th Iteration of the PostSA. The PostSA also follows REGDOC 2.11.1 on the safety case for the disposal of radioactive waste from the Canadian Nuclear Safety Commission (CNSC).

Human health criteria for radioactive contaminants have been defined in the PostSA according to the CNSC. Corresponding criteria for chemical contaminants are based on federal and provincial guideline concentrations for groundwater, surface water, soil and sediment.

FEPs & Scenarios

The PostSA's scenarios and calculation cases were developed in a systematic way, using a standard list of factors that could be important for postclosure safety. These factors are referred to as the FEPs (Features, Events and Processes). A list of over 200 FEPs was compiled and reviewed for their relevance to the NPDDF. Each FEP was considered and categorized using a systematic screening process taking into account the potential consequence and probability.

For the NPDDF PostSA, this categorization produced a reference scenario (called "Normal Evolution" Scenario (NES), which represents the expected evolution of the system) along with four (4) other key scenario categories:

1. **Normal Evolution:**
   - Institutional control period is a minimum of 100 y
   - The Facility, including the reactor vault, is backfilled with grout
   - Calandria and all systems remain in place
2. **Sensitivity Calculations**
   a) Measured Radionuclide Inventory – an alternative estimate of the radionuclide inventory, using measured data on radionuclide concentrations, without any uncertainty factors, where possible
   b) Increased Modelled Radionuclide Inventory – a conservative upper estimate of the modelled inventory
   c) Reduced Near-field Sorption – conservative use of lower estimate sorption values for the NPDDF which results in less containment of radionuclides within the structure
   d) Reduced Far-field Sorption – conservative use of lower estimate sorption values for the geosphere which results in more rapid transport through the bedrock and overburden
   e) Reduced Sorption in Near-field and Far-field – reduced sorption in the NPDDF and geosphere leading to more rapid release and transport to the surface environment
   f) Rapid Degradation –rapid degradation of the grout and concrete of the NPDDF
   g) Increased Geosphere Bedrock Hydraulic Conductivity – increased flow in bedrock compared to NES, leading to more rapid release and transport of radionuclides
   h) Increased Geosphere Overburden Hydraulic Conductivity – increased flow in overburden compared to NES, leading to more rapid release and transport of radionuclides
   i) Increased Dilution in the River – increase in the assumed amount of downstream dilution of radionuclides in the river
   j) Self-sufficient Indigenous Receptor – receptor intended to represent traditional Indigenous lifestyle, with conservative exposure characteristics
3. **Disruptive Event Scenarios**
   a) Site Investigation (Inadvertent Human Intrusion) – drilling and extracting of drilling waste and mixing it with soil
   b) Surface Erosion – erosion of the overburden, exposing contaminated bedrock which is then used by people
   c) Extreme Degradation – extreme degradation (i.e., due to severe seismic event) of the facility concrete and grout, occurring at 1000 y after closure
   d) Fault Zone Activation – extreme seismic event occurring and damaging the facility (i.e., in the same manner as the Extreme Degradation case), but also creating a fracture zone in the bedrock between the facility and the river
   e) Excavation of Above-Bedrock Facility – the above-bedrock portion of the facility is excavated and mixed with soil
   f) Overburden Well – resident receptor using an overburden well intersecting water in the pipe trench
   g) Bedrock Well – resident receptor using a bedrock well intersecting the contaminant plume in the bedrock between the facility and the river
4. **Defence-in-Depth Scenarios**
   a) Role of Existing Facility Structure – examines the significance of the concrete structure in limiting radionuclide release

b) Role of Grout – examines the significance and role of grout

5. **"What If" Cases**
   a) Mass Excavation – the entire facility is dispersed in surface soils that are subsequently used (e.g., for cultivating foods)
   b) River Level Fall – fall in the river level of several meters, sufficient to permit groundwater to be released directly to the shore
   c) Undetected Fracture Zone – examines the impact of undetected fracture zone in the bedrock.

PostSA Model

The PostSA model is developed based on the resulting FEPs and scenarios. The model is comprised of:

- the existing concrete structure, including its geometry and "rooms";
- the infill between the NPDDF structure and the surrounding bedrock and overburden (concrete infill for the portion of the facility within the bedrock, earthen infill for the portion of the facility within the overburden);
- the grout backfill within the structure;
- metal components including the Calandria, distinguishing between aluminum, carbon steel, stainless steel and Zircaloy (particularly important for modelling is their position within the facility and their surface area – which influences corrosion rates, and in turn the timing and rate of release of contaminants);
- the activated concrete walls of the Reactor Vault;
- surface contamination present on structure surfaces that will remain in the various rooms;
- chemical contaminants such as lead (from lead paint and shielding) and mercury (from equipment);
- the release pathway and geosphere from the facility to the river: Detailed groundwater modelling was used to account for important site features, such as the cooling pipe trench, tile drains, and overburden characteristics. For example, the cooling pipes will be sealed and will not provide a direct pathway, but the *trench* they travel through will continue to act as a preferential below-grade pathway for facility releases to flow through;
- the surrounding biosphere (including appropriate environmental media and human receptors).

The chemical degradation of cementitious materials (the grout and the existing concrete structure) is an important process represented in the model. This degradation results in changes to the pH and dependent properties such as sorption coefficients.

Results

Table ES-1 provides a summary of dose results for the NES, and for all other scenarios. It is important to note that all doses are below corresponding acceptance criteria (e.g., 0.25 mSv y^{-1} for the Normal Evolution Scenario). Comparing the results of these additional scenarios to the NES results gives perspective on the influence of many key system features. For example, comparing the NES results to the 'Role of Grout' results reveals how the retardation by the grout in the system influences dose results.

Table ES-1 NPDDF PostSA – Dose Summary by Scenario

Scenario	Peak Dose (mSv y^{-1})	Time of Peak (y)	Dominant Radionuclide	Exposure Group
Normal Evolution	8E-05	12,000	Cl36	Resident (Infant)
Sensitivity Cases				
Measured Radionuclide Inventory	1E-05	1,500	Cl36	Resident (Infant)
Increased Modelled Radionuclide Inventory	2E-04	12,000	Cl36	Resident (Infant)
Reduced Near-field Sorption	1E-04	2,600	Cl36	Resident (Infant)
Reduced Far-field Sorption	8E-05	12,000	Cl36	Resident (Infant)
Reduced Sorption in Near-field and Far-field	1E-04	2,600	Cl36	Resident (Infant)
Rapid Degradation	8E-05	12,000	Cl36	Resident (Infant)
Increased Geosphere Bedrock Hydraulic Conductivity	3E-05	1,100	C14	Resident (Infant)
Increased Geosphere Overburden Hydraulic Conductivity	1E-05	1,400	C14	Resident (Infant)
Increased Dilution in the River	8E-05	12,000	Cl36	Resident (Infant)
Self-Sufficient Indigenous Receptor	4E-05	1,500	C-14	Self-sufficient Indigenous (Infant)
Disruptive Event Cases				
Site Investigation (Inadvertent Human Intrusion)	5E-04	100 y	Ag108m	Borehole driller
Surface Erosion	4E-03	10,000 y	Ca41	Resident (Child)
Extreme Degradation	3E-4	1,100 y	Cl36	Resident (Infant)
Fault Zone Activation	5E-4	8,000 y	C14	Resident (Adult)
Excavation of Above-Bedrock Facility	1E-02	12,000 y	Cl36	Resident (Infant)
Overburden Well	1E-04	10,000 y	Cl36	Resident (Infant)
Bedrock Well	3E-02	1,300 y	C14	Resident (Infant)
Defence-in-Depth Cases				
Role of Existing Facility Concrete Structure	4E-03	100 y	Cs137	Indigenous (AOPFN)
Role of Grout	9E-04	1,000 y	Cl36	Resident (Infant)
“What If” Cases				
Facility Mass Excavation	1E+00	100 y	Cl36	Resident (Infant)
River Level Fall	8E-05	12,000	Cl36	Resident (Infant)
Undetected Fracture Zone	3E-05	1,100	C14	Resident (Infant)

In addition, concentrations of lead and mercury were estimated in groundwater in the postclosure period. The concentrations are very small in comparison to environmental criteria.

Conclusions

The PostSA has undertaken a quantitative assessment of the postclosure safety of the NPDDF. This has involved applying Canadian regulatory and international guidance. The PostSA presents considerable detail on the current understanding of the NPDDF and its environment, and how these may evolve. Analysis of a wide range of scenarios and presentation of a wide range of results provides a robust basis for its conclusions. Uncertainties were addressed using sensitivity analyses.

The PostSA shows that the decommissioned facility can be expected to contain the dominant radionuclides effectively. For most of the assessed period, the releases from the facility are less than 9E+06 Bq y^{-1}, a small fraction of typical levels of permitted discharges to air and water from nuclear facilities. By 10,000 y after closure, 99% of the remaining radioactivity is still contained within the Facility.

The main features containing the radionuclides are the concrete walls of the vault, and the fact that the majority of the radioactivity is present within the matrix of materials such as steels and Zircaloy, which will corrode very slowly in the facility's chemical environment. The grout backfill also contributes to safety.

The result for Normal Evolution is that the peak dose to a person is approximately 8E-05 mSv y^{-1} occurring approximately 12,000 y post closure. This is more than three orders of magnitude below the dose criterion of 0.25 mSv y^{-1} for Normal Evolution and occurs just beyond the main assessment timeframe.

1.0 INTRODUCTION

1.1 Background and Purpose

As part of its decommissioning planning, Canadian Nuclear Laboratories (CNL, acting on behalf of Atomic Energy of Canada Limited, AECL) is proposing the in-situ disposal of the former Nuclear Power Demonstration Facility located adjacent to the west bank of the Ottawa River in south-eastern Ontario. This historic prototype CANada Deuterium Uranium (CANDU) reactor is a Class I nuclear facility and is housed in a subsurface concrete structure set in the rock of the Canadian Shield.

CNL has developed an Environmental Impact Statement (EIS) to inform the decommissioning plan (Arcadis, 2023). This examines the range of environmental consequences of the activity, including the long-term implications. These long-term implications are analysed using a Postclosure Safety Assessment (PostSA), a detailed description of which is presented in this report. "Postclosure" refers to the period after decommissioning is complete and there are no further activities to manage the Facility, beyond a period of institutional control (which might involve surveillance, access controls and monitoring).

The purpose of the PostSA is:

- To undertake a quantitative assessment of the postclosure radiological and non-radiological safety of the in-situ disposal of the former Nuclear Power Demonstration Facility - subsequently referred to as the Nuclear Power Demonstration Disposal Facility (NPDDF) - according to CNL's reference strategy, following a recognized credible methodology.
- To identify those uncertainties that have the greatest potential impact on the long-term performance of the NPDDF and determine their significance.
- To address the requirements of relevant Canadian regulations and legislation and provide necessary information to support an Environmental Impact Statement which will address the requirements of the *Canadian Environmental Assessment Act (CEAA)*, 2012. The NPD Closure Project was initiated in 2016 under the CEAA 2012 regulatory framework, thus the CEAA 2012 framework remains applicable to this project though a newer regulatory framework now exists.
- To form part of CNL's licensing submission to the Canadian Nuclear Safety Commission (CNSC), seeking approval for a licence amendment to allow in-situ disposal to occur. The following documents establish the framework for the assessment of long-term safety made in support of the licensing submission:
    - REGDOC-2.11.1, Waste Management, Volume III: Safety Case for the Disposal of Radioactive Waste, Version 2 (CNSC, 2021a).
    - REGDOC-2.11, Framework for Radioactive Waste Management and Decommissioning in Canada, Version 2 (CNSC, 2021b).
    - IAEA SSR-5: Disposal of Radioactive Waste.
    - IAEA SSG-23: The Safety Case and Safety Assessment of Disposal of Radioactive Waste.
    - IAEA SSG-29: Near Surface Facilities for Radioactive Waste.

Evaluating postclosure safety requires projections of the future condition of the NPDDF and its environment and how people might interact with the Facility. Systematic approaches have been developed to undertake such evaluations, centred on a "system analysis" method (IAEA, 2004). This involves representing the NPDDF, the contaminants present, and all potentially relevant media, with mathematical models to represent the key processes that may occur (e.g., corrosion of wastes, dissolution into groundwater, uptake by plants). It is essential that the models are relevant, well-grounded and auditable. This is achieved through a systematic approach to safety assessment. The international community has developed best practice guidance on the process, which is documented in a report from the Improvement of Safety Assessment Methodologies (ISAM) programme of the International Atomic Energy Agency (IAEA) (IAEA, 2004) and incorporated into a more recent safety guide (IAEA, 2012). This process has been applied internationally since its publication, is consistent with Canadian regulatory requirements, namely CNSC REGDOC 2.11.1, Vol. III, Version 2 (CNSC, 2021a), and underpins the analysis presented in this report.

The study uses the best available information on the NPDDF and its environment to underpin the mathematical models developed specifically to represent the system. These have been used to calculate results that can be compared with relevant Canadian criteria and standards, as well as inform on uncertainties and identify the most important aspects of the system.

1.2 Iterations

International best practice (IAEA, 2012), advocates an iterative approach to postclosure safety assessment in which successive studies are undertaken to progressively reduce uncertainties and build confidence in the projected outcomes.

This is the 4th iteration of the PostSA for the NPDDF. The following provides a brief chronology of the PostSA and its key supporting studies.

1st Iteration PostSA

The first preliminary analyses of the in-situ disposal of the NPDWF were undertaken early in the process of planning for its decommissioning, in ECOMatters *et al.,* (1999). The 1st iteration of the current PostSA began in 2016 and was finalized in early 2017 (Arcadis & Quintessa, 2017a), which built on information in ECOMatters *et al*., (1999) and introduced a considerable amount of new information and modern modelling methods. The 1st iteration PostSA (Arcadis & Quintessa, 2017a) had similar context but was focused on establishing the basis of the PostSA analysis and building an understanding of the key issues.

The 1st iteration used a simple representation of the facility with the rooms filled with grout. Grout was modelled as typical Portland cement. The reactor vault and cooling water pipes were assumed not to be grout-filled as part of the NES, though an alternative case examined the impact of grouting the reactor. The assessment timeframe chosen for the 1st iteration was 100,000 years, based on the next glaciation occurring approximately 1000,000 years in the future (Ganopolski *et al.*, 2016). Bedrock was not specifically modelled in the 1st iteration, the focus was instead on the overburden through which contaminated groundwater was assumed to flow. Seismic effects were examined using an alternative evolution scenario in which conductivity of the grout and concrete were increased by an order of magnitude compared to the

NES. The radionuclide inventory derived for the 1st iteration was based on information in EcoMatters (1999) and modelling performed in Smith (1988) and Trottier & Edwards (2012). The 1st iteration's NES included a site resident receptor group as well as a hunter receptor group. Other scenarios included a driller receptor as well as a resident with a groundwater well.

There were a number of areas in the 1st iteration PostSA (Arcadis & Quintessa, 2017a) where uncertainties existed due to limited information, and these, in part, were drivers for completion of the next iteration.

2nd Iteration PostSA

The 2nd iteration of the PostSA for the NPDDF (Arcadis & Quintessa, 2017b) began in early 2017 and was completed in September 2017. It was substantially updated to address the uncertainties identified by the 1st iteration, and to refine the modelling approach for aspects that were identified as being of the greatest importance. These included:

- a considerably more detailed inventory of radioactive and non-radioactive hazardous material in the NPDDF, making use of new measurement results from NMNTI (2017), updated modelling in Edwards (2017), and other estimates of radiological and non-radiological contaminants from Vickerd (2017) and ORAU (2016);
- a much more detailed representation of the NPDDF itself, and the key "engineered barriers" within the system. For example, the model was updated to use separate representations of the existing concrete structure, the grout-filled rooms, the concrete cap, and the fill material between the facility's exterior walls and the surrounding bedrock. The entire facility was modelled as being grout filled, including the reactor vault (including the Calandria). The Fueling Machine Room was assumed to be filled with a different, low-pH, grout formulation. The cooling water pipes were not assumed to be grout-filled. Similar to the 1st iteration, grout was modelled as typical Portland cement. The model was also updated to represent the surrounding bedrock separately from the overburden;
- updated scenarios and calculation cases, with increased focus on the key uncertainties in the future evolution of the NPDDF, the models, and associated data. For example, seismic effects were examined in a disruptive event scenario in which the conductivity of concrete and grout were increased by an order of magnitude compared to the Normal Evolution Scenario, at 100 years post-closure. The receptors examined among the PostSA's cases were similar to those in the 1st iteration.

The 2nd iteration also incorporated new information generated by supporting studies – such as groundwater modelling in Arcadis & Geofirma (2017a), and solubility calculations (for lead (Pb)) in Arcadis & Quintessa (2017c) – which were initiated subsequent to the 1st iteration of the PostSA. Supporting modelling was also performed to estimate the resaturation time of the facility (Arcadis & Geofirma, 2017b).

The assessment timeframe chosen for the 2nd iteration was the first 50,000 years post-closure, though calculations extended out to 100,000 years post-closure for perspective.

Addendum to the 2nd Iteration PostSA

The 2nd iteration PostSA (Arcadis & Quintessa, 2017b) was submitted to regulatory agencies in September 2017. Regulatory feedback was received, and a PostSA Addendum (Arcadis & Quintessa, 2018a) was prepared in response. The PostSA Addendum (Arcadis & Quintessa, 2018a) included the following:

- **Probabilistic analyses** which: examined multi-variate influences on the results (complementing the one-at-a-time parameter sensitivity cases of the 2nd iteration); identified the potentially most important parameters (those that dose results are most sensitive to); and, took into account data uncertainties identified in the 2nd iteration.
- **Seismic effects analyses** which incorporated information from a Seismic Effects Analysis (CNL, 2018) into the PostSA. The additional calculations assessed a Design Basis Earthquake (DBE) as well as a more severe beyond-design-basis earthquake (BDBE) using an equivalent porous medium (EPM) modelling approach as well as a network of cracks modelling approach.
- **More detailed results documentation**, providing details such as doses broken down by different pathways (driven by specifics requested through regulatory comments).

Supporting Documents

Although not an iteration of the PostSA itself, it is important to note that following completion of the PostSA Addendum (Arcadis & Quintessa, 2018a), several key supporting documents were also completed (or updated). These included:

- Updated Groundwater Modelling Study (2018) (Arcadis & Geofirma, 2018a);
- Completion of a Cementitious Materials Synthesis Report (2018) (Arcadis & Quintessa, 2018b);
- Compilation of a Geosynthesis Report (2018) (Arcadis & Geofirma, 2018b);
- Updated Grout Geochemical Modelling Report (2019, 2020) (Arcadis & Quintessa 2019a, 2020b);
- Completion of Grout Scoping Calculations (2019) (Arcadis & Quintessa, 2019b);
- Completion of a Geoscience Verification Plan (2018) (Arcadis & Geofirma, 2018c);
- Completion of a detailed field characterization campaign (Geofirma, 2019);
- Updated Geosynthesis Report (2019) (Arcadis & Geofirma, 2019a);
- Updated Groundwater Modelling Report (2019) (Arcadis & Geofirma, 2019b);
- Updated Resaturation Modelling Report (2020) (Arcadis & Geofirma, 2020);
- Completion of a Groundwater Transport Study (2019) (Arcadis & Geofirma, 2019c);
- Updated Lead Solubility Report (2020) (Arcadis & Quintessa, 2020c).

These studies reflect ongoing improvement as the project evolved, and close several information gaps that were previously identified. The 3rd Iteration PostSA made use of the information from these studies.

3rd Iteration PostSA

The 3rd iteration PostSA (Arcadis & Quintessa, 2020a) supported the 2020 EIS submission (Arcadis, 2020a). The assessment consolidated the understanding developed in the 2nd iteration with information from supporting studies (namely, those listed above). The main improvements included:

- further updates to the inventory of radioactive and non-radioactive hazardous material in the NPDDF. This included the results of building surveys (McVeigh, 2019a,b), updated modelling calculations (Edwards & Adams, 2019), and more refined estimates of generic contamination in the facility;
- the incorporation of a much more detailed representation of groundwater flow within and around the NPDDF, and with it, a significantly enhanced spatial model of these aspects. As outlined above, many supporting studies were completed, including a field measurement campaign and geosynthesis study, to gain a detailed understanding of the surrounding geology and hydrogeology. The near-field and far-field groundwater models were updated with enhanced spatial resolution based on the geosynthesis study;
- further refinements to the representation of the geochemical evolution of the concrete and grout that constitute the NPDDF structure. The degradation of cement-based materials is important; a report was therefore prepared to clarify this. This specific nature of the grout being used is also important; a grout flushing report was therefore prepared to define the degradation of CNL's site-specific BFS/PC grout composition. Grout scoping calculations (Arcadis & Quintessa, 2019b) were also completed to compare the results using different backfill materials (e.g., bentonite, sand, low-pH grout, BFS/PC grout, etc.); and,
- updated scenarios and calculation cases, models, and associated data. These new cases included the introduction of new receptors: an off-site public receptor (residing along the Ottawa River downgradient of the facility), a self-sufficient indigenous receptor, and a site resident that occupies the site after drilling has occurred.

In the 3rd iteration, the facility entire facility was modelled as being grout filled, including the reactor vault (including Calandria). The Fueling Machine Room was assumed to be filled with the same grout as used elsewhere in the facility. The cooling water pipes were not assumed to be grout-filled. The properties of the facility were updated to reflect the impacts of seismicity, in the NES and other cases, as appropriate.

Another important improvement in the 3rd iteration was in how seismic effects were accounted for. The model was updated to distinguish between seismic affects to the above-bedrock and below-bedrock portions of the facility. The NES was updated to account for the effects of a design-basis event (i.e., a 1-in-2250 year event), and a 1-in-10,000 year event, based on information from CNL's updated Seismic Assessment (CNL, 2019a). A disruptive event scenario “Extreme Degradation” was also added, examining the impact of a much larger 1-in-50,000 year seismic event occurring 1000 years post-closure, based on information from CNL's updated (2019) Seismic Assessment.

The assessment timeframe chosen for the 3rd iteration was the first 10,000 years post-closure, based on a detailed consideration of the factors outlined in CNSC REGDOC 2.11.1 (Vol. III) (CNSC, 2018). These included: the results of previous iterations; the hazardous lifetime of the contaminants; the duration of the operational period (for this project, the decommissioning phase); the design life of the engineered barriers; the duration of institutional controls; and the frequency of natural events.

4th Iteration PostSA (This Report)

This document presents the 4th Iteration of the PostSA. The 4th Iteration update involves several new cases (arising from feedback received on the previous iteration) among the PostSA and its supporting model reports. Updates include for example:

- updated model geometry to improve consistency with the updated groundwater model, including better representation of the NPDDF rooms and separate model compartments for the grout-filled pipe, the trench, the overburden, and updated representation of the concrete cap geometry;
- updated flows based on updated groundwater modelling, resaturation modelling, and near-field modelling;
- updated corrosion information from the Waste Form Synthesis Report (CNL, 2021);
- updated stability information from the Slope Stability Assessment (Arcadis & Geofirma, 2021a);
- site-specific distribution coefficients (Kd values) for silver from (Arcadis, 2020);
- updated inventory information from Porter (2022), which consolidates the results of several facility characterization initiatives completed up to 2022;
- updated radionuclide screening methodology;
- updated and new cases, models, and associated data. For example, sensitivity cases are included to examine the impacts of higher hydraulic conductivity in the bedrock and overburden, and a new disruptive event has been included to examine the hypothetical impacts of a severe seismic event damaging the facility and increasing the hydraulic conductivity of the bedrock; and,
- an additional indigenous receptor has been added based on the results of a diet study performed by the Algonquins of Pikwàkanagàn First Nation (AOPFN) (Fediuk *et al.,* 2021) and involving additional pathways.

In this 4th iteration, the facility is assumed to be grout-filled, including the reactor vault (including the Calandria) and the cooling water pipe outside of the facility.

This 4th Iteration of the PostSA will support CNL's final EIS submission. In the future it may be updated periodically should relevant new information arise. Until, and if, it is superseded, it is to be considered the reference analysis of postclosure safety of the NPDDF. The PostSA is also the primary document used to demonstrate the long-term safety of the NPDDF in support of the NPDDF Decommissioning Licence Amendment application, as per the requirements of CNSC REGDOC 2.11.1 Volume III, Version 2 (2021a).

1.3 Structure of the Report

The PostSA has been developed systematically using the ISAM approach. The structure of the report reflects this and Section 5 of IAEA (2012). The main report provides the most pertinent information as follows:

- **Section 2.0** presents the assessment context, which outlines the scope, context and required outcomes;
- **Section 3.0** describes key aspects of the NPDDF and its environment – the system being assessed;

- **Section 4.0** explains the development of the assessment scenarios, calculation cases, the related models, and the approach taken to analysing the scenarios;
- **Section 5.0** sets out the key results, and discusses what can be learned from them; and
- **Section 6.0** presents the conclusions of the PostSA study.

There is considerable detail included in the supporting appendices, which correspond to the key stages in the ISAM approach:

- **Appendix A** presents additional details of the assessment context;
- **Appendix B** gives a detailed description of the system;
- **Appendix C** describes the process used to analyze the system and provides the basis for models, by reviewing the Features, Events and Processes (FEPs) that are relevant to the Facility and its environment;
- **Appendix D** presents the identification of “scenarios” that describe the future conditions that need to be considered in the PostSA and calculation cases of interest;
- **Appendix E** presents the conceptual models and numerical data used to represent the scenarios and other cases;
- **Appendix F** discusses the mathematical modelling approach; and
- **Appendix G** provides a detailed compilation of results.

1.4 Audience

This report serves two main purposes: (1) to support and provide input to the EIS for the NPD Closure Project, and (2) to provide the information required by the Canadian Nuclear Safety Commission (CNSC), with specific reference to regulatory guidance concerning the safety case for the disposal of radioactive waste, i.e., REGDOC 2.11.1 – Vol. III, Version 2 (CNSC, 2021a).

The PostSA also informs CNL’s project team, highlighting issues that may merit further consideration in the future (e.g., to reduce conservatism in the assessment), and areas of the decommissioning plans that may be subject to further optimization. Thus, the main audience of the postclosure safety assessment is expected to be technical specialists.

The documentation is structured in a hierarchical way, so that the main report is broadly accessible but greater detail can be found in the underpinning appendices.

2.0 APPROACH AND ASSESSMENT CONTEXT

2.1 Approach

The CNSC has issued a regulatory document (REGDOC 2.11.1, Vol. III, Version 2) on the safety case for the disposal of radioactive waste (CNSC, 2021a) which describes its expectations in relation to the assessment of postclosure safety. The CNSC expects a well-structured, transparent and traceable approach to analysing the long-term performance of the radioactive waste disposal system. The approach should: facilitate comparison of results with regulatory requirements; enable uncertainties to be identified and analysed; provide clear links to other aspects of the Environmental Impact Statement and decommissioning program; demonstrate use of appropriate quality assurance; be amenable to review; and provide a basis for future iterations. REGDOC 2.11.1 specifies the information that should be included in the documentation of a safety assessment, which maps onto the approach used for the PostSA (Figure 2-1).

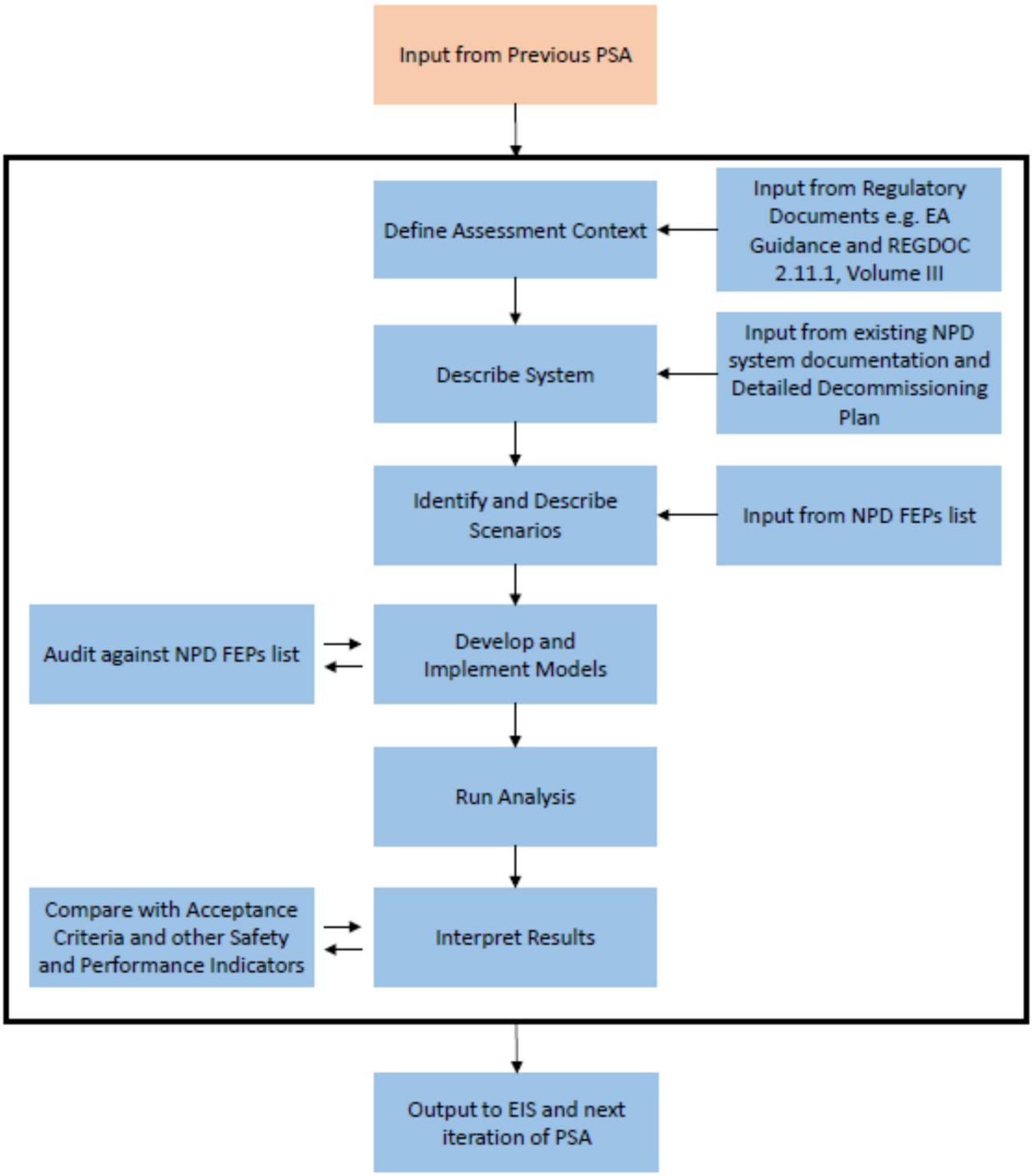
The methodology for the safety assessment is based on international best practice, as embodied in the safety standards on the safety case and safety assessment for radioactive waste disposal from the International Atomic Energy Agency (IAEA) (IAEA, 2012) and the recommendations of the IAEA ISAM programme (IAEA, 2004).

The approach used for the Post SA comprises of the following steps, shown in Figure 2-1.

- The context of the assessment is defined, documenting the high-level assumptions, the constraints (reflecting the regulatory requirements), and the assessment's purpose, end points, treatment of uncertainties, and timeframes.
- The current information on the waste, repository, geological setting and surface environment relevant to postclosure safety is reported.
- A range of internally consistent potential future evolutions of the system (scenarios) is systematically identified, together with a suite of calculation cases that examine the performance of the disposal system under other conditions of interest and explore its sensitivity to key uncertainties.
- Conceptual and mathematical models and data are developed for the scenarios and a range of calculation cases, which explore key areas of uncertainty, are identified and implemented in an appropriate software tool.
- The results are analysed, interpreted and discussed to inform on the performance of the system, its overall robustness, and the nature and role of key uncertainties. Particular emphasis is given to the comparison of the results for the identified safety and performance indicators against the guidance by CNSC (2021a).

Further details of each step are presented in the main sections and corresponding appendices of this report and correspond to the main steps in the ISAM approach.

Figure 2-1 Approach Used in the Postclosure Safety Assessment (Adapted from ISAM (IAEA, 2004))



2.2 Assessment Context

2.2.1 Regulatory Requirements and Guidance

The NPDWF is presently in the Storage with Surveillance (SWS) phase of decommissioning. The next step, which is being considered, is in-situ disposal (ISD). This would leave a radiological inventory encased within the NPDDF structure. The focus of the PostSA is to evaluate the potential long-term impact of this inventory on the health and safety of humans and the environment. This includes considering the potential for radionuclide releases to groundwater from the disposal facility and radionuclide migration to the Ottawa River. It is also necessary to assess the possible consequences of any unlikely situations that could lead to the disturbance and disruption of the Facility, after institutional controls. For all these situations, the potential effects on people and the environment of non-radioactive hazardous materials remaining in-situ are also evaluated.

Generic guidance on safety case for the disposal of radioactive waste is set out in the regulatory guide REGDOC-2.11.1, Vol. III, Version 2 (CNSC, 2021a). This provides guidance on performing long-term assessments and interpreting the results. Key requirements and recommendations are summarized in Appendix A, which also provides a mapping to the parts of the PostSA documentation where the requirements have been addressed.

2.2.2 Acceptance Criteria

Acceptance criteria are derived from current regulatory limits, standards, objectives, and benchmarks, where appropriate applying an additional margin of safety, such as a dose criterion. In light of the Canadian regulatory requirements and guidance and international standards and guidance from organizations such as the International Commission on Radiological Protection (ICRP), specific criteria have been proposed for:

- The radiation exposure of people that may arise from the expected evolution of the NPDDF and its environment, referred to as the Normal Evolution scenario;
- The radiation exposure of people that may arise as a result of events with uncertain or low probability which could disrupt the NPDDF, Disruptive Event scenarios;
- The radiation effects on non-human biota (NHB); and
- The effects of non-radioactive contaminants.

As well as Normal Evolution and Disruptive Event scenarios, illustrative calculations are also made for some deliberately extreme assumptions so as to understand the limits of safety performance (“What If” cases). These are not compared with any criteria because they are extremely unlikely, and in some cases implausible.

Human health criteria have been defined according to CNSC REGDOC-2.11.1 (CNSC, 2021a) which requires reasonable assurance that:

- the regulatory radiological dose limit for public exposure (1 mSv y^{-1}) will not be exceeded;
- the possibility of exposure to multiple sources is allowed for; and
- that doses are As Low as Reasonably Achievable (ALARA).

The criteria used in the safety assessment are based on those presented in the Project Description (CNL, 2016) and are consistent the ICRP's 2007 recommendations (ICRP, 2007) and with specific guidance on radioactive waste disposal (ICRP, 2013; IAEA, 2014a; IAEA, 2011). They also draw on those proposed in relation to Ontario Power Generation's proposed Deep Geological Repository for low and intermediate level radioactive waste (Quintessa *et al.*, 2011).

- The criterion proposed for public radiological exposure as a result of the Normal Evolution scenario is that the dose to the public and to workers will be ALARA and subject to a dose constraint of 0.25 mSv y^{-1}.
- A tiered approach is adopted for Disruptive Event scenarios, recognising their speculative nature. The probability of exposure is considered during the scenario definition process; very low probability provides a basis for screening scenarios from detailed assessment. A dose criterion of 1 mSv y^{-1} is then used for radiation exposure of humans for unlikely but credible scenarios. If calculated dose exceeds 1 mSv y^{-1}, the scenario is examined on a case-by-case basis, taking into account the likelihood and nature of the exposure, conservatism and uncertainty in the assessment, and conservatism in the dose rate criterion. If the probability of exposure can be quantified, a reference health risk criterion of $\leq 10^{-5}$ y^{-1} (ICRP, 2013; IAEA,2011) can be used.

Inadvertent human intrusion and Excavation of Above-Bedrock Facility are special cases of Disruptive Event scenarios that are assessed separately. Reasonable efforts should be made to limit the dose from a high-consequence intrusion scenario and to reduce the probability of the intrusion occurring (CNSC, 2021a). In this respect, the in-situ disposal concept would encase the most active parts of the NPDDF within concrete and grout, and cover the parts of the nuclear area footprint with a reinforced concrete cap. An engineered cover will then be placed over the entire grouted Facility to minimize infiltration. This provides a substantial deterrent and limits the range of situations that could lead to intrusion.

The PostSA also considers the potential impacts on NHB to ensure these are within acceptable limits; though potential radiological impacts on NHB are assessed in a separate Ecological Risk Assessment report (Arcadis, 2020b), drawing on guidance and recommendations from CSA N288.6 and CSA N288.1 standards. The radiation dose rate criterion for terrestrial biota is 100 µGy h^{-1} (2.4 mGy/d) and for aquatic biota is 400 µGy h^{-1} (9.6 mGy/d). These benchmarks were adjusted by a factor of 1/10 for terrestrial and aquatic species at risk.

Potential impacts from non-radioactive elements or chemical species are assessed for environmental media that are relevant to human health and environmental protection. The environmental quality standard criteria for soil, sediment and water are designed to protect against adverse effects due to exposure by food chain and/or other pathways. Consequently, the explicit assessment of the uptake of these substances into biota is not required within this PostSA report (noting that it is included in the Ecological Risk Assessment (Arcadis, 2020b) as part of the assessment of potential impacts on NHB). Criteria for non-radioactive elements or chemical species are presented in Appendix A. Criteria are based on federal and provincial guideline concentrations for groundwater, surface water, soil and sediment.

A tiered approach is applied to the assessment of non-radioactive contaminants. Contaminants are screened first based on a comparison with the criteria given above. If any criteria are exceeded under the Normal Evolution Scenario, these species will be assessed further using more realistic models.

If any dose rates/concentrations exceed the criteria under Disruptive Event scenarios, then the acceptability is judged on a case-by-case basis taking into account the likelihood and nature of the exposure, uncertainty in the assessment, and conservatism in the criteria.

2.2.3 End Points

Assessment end points are the calculation results used to assess the impact of radioactivity and hazardous substances. In order to demonstrate that the postclosure acceptance criteria can be achieved, the following end points are calculated:

- Peak radiation dose rate to adults, children and infants in the critical group and to NHB;
- Peak environmental concentrations of radionuclides; and
- Peak environmental concentrations of non-radioactive hazardous substances.

“Radiation dose rate” includes the contribution of external irradiation and the committed effective dose rate equivalent from intakes of radionuclides by ingestion and inhalation. Dermal absorption is also considered in the special case of immersion in water containing tritium.

The focus is on the parts of the environment that are expected to receive the highest concentrations of contaminants released from the Facility, i.e., within a few hundred meters of it. Potential effects beyond this will be substantially lower as contaminants are diluted and dispersed.

In addition, the various results are useful performance indicators which can help to show the way in which the system is behaving. These include:

- Contaminant amounts within various media (e.g., the NPDDF structure, the surrounding rock, surface media) on various timescales; and
- Fluxes of contaminants at various points in the NPDDF and surrounding materials.

To demonstrate barrier robustness and the performance of the facility during the post-closure period, additional facility performance indicators are derived:

- Comparison of radiotoxicity concentrations in the environment, due to releases from the facility, to natural background radiotoxicity concentrations at the NPD site;
- Comparison of radiotoxicity concentrations in soil, due to releases from the facility, to naturally occurring surficial uranium ore deposits in the region;
- Comparison of radionuclide concentration in the environment, due to releases from the facility, to environmental limits where available (e.g., tritium);
- Comparison of concentrations of mobile radionuclides (e.g., Cl-36, tritium, C-14) to background levels, where data are available from the NPD EIS (Arcadis, 2023a).

2.2.4 Assessment Timeframe

According to REGDOC 2.11.1, Vol. III, Version 2 (CNSC, 2021a):

> *"The licensee or applicant shall ensure that future impact that may arise from the radioactive waste includes the period of time during which the maximum impact is predicted to occur.".*

This period is referred to as the assessment timeframe. The basis for the timeframe of relevance to the PostSA has been developed in Appendix A, based on:

- Peak dose rate results from the prior three (3) iterations of the PostSA; and
- Additional considerations from REGDOC 2.11.1, Vol. III, Version 2 (CNSC, 2021a).

Although it is appropriate to begin the assessment calculations immediately following the short 1-to-2-y decommissioning period, the facility will be closed and a period of institutional control (IC) will take effect for at least 100 y. This institutional control period will include long term care and maintenance of the facility, and will ensure that members of the public are not present at the NPDDF. Therefore, the first hundred years of the PostSA timeframe *does* involve modelling the evolution of the Facility and its environment, but *exposures* will be prevented by these controls.

An Institutional Control Surveillance Plan (CNL, 2019b) has been prepared for the proposed NPD Disposal Facility licensed area; including the in-situ disposal closure cap, the former ventilation stack and all remaining areas bound by a permanent fence which surrounds the licensed area. The plan also covers any fencing, the road from the facility up to the outer gate near Highway 17, and the previously closed operational landfill site.

The Surveillance Plan describes the proposed activities to be performed at the NPDDF to meet the anticipated requirements of a future CNSC issued license, current applicable laws and regulations, the EA Follow-up Monitoring Program (Arcadis, 2018), and requirements of CNL management systems as outlined in the Licence Conditions Handbook (CNL, 2023). These activities are designed to meet expectations for post closure surveillance of passive safety features (as recommended by the IAEA Specific Safety Guide, SSG-31 (IAEA, 2014b)), and to also inspect and maintain other components of the facility.

Thereafter, it is necessary to consider how far into the future the assessment calculations should extend. The 1st Iteration PostSA (Arcadis *et al*., 2017a) selected its assessment timeframe of 100,000 y based on the anticipated timing of the next glacial event. Based on information such as presented by Ganopolski *et al*. (2016) the next ice age was estimated not to occur for 100,000 y as a result of anthropogenic climate change. The results of the 1st Iteration PostSA showed that the estimated peak dose rate for the Normal Evolution Scenario (NES) occurred at approximately 13,000 y postclosure.

The 2nd Iteration PostSA (Arcadis *et al*., 2017b) adopted a shorter assessment timeframe of 50,000 y taking into account findings from the 1st iteration PostSA showing the peak doses occurred well within this period. The results of the 2nd Iteration PostSA (Arcadis *et al*., 2017b) showed that the estimated peak dose occurred at approximately 1,200 y postclosure. The results differed from the first iteration as a better source of

information on sorption in cementitious environments had been obtained (Ochs *et al.,* 2016). This recommended increased sorption coefficients for C-14, the radionuclide that dominated in the first iteration. As a consequence, the significance of C-14 in terms of dose to people was much reduced, the results being dominated instead by external irradiation by Ag-108m at around 1,200 y after closure.

Given this finding, with additional model refinements and site-specific information, the assessment timeframe was further refined to 10,000 y for the 3rd Iteration PostSA (Arcadis & Quintessa, 2020a) consistent with guidance in REGDOC 2.11.1 Vol. III (CNSC, 2018).

The 4th Iteration PostSA is consistent with the most recent guidance in REGDOC 2.11.1 Vol III, Version 2 (CNSC, 2021a).

REGDOC 2.11.1 Vol. III, Version 2 (CNSC, 2021a) indicates that the assessment timeframe should take into account the following elements:

> *"1. Hazardous lifetime of the contaminants associated with the waste;*
>
> *2. Duration of the operational period (before the disposal facility reaches its end state);*
>
> *3. Design life of engineered barriers;*
>
> *4. Duration of both active and passive institutional controls;*
>
> *5. Frequency of natural events and human-induced environmental changes (e.g., seismic occurrence, flood, drought, glaciation, climate change); and.*
>
> *6. The degree of protection and isolation required against inadvertent intrusion over the long term."*

Each of these aspects has been re-considered in detail for the 4th Iteration PostSA, and discussion is presented in Appendix A.

Given the early expected peak dose rate time, the fact that safety assessment studies for near-surface disposal facilities typically consider timeframes of 10,000 to 100,000 y (common practice), and the other main aspects discussed in Appendix A, *the focus of the assessment calculations is on the first 10,000 y, and the emphasis in the PostSA is on interpreting the potential consequences within this timeframe*. However, results have still been calculated to 100,000 y past closure in order to demonstrate that the peak dose rates have been captured and to capture the effects of the loss of engineered barrier functions (concrete, steels) in the far future. Calculations beyond 100,000 y are subject to very large uncertainties and so calculations are not appropriate.

After the 4th iteration PostSA was completed (as described later in this report) it became clear that the peak dose of the Normal Evolution Scenario in the 4th iteration occurs around 12,000 years. However, the assessment timeframe of 10,000 years was not changed in the 4th iteration for the reasons outlined in Section 6.1 below.

For context, historical events occurring during an equivalent period of time to the assessment timeframe are shown in Table 2-1.

It is important to recognize that the reliability of quantitative calculations diminishes with increasing time. Therefore, the long-term quantitative estimates of impacts, such as dose rate, presented in this report should be seen as indicators rather than absolute measures of impact.

Table 2-1 Timeline of Historical Events Covering the Same Timeframe as the PostSA

Time	Historical Event
100,000 y ago	Humans begin to move beyond Africa
70,000 y ago	Severe Ice Age results from an eruption in Sumatra, humans almost extinct as a result
50,000 y ago	Transient agriculture begins in temperate regions
50,000 y–- 17,000 y ago	Wisconsin Glaciation, with the last glacial maximum 20,000 y ago
10,000 y ago	Settled agriculture established in suitable climates; Hunter-gatherers in Canada
9,000–- 7,000 y ago	Domestication of animals for food
3,000 y ago	Bronze Age
2,000 y ago	Woodland settlements in Ontario
1,500 y ago	Aboriginal river settlements in Canada
500 y ago	Colonization of North America by Europeans
150 y ago	Colonies of Canada, Nova Scotia, and New Brunswick united as the Dominion of Canada
100 y ago	First World War

2.2.5 Dealing with Uncertainties

The treatment of uncertainty is a key issue in safety assessment because of the range and nature of uncertainties over the typical assessment timescale. The uncertainties can be categorized into three types (Marivoet *et al.*, 2008).

- Future or scenario uncertainty: uncertainty in the evolution of the system and human behaviour over the timescales of interest;
- Model uncertainty: uncertainty in the models used to simulate the system (especially any approximations and simplifications); and
- Data uncertainty: uncertainty in the data and parameters used in the modelling.

These uncertainties are managed in the current assessment in the following way:

- The assessment of a range of scenarios, models and data with a suite of calculation cases; and
- The adoption of conservative scenarios, models and data.

It should be noted that care is needed as the net effect of an aggregation of many conservative assumptions can be an unrealistic estimate of impacts. Furthermore, some analyses (e.g., optimisation studies) can be meaningless if the assessment is dominated by conservative assumptions. Where possible, scientifically informed, physically realistic assumptions are made for processes that are understood and can be justified on the basis of the results of research and/or site investigation. Where there are high levels of uncertainty associated with processes and data, conservative assumptions are adopted to allow uncertainties to be bounded.

In this study, uncertainty in the future evolution of the site is addressed by the consideration of a range of scenarios that encompass its expected futures. Key conceptual and mathematical model uncertainties are assessed in a similar way, through a series of alternative calculation cases, identified via a structured model development process making use of a FEPs analysis. Discrete alternative calculations can be easier to interpret than probabilistic analyses.

Multi-Variate Sensitivity Analyses

In order to better understand data uncertainties and their influence on the results, multivariate sensitivity analyses were performed using the results of the 2nd iteration PostSA (Arcadis & Quintessa, 2017b), in Arcadis & Quintessa (2018a). The multivariate sensitivity analyses in Arcadis & Quintessa (2018a) encompassed several parameters: inventory, corrosion rates, number of pore flushes/degradation time, sorption coefficients, solubility limits, river flow rate, and transfer factors. Results from Arcadis & Quintessa (2018a) indicated that the parameters whose uncertainties have the most influence on the results of the assessment are:

- Corrosion rates;
- Inventory; and,
- Cement sorption coefficients.

The 3rd Iteration of the PostSA (Arcadis & Quintessa, 2020a) investigated the role of the wasteform as a barrier to radionuclide release by increasing the corrosion rates for carbon steel, stainless steel and Zircalloy to ten times the values used in the Normal Evolution Scenario. Although the corrosion rate was increased by a factor of 10, the highest increase in the rate of release into the geosphere was a factor of 3. Additional examination of the influence of metal corrosion rates on dose can be found in CNL (2021a).

Uncertainties related to inventory and cement sorption coefficients are considered in the 4th Iteration PostSA.

2.3 Quality Assurance

The regulatory guidance prepared by CNSC (2021a) emphasizes the importance of Quality Assurance (QA) within safety assessment studies. This subsection summarizes the QA status of the work that has been undertaken under a quality management system accredited to ISO 9001:2015.

2.3.1 Models and Data

All data used in the model are verified and, where possible, validated. The following steps are applied to all the models and data used in the PostSA.

1. The basis (rationale) for selected data is checked independently by a safety assessment specialist to ensure it is reasonable, consistent with the assessment context, and adopts an appropriate degree of conservatism.
2. All data presented are checked back to the stated source document (except where an assumption has been made, in which case the appropriateness of the data is checked in Step 1).
3. The correct transcription of the data into reports and the assessment code is checked.

Records for the checking of data are included in the data forms presented in Section E.3 of Appendix E. Parameters are assigned the same name in the models as given in the documentation to facilitate checking.

In addition, all equations used in the model, documented in Appendix F, are checked for dimensional consistency and, where possible, related to the underlying science. All equations are independently checked for their validity by a safety assessment specialist.

Due to the nature of long-term modelling there is relatively limited scope to validate the model's behaviour as suitable observations and points of comparison are not available. This is addressed by basing models where possible on well-established physical and chemical processes, as documented in Appendices E and F, and/or models and relationships developed independently of this study with a track-record of recommendation for (or use in) equivalent safety assessment studies (e.g., CSA (2022), Davis *et al.* (1993), IAEA (2010), Oatway & Mobbs (2003)). Furthermore, where possible, models and data, such as soil-plant transfer factors, are based on validated models and datasets that are themselves based on observations. To reduce uncertainty in the NPDDF long-term models, comparison with natural analogues, archaeological artifacts and other complementary safety indicators has been made (for example, naturally occurring surficial uranium ore deposits in the region, obtained from OGS (1981)).

2.3.2 Software

The models and data are implemented in the general-purpose modelling software tool AMBER. AMBER is managed and developed under an ISO 9001:2015 registered QA system that incorporates the requirements of TickIT software quality system (www.TickIt.org). Each release is extensively tested against a broad set of verification and validation tests (Quintessa, 2021a). AMBER's capabilities are fully described in a Reference Manual (Quintessa, 2021b). AMBER has been verified to ensure that models are solved correctly in accordance with what has been specified (Quintessa, 2021c). This involves implementation and analysis of set of test cases specifically developed to check the correct functioning of the code.

AMBER meets the requirements of CNL's Code Management Program and has also been validated in accordance with CNL's management system document, *Guideline for Application of Quality Assurance for Analytical, Scientific, and Design Computer Programs* (CNL, 2019c).

The results calculated by the code have also been compared with those calculated by other similar tools. For example, the deterministic and probabilistic functioning of AMBER has been compared against the documented results from a number of participant members of the Nuclear Energy Agency (NEA) PSAG group for their “PSAG Level 1B exercise”.

In addition to these formal mathematical tests, the software has a proven track record for performance assessment of radioactive waste disposal facilities and a strong quality assurance status (e.g., see Medri (2015), Thomson *et al*. (2008), Walke *et al*. (2011)). AMBER also has features that facilitate the quality assurance of specific models. For example, equations and data are defined in AMBER parameters which are saved in text-based case files which allow easy checking of the model. AMBER also automatically checks the dimensionality of equations on the basis of the units assigned to parameters. The code generates Microsoft Excel® compatible output files, which are time-stamped and include model filenames, minimising the amount of post-processing of data that is required.

A specific validation activity was also performed using RESRAD-OFFSITE Version 3.1 in CNL (2017), to provide confidence in the model developed in the first iteration of the NPD post-closure safety analysis. The results of this assessment were verified against the long term radiological dose consequence acceptance criteria of 0.25 mSv y^{-1} and analyzed post-closure normal evolution scenarios. The normal evolution scenario modeled were:

- Adult Receptor Agricultural Land Use Scenario; and
- Adult Receptor Parkland Use Scenario.

The CNL (2017) RESRAD-OFFSITE analysis peak dose was 2.34×10^{-4} mSv y^{-1} to the agricultural land use receptor, which is less than the 0.25 mSv y^{-1} limit. The dose to the parkland receptor was estimated to be 1.55×10^{-5} mSv y^{-1}. The peak dose to the agricultural land use receptor and parkland receptor were both within an order of magnitude of the peak doses in the 1st iteration PostSA calculated using the AMBER code. It was concluded that the RESRAD results were able to verify the AMBER analysis results, and that the dose consequences between the two models vary within a set margin and are well below the 0.25 mSv y^{-1} limit.

2.3.3 Documentation

The documentation of the PostSA is intended to be sufficiently comprehensive to enable the models and data to be implemented independently and has been reviewed to ensure that it is clear, accurate and comprehensive.

All documents are subject to at least one round of internal review by a specialist member of the project team who is not the main author of the report. The review considers the technical details from the perspective of their appropriateness to the scope of work and the associated justification. This also includes checking that the work addresses the relevant regulatory standards (CNSC, 2021a) and applies national and international best practice guidance.

Documents are also reviewed by CNL prior to finalisation. Comments and suggestions from CNL are considered before finalising the document. Formal records of the comments and how they have been addressed are maintained.

3.0 SYSTEM DESCRIPTION

3.1 NPDDF

Location

The NPD site is on the southwest bank of the Ottawa River, in the Province of Ontario, ~160 km WNW from the city of Ottawa (Figure 3-1). It is 25 km northwest of the nuclear research facility Chalk River Laboratories (CRL), near the town of Rolphton and is 3 km downstream from the Des Joachims Dam and hydro-power generating station (Figure 3-2, Figure 3-3).

Figure 3-1 Location of the NPD Site

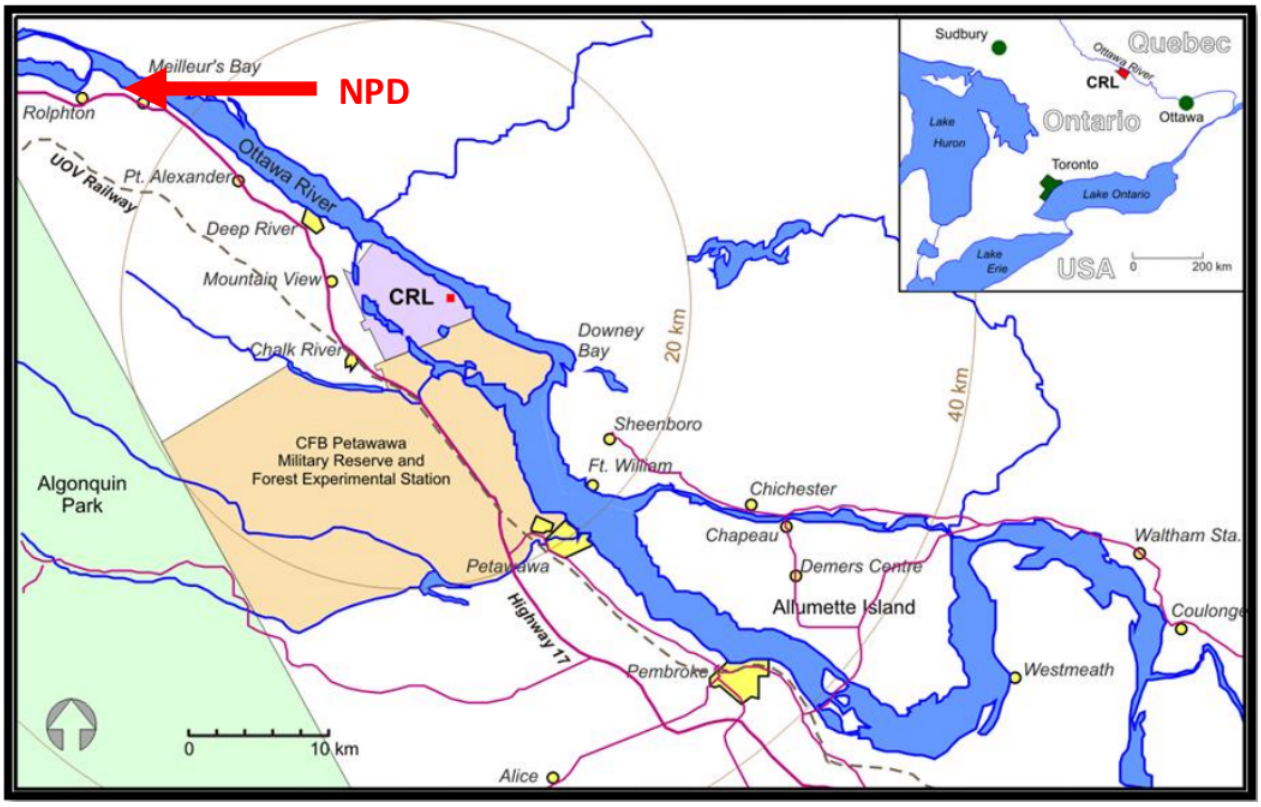


Figure 3-2 Topographic Map of Land Surrounding the NPD

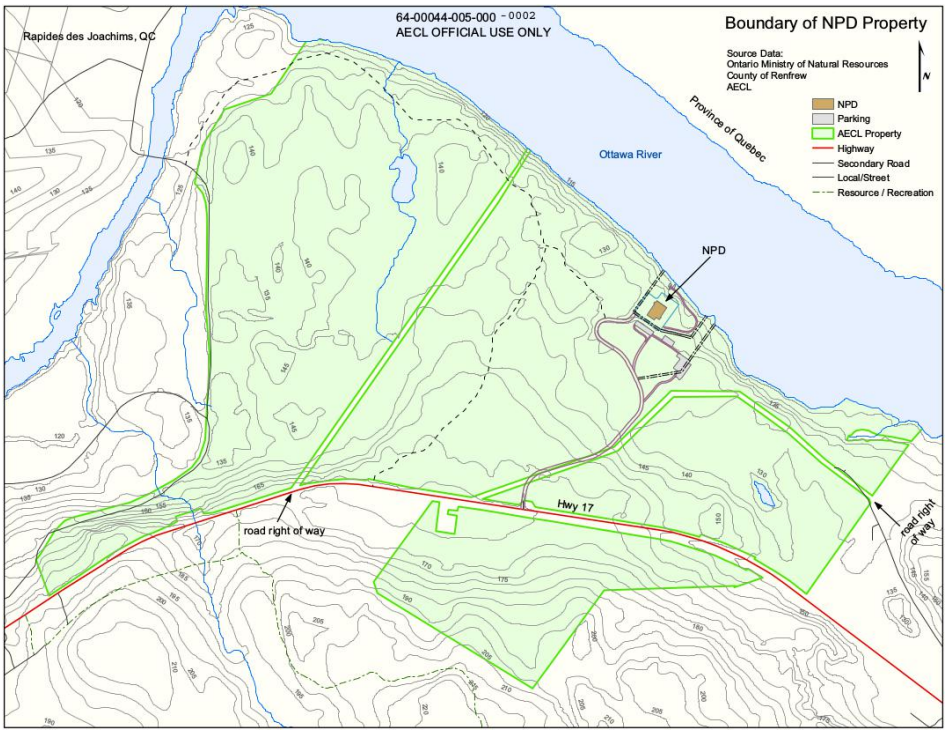


Figure 3-3 Photograph of the NPDDF taken during Storage with Surveillance



Construction

The Nuclear Power Demonstration, NPD, was constructed between 1956 and 1961. During construction of the Facility, the landscape was significantly altered to create man-made terraces on which the buildings could be sited. The reactor building was constructed in a pit dug through overburden and into bedrock (Figure 3-4). The concrete for the facility walls was poured into a shuttered frame, leaving a gap between the rock/overburden and the exterior walls of the facility. The gap between the exterior building walls and rock/overburden was backfilled with concrete. Drains were constructed in the top surface of the bedrock to direct water away from the reactor building. In addition, a trench was excavated through the overburden, into bedrock, for cooling water pipes that drew water from the river and which also contained effluent drainage pipes which extended into the Ottawa River.

Design

The NPD reactor itself was a 20 MWe prototype for the CANDU reactor design, fuelled with natural uranium and was operated between 1962 and 1987. The reactor, heat transport system, turbine, and electrical power generator equipment are shown in Figure 3-5. The reactor core, or Calandria, contains 132 horizontal pressure tubes in which fuel was inserted and was surrounded by the heavy water moderator. The Calandria was constructed from aluminum and the fuel channels contained within are constructed of Zircaloy with stainless steel end fittings.

Figure 3-4 Construction of the NPD

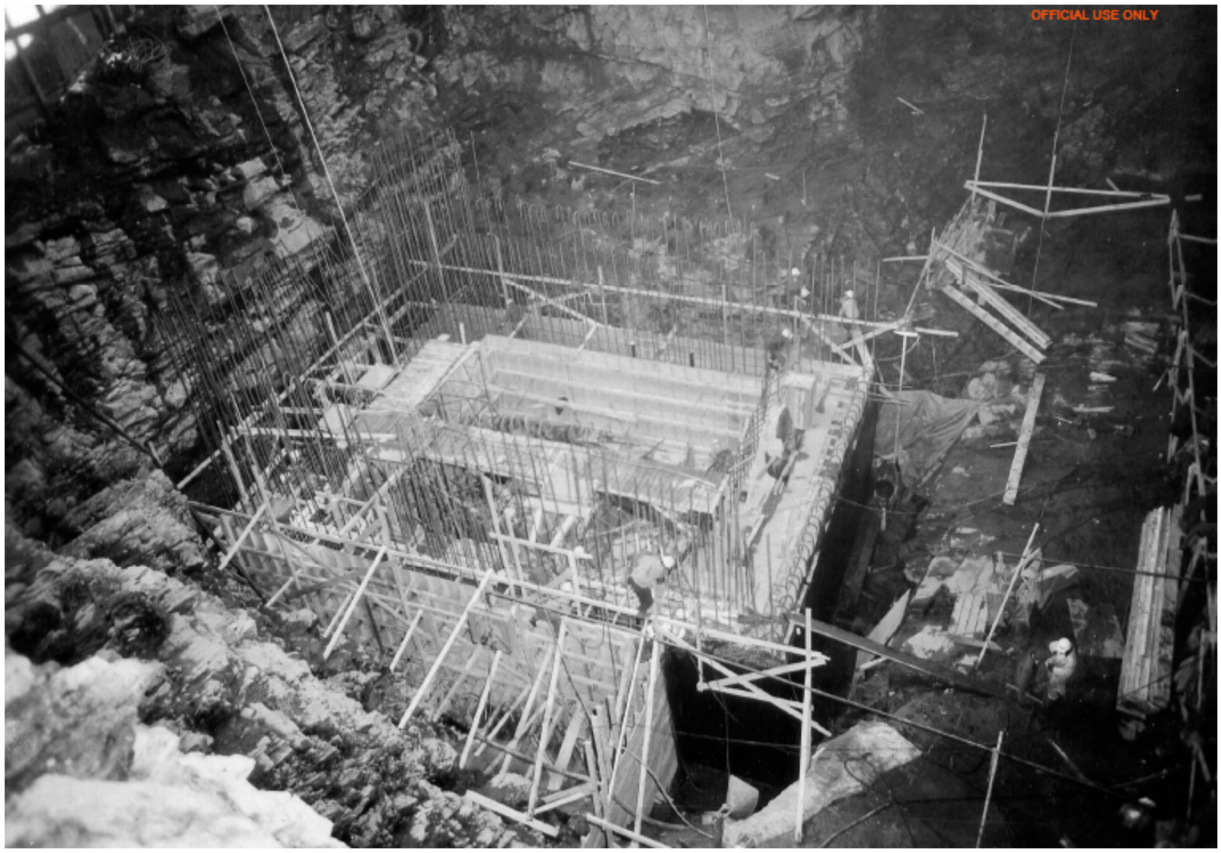
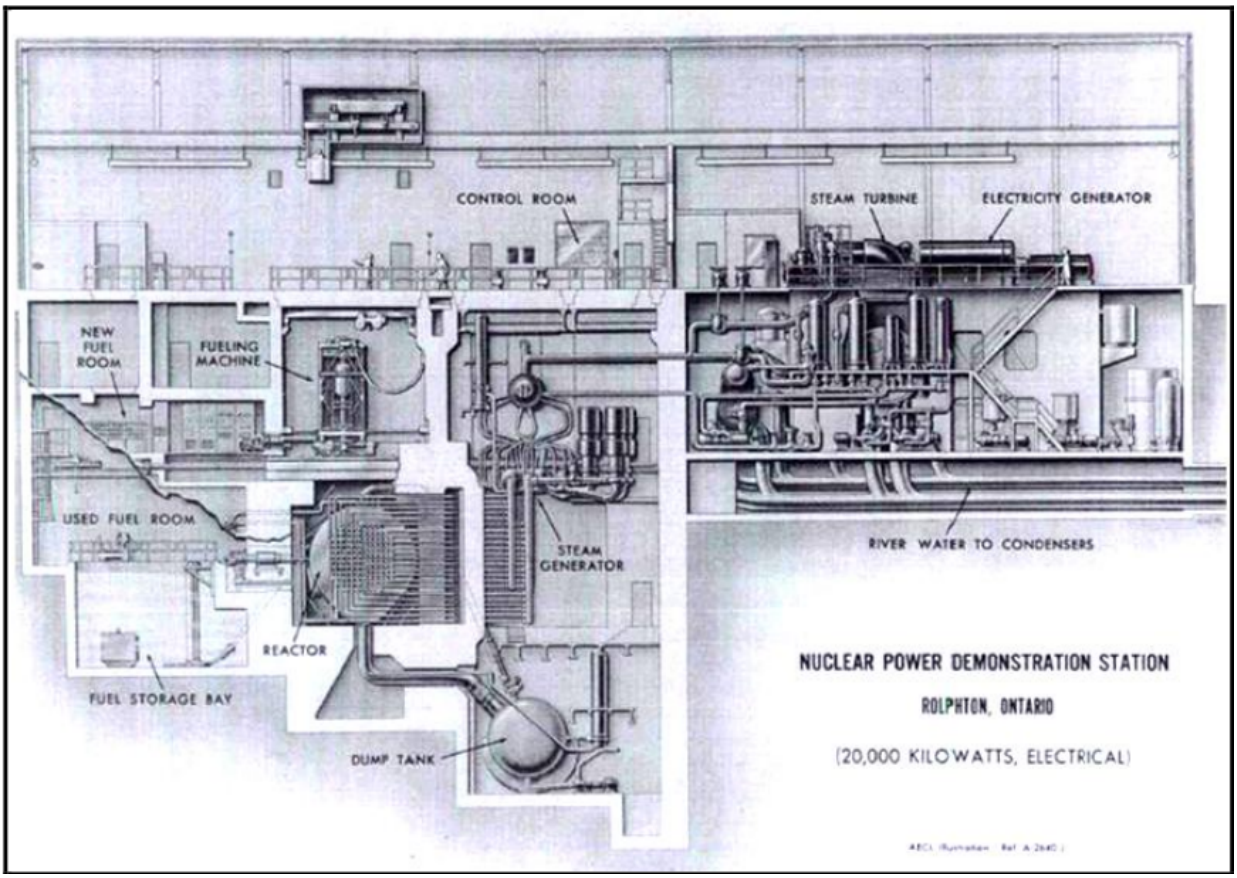


Figure 3-5 Key Features of the NPD Facility during Operations

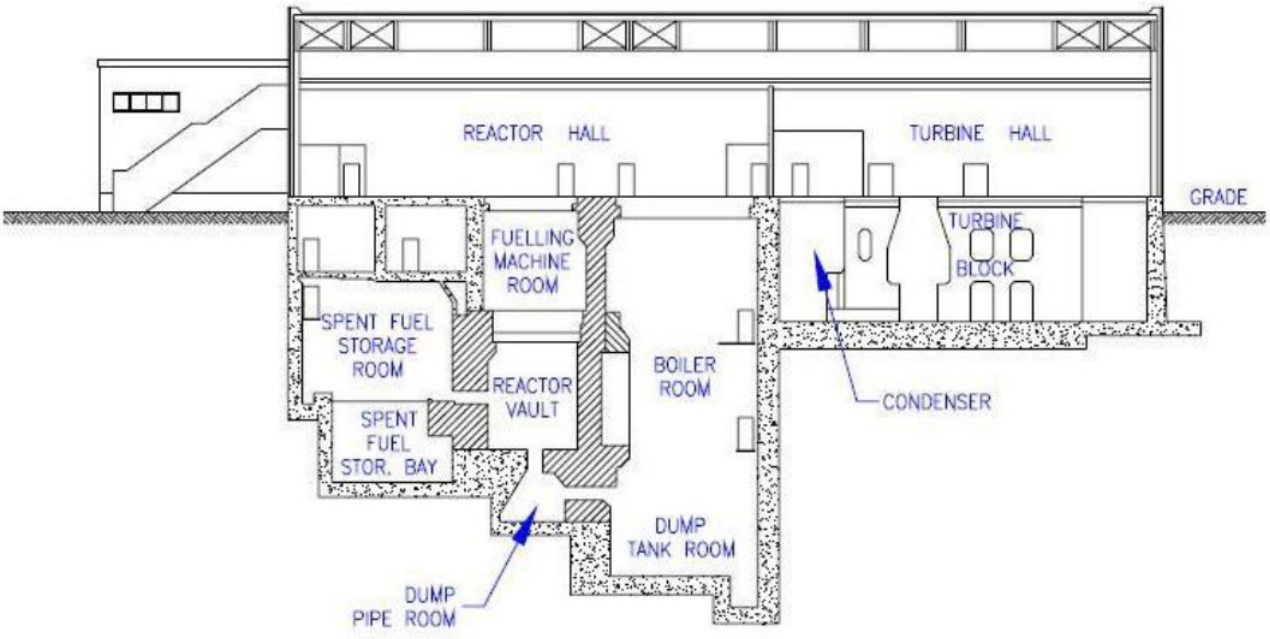


Decommissioning

The NPD was permanently shut down on 24th May 1987 and a three-phase decommissioning plan put in place. Phase I brought the Facility to a safe, sustainable shutdown. This involved draining the primary heat transport system (PHTS) and moderator system of heavy water and de-fuelling the reactor, with the resulting materials being transferred off-site. Demineralizer system equipment, and other nuclear process systems, were also removed from the site. The remaining plant and structure were subject to decontamination and the Facility was functionally divided into nuclear and non-nuclear areas. Connections between the two areas were sealed. Various non-nuclear ancillary buildings were also demolished, and the resulting waste removed from the site.

Phase II is a period of storage with surveillance (SWS); Phase III is final and complete decommissioning of the site. All of the above grade structures will be removed during decommissioning, except for the ventilation stack which will remain for a period of time as supporting habitat for recovery of the Chimney Swift species at risk (which presently use the stack as a roost). The above-grade portion of the Main Building, specifically, will be demolished and its rubble disposed of in the subsurface rooms below the Main Building, such as those previously containing the turbine/condenser.

Figure 3-6 Cross Section of the Main Building, Boiler Room



The below grade structure (shown in Figure 3-6) will be sealed by grouting with an engineered cementitious material – a grout formulation involving blast furnace slag (BFS) and Portland cement (PC). The grout will be flowable such that it fills all voids as well as possible. Once the below-grade structure is grouted, a reinforced concrete cap will be emplaced to cover parts of the nuclear area footprint of the below grade monolith (the Spent Fuel Storage Room, Fuelling Machine Room and Reactor Vault, and Boiler Room). The entire Facility footprint will be covered by a multi-layer earthen cover, contoured to shed water.

Wastes

The focus of the PostSA is the contaminants that would remain in the NPDDF as part of the in-situ disposal strategy. These will primarily be associated with reactor vessel (pressure tubes, Calandria, and associated structures), as well as contamination within the heat transfer system, fuel storage and handling, and other parts of the Facility.

Radionuclides

The following is a summary of the detailed description of the inventory provided in Appendix B.

Radionuclides will be present in these materials in two forms:

- radionuclides embedded within metals and other materials known as activation products, present due to the interaction of neutrons from the reactor operation with the structures; and

- as contamination on surfaces, mainly resulting from corrosion products and the handling of fuel elements which had suffered failure of their protective cladding, enabling the release of some radionuclides.

The 3rd Iteration of the PostSA used radionuclide inventories from Edwards & Adams (2019) who re-calculated the activity of the NPD reactor components (see Table 3-1). This re-calculation, using the ORIGEN code, replaced the 2-D neutron transportation code used by Smith (1988) with MCNP, a 3-D solver, and provided a detailed examination of potential impurities and uncertainties in the material compositions. This calculation supersedes the previous work which was originally performed soon after shutdown in 1988 and subsequently verified in 2012.

The NPD Closure Project also completed sampling of the various activated reactor materials to build confidence in the calculated inventory. This included sampling and laboratory analysis of the activated inner concrete of the Reactor Vault walls, carbon steel vault liner, aluminum Calandria vessel and a Calandria tube as well as the Zircaloy from a pressure tube. Sampling of the Calandria was undertaken by New Millennium Nuclear Technologies Incorporated (NMNTI). Collection of a sample of the stainless-steel components was not possible. These sample results, NMNTI (2017), used the empirical data, as well as re-estimates of the various reactor material masses from 3D modeling (based on original design drawings), to validate the activation product inventory modelled by Smith (1988), Edwards (2017) and subsequently, Edwards & Adams (2019).

A comparison of the results of Edwards & Adams (2019) and NMNTI (2017) indicates that:

- The total activation product inventory estimated using Edwards & Adams (2019) (1.04E+14 Bq) is conservative in comparison to the total activation product inventory estimated by sample results alone (1.01E+13 Bq) in NMNTI (2017).
- The modelled activation product inventory of the NPD reactor components appears to be largely conservative for the aluminum and Zircaloy reactor components.
- Tritium was overestimated in the aluminum components by Edwards & Adams (2019) and underestimated in the concrete. The total tritium inventory estimated by sampling results (NMNTI, 2017) was approximately 20 times lower than Edwards & Adams (2019).
- Edwards & Adams (2019) underestimates C-14 by 4 orders of magnitude in the bioshield concrete. This discrepancy is potentially due to errors in the starting N-14 composition or impurities in reactor materials. However, the total C-14 inventory estimated by Edwards & Adams (2019) is still approximately 20 times higher than the total inventory determined by sampling results (NMNTI, 2017).

Table B-1 (in System Description – Appendix B), taken from Porter (2022), provides a comparison of the sample results obtained (from NMNTI (2017)) and the most up-to-date modelling results Edwards & Adams (2019). As sampling of the stainless steel was not possible (NMNTI, 2017), the comparator used is the verification work undertaken in 2017 which looked specifically at the NPD end fitting components (Edwards (2017)). Porter (2022) presents a composite total activity derived by using the higher activity between the NMNTI (2017) measurements and the Edwards & Adams (2019) estimates for each radionuclide in each material, expect for a small number of values where the measurement was used in preference, as it was thought more reliable (e.g., H3 in aluminum).

The resulting reference inventory used in this 4th Iteration PostSA is shown in Table 3-1 and Table 3-2 below, which corresponds to Table E-17 and Table E-18 of Models & Data – Appendix E. In deriving the reference inventory for other rooms (i.e., not the reactor vault) (as shown in Table 3-2 below), a further factor of 3 was applied to the inventory outlined in Appendix B to account for uncertainty (for further details, the reader is referred to Appendix E).

Table 3-1 Reference Activity (Bq) of the Reactor Vault for the Postclosure Safety Assessment

(See Appendix B and Appendix E for derivation details)

Radionuclide	Aluminum	Concrete	Carbon Steel	Stainless Steel	Zircaloy	Contamination
H3	9.13E+09	1.41E+12	2.35E+08	2.04E+09	7.36E+11	2.29E+09
C14	1.00E+11	2.40E+10	1.25E+09	1.05E+11	1.36E+12	8.91E+09
Cl36	4.58E+09	1.74E+08	1.09E+07	2.64E+05	2.50E+10	8.37E+07
Ca41	9.21E+08	7.62E+09	5.80E+06	3.28E+08	1.25E+09	-
Fe60	7.25E+04	0.00E+00	0.00E+00	1.80E+05	1.74E+05	-
Co60	5.28E+11	3.18E+11	1.61E+11	1.34E+13	2.63E+12	7.56E+08
Ni59	2.17E+09	1.68E+06	8.37E+08	1.54E+11	2.16E+11	-
Ni63	5.22E+11	6.83E+10	3.96E+10	1.44E+13	3.36E+13	3.15E+09
Se79	1.06E+04	2.06E+00	6.08E+05	1.77E+07	1.04E+05	-
Sr90	3.11E+09	1.01E+06	1.68E+08	3.55E+10	2.55E+10	8.04E+10
Zr93	2.76E+06	2.80E+03	3.67E+03	2.06E+06	2.40E+11	-
Nb93m	4.97E+06	2.25E+03	2.55E+07	1.41E+09	1.94E+11	-
Nb94	0.00E+00	1.62E+05	5.84E+07	4.40E+09	1.13E+10	-
Tc99	2.17E+06	3.94E+02	7.53E+06	4.12E+08	1.45E+08	5.28E+07
Ag108m	3.42E+08	3.96E+03	8.63E+08	7.74E+10	2.16E+10	-
Cd113m	4.13E+07	2.15E+01	6.28E+08	2.21E+09	2.71E+07	-
Sn121m	6.19E+07	1.60E+02	1.94E+06	7.56E+07	2.08E+11	-
Sb125	2.67E+07	1.55E+01	1.15E+06	2.52E+07	9.05E+10	-
Cs137	6.91E+09	1.07E+06	1.87E+08	4.82E+10	7.79E+10	1.23E+11
Sm151	4.71E+08	5.51E+05	3.07E+08	2.25E+09	7.60E+07	-
Eu152	7.78E+09	1.23E+11	5.92E+07	1.26E+08	3.48E+09	-
Eu154	2.51E+10	1.38E+06	8.78E+05	6.75E+08	1.16E+09	4.80E+08
Ho166m	3.73E+07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	-
Hf182	0.00E+00	0.00E+00	0.00E+00	2.69E+03	4.44E+06	-
Th229	0.00E+00	2.25E+02	1.32E+04	1.24E+06	0.00E+00	-
Th230	0.00E+00	3.15E+03	9.66E+04	2.59E+04	0.00E+00	-
Th232	3.28E+04	3.14E+05	9.19E+06	1.98E+06	0.00E+00	-
U232	8.52E+05	0.00E+00	1.33E+03	1.15E+07	1.84E+03	-
U233	1.52E+06	5.72E+04	8.26E+06	3.13E+08	0.00E+00	-
U234	7.04E+05	4.35E+05	2.76E+07	1.18E+07	1.35E+05	-

Radionuclide	Aluminum	Concrete	Carbon Steel	Stainless Steel	Zircaloy	Contamination
U235	2.08E+04	2.02E+04	1.26E+06	2.45E+05	0.00E+00	-
U238	4.68E+05	4.40E+05	2.79E+07	6.04E+06	9.24E+04	-
Np237	0.00E+00	0.00E+00	0.00E+00	2.97E+04	3.09E+04	-
Pu238	8.96E+07	8.30E+08	7.26E+02	3.27E+08	1.05E+09	4.44E+08
Pu239	6.44E+07	2.06E+07	1.08E+08	1.49E+09	4.22E+08	2.99E+09
Pu240	4.24E+07	2.29E+01	1.39E+05	9.71E+08	4.80E+08	-
Pu241	1.12E+09	0.00E+00	1.50E+04	1.30E+10	1.56E+10	-
Pu242	6.73E+05	0.00E+00	0.00E+00	3.57E+05	1.11E+07	-
Am241	1.36E+08	0.00E+00	0.00E+00	1.88E+09	1.80E+09	4.47E+09
Am242m	3.37E+05	0.00E+00	0.00E+00	7.91E+06	3.39E+06	-
Am243	9.67E+06	0.00E+00	0.00E+00	3.48E+05	1.64E+08	-
Cm243	5.45E+05	0.00E+00	0.00E+00	3.10E+05	9.27E+06	-
Cm244	9.95E+08	0.00E+00	0.00E+00	1.19E+06	1.58E+10	-
Cm245	1.14E+05	0.00E+00	0.00E+00	0.00E+00	1.83E+06	-
Cm246	3.64E+05	0.00E+00	0.00E+00	0.00E+00	5.25E+06	-

Table 3-2 Reference Inventory of Fission Products and Actinides in Other Rooms for the Postclosure Safety Assessment

(See Appendix B and Appendix E for derivation details)

Radionuclide	Boiler Room, i_{BR} (Bq)	Fuelling Room, i_{FR} (Bq)	Turbine Room, i_{TR} (Bq)	Generic Contamination, ic_{Struct} (Bq)*
H-3	1.76E+11	2.80E+08	1.97E+12	5.25E+12
C-14	9.99E+07	9.21E+05	8.15E+08	2.35E+11
Cl-36	1.10E+06	-	7.47E+07	5.07E+07
Co-60	1.51E+10	8.46E+07	1.09E+06	9.69E+06
Ni-63	1.16E+10	3.00E+08	3.55E+07	2.14E+07
Sr-90	1.88E+10	3.51E+09	1.44E+07	3.63E+07
Tc-99	-	4.35E+06	4.55E+06	1.02E+07
Cs-137	1.13E+09	6.18E+09	4.18E+06	1.38E+08
Eu-154	2.39E+08	1.31E+07	-	-
U-235	-	-	5.33E+06	5.79E+06
U-238	-	-	7.66E+07	9.36E+07
Pu-238	2.60E+08	8.07E+07	8.37E+06	2.91E+07
Pu-239	2.70E+09	3.21E+08	2.99E+06	6.45E+06
Pu-241	2.10E+10	3.81E+09	-	-
Am-241	2.86E+09	4.47E+08	4.31E+06	2.29E+06

Note: * Generic contamination levels are applied to the whole of the concrete structure of the NPDDF, with the inventories of specific rooms (e.g., the Boiler Room) being additional quantities of radioactivity located within rooms.

Non-Radioactive Contaminants

The inventory of non-radioactive contaminants is dominated by those frequently found at historic industrial facilities.

There is lead paint throughout the Facility and there is also a significant quantity of lead associated with shielding, mainly in the Fuelling Machine Room. The total quantity of lead present is estimated to be approximately 225 metric tonnes (nearly 174 tonnes of which is located among the Fuelling Machine Room and New Fuel Room), based on information in Schruder & Vickerd (2017) and Arcadis & Quintessa (2019b).

Small residual quantities of mercury are possible in the Facility, associated with historic incidents or operations leading to contamination (i.e., spill). This is estimated to be less than 0.01 kg, in the Boiler Room (Schruder & Vickerd, 2017).

It should be noted that CNL will be removing all polychlorinated biphenyl (PCB) ballasts in the facility either before, or as part of, the decommissioning work. Therefore, there will be no PCBs above exemption levels remaining in the NPDDF at the time of closure.

Asbestos is present in the form of pipe insulation, floor tiles and building cladding. Around 230 m^3 of asbestos is present and is assumed to be disposed of in the NPDDF at closure.

There will be some organics in the waste disposed within the NPD building, including organic additives in cement grout, polythene (polyethylene) bags, and asphalt from the roof, which will be dismantled and its debris emplaced in the disposal facility (Arcadis & Quintessa, 2021). The available evidence suggests that the organic materials are unlikely to be significantly detrimental with respect to radiological risk. In addition, in safety assessments for radioactive waste disposal facilities in other countries, these (or similar) materials are not considered detrimental to safety. For more details, the reader is referred to Arcadis & Quintessa (2021). The organic materials are therefore not explicitly considered in this safety assessment.

3.2 Environmental Setting

3.2.1 Subsurface Setting

Geology

The NPD site lies on the eastern edge of the Ottawa-Bonnechere Graben, an ancient rift valley in the Canadian Shield of Northeastern Ontario and Quebec. This was formed from two major fault zones which are still active. The Temiskaming earthquake of 1935 had magnitude 6.2 and in 2000 the Kipawa earthquake had magnitude 5.2. The NPD site lies within a zone categorized as a region with moderate seismic risk.

The outcome of the NPD Underground Structure Seismic Assessment (CNL, 2021b) indicates that parts of the underground structure of NPDDF are not able to withstand a CRL DBE, 1/10,000 y, and 1/50,000 y seismic event after grouting of the structure. As per the results obtained in this assessment, shear

failures/cracks are the dominant failure modes for all cases. Below the bedrock elevation level, the NPDDF structure is socketed into surrounding bedrock on all sides and does not experience structural failure/cracking due to the continuous lateral support provided by the bedrock. The grouted structure, as well as the lateral support provided by the bedrock increases the stiffness of the NPDDF structure.

The preliminary slope stability assessment (Arcadis & Geofirma, 2021a) that considers earthquake-induced soil liquefaction, shows that the North Slope under current water level conditions is stable under static loading conditions and under loading conditions associated with a 1:2,250-y earthquake. Parts of the North Slope are stable, while some parts of the North Slope are unstable under a 1:10,000-y earthquake. The North Slope is likely to fail during a 1:50,000-y earthquake. It is unlikely that the predicted failures of the North Slope will result in the direct exposure of groundwater to a new ground surface that would be established following earthquake induced slope failures.

The bedrock local to the NPD and in the wider region is Precambrian Canadian Shield. To date there has been little mineral exploitation in this geological area due to its low resource potential. On the NPD site, the bedrock is comprised of a number of different types of gneiss and lies about 2 m beneath the surface near the Ottawa River; 5 to 6 m beneath the surface near the NPDWF building; 15 to 18 m beneath the surface southwest of the NPDWF facility; and 5 to 7 m beneath the surface near the Highway 17 (Arcadis & Geofirma, 2022).

The overburden comprises generally sand and gravel overlying silty sand to sand, overlying bedrock. The sand and gravel are highly permeable, providing good drainage and low water holding capacity. The sediments overlying the bedrock at the NPD site were deposited during the last glacial period. Further details are provided in Appendix B, based on detailed descriptions from Arcadis & Geofirma (2022).

Hydrogeology

Water table contours interpolated from static water elevations in monitoring wells show that gradients in head, which drive flow, are roughly perpendicular to the Ottawa River (see Figure 3-7). The water table can vary considerably. Data from field studies completed in 2019 indicate that groundwater levels are typically within the fluvial sand and gravel unit in the vicinity of the NPDDF, and within the overlying silt to cobble glacial till unit southwest, northwest, and southeast of the NPD site, a few meters above the bedrock surface (Arcadis & Geofirma, 2022) (e.g. see Figure 3-8). Water levels within the shallow bedrock are typically within 1 to 2 m of the water levels seen in the overburden (Arcadis & Geofirma, 2022).

A tile ring drain system at the bedrock surface surrounds the NPDDF on the east, south and west sides, as shown in Figure 3-9. This intercepts water flowing towards the NPDDF and diverts it around the Facility to outlets on the rock and cobblestone at the shoreline of the Ottawa River.

Figure 3-7 Shallow Groundwater Elevations and Flow Directions At NPD (Arcadis & Geofirma, 2022)

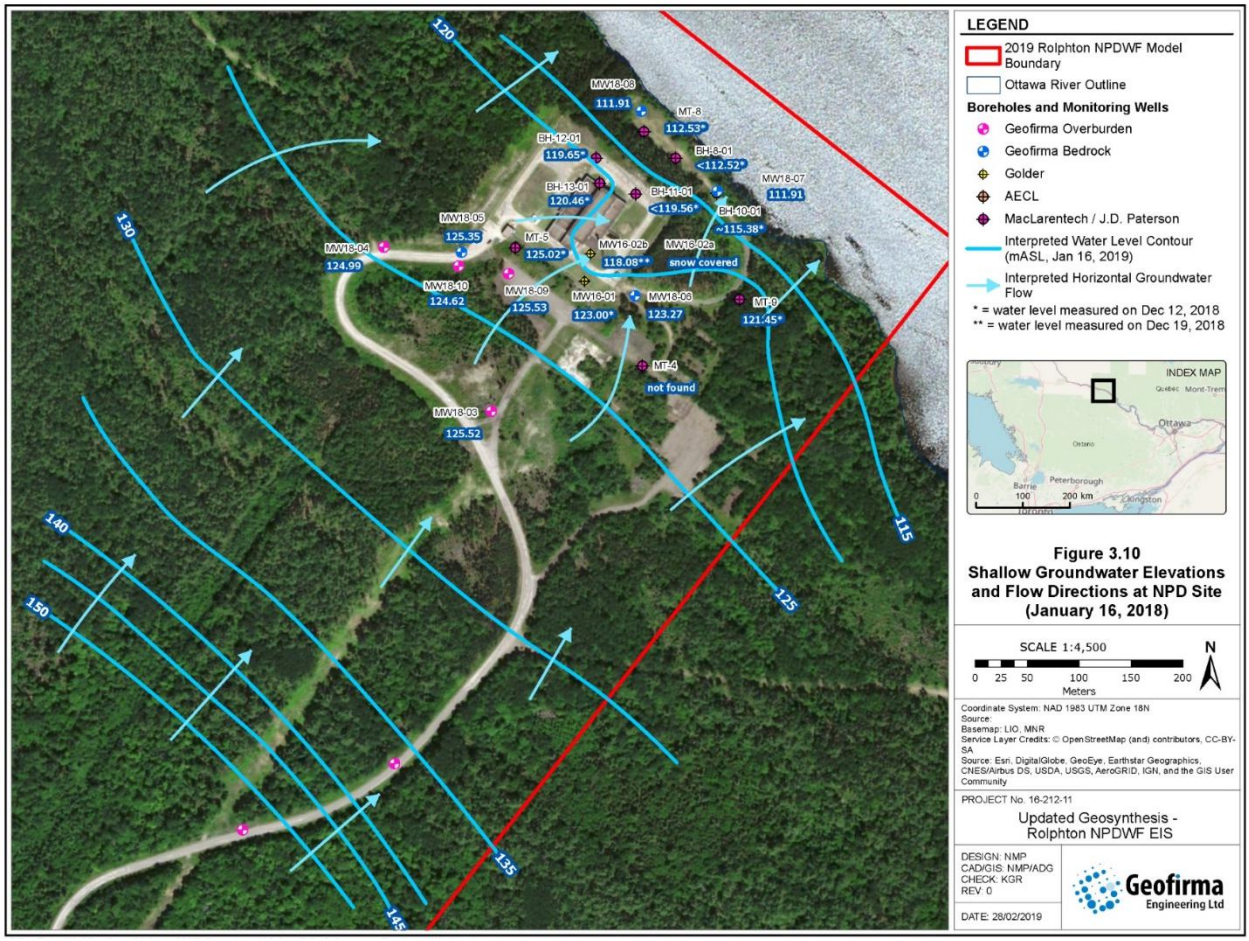
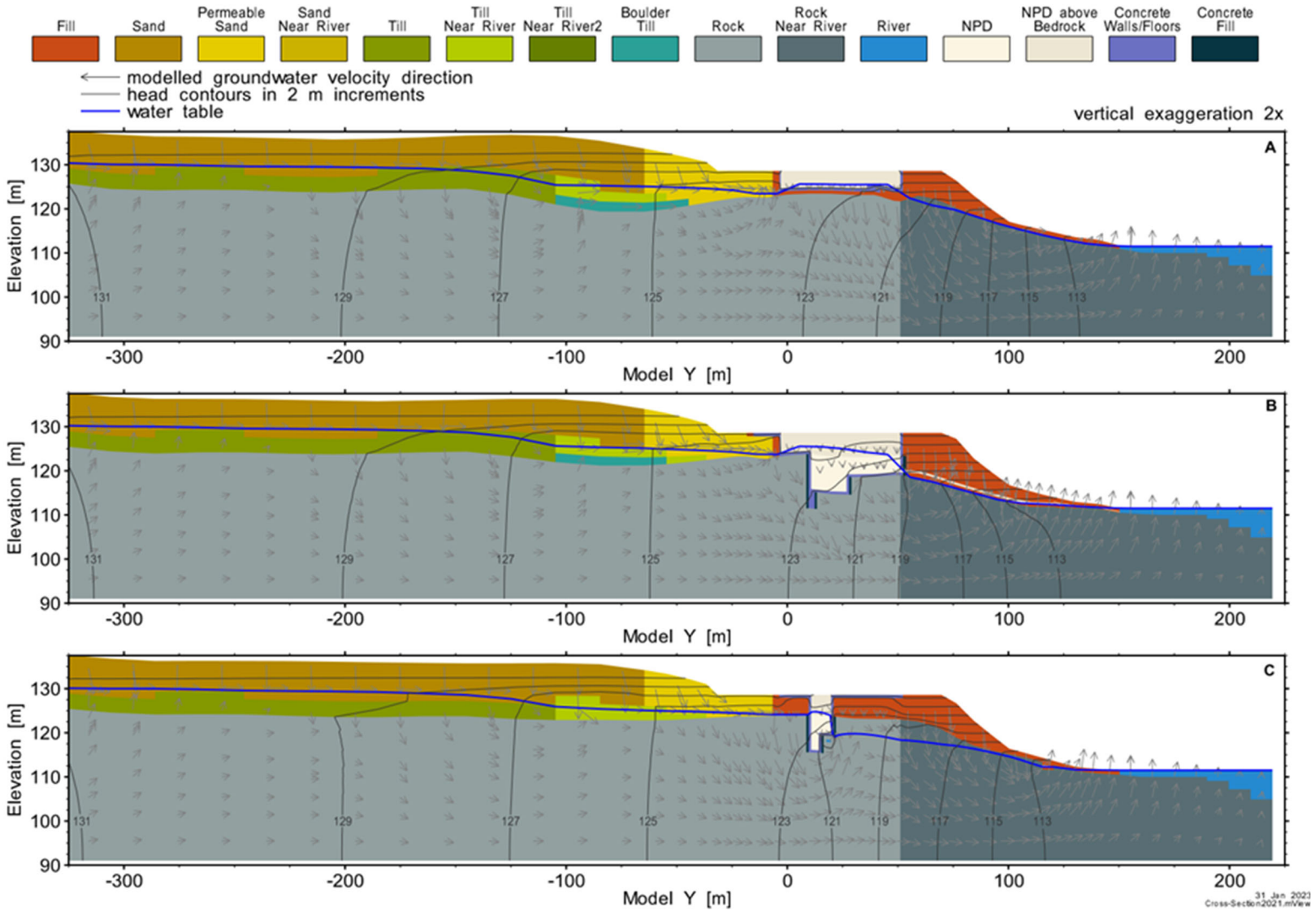


Figure 3-8 Cross-Sections Showing Calibrated Model Head Contours, Velocities and Water Table (Arcadis & Geofirma, 2023a)



Note: see Arcadis & Geofirma (2023a) for plan view showing location of cross-sections A, B, C above.

Figure 3-9 Tile Drain Layout and Invert Elevations (Arcadis & Geofirma, 2023a)



Geochemistry

Groundwater pH is generally in the range 5.7 to 7.0. Levels of chloride are generally low. Apart from the low levels of road salt contamination, the local groundwaters have major ion characteristics that are consistent with short-residence-time groundwaters in soils low in carbonate minerals. The very low iron concentrations and the presence of moderate concentrations of sulphate show that the local groundwaters are oxidizing.

3.2.2 Surface Environment

Landscape

The regional terrain consists of gently rolling hills, interspaced with many small lakes. The NPD site is situated next to the Ottawa River; the ground surface at the NPD facility is at an elevation of approximately 129 m above sea level (Geobase, 2011). During the construction of the NPD Facility, numerous man-made terraces and steep interconnecting benches were created for construction and security purposes. This activity has resulted in a highly modified landscape at the site. The Ottawa River is a dominant feature of the area. All surface drainage on the NPD site is to the Ottawa River. The Ottawa River is a large river with an average flow of 807 m^3 s^{-1} with widths of several hundred meters (ORRPB, 2020). The Des Joachims Generating Station, approximately 3 km upstream from NPDDF controls flows and river levels.

The river terraces in the area are overlain with a fluvial deposit of uplands series soil. The topsoil is generally relatively thin but is sufficient to support forest. It is possible that in the future soil could develop if the processes that washed fine particles away from the ground surface no longer occur.

The NPD site is mainly wooded with the exception of open wetland areas. Wooded uplands generally range from 40-80 y old. Wetland areas on the NPD site are mainly found on the western half of the property, away from the well-drained margins of the river on which the NPD is constructed (Wills, 2013). The ecology is typical of the local natural and semi-natural environment.

Climate

The climate of the area is classified as humid continental, with warm summers, cold winters, and no distinct dry season. The average annual precipitation (rain and snow) is around 859 mm (Government of Canada, 2016). Daily mean temperatures range from -12°C in January to 20°C in July with historic minima and maxima of -36.3°C and 36°C (Leeson, 2016). The winds are predominantly northwest and southeast, parallel to the Ottawa River. A tornado occurred in 1984 between Deep River and Rolphton but property damage was low (Athauda-Arachchige, 2015). The area is susceptible to forest fires, and firebreaks are cut into the forest (Athauda-Arachchige, 2015).

Population and Land Use

The NPD site is in a remote area, with relatively low population density. The Town of Laurentian Hills has a population of approximately 2,800 distributed over an area of 640 km^2 and contains the former village of Chalk River and the former hamlets of Point Alexander, and Rolphton. With the exception of the Rapides des Joachims dam, there are no nearby industrial activities. The surrounding land is primarily used for recreational activities, and traditional land use by local Indigenous communities. Sport fishing occurs in lakes and in the Ottawa River, but there is no commercial fishing in the area. Agricultural activities in the area are limited to garden plots managed by residents. The relatively short growing season and the typically poor soil quality mean that there are no significant commercial agricultural uses of the land, although logging takes place within Renfrew County (Wills, 2013).

Ecology

The ecology of the region is characteristic of the Eastern forest-boreal transition which includes broadleaf and mixed forest. No nationally or provincially endangered or threatened species of plants have been identified or recorded on the NPD site although a number of species at risk have been identified in the NPD EIS, including: chimney swift, eastern milksnake, bald eagle, common nighthawk, eastern wood pewee, eastern small-footed bat, little brown myotis, northern myotis and monarch butterfly (Arcadis, 2023).

The less disturbed forest can be home to a complex and well-established wildlife ecosystem including many invertebrates, reptiles and birds. The region also supports larger mammals (although not in high density) including wolves, coyotes, cougar, moose, black bear, lynx, snowshoe hare and white-tailed deer (Wills, 2013).

The Ottawa River supports diverse warm-water and cool-water fish communities consisting of at least 55 documented species. The provincially-rare fish species in the Ottawa River includes the American eel, lake sturgeon and river red horse. Typical catches from the river include walleye, northern pike, channel catfish, smallmouth bass, and lake sturgeon (Wills, 2013).

4.0 SCENARIOS, CALCULATION CASES, MODELS AND DATA

4.1 Scenarios and Calculation Cases

4.1.1 Process for Identifying Scenarios and Calculation Cases

Scenarios are descriptions of alternative, but internally consistent, futures for the NPDDF and its environment. Using the PostSA to examine a number of scenarios provides an important way of capturing and quantifying uncertainties in the future conditions at the site. Careful selection of scenarios is essential, so a structured approach is used, developed from international guidance (IAEA, 2004). Scenarios can be accompanied by calculation cases, which are defined so as to examine the response of the system to issues of interest, such as alternative design options, or aspects that are uncertain.

Scenarios represent a link between factors beyond the modelled system and the modelled system itself. An example is climate change. This has been considered within the Normal Evolution scenario. However, it would be impractical and disproportionate to include a climate change model in the assessment. Instead, a description of climate evolution sits outside of the model itself and modelling decisions make reference to a set of assumptions about climate evolution. Uncertainties in key factors can then be captured with scenarios and calculation cases. For example, uncertainty in the timing and consequences of seismic activity in the vicinity of the NPDDF implies the need to consider a scenario to represent this possibility. The way in which scenarios and calculation cases are developed in a systematic way is to make reference to a standard list of all the factors that could be important for postclosure safety. These are referred to as the “Features, Events and Processes” or FEPs. A list of over 200 FEPs have been reviewed for their relevance to the NPDDF, the outcomes presented in Appendix C. Each FEP was categorised in the following way:

- FEPs screened out of the assessment:
  - the FEP is **outside** the scope of the assessment or is simply not relevant.
  - the FEP is not significant on the basis of insignificant **consequence**.
  - the FEP is not significant on the basis of low **probability**.
- FEPs included in the assessment:
  - FEPs considered in the Normal Evolution Scenario (NES) are by default also included in other scenarios.
  - FEPs giving rise to Disruptive Event (DE) scenarios, or of very low probability, but provide useful information on system performance.
  - FEPs that are at the bounds of plausibility, but a “What If” (WI) calculation may be of interest to examine its implications for the performance of the system.

This categorization results in a reference scenario called “normal evolution” along with a set of alternatives which describe potential deviations from the expected evolution of the system. The approach also enables the identification of conditions that are useful to examine to understand the behavior of the system – for example, by asking “what if” a certain event happens. In this vein, the scenario identification process is extended to define calculation cases that examine the robustness of the planned disposal strategy:

- Defence-in-Depth cases are aimed at building confidence in the performance of the NPDDF after closure. These cases examine the extent to which the NPDDF depends on engineered barriers, and what would happen if those barriers were not present.
- Sensitivity/Uncertainty cases examine the extent to which the safety performance of the NPDDF is affected by uncertainties in key aspects of the model, in particular model data. The key parameters that are examined have been identified based on a sensitivity analysis undertaken as part of the second and third iterations of the PostSA (Arcadis & Quintessa, 2018a; Arcadis & Quintessa, 2020a).

Generally, scenarios and factors considered in calculation cases that are uncertain in their timing are assumed to be possible at any time after the end of Institutional Control. Thus, Disruptive Event scenarios are typically assumed to occur at any time greater than 100 y from the end of decommissioning. For context, a historical timeline of key events in the evolution of people is shown in Table 2-1.

4.1.2 Normal Evolution Scenario

The Normal Evolution scenario is a reference description of a defensible scenario with conservative bias built into the assumptions of the evolution of the Facility and its surrounding environment.

The Facility is closed as planned with no unforeseen events. A period of institutional control is initiated and lasts for at least 100 y during which the Facility remains under surveillance. No human intrusion occurs within this timeframe or thereafter.

In the surrounding environment there may be minor earthquakes. Cautiously, they are assumed to contribute to the degradation of the engineered structures with a 1:2,250 earthquake happening immediately after closure and a 1:10,000 y event happening at 1,000 y. There are no other significant geological events or developments that affect the Facility and its surrounding environment. The climate evolves according to the current best knowledge of climate change. This is anticipated to include global warming of several degrees centigrade, deferring the next scheduled ice age to beyond 100,000 y from now. During the warm period, the environment is assumed to remain broadly as the present day.

Wastes

The waste inventory in the Facility includes the reactor vessel and internals, together with some contaminated material (e.g., the primary heat transport circuit). At closure, the Facility will be filled with grout. The Facility will gradually fill with groundwater, which slowly flows through the pores of the concrete and grout. Once it reaches the wastes, contaminants can dissolve into the groundwater. Surface contamination and contaminated aluminum is conservatively assumed to dissolve instantly, but radionuclides embedded in steel and Zircaloy are only released at the rate of corrosion of the metal. The

high pH of the porewater in contact with cementitious materials will result in very low corrosion rates of these metals. The radionuclides in groundwater will partition between water and solids according to their characteristic properties, represented with a “sorption coefficient”.

Corrosion of metals is the only mechanism by which radioactive gas could be generated. Because the Facility is expected to resaturate quickly (Arcadis & Geofirma, 2023c), any small quantities of radioactive gas that might be evolved from the aluminum would be released while the Facility remains under Institutional Control. This could migrate through the pores of the grout ultimately to be released to the open air and a portion may dissolve in groundwater. The corrosion rate of aluminum under high pH conditions is quite rapid, i.e., 15 mm/y, as shown in Appendix E. This indicates that the aluminum in the NPD facility would oxidise extremely rapidly after grouting of the facility. For example, the maximum thickness of the walls of the calandria vessel is less than 4 cm. Hence, at a corrosion rate of 15 mm/ y, this wall would corrode in less than 3 y after resaturation of the facility. Thus, even if resaturation takes decades to complete, any radioactive gases that might be evolved from the aluminum would be released during the 100-y institutional control period.

Any radioactive gas from the corrosion of other metals would be generated at such a slow rate that it would be dissolved in groundwater rather than accumulate as a bulk gas. Because the gas from the aluminum oxidation will be evolved quickly and be released during the institutional control period when exposures can be prevented, it is not necessary to model. Because gas from corrosion of the other metals will evolve very slowly, and therefore will not migrate as a bulk gas but would be expected to dissolve in groundwater, it can be modelled in the same way as tritium in groundwater.

Facility

The rate that the NPDDF fills with groundwater will be controlled by the hydraulic conductivity of its walls and the BFS/PC grout backfill. Initially the grout is expected to be close to fully saturated after curing, and facility concrete is expected to be unsaturated. After closure, groundwater will begin to flow through the pores of the concrete and grout. Hydrogeological calculations (Arcadis & Geofirma, 2023c) indicate that this period of “resaturation” may occur quickly, i.e., over several decades. During the resaturation period contaminants will only be released from the Facility by diffusion, as groundwater will be flowing into the Facility. The low hydraulic conductivity of the Facility structure and grout will mean that the flows initially into and subsequently through the Facility will be very small, a few m^3 per year, as demonstrated by Arcadis & Geofirma (2023c). In addition, the water will be alkaline due to the conditioning effect of the cement. This increases the sorption of some radionuclides, which reduces the rate at which they can migrate.

Over time, the flow of groundwater through the Facility’s walls and grout backfill will gradually degrade them. The pH will fall and the porosity of the structures will increase. The cement and concrete will gradually lose strength and may begin to crack and fracture. Earthquakes might add to the cracking. Cracking results in an increase in hydraulic conductivity and, in turn, the groundwater flows through the Facility. Ultimately, the cement constituents will be largely removed and the remaining material will resemble inert aggregate. The timescales for this are dependent on the properties of the Facility, but it will take more than ten thousand years for complete chemical degradation of the cement.

Transport in Groundwater

Groundwater flows in the vicinity of the NPDDF are predominantly at the base of the overburden but with a significant component of flow in the bedrock.

Prior to any significant physical degradation of the NPDDF structure (e.g., cracking), tile drains deflect much of the groundwater around the Facility. The tile drains are assumed to remain in service until the end of institutional control. This is conservative as it provides a rapid transport pathway for any contaminants released in this period.

Downgradient of the Facility, groundwater flows towards the river and discharges at the riverbed, close to the shore. The disturbed ground associated with the cooling water pipes provides a preferential pathway for contaminants released in the upper portions of the Facility, as indicated by detailed groundwater flow modelling (Arcadis & Geofirma, 2023b). This also indicates that, when the tile drains fail, springs may emerge from the overburden, close to the shore. The modelling also shows that contaminants released from the part of the NPDDF lying within the bedrock are expected to be transported through the bedrock.

Once contaminants begin to be gradually released from the Facility in groundwater, the majority will follow these pathways and be released directly into the river (from the bedrock) and potentially via springs (from the overburden). The concentrations of contaminants in the groundwater will nevertheless be very low due to their low rate of release.

Surface Environment

Contaminants released into the Ottawa River may sorb to sediments or be taken up by aquatic flora and fauna. The dominant process will, however, be advection, dispersion and subsequent dilution in the water. Over the course of the assessment timeframe, the level of the river may vary slightly due to e.g., changes in rainfall and temperature changes. However, this variation in river level is expected to be minor (the river is very large) and the river level is therefore taken as constant in the NES. The water balance may be affected by changes in average rainfall (e.g., due to climate change) and changes in average annual temperatures (e.g., due to climate change). It should be noted that a case of river level fall is assessed separately. The temporary flood elevation, resulting from a dam failure, has been examined; it is discussed in Appendix B and incorporated into calculation cases as outlined in Appendix C.

People living downstream and using water from the river may be exposed to contaminants released into the river water. As such, down-river public receptors are included among the receptors assessed in this PostSA.

Once the institutional control period ends, it is possible for people to access the site. Therefore, it is conservatively assumed that a resident establishes a household on the site. Water is assumed to be extracted from the river for domestic use. It is assumed to be used as drinking water by people and livestock, and to irrigate soil for crops that are subsequently consumed. Radionuclides in the irrigated soil are also assumed to constitute a source of external irradiation to the resident receptor. Residents are also assumed to source fish from the river.

In addition to a resident receptor, it is also possible that people might access the site for hunting and recreation once the institutional control period ends. Therefore, a recreational hunter receptor is included in the assessment. This receptor is assumed to be exposed to contaminants sorbed onto bank sediments. They are also assumed to swim in the river and use it for washing.

As a result of Indigenous stakeholder feedback, the NES examines an Indigenous receptor intended to represent traditional Indigenous lifestyles, based on a new study of the diet and harvest of the AOPFN (Fediuk *et al*., 2021) which shows that today, members are more likely to supplement their diet with additional groceries purchased from local shops. The Indigenous receptor does not live on the NPD site but uses the land surrounding the facility for some traditional activities (such as hunting, fishing, and harvesting of wild plants). As noted, this receptor has a diet that includes harvested and gathered food (from the area around the site) as well as purchased foodstuffs (based on AOPFN diet and harvest study). Another Indigenous receptor, which is referred to as the Self-Sufficient Indigenous Receptor (based on SENES (2014) and which has more conservative exposure characteristics than the AOPFN receptor, is considered in a Sensitivity Case (See Section 4.1.3).

Contaminants may also be released directly into soils; groundwater modelling in Arcadis & Geofirma (2023b) suggests that it is possible, once the tile drains have ceased to function, for springs to form close to the river, from which potentially contaminated groundwater my be released from the overburden. Thus, a person could subsequently be exposed to the contaminated soils. It is also possible that, once it has resaturated and the tile drains have failed, a small fraction of the contaminated water in the upper part of the NPDDF might enter the cap overlying it (e.g., as a result of seasonal variations in water table). Subsequently, these contaminants may move from the cap to the adjacent areas and expose people using that area of land, e.g., for a garden.

Each of these receptors has been considered in detail and are discussed in Appendix E.

4.1.3 Sensitivity Calculations

Analysis of the FEPs indicates several aspects that are both uncertain and to which the performance of the system may be sensitive to. Calculation cases have been defined to explore these factors and inform on areas in which further analysis may be required in future iterations of the PostSA. The key areas of interest are related to the flow and transport of contaminants through the main barrier to their release to the surface, the Facility itself, and the inventory of radionuclides that may remain in the Facility.

Inventory

The contaminant inventory of the NPDDF is fundamental to the potential health effects that might occur in the future. Recognising the importance of this, an approach has been adopted in the Normal Evolution scenario, which uses the inventory based, where possible, on measured and modelled bounding inventory (i.e., the reference inventory from the 3rd Iteration PostSA's NES, updated with information from Porter (2022)).

The importance of the inventory is illustrated with two alternative calculation cases. The first one uses the sampling data collected by CNL during the decommissioning works (i.e. the measured inventory from the

3rd Iteration PostSA's inventory sensitivity case, updated with information from Porter (2022)), while the second one uses the NES inventory multiplied by a factor of two.

Sorption

Sorption is the ratio of the concentration on solid to that in solution in a saturated medium, and controls the rate at which contaminants can migrate relative to groundwater. The parameter can be very uncertain as it is sensitive to groundwater chemistry and the minerals present to which sorption can occur. Data reviews (e.g., Ochs *et al.* (2016)) show the values vary by differing amounts, sometimes in excess of an order of magnitude. Three alternative calculation cases have therefore been considered to reflect the importance of radionuclide sorption. Reference values used in the PostSA for grout and concrete, as well as overburden and bedrock are reduced in these calculation cases, to illustrate the effects of greater than anticipated contaminant mobility.

Degradation

The Normal Evolution Scenario assumes that everything is degraded after 1000 y post-closure. However, there is an uncertainty associated with the degradation of the barriers and the time at which such process occurs.

The sensitivity case assumes that the barriers are degraded earlier, i.e., the grout and facility structures are assumed to degrade much faster than expected and they are assigned significantly higher hydraulic conductivities than in the Normal Evolution Scenario at 100 y.

Hydraulic conductivity

Groundwater flow velocities in shallow and deep geosphere pathways might change over time, so two sensitivity cases consider increased hydraulic conductivity (and thus flow) compared to the Normal Evolution Scenario in the: overburden fill material between the facility and the river; and in bedrock (near river).

River Dilution Factor

For the Normal Evolution Scenario, contaminant concentrations in river water at Deep River are conservatively assumed to be the same as those at the initial point of discharge of groundwater to the river at NPDDF. Contaminant concentrations at Ottawa are determined by the ratio of river flow rate at Des Joachims station (immediately upstream of NPDDF) and the reported flow rate measured at the Britannia hydrometric gauge just downstream of Gatineau, giving a dilution factor of 0.658.

To reflect the uncertainty in river flows, as river characteristics may vary throughout the year due to seasonal patterns and climate changes, a sensitivity case is considered with a smaller dilution factor than the one used in Normal Evolution Scenario.

Receptors

The Normal Evolution Scenario considers a range of receptors and age groups, including resident (adult, child, infant), hunter (adult, child, infant), offsite resident (adult, child, infant), and Indigenous receptor based

on the AOPFN Diet study (Fediuk *et al.,* 2021) (represented by an adult receptor, but including the "child" higher incidental soil ingestion rate identified by Indigenous feedback).

To examine impacts to a very conservatively characterized receptor, the sensitivity case considers a self-sufficient Indigenous receptor whose exposure characteristics bound the dietary and lifestyle of Indigenous community in the area (based on the results of the lifestyle surveys in SENES, 2014). All age groups are assumed (i.e., adult, child, and infant) using a high "child" incidental soil ingestion rate.

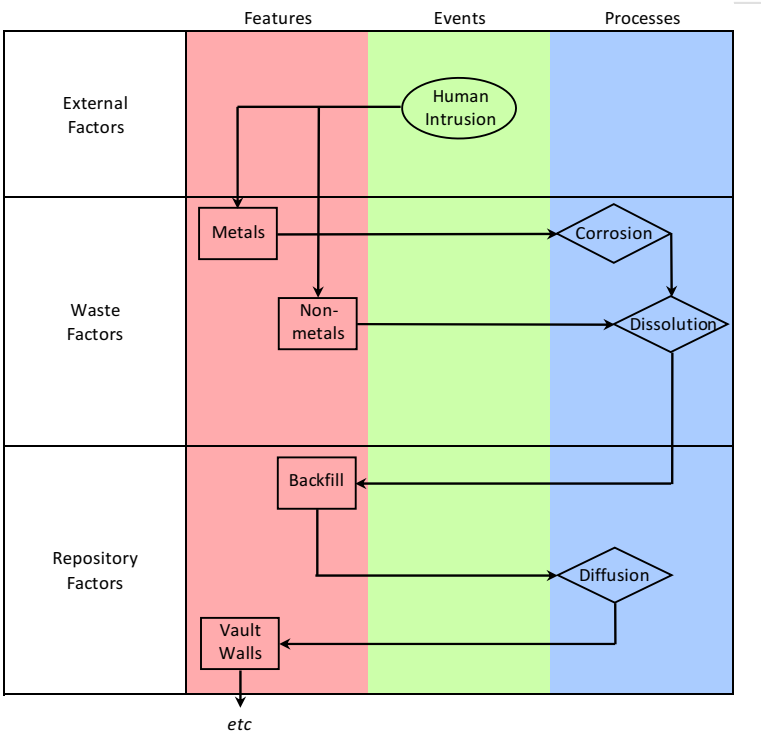
Each of these receptors has been considered in detail and discussed in Appendix E.

4.2 Models

4.2.1 Model Development Process

The FEPs are used to develop the models that represent the NPDDF and its environment as well as the scenarios. Models are developed after the scenarios, as the latter will determine some aspects of the models. The conceptual model development process is also based on IAEA's guidance (IAEA, 2004). The approach involves determining the significant FEPs and their linkages (see Figure 4-1). The FEPs are organised into groups concerning: "external" factors (related to scenarios); contaminants and waste; the Facility; the geosphere; and the "biosphere" (the surface environment). The FEPs identified as being potentially significant to the PostSA have been identified and used to define the conceptual model.

Figure 4-1 Process for Development of Conceptual Models



The FEPs are used to determine the physical components of the system (the "media") and the processes that can act on/between them (primarily related to contaminant transport). The outcome is a network of media that are connected by processes, which constitutes the conceptual model. This provides the basis for a mathematical model which can quantify the size, scale and characteristics of the media, and the dynamics of the processes operating between them.

4.2.2 Waste and Facility Model

Model Components

The Facility comprises the radioactive material within the NPDDF structure, the grout backfill within the structure, and the structure itself. This part of the model also includes the infill between the NPDDF structure and the surrounding bedrock and overburden. The different types of metals, concrete, and other contaminated materials need to be represented separately, as the contaminants will be released at different rates from each. The conceptual model therefore needs to represent:

- the Calandria, distinguishing between aluminum, carbon steel, stainless steel and Zircaloy;
- the activated concrete walls of the Reactor Vault;
- surface contamination present on surfaces of structures that will remain in the various rooms of the NPDDF;
- the existing NPDDF concrete structure, including its geometry and the presence of different "rooms";
- the grout backfill added to the NPDDF; and
- infill surrounding the NPDDF (assumed to be concrete).

Geometry

The metal wastes (the reactor vessel) are of complex geometry. For the purposes of the PostSA, the most important factor is the surface area from which corrosion can take place. By simply taking the total mass, and an average thickness of metal plate, this area can be estimated, and the model represents the metals in this way. The rate of release of contaminants is determined by the concentration in the metal, the surface area and the metal's corrosion rate (in m y^{-1}). Corrosion is modelled for stainless steel, carbon steel and zirconium, with a metal-specific corrosion rate that is appropriate for the anticipated conditions in the Facility. (Aluminum will corrode very quickly within the alkaline conditions in the NPDDF, and so contaminants associated with this material are assumed to be instantaneously released.)

The geometry of the Facility structures is also important in terms of the timing and rate of release of contaminants. A simplified geometry based on the design drawings is adopted for the PostSA in which the main components of the NPDDF are represented by a number of cuboids (in some cases multiple cuboids joined together) that represent the main voids in the structure:

- Fuel Storage Room;
- Fuelling (Machine) Room;

- Reactor Vault;
- Room to the east of the Reactor Vault;
- Room to the west of the Reactor Vault;
- Dump Pipe Room;
- Boiler Room; and
- Turbine Room.

The location of the components also determines their connectivity. Each is assumed to be surrounded by "walls" (including roof and floor) of varying thickness. For simplicity, it is assumed that the top of the Fuel Storage room, Fuelling Room, Boiler Room and Turbine Room is at the same elevation, which is taken to be ground level. The base of the Fuelling Room and Turbine Room is assumed to be at the same elevation as the bedrock surface. The geometrical arrangement is shown in Figure 4-2, with the key dimensions of rooms and walls marked. The total internal width of all the NPDDF rooms varies depending on the room and depth, as detailed in Figure 4-3 and Figure 4-4. Side walls are assumed to be 0.6 m thick on either side of the Facility. In addition, there is assumed to be a 0.6 m thick layer between the NPDDF outer walls and the native rock which has been infilled.

Figure 4-2 Components of the NPDDF Conceptual Model for the PostSA (Cross Section)

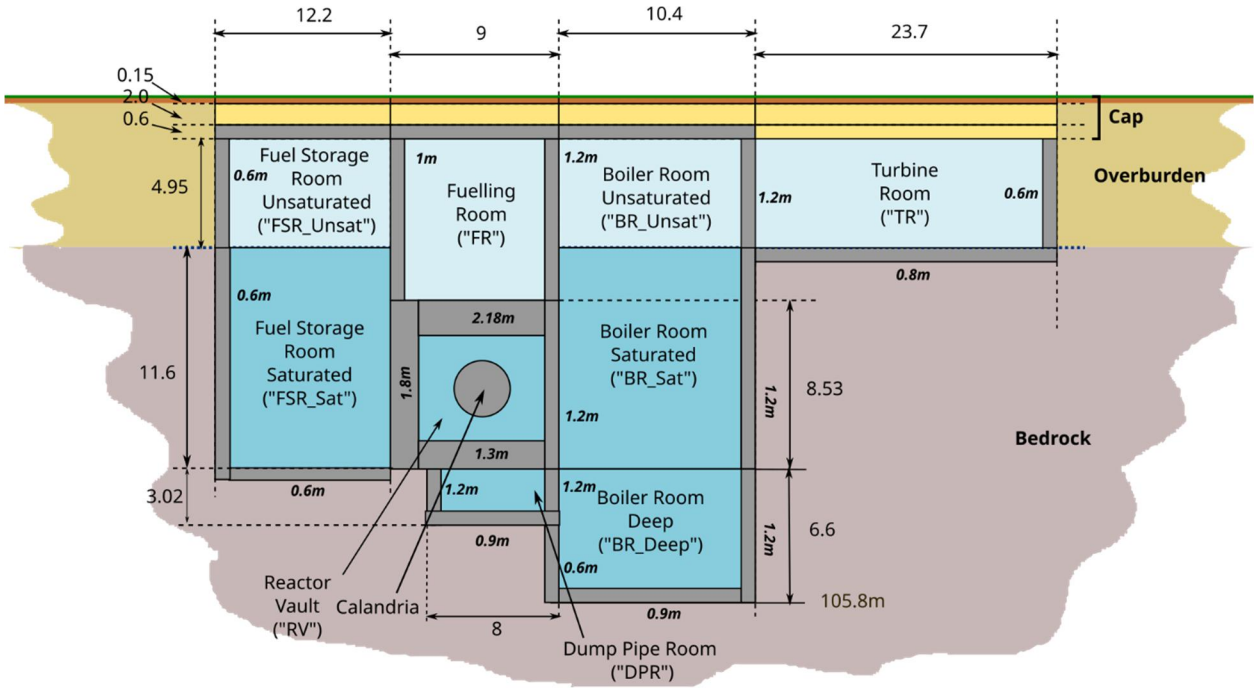


Figure 4-3 Components of the NPDDF Conceptual Model for the PostSA (Plan View) at the three different levels

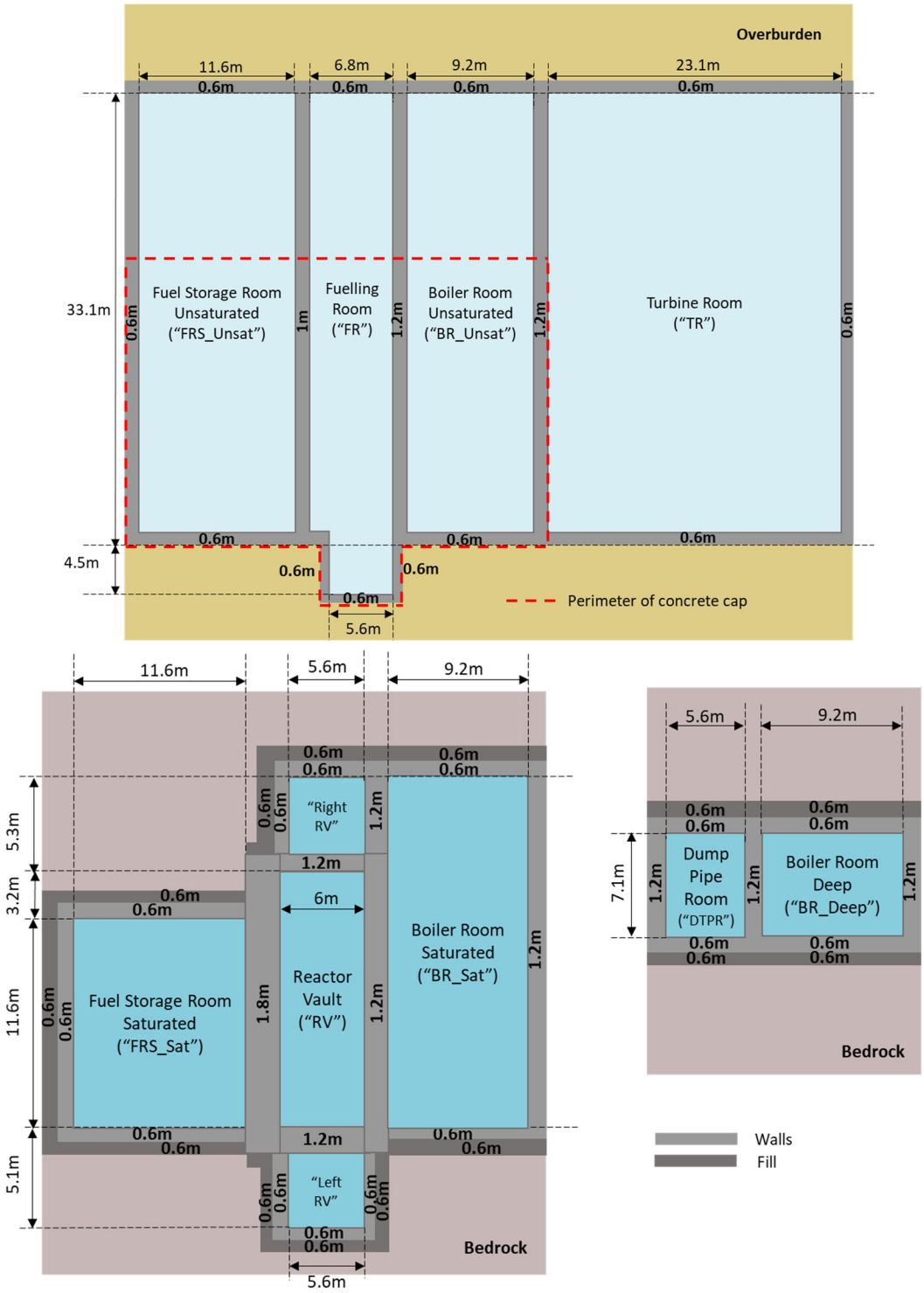
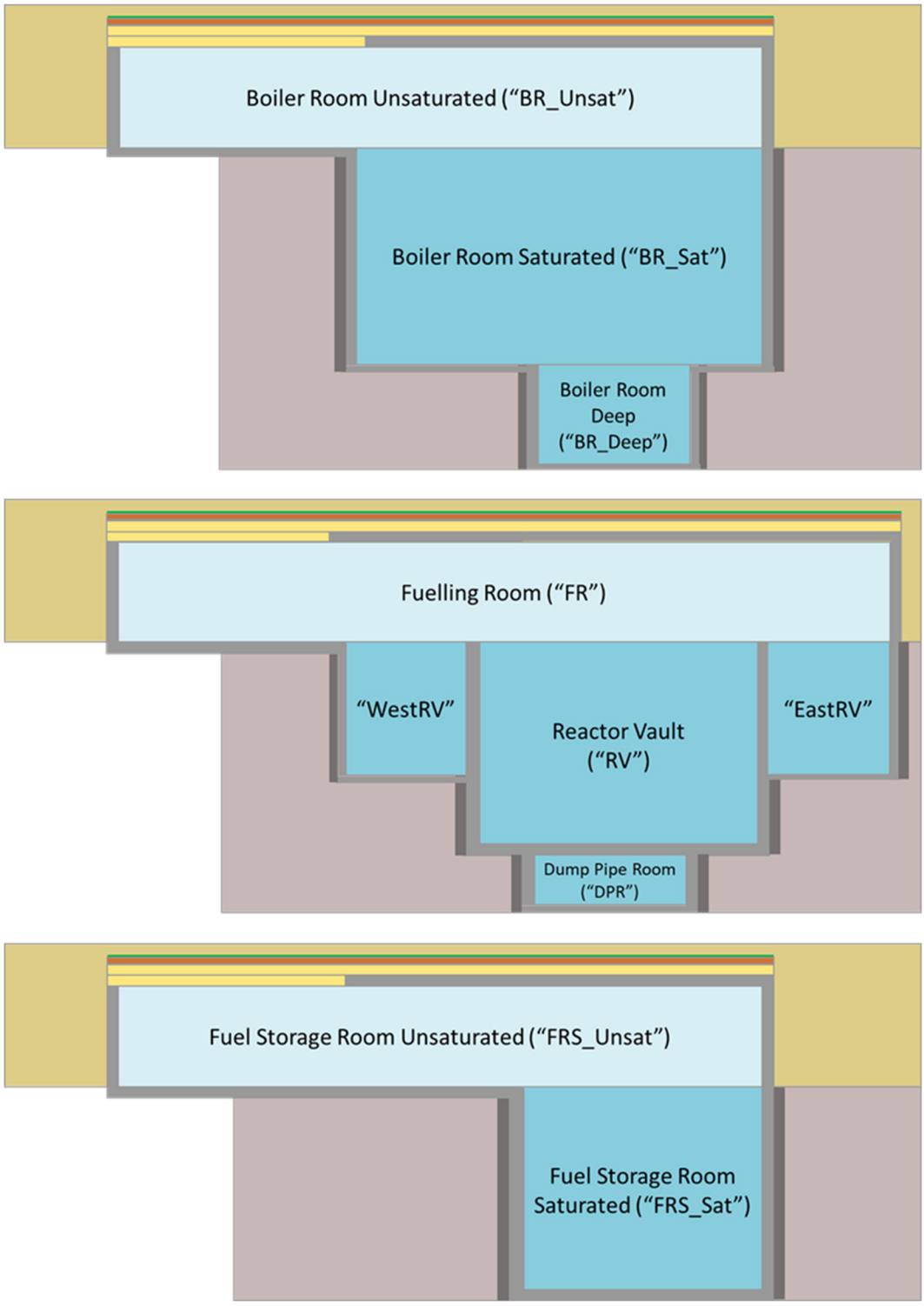


Figure 4-4 Configuration with Depth of the Components of the NPDDF Conceptual Model for the PostSA (facing downstream/north)



Degradation of the Structure

The concrete and grout degrade both physically and chemically. Chemical degradation (or evolution) of the concrete and grout occurs on a different time scale to the physical degradation process. Chemical degradation of grout and concrete is due to the chemical interactions between the water passing through these materials and the chemical constituents of these materials. Thus, this process is controlled by the rate at which water passes through these materials and, hence, is affected by the physical degradation of the grout and concrete that is assumed to occur at 1,000 y.

Concrete and grout, when first cured, produce a high-pH plume, which is derived, initially, from pore fluids in the cements containing strongly alkaline compounds such as NaOH and KOH. Such pore fluids are not in chemical equilibrium with the surrounding pore water. As pore water moves through cementitious materials, dissolution and precipitation reactions occur. The pH will change in steps as it will be constant until a particular mineral phase (e.g., portlandite) has been completely dissolved. High pH corresponds to high sorption, so changing the pH in steps is conservative because the pH decreases as soon as a mineral is dissolved rather than gradually decreasing once the mineral has dissolved.

The chemical degradation of cementitious materials is an important process to represent, as it results in changes to the pH and dependent properties like sorption coefficient. For the PostSA modelling of concrete, four characteristic phases are represented (based on Berner (1992)):

- Stage I – 'fresh' cementitious material with pH 12.5-13;
- Stage II – partially degraded cements, with portlandite partially removed by leaching;
- Stage III – portlandite removed, with properties controlled by Calcium-Silicate-Hydrate (CSH) gel (pH < 12); and
- Stage IV – the alkalinity provided by the grout and secondary calcite is completely lost and pH returns to the background value.

These phases are related to the integrated flow of water through the concrete. Stage I ends after around 100 flushes of the porespace; Stage II ends after 1000, and Stage III is complete after around 7500 flushes. Stage IV is assumed to then persist indefinitely. Concrete is assigned specific properties for each phase.

The BFS/PC grout intended to be used in backfilling the NPDDF evolves differently to concrete due to differences in its formulation. As there is a low proportion of PC, it has cautiously been assumed that Stage I does not occur as there are limited alkali (Na and K) species present to be leached, and Stage II is also assumed not to occur, as there is limited portlandite. Therefore, only Stage III behaviour occurs, which lasts until depletion of CSH gel, at which point secondary solids (such as calcite) or residual materials determine pH (sometimes referred to as Stage IV (Ochs *et al*., 2016)). Chemical modelling (Arcadis & Quintessa, 2020c) has been used to understand the pattern of physical and chemical changes to the grout as it ages; in particular, the more subtle variation in pH. The Arcadis & Quintessa (2020c) work has been used to determine an alternative pattern of chemical evolution to be modelled for the grout, with six rather than four stages (Stages A – F). Values for grout, including porosity and sorption coefficients, have also been assigned to each grout degradation stage.

The number of pore flushes needed to degrade concrete and grout depends on the groundwater composition. In the NPD, some water entering a room has already passed through another room. This "conditioned" water is less effective in degrading concrete or grout than "fresh" groundwater and so more pore flushes would be needed to degrade the concrete or grout. This effect is - conservatively - not accounted for in model calculations. Consequently, the duration of each Stage is underestimated in the model; because pH decreases with time, the duration of high pH conditions is underestimated in the model; and since high pH conditions correspond to high sorption, the sorption properties of the concrete or grout are underestimated in the model (meaning the model is more likely to overestimate releases from the facility).

The timing of the transitions between the degradation stages for the grout and concrete is calculated for each room, using the AMBER model, as it depends on the integrated flow of water through the room. This in turn is dependent on the geometry of the room and the water flowing in and out of each face. The timescales are presented for the Normal Evolution Scenario in Section 5, and further details are presented in Appendix E and Appendix G. Physical degradation of the concrete is modelled on a separate timescale as this is assumed to be controlled by cracking due to internal and external stresses. Cracking is assumed to increase the hydraulic conductivity from an undegraded to degraded state at a defined time.

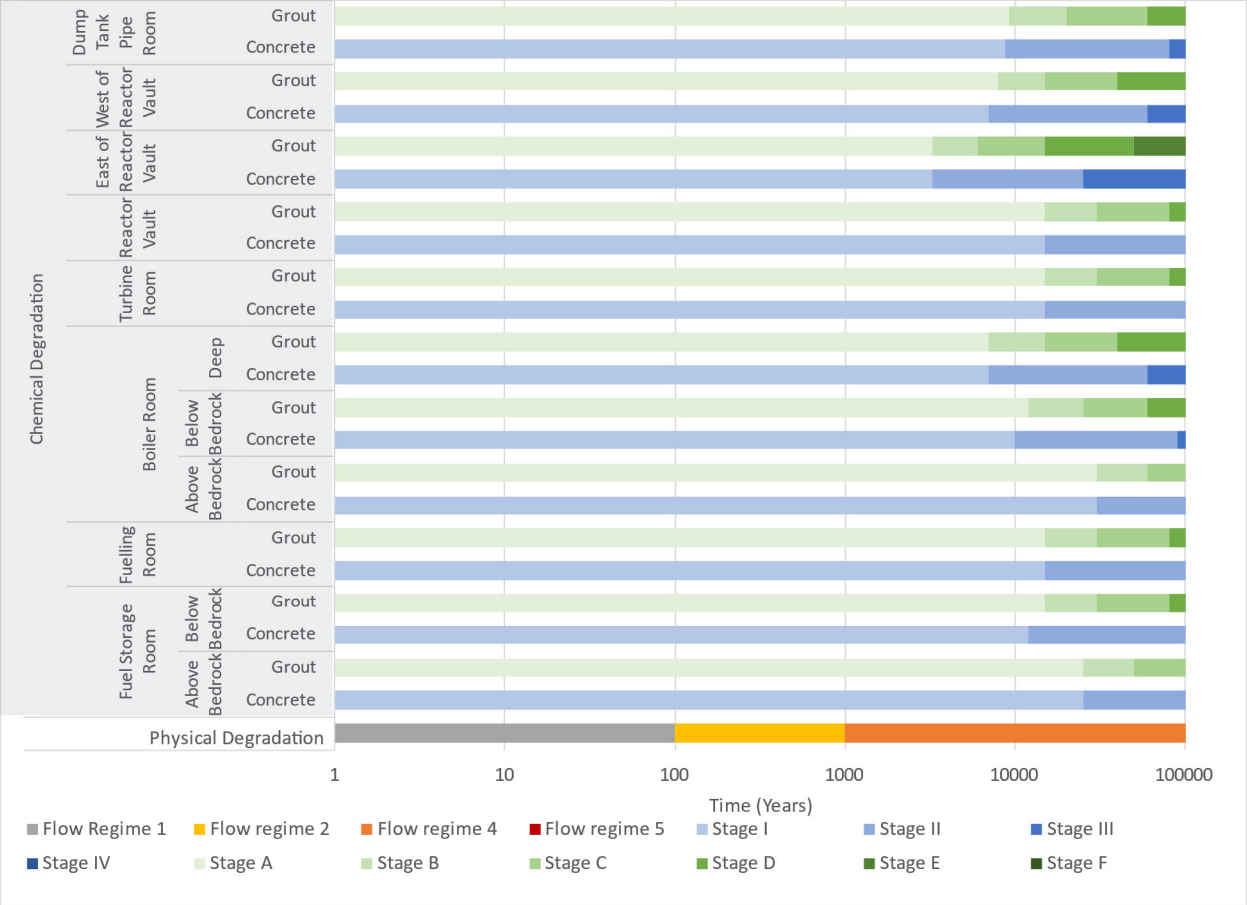
Arcadis & Geofirma (2023b) has calculated water flows through the NPDDF for undegraded and degraded concrete and grout. These water flows are used directly in the AMBER model. Table 4-1 shows the assumed hydraulic conductivity of grout for each of the flow regimes and outlines the times at which each regime is assumed for the three cases with differing degradation models. Figure 4-5 illustrates the timelines for degradation of each of these cases.

Specific aspects describing the chemical and physical degradation of the structure have been considered in detail and are discussed in Appendix E.

Table 4-1 Physical Degradation Timescales

Flow regime	Time at which flow regimes begin			Hydraulic conductivity of grout (above-bedrock) (m/s)	Hydraulic conductivity of grout (Below-bedrock) (m/s)
	Normal Evolution Scenario	Rapid Degradation Case	Extreme Degradation Case		
Flow regime 1 (undegraded facility with tile drains)	0 y	0 y	0 y	6.3E-10	6.3E-11
Flow regime 2 (undegraded facility with degraded cap and tile drain failure)	100 y	-	100 y	6.3E-10	6.3E-11
Flow regime 4 (degraded facility with tile drain failure)	1000 y	100 y	-	1E-08	1E-08
Flow regime 5 (extremely degraded facility with tile drain failure)	-	-	1000 y	1E-06	1E-06

Figure 4-5 Timeline of Chemical and Physical Degradation in the NES

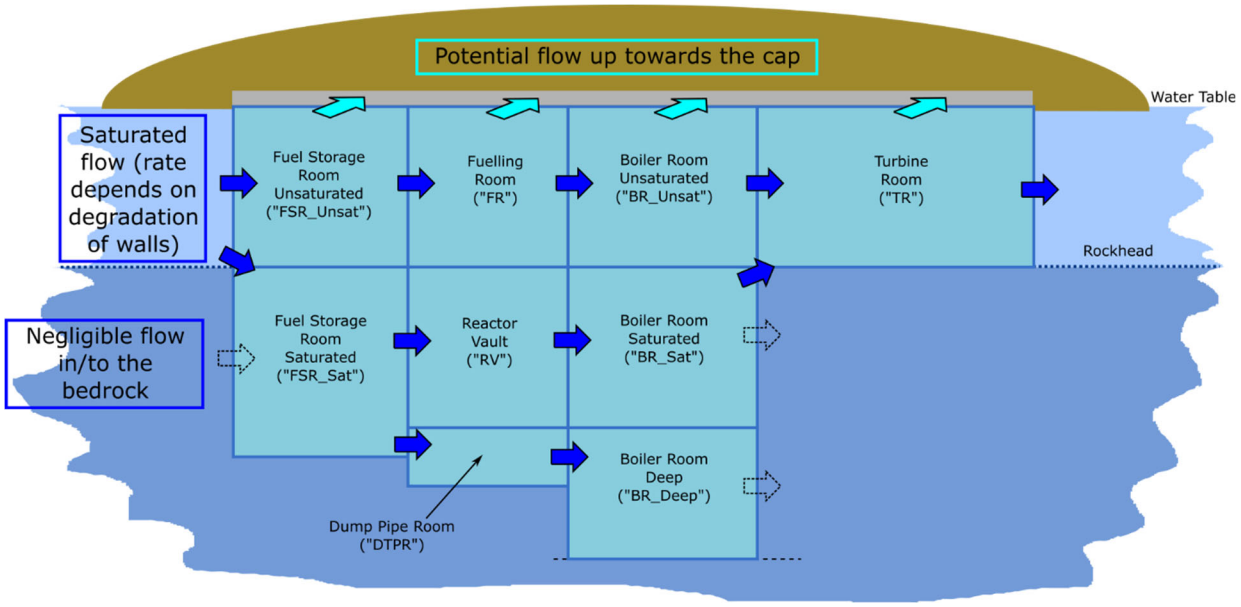


Note: All other scenarios and calculation cases have the same pattern of physical degradation as the Normal Evolution Scenario, NES.

Contaminant Release and Transport

While the vault is resaturating there will be a net inflow of water into the NPDDF. Once water is present in the NPDDF, and in contact with contaminants, they may be released by advection and diffusion. Diffusion will occur radially from the source of contaminants, while advection can occur in any direction, depending on the pattern of groundwater flow through the Facility. However, the general direction of groundwater flow in the vicinity of the NPDDF is towards the Ottawa River (Figure 4-6).

Figure 4-6 Illustration of the Groundwater Flows through the NPDDF



Sorption will occur within the grout backfill and Facility structure, determined by the prevailing chemical conditions. Advective transport is the principal method by which contaminants migrate. The rate of transport is also dependent on the integrity of the concrete cap (and thus its ability to deflect infiltrating water), a time-dependent factor. Sorption also applies as all rooms are filled with grout.

4.2.3 Geosphere

Geosphere Media

The geological environment within which the Facility sits has a relatively simple structure. A broadly homogeneous loosely compacted overburden (sand, gravel and larger cobbles) overlies weathered bedrock. Within both media are regions that have been disturbed as a result of the NPDDF construction (e.g., the excavated bedrock, buried drains, etc.). The conceptual model therefore includes:

- undisturbed overburden;
- disturbed overburden;
- weathered bedrock;
- pipe trench;
- tile drains.

Groundwater flow modelling (Arcadis & Geofirma, 2023a) indicates the role of the overburden and weathered bedrock, as well as the pipe trench and tile drains in the transport of contaminants released from the NPDDF. All are explicitly represented in the model.

Geometry

The geometry to be represented in the PostSA focuses on the pathways for contaminated groundwater migration from the NPDDF. These are inferred from the detailed groundwater flow modelling (Arcadis & Geofirma, 2023b) which indicates four significant groundwater pathways:

- tile drains;
- overburden;
- cooling pipe trench; and;
- saturated bedrock.

This concept is illustrated in Figure 4-7.

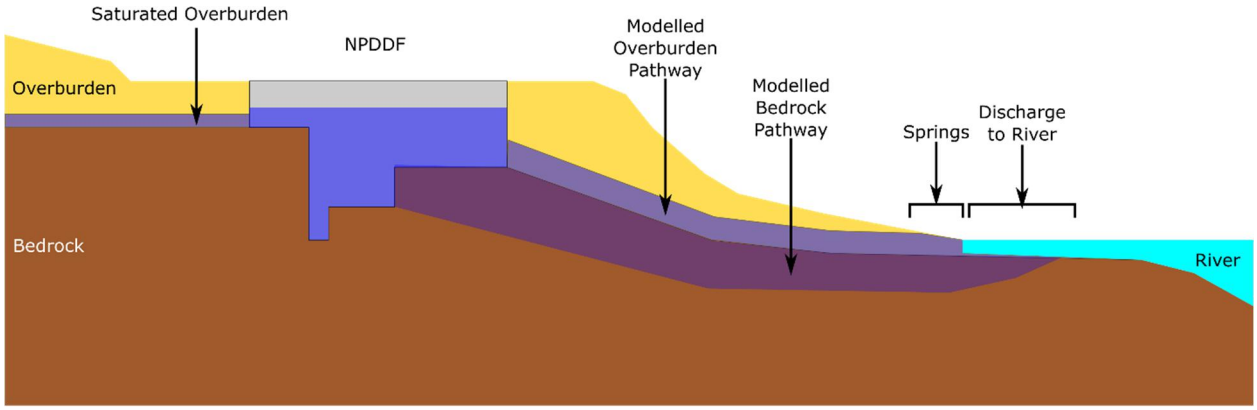
Contaminant Transport

In each of the pathways, the main mechanism for contaminant transport is advective water flow, but there are specific characteristics of each pathway.

- Overburden and Cooling Pipe Trench: The groundwater flow from the parts of the Facility in the overburden is expected to primarily flow via this pathway. Advection is the dominant transport mechanism and there will be sorption on the fill. Contaminated groundwater flowing through the overburden is expected to be released via springs close to the shore, while the contaminated groundwater flowing through the pipe trench is released at the shore.
- Tile drains: While functioning, a portion of contaminants released from the Facility are assumed to be captured by the drains and transported directly to the shore. Since the tile drains are modelled as overburden, it is assumed that there is sorption along this pathway. The tile drains are assumed to fail immediately after the institutional control period and thereafter cease to constitute a pathway. After the tile drains have failed, the majority of contaminated groundwater migrates either via the overburden or cooling pipe trench, while a minor portion migrates through the bedrock.
- Bedrock: The groundwater flow from the parts of the Facility within the bedrock is expected to flow via this pathway. Advection is the dominant transport mechanism and there will be sorption within the rock. Contaminated groundwater is expected to be released to the river bed sediment.

The volumes of water flowing via these pathways is time-dependent, being related to the condition of the tile drains and the condition of the engineered structures of the NPDDF. The volumes flowing through the Facility are obtained from calculations by Arcadis & Geofirma (2023b). For the geosphere, groundwater velocities have been obtained from Arcadis & Geofirma (2023a,b) and combined with simple assumptions regarding the dimensions of the pathways.

Figure 4-7 Location of Groundwater Pathways



4.2.4 Biosphere

For the Normal Evolution scenario, the main contaminant release pathway to the biosphere is via groundwater discharge to springs and the river bed sediments adjacent to the site, from where contamination may pass into the river water. The biosphere conceptual model therefore includes a range of FEPs that encompass a range of biosphere media, processes, and exposure pathways. Conservatively, a small fraction of the groundwater within the NPDDF is also assumed to potentially migrate into the cap and overlying soils.

Model Components

The area of interest includes water bodies and soils, both of which can support biota including humans. The environmental media represented in the model are therefore:

- river water;
- river bed sediments;
- shoreline sediments;
- soil through which springs seep;
- soil used for horticultural production;
- soil used for grazing;
- soil overlying the Facility cap;
- atmosphere;
- plants: horticultural and garden plants, pasture; and
- animals: livestock, fish, game.

River Geometry

The river water and associated sediments, and soil, are split up so as to represent the spatial area of interest, and the fact that humans may preferentially use particular locations. Four potentially exposed groups are considered in the NES, and one additional potentially exposed group is considered in a Sensitivity Calculation:

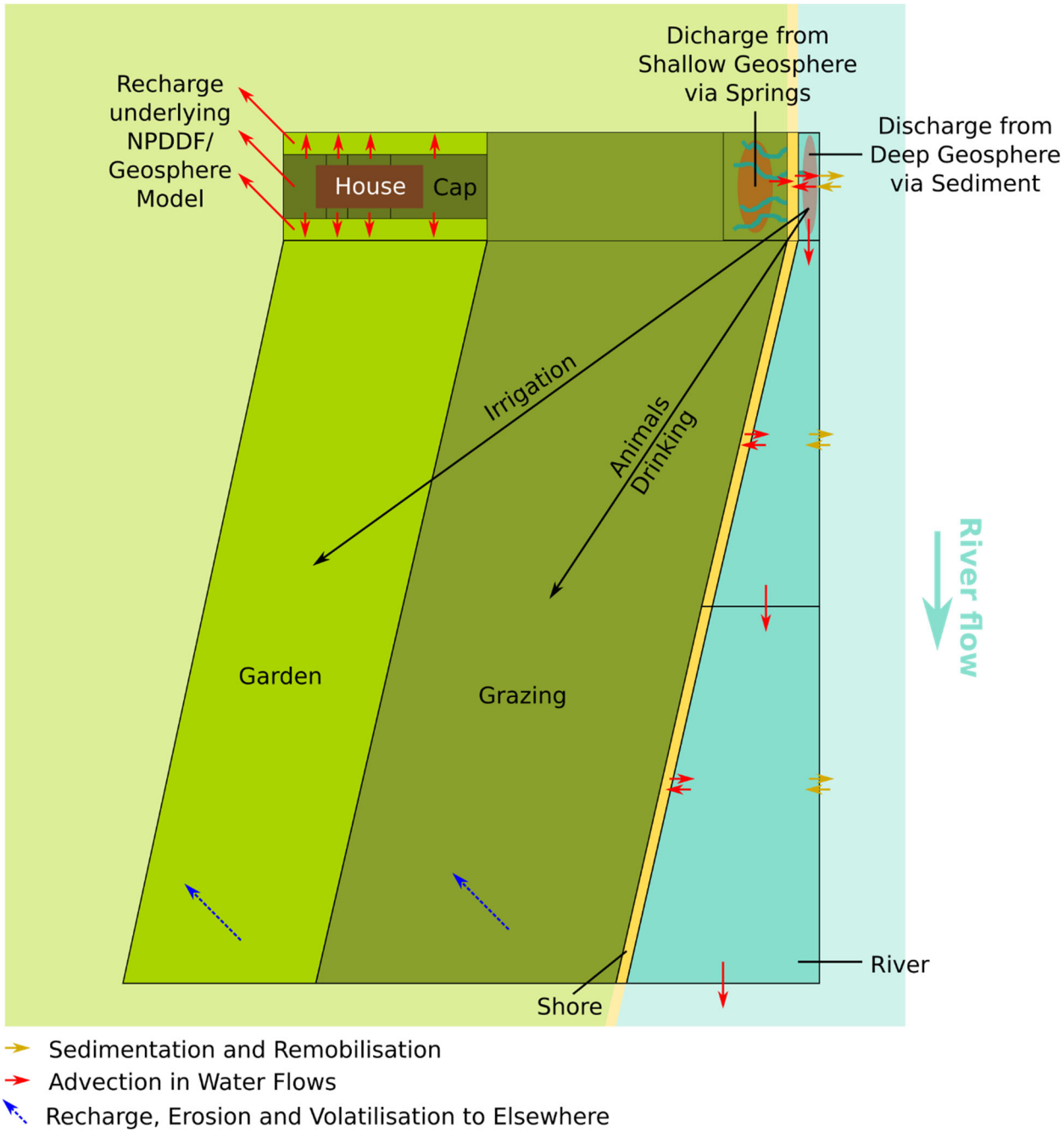
- A highly conservative group that maximises potential exposures. This is reflected by a small household (comprising two adults, a child and an infant) residing directly over the decommissioned Facility and pursuing a self-sufficient lifestyle. This includes use of potentially contaminated river water for domestic and agricultural purposes.
- An offsite group (adult, child, infant), representing people living downstream of the Facility and using water containing radionuclides released into the Ottawa River.
- An Indigenous receptor group represented by adults, following a similar lifestyle to the self-sufficient receptor group, using the area around the NPDDF, including the Ottawa River, for hunting, fishing and gathering wild plants. However, the Indigenous receptor group does not live on the NPD site and, based on the AOPFN study (Fediuk *et al.,* 2021), is assumed to supplement their diet with additional groceries purchased from shops and to make use of medicinal plants.
- A Hunter group, represented by a small number of adults and children making hunting and/or recreational use of the river and the area surrounding the NPDDF.
- A self-sufficient Indigenous receptor group following a traditional lifestyle (considered in a Sensitivity Calculation). The group is represented by adults and children using the area around the NPDDF, including the Ottawa River, for hunting and gathering.

Each of these receptors has been considered in detail and discussed in Appendix E.

The proximity of the river means that a well is not represented as a water source in the Normal Evolution scenario, although this is considered in two Disruptive Event cases (in the first case, a well is located in the overburden and it intersects the water in the pipe trench, while in the second case a well is placed between the facility and the river intersecting the bedrock release plume).

Figure 4-8 illustrates the general location of the biosphere media. The area (in particular that for grazing) would likely have to be larger than that represented to support the food intake requirements by the site resident group, but assuming that all food is sourced from close to the point of groundwater release is conservative. It is also conservative to assume that these areas of land are used extensively for agriculture, as they would require clearing and potentially terracing, as many parts are steep.

Figure 4-8 Illustrative Location of the Site Resident House, Garden/Horticultural Area and Grazing/Forage Area



Contaminant Transport and Exposure Pathways

Modelling transport within the biosphere involves a range of processes which can be found in most temperate surface environments, such as infiltration and recharge of water, irrigation, aeolian erosion, volatilisation of gas, and uptake of contaminants into plants and animals. The Canadian Standards Association has defined reference models for the biosphere for use in the modelling of contaminant transport (CSA, 2022), and these are adopted for the PostSA.

The lifestyle for the site resident group determines which of the contaminant transport and exposure pathways are relevant to consider in the biosphere model. These include:

- use of river water for domestic purposes, including drinking, bathing and washing;
- use of river water to irrigate garden crops, including fruit, vegetables and feed (for animals);
- use of river water as drinking water for livestock (chickens, pigs, sheep, goats, cattle); and
- fishing from the river adjacent to the Facility.

Spring water is intermittent and considered inappropriate for use as drinking water etc. in preference to the very large volume of clean river water close to the discharge zone. However, residents can spend time in the area where the spring water has contaminated soils and receive exposure from those soils.

The self-sufficient Indigenous and the Indigenous groups do not live on the NPD site but use the area around the NPDDF, including the Ottawa River, for hunting, fishing and gathering wild plants. Exposure pathways can include time spent on the shoreline for recreation and fishing; ingestion of fish caught from the river, game and wild foods. The Indigenous group also makes use of medicinal herbs grown nearby via smoking and application to skin. The offsite (down-river) receptor group is only exposed to river water used for drinking, bathing and washing.

4.3 Data

4.3.1 Contaminants of Interest

Radionuclides

Radioactive inventory data is available for a large number of radionuclides. Many of these have relatively short half-lives which mean they will decay while the Facility remains under institutional control, and will not pose a hazard in the postclosure period. Other radionuclides are present with very low activity in the wastes so constitute a trivial hazard. The radionuclide inventory has therefore been screened to remove radionuclides with a trivial risk in the PostSA.

The process of screening involves assuming 100 y of radioactive decay (i.e., timeframe of institutional control), taking this as the minimum period before which exposure to radionuclides could occur. A highly conservative assessment of dose is then made, assuming that the entire inventory is dispersed in water in the Reactor Vault which is then drunk by a person at the reference water consumption rate for an adult person (0.6 m^3 y^{-1}) and a child (0.35 m^3 y^{-1}) (Smith & Jones, 2003). The volume of the Reactor Vault is used as the volume of water. Standard radiation dose coefficients for ingestion by an adult member of the

public are used (ICRP, 2012). Radionuclides are screened out from further consideration if the dose calculated under these extremely cautious assumptions contributes less than 0.001% of the total dose. From this, a total of 45 radionuclides remain for inclusion in the assessment.

- H-3, C-14, Cl-36, Ca-41, Fe-60, Co-60, Ni-59, Ni-63, Se-79, Sr-90, Zr-93, Nb-93m, Nb-94, Tc-99, Ag-108m, Cd-113m, Sn-121m, Sb-125, Cs-137, Sm-151, Eu-152, Eu-154, Ho-166m, Hf-182, Th-229, Th-230, Th-232, U-232, U-233, U-234, U235, U-238, Np-237, Pu-238, Pu-239, Pu-240, Pu-241, Pu-242, Am-241, Am-242m, Am-243, Cm-243, Cm-244, Cm-245, Cm-246

As the final step, an additional 10 radionuclides have been included in the model as they are radioactive progeny of one or more of the radionuclides included above, and therefore will grow in during the assessment timeframe (e.g., Pb-210, Ra-226, Th-228).

Thus, a total of 55 radionuclides are included in PostSA modelling.

Non-radioactive Contaminants

Inventory data is available for lead and mercury, asbestos and PCBs. Asbestos will be encapsulated within the grout backfill and therefore will not be released from the Facility. CNL will remove all PCB ballasts from the facility before or during decommissioning work. As previously noted, organic materials are not explicitly considered in the PostSA as they are unlikely to be significantly detrimental with respect to radiological risk (Arcadis & Quintessa, 2021). The second iteration PostSA illustrated that, even with conservative assumptions, mercury is very effectively contained within the grout in the NPDDF. Therefore, the present iteration of the PostSA focuses on lead in the subsequent sections of this report.

4.3.2 Data Sources and Values

Accompanying each conceptual model is the specific information needed to describe it, i.e., the model data. Consistent with the assessment context (see Section 2.2 and Appendix A), an attempt has been made to define realistic parameter values, where possible, but often including deliberate cautious bias to manage uncertainty, noting that in many cases there are uncertainties. Site-specific model data have been drawn from the data sources referred to in the System Description (Section 3.0 and Appendix B), supplemented with other data sources as required. There is also a range of data that are not site-specific and which are drawn mainly from international compilations of data (e.g., radiation dose coefficients (ICRP, 2012)) and Canadian guidance (e.g., generic biosphere data such as edible crop yield (CSA, 2022)).

Appendix E presents the data used in the models. For each parameter, the basis for the data has been set out, together with an indication of the degree of uncertainty associated with the data. Other information presented includes the units and a parameter name. Data are grouped according to each part of the system: the wastes, the Facility, the geosphere, the biosphere and potential exposure groups. The reference data are used in the assessment of the Normal Evolution scenario. For other scenarios and cases, some of the parameters are modified in order to represent different assumptions. Details of the parameter values used in other scenarios and cases are presented in Appendix E.

4.4 Mathematical Modelling

4.4.1 Method

A variety of mathematical approaches can be used to represent the conceptual models discussed in Section 4.2. There are two main approaches used for the PostSA model.

- Equilibrium models are used where the transport from one medium to another is rapid in the overall timescale of the assessment (e.g., the uptake of contaminants by plants).
- Dynamic models are used for those processes that more gradually transport contaminants through the environmental system (e.g., advection in groundwater).

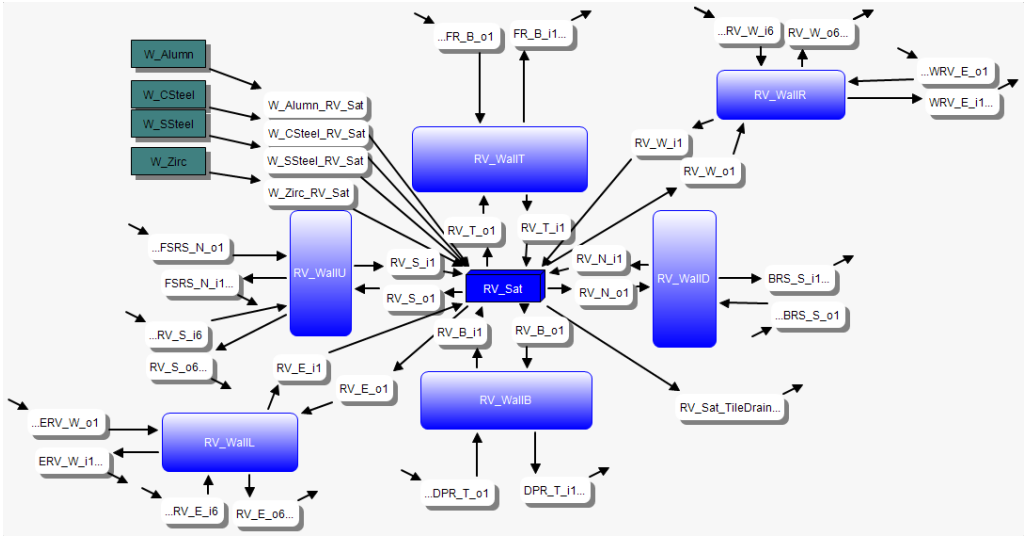
The equilibrium parts of the model can be represented with algebraic expressions (e.g., the dose to a person from ingestion of vegetables is the product of an assumed annual ingestion rate, the concentration of radionuclides in the vegetables at a given time, and dose conversion factors).

Dynamic modelling requires first- and second-order differential equations to be solved. The most common approach used is compartment modelling. This involves representing key media as ‘compartments’ and assuming that the concentration of a contaminant in a compartment at a given time is uniform throughout the compartment’s volume. Compartments are linked by transfer functions that describe the fraction that is moved from one compartment to another in unit time. Radioactive decay and ingrowth are also represented as a rate of a loss (decay) or gain (ingrowth). Figure 4-9 illustrates transfers that represent the release of contaminants by metal corrosion, and flows of water into and out of the NPDDF Reactor Vault.

Because the concentration of a contaminant throughout a compartment is assumed to be constant, a number of separate compartments can be needed to represent parts of the environment in which contaminants gradually disperse. For example, a stretch of river may be split into a number of adjacent compartments (each of which has the same physical properties). Figure 4-10 illustrates how the Ottawa River adjacent to the NPD site has been split into three sections, each with an associated water, sediment and shoreline compartment, with various types of transfer processes between them.

Figure 4-9 Illustration of Part of the Compartment Model of the NPDDF (a) AMBER Model and (b) Structures and Processes Represented

a)



b)

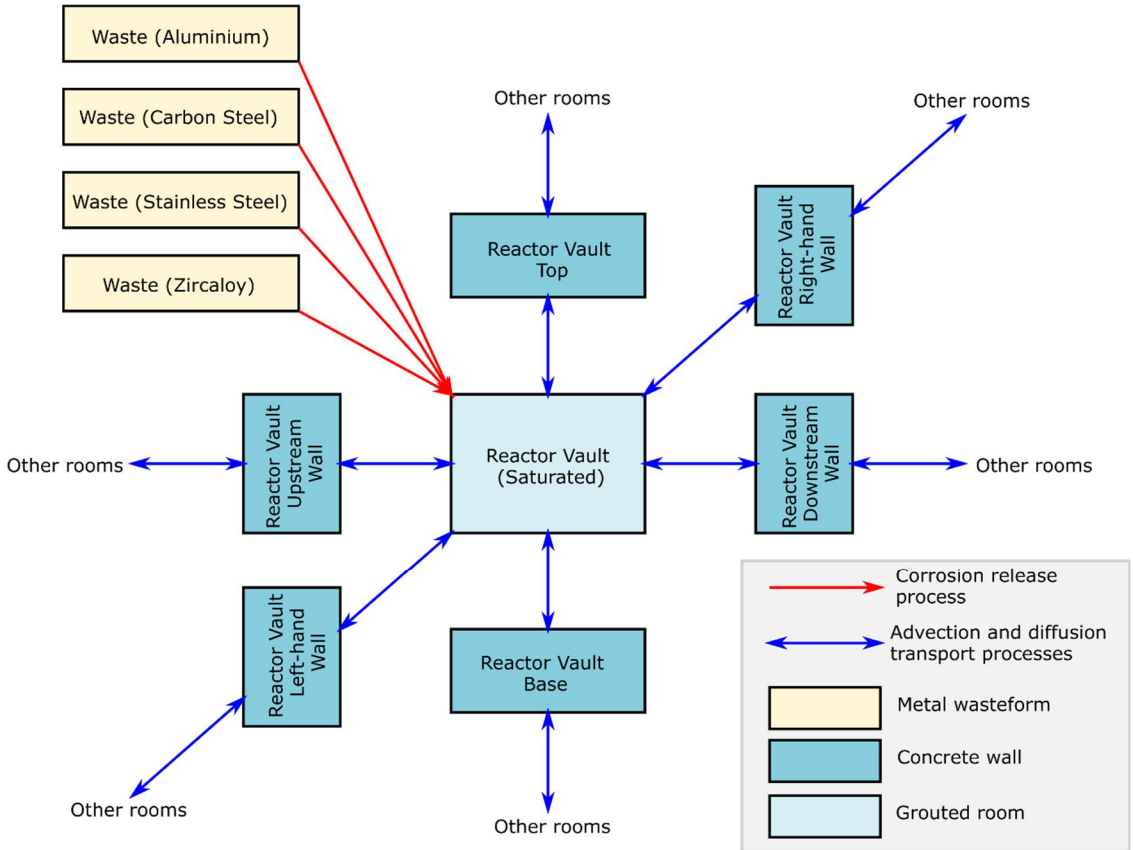
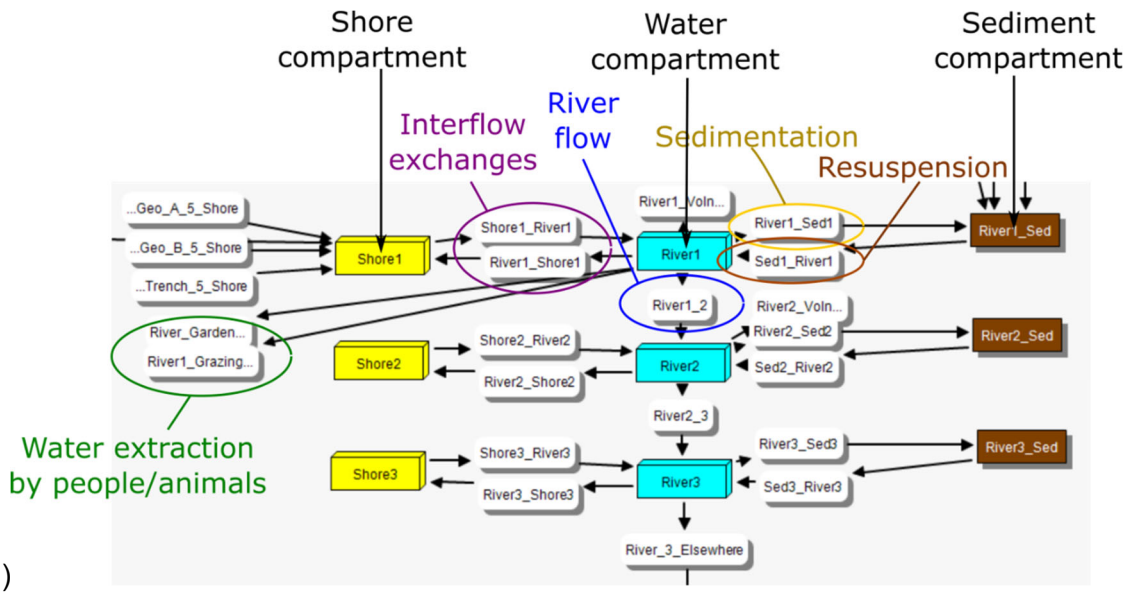
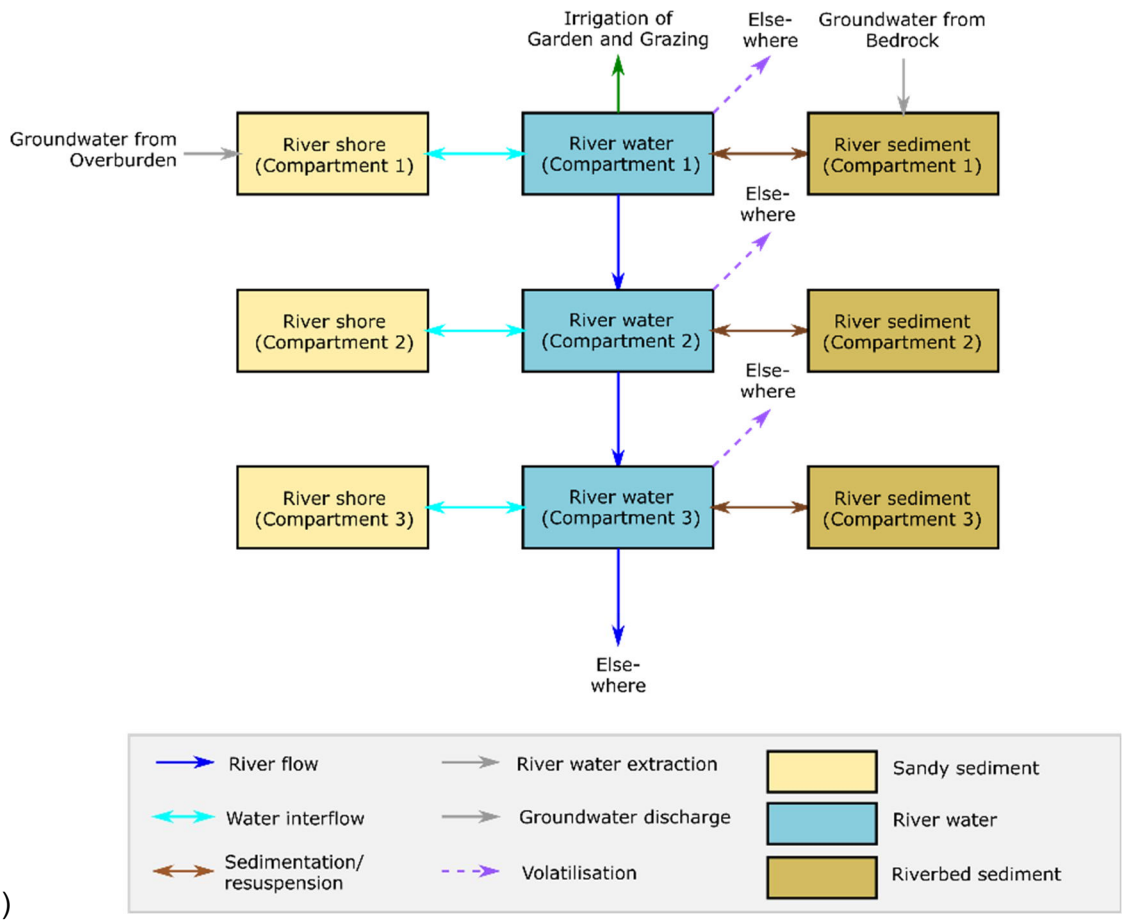


Figure 4-10 Illustration of a Compartment Model for the Ottawa River (a) AMBER Model and (b) Structures and Processes Represented

a)



b)



4.4.2 Code

Modelling Requirements

The identified scenarios and calculation cases (see Appendix D) and conceptual models (Appendix E) make it clear that the assessment-level code needs to represent a wide variety of different features. A range of different natural and engineered media need to be represented, with the properties of the latter changing with time to represent material degradation (physical and chemical). Other aspects of the model require time-dependent events and processes; for example, the capability to switch off the tile drain pathway.

The capability for representing spatially complex features (such as the Reactor Vault, enclosed by walls within the NPDDF, surrounded by a layer of infill) is also important, to ensure that the model is physically self-consistent. Allied to this, spatial properties are important – e.g., the volume of the NPDDF rooms determines the timescale for resaturation.

It is also important for the model to provide an open and unconstrained framework in which the models described in Section 4.2 can be implemented without significant constraint. The specification of transfer rates and other equations needs to be enabled in an efficient way.

Finally, good quality assurance features are needed, along with a strong track record to demonstrate that the code itself is fully verified and validated.

Key Features of AMBER

The modelling requirements are fulfilled by the AMBER compartment modelling code (Quintessa, 2021c). Other similar applications are available, e.g., GoldSim, but AMBER offers greater efficiency in the model development process, in particular the ability to create a spatial representation of the system. AMBER also has features that aid quality assurance of models, such as text-based model files.

AMBER was originally developed for modelling contaminants from radioactive waste repositories and this remains its core area of application and development. AMBER is a very ‘open’ modelling tool that does not prescribe any particular ways of representing processes or geometry of the modelled system, but does provide methods for developing equations and data to describe relevant processes in a time-dependent way.

AMBER is unique in its field in including the capability to represent model components spatially (see Figure 4-11, Figure 4-12 and Figure 4-13); the user is able to define three-dimensional ‘cells’ that can be linked to the model compartments, allowing AMBER to automatically compute key properties such as volumes and the areas of interfaces between compartments. This greatly enhances the self-consistency of the model and reduces the scope for inconsistencies and errors related to the geometry of the model.

Figure 4-11 AMBER Spatial Model of the NPDDF

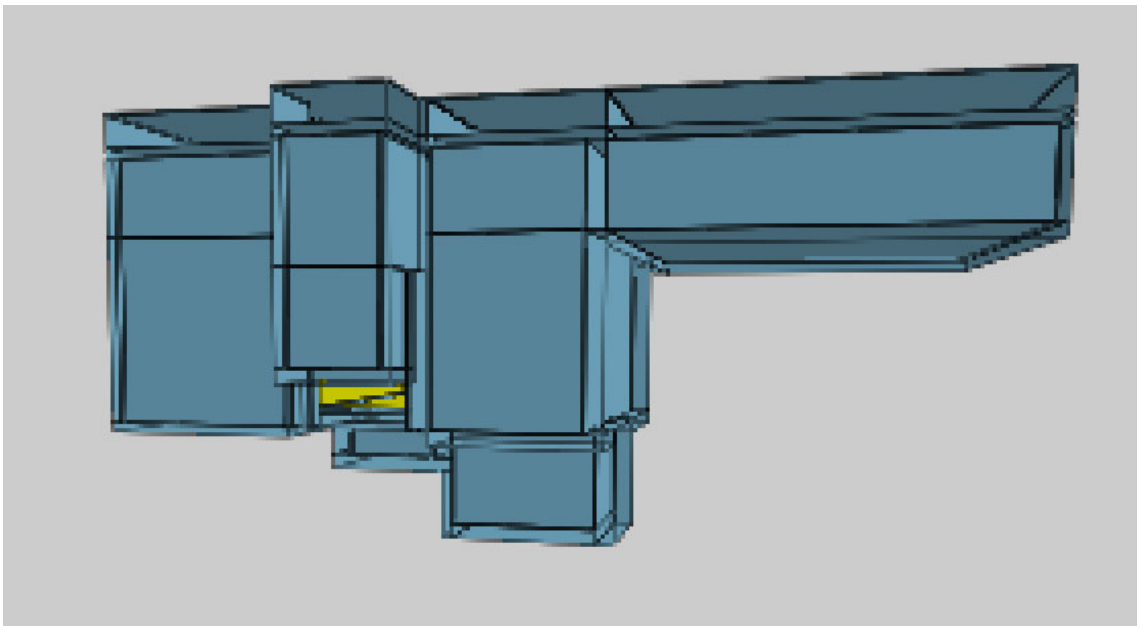


Figure 4-12 AMBER Spatial Model of the Overburden and Trench Geosphere Pathways, Each Split into 5 Sections

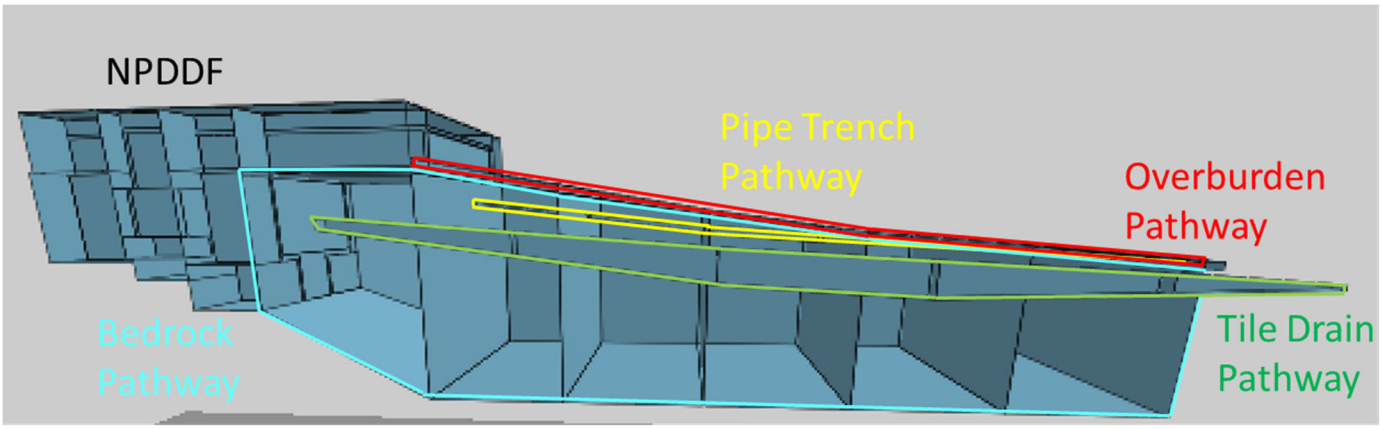
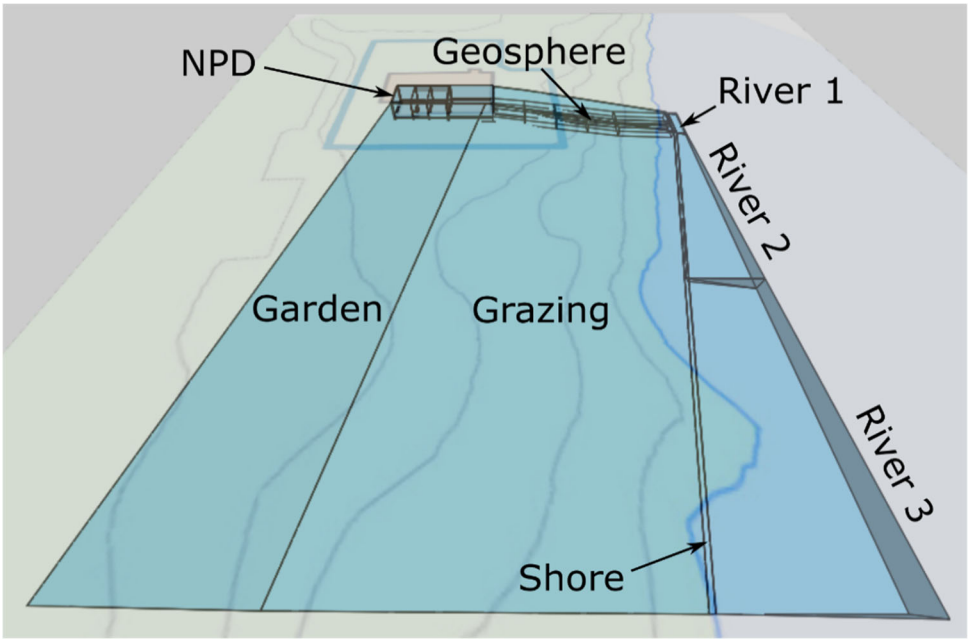


Figure 4-13 Spatial Model of the Biosphere in AMBER



The code is flexible and allows any number of contaminants, compartments and transfers to be represented. The user can define complex algorithms and data sets and can import/export data to facilitate its integrated use with other software tools and databases. In addition to using the graphical interface, AMBER also allows text-based editing, auditing and 'future-proof' recording of case files, with in-built parameter checking and "units' awareness". The code has two fast solvers that permit complex time-varying source terms, environmental properties and transfer processes, which may be linear or non-linear, to be represented.

5.0 RESULTS AND ANALYSIS

This section presents the results of the PostSA. It is organised according to the scenarios and calculation cases that have been assessed. The focus is on the main assessment timeframe of 10,000 y. During the first 100 y after closure, it is assumed that Institutional Controls will remain over the NPDDF. In graphs, this period is shaded yellow to indicate that the controls could mitigate any adverse consequences. Graphs and tables also give values out to 100,000 y to illustrate the potential consequences beyond the main assessment timeframe. To emphasise that these results are illustrative, and are subject to greater uncertainty, the region is shaded grey.

More detailed results are presented in Appendix G.

5.1 Normal Evolution Scenario

The Normal Evolution scenario is a reference description of the most plausible expected future evolution of the disposal system, with conservative bias built into the assumptions. The key interactions are presented in Table 5-1. The following subsections present the key results for the scenario.

Table 5-1 Interactions Assessed in the Normal Evolution Scenario

Environmental Component	Consideration
Air	Inhalation of C-14 volatilised from surface media.
Surface Water	Springs close to the river are not suitable for drinking or other uses but can contaminate soil. River water used for drinking, crop and forage irrigation, bathing and swimming. Fish, shellfish, aquatic plants and wildfowl live in the river. Livestock and wild animals drink from the river.
Soil	“Garden” soil used for growing crops (vegetables, potatoes, fruit) and animal feed. “Grazing” soil used as forage for livestock. Residence in a house built on the Facility cap.
Groundwater	Groundwater transports contaminants from the Facility to the river and to groundwater springs, but is not used by people directly. Groundwater upwelling into the engineered cover may also enter soils adjacent to it.
Sediment	Contaminated groundwater is released in seepages and springs, and through the riverbed sediment to the river. People fishing the river are exposed to the shoreline sediments.

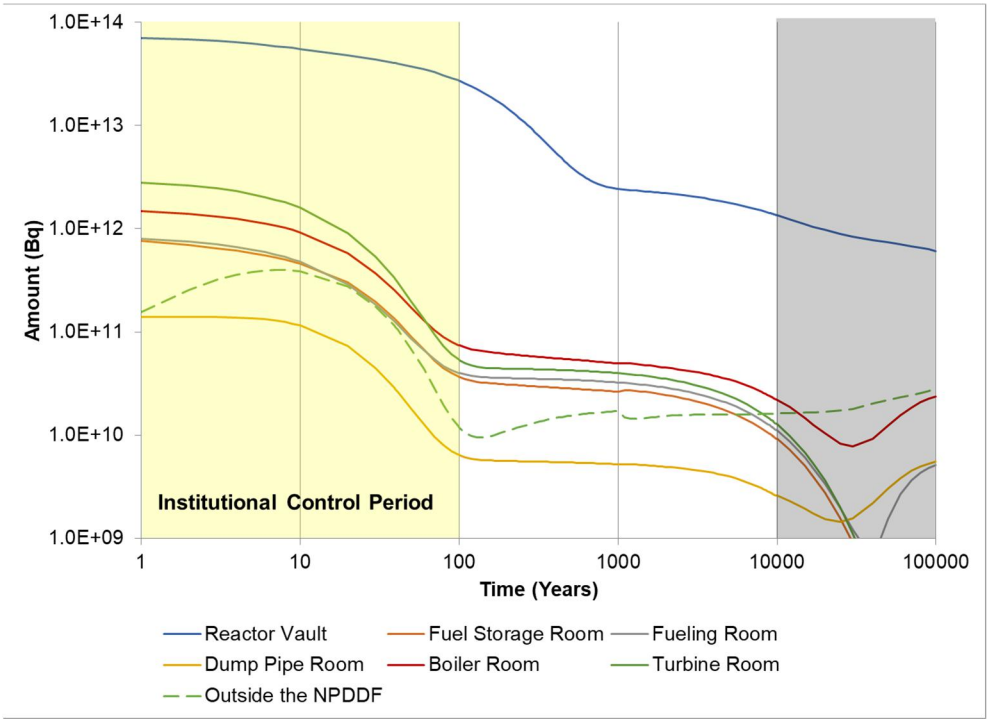
5.1.1 Containment by the Facility

5.1.1.1 Inventory in the NPDDF

The amount of radioactivity within the Facility at any time is determined by the decay of radionuclides and the extent to which the engineered structures and grout has contained the radionuclides. As such, the total activity is an important indicator of the effectiveness of the barriers within the NPDDF to the release of contaminants. Containment is also recognized to be a key safety function for the Facility. The PostSA model shows that the amount of radioactivity within the NPDDF is always greater than the amount that has

been released. By 10,000 y after closure, 99% of the remaining activity in the system is contained within the NPDDF (Figure 5-1). The main factor containing the radioactivity on long timescales is that the majority of the initial inventory in the Reactor Vault is embedded within steels and Zircaloy which corrode very slowly. In particular, the inventory of the Zircaloy components is dominated by longer lived radionuclides, principally Zr-93, Ni-59/63 and C-14. By contrast, the inventory in other rooms is dominated by shorter-lived radionuclides including H-3, Cs-137 and Pu-241. The inventory of these rooms can be seen to fall rapidly over the first 100 y largely due to the decay and release of tritium. By the end of the assessment timeframe, 10,000 y, the total amount of radioactivity in the NPDDF has decreased by more than a factor of 50, from 8E+13 Bq to 1E+12 Bq. Because of the effective containment offered by the engineered barriers, the reduction is mainly a result of radioactive decay.

Figure 5-1 Amount of Radioactivity Within and Outside of the NPDDF



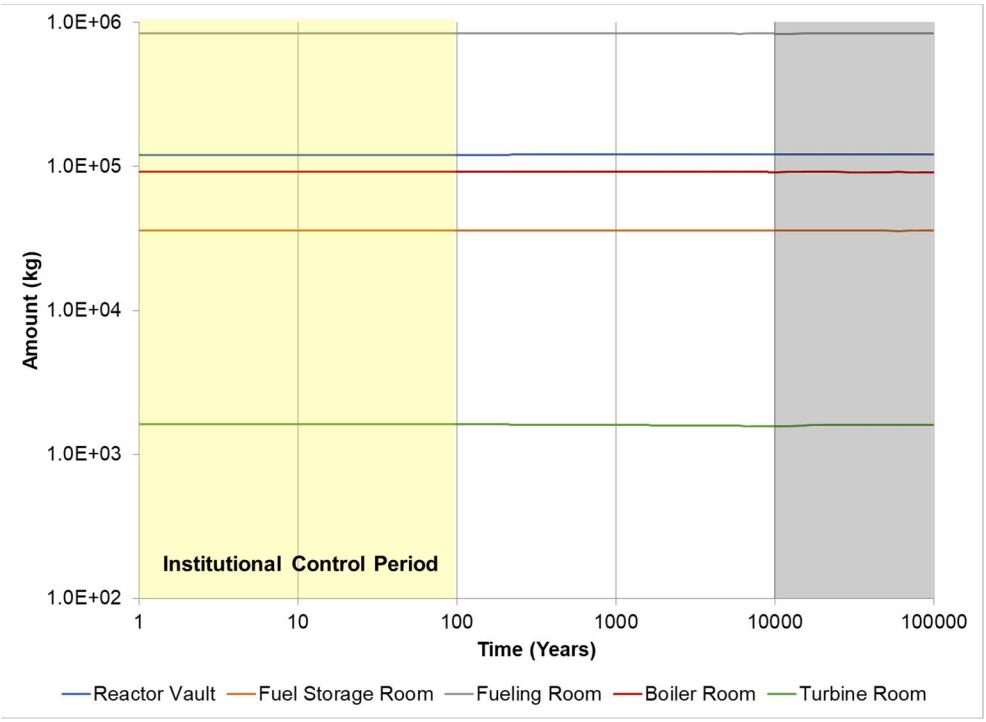
Note: for information on radioactivity outside of the NPDDF see Section 5.1.1.3 which discusses releases from the facility and Section 5.1.2 which discusses contaminants in the environment.

The radioactivity outside the facility rises rapidly at short times due to release of tritium (H-3) and then decreases after 10 years due to decay of the tritium in the environment. Thereafter releases of other radionuclides from the facility increases the radioactivity outside the facility. The NPD structures become more permeable around 1000 y due to degradation resulting in changes in flows and hence change in concentrations (see Figure 5-1).

There is very little transport of non-radioactive lead because of its high sorption and very limited solubility within the BFS/PC grout (see Figure 5-2). Due to its low Portland cement content, the grout's pH decreases relatively quickly and indeed is at around pH 8 for the majority of the grout lifetime. Further details are

presented by Arcadis & Quintessa (2019a). The main sources of lead are the Fuelling Machine Room, Boiler Room and Reactor Vault.

Figure 5-2 Amount of Lead Within the NPDDF



One of the key features of lead is that the large mass that is present means that releases can be solubility-controlled. Furthermore, its solubility is highly dependent on pH. This has been explored by Arcadis & Quintessa (2020c) who has calculated solubility limits for the NPDDF for various concrete and grout compositions.

5.1.1.2 Concentrations in the NPDDF

The average concentration of radionuclides (expressed per total mass of materials associated with each room) in the various rooms in the NPDDF is shown in Figure 5-3. The Reactor Vault, containing the Calandria, is dominant. Figure 5-4 shows the average concentration of key radionuclides in the Reactor Vault. With the exception of Nb-93m, a daughter of Zr-93, all concentrations fall with time, largely due to radioactive decay. Initially, the average total concentration exceeds 2E+07 Bq kg^{-1} but this declines to 3E+06 Bq kg^{-1} after 300 y and 8E+05 Bq kg^{-1} after 1,000 y, as the initially dominant radionuclides decay. The average concentration has dropped to 5E+05 Bq kg^{-1} by 10,000 y.

Figure 5-1 indicates that the amount of radioactivity outside the facility after 100 years has changed an insignificant amount relative to the decrease in the amount of radioactivity inside the facility. This illustrates that the Facility is very effective in containment of radionuclides within the structure thereby allowing for substantial radionuclide decay.

Figure 5-3 Average Concentrations of Radionuclides in the Various Rooms of the NPDDF

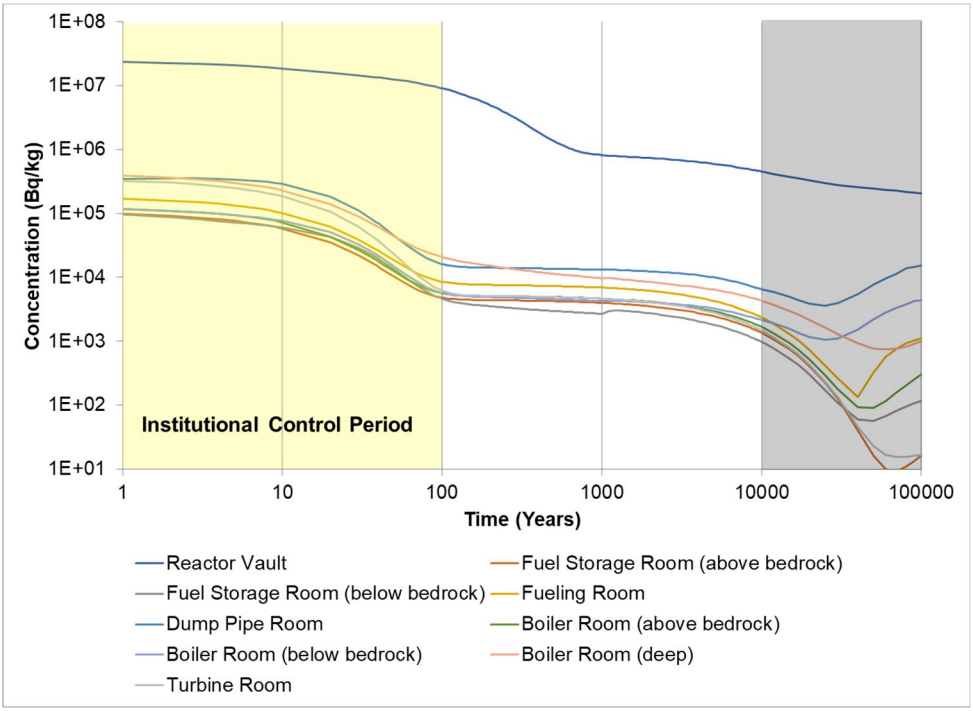
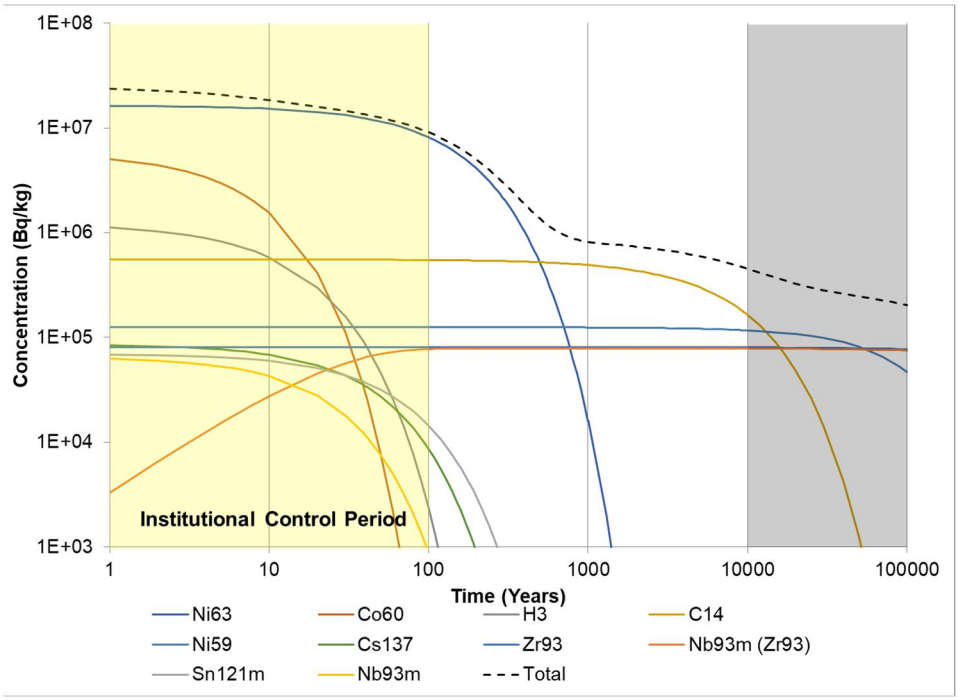


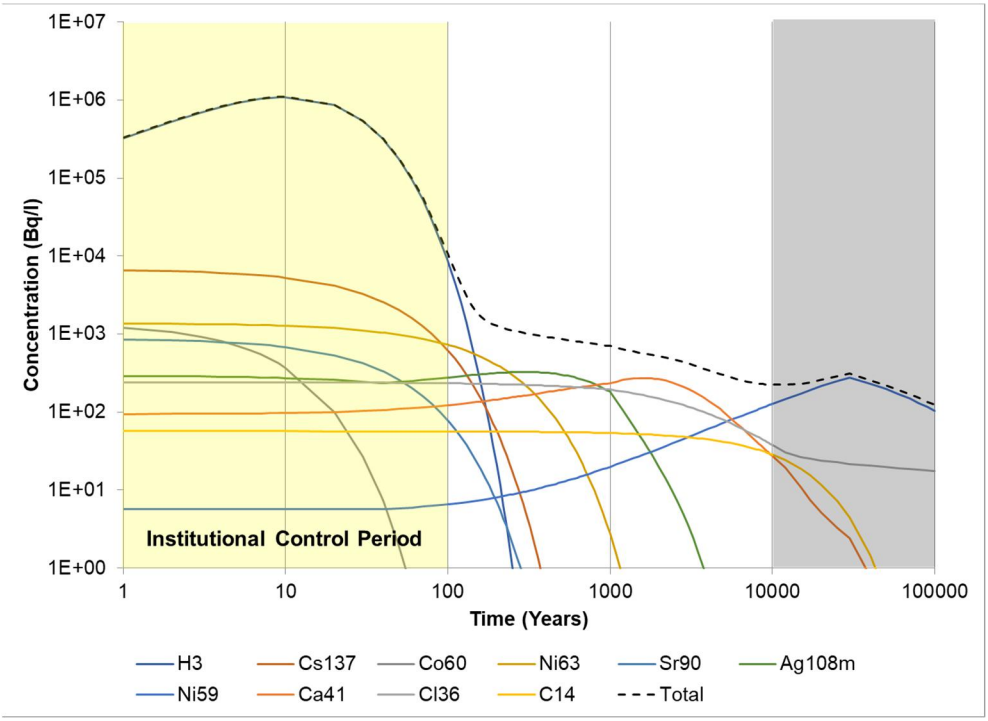
Figure 5-4 Average Concentrations of Radionuclides in Reactor Vault



Note: Radionuclides in brackets indicate the parent of the radionuclide that was present in the initial radionuclide inventory of the NPDDF.

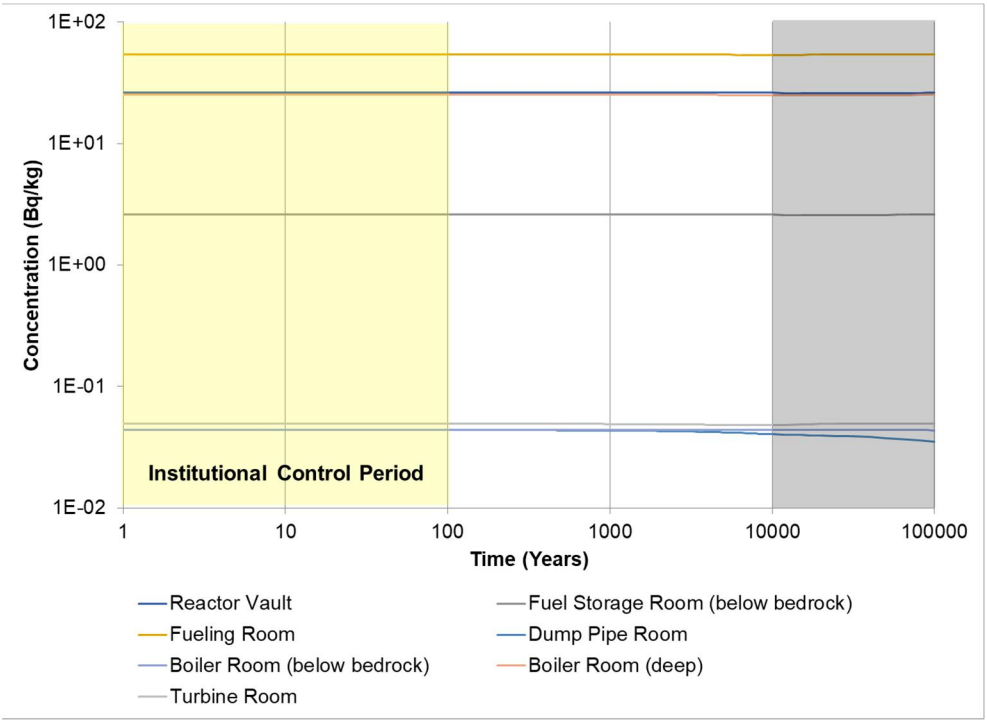
The concentrations in water that fills the Reactor Vault are up to 1E+06 Bq l^{-1}, dominated by different radionuclides through time (Figure 5-5). Initially, tritium is dominant but decays rapidly after 100 y. From 150 to 240 y Ni-63 is dominant followed by Ag-108m up to 800 y. Beyond this, the long-lived radionuclides remain well contained in the Reactor Vault for thousand of years and concentrations in the water remain below 1,000 Bq l^{-1}, with Ca-41 and then Ni-59 being dominant. Concentrations of most radionuclides monotonically decrease, but Ca-41, Ag-108m and Ni-59 can be seen to increase before peaking and then decreasing. This is because these radionuclides are dominantly present in activated metals and are released by corrosion faster than they are released from the Reactor Vault in groundwater. It is only once radioactive decay dominates the rate of accumulation that the concentrations fall.

Figure 5-5 Radionuclide Concentrations in Water in the Reactor Vault



At closure, some lead is present in most rooms, albeit in very much smaller quantities compared to the Fuelling Machine Room and Reactor Vault (the main sources of lead in the NPDDF). The concentrations of non-radioactive contaminants change very little as the chemical conditions in the rooms mean that lead has a very low solubility limit. Figure 5-6 shows lead concentrations through the Facility.

Figure 5-6 Concentrations of Lead within the NPDDF Rooms



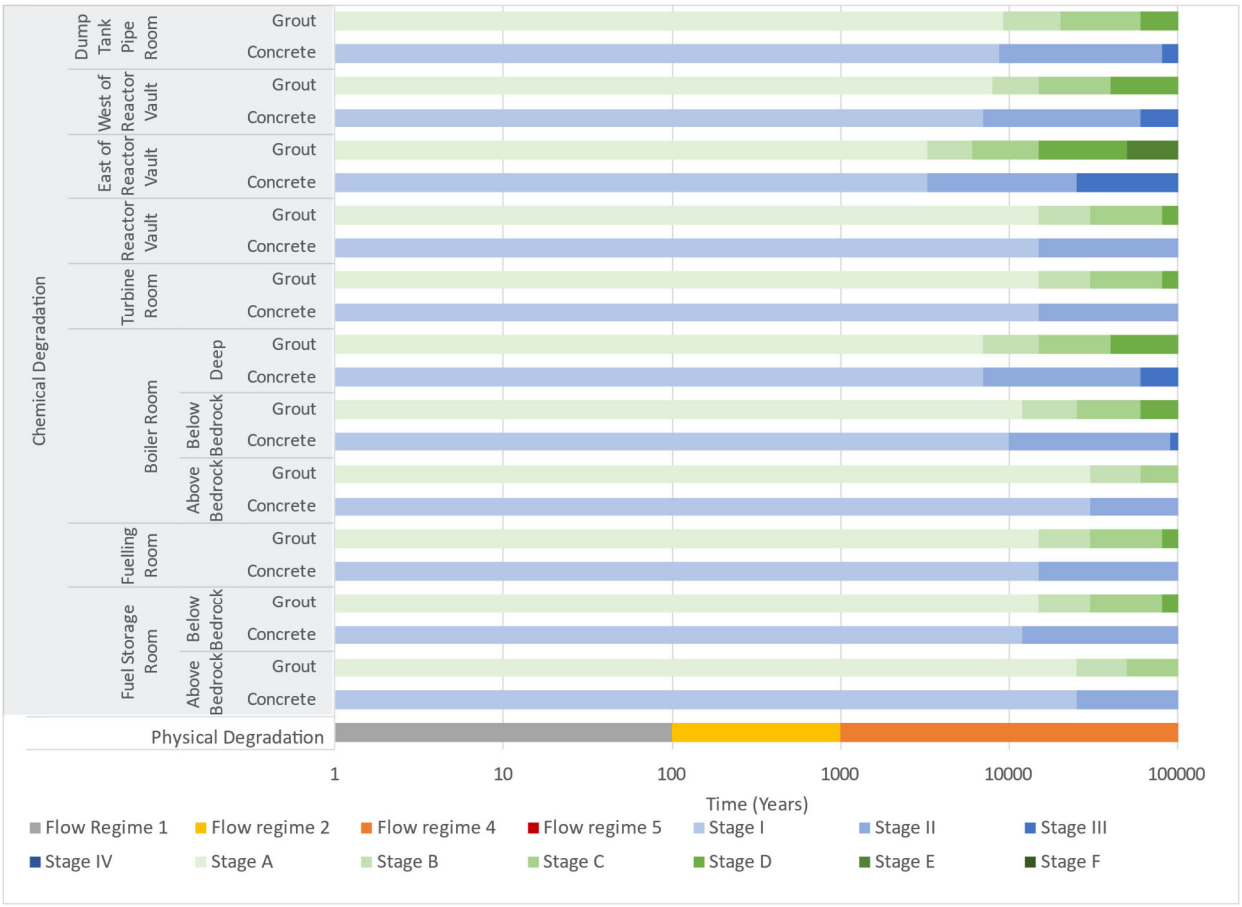
The model illustrates the importance of the chemical regime on the retention or release of radionuclides. As discussed in Section 4.2 and Appendix E, the water chemistry in the Facility is controlled by the large mass of cementitious material. This conditions the porewater to a high pH (initially this can be in excess of 11). The alkaline conditions influence the mobility of the radionuclides and non-radioactive constituents by determining the chemical regime and thus influencing the extent to which they are sorbed (through a variety of chemical processes) to the surfaces of the porous media that characterise the materials in the Facility. Sorption coefficients (from international compilations, discussed in Appendix E) are used to describe the ratio of the element in solution to that associated with solids, for high pH conditions.

Over time, groundwater flowing through the cementitious material will leach its constituents. Berner (1992) describes this process and the characteristic phases of chemical degradation of cement, which can be related to the volume of water that has leached the cement. Arcadis & Quintessa (2019a) has undertaken additional modelling of the leaching process, considering the specific grout formulation that may be used in the NPDDF. This process is used to model the chemical degradation of cement and grout and with it the reduction in pH, and consequent changes to sorption, which are related directly to the volume of water that flows through each room, thereby estimating the times at which the cement and grout reach key degradation states. The model results indicate that the chemical effects of the cement and grout will last for many tens of thousands of years, far outlasting the physical performance of the structures (Table 5-2). Furthermore, the chemical degradation will be much slower than the physical degradation of the concrete and grout due to cracking by internal and external stresses. The timescales for chemical and physical degradation are illustrated in Figure 5-7.

Table 5-2 Time (y) at which Chemical Degradation is Complete and pH Returns to Neutral

Room	Concrete Walls	Grout
Above Bedrock		
Fuel Storage Room	>100,000	80,000
Fuelling Room	>100,000	80,000
Boiler Room	>100,000	90,000
Turbine Room	>100,000	100,000
Below Bedrock		
Fuel Storage Room	>100,000	>100,000
Reactor Vault	>100,000	>100,000
East of Reactor Vault	>100,000	>100,000
West of Reactor Vault	>100,000	>100,000
Dump Tank Pipe Room	>100,000	>100,000
Boiler Room	>100,000	>100,000
Boiler Room (deep)	>100,000	>100,000

Figure 5-7 Timelines of Chemical and Physical Degradation in the Normal Evolution Scenario



As previously mentioned, international compilations of measured sorption coefficients are available for each stage of the degradation process and are used to represent the changing mobility of the elements. The timescales associated with the phases of chemical degradation are derived from the hydraulic conductivity of the cement.

5.1.1.3 Rates of Release from the Facility

Another way of examining the performance of the Facility in retaining radionuclides is to examine the rate at which radionuclides are released from it. Initially, there is a high rate of release as the very mobile radionuclide tritium is released, largely via diffusion through NPDDF walls (Figure 5-8).

This is a result of a conservative approach to representing diffusive releases in this iteration of the PostSA. This, in turn, is a consequence of the use of detailed hydrogeological modelling data for the modelled groundwater flows in the Facility, rather than them being inferred from the assumed hydraulic conductivity of the materials. Flows are calculated for a number of fixed "states" of the Facility (e.g., undegraded materials and tile drains operating). Transitions between conditions are not modelled. This means that it is not possible to represent the gradual resaturation of the facility in the PostSA model.

In the 3rd Iteration PostSA, a considerable improvement to the modelling was the use of more detailed information on water flows within the NPD. These data were obtained directly from Arcadis Canada Inc. & Geofirma Ltd. (2019c), which contains a detailed groundwater flow model of inflows and outflows from each face of each major room in the facility. The data in Arcadis Canada Inc. & Geofirma Ltd. (2019c) were calculated for a range of assessment assumptions, including functioning versus degraded tile drains, and intact versus degraded concrete structure. However, a compromise that this approach imposed was that processes such as grout and concrete degradation could not be modelled with gradually increasing hydraulic conductivities, because flow-field data are only available in Arcadis Canada Inc. & Geofirma Ltd. (2019c) for fixed sets of conditions. This constraint also applies to the period of resaturation that occurs immediately after the closure of the facility. During this period, there is a net *inflow* of water rather than a net release. The majority of the inventory is within the Reactor Vault which is one of the later rooms to resaturate. These radionuclides will also not be released instantly as they are present in the matrix of the material and not instantaneously available for dissolution. It is also noted that groundwater flow modelling estimates that this resaturation period has a very short duration (a few decades) in the overall context of the assessed time period, and occurs when engineered structures can be expected to have good performance in limiting releases. Finally, it is noted that the dominant release in this period, that of tritium, is unaffected because it is assumed that diffusion can occur even during the resaturation period, and this is the dominant mechanism for radionuclide release when the engineered structures remain intact and of low hydraulic conductivity.

The 4th iteration uses the same approach to modelling water flows through the NPDDF as described above for the 3rd iteration, with water flow data taken from Arcadis Canada Inc. & Geofirma Ltd. (2023b). Furthermore, in this 4th iteration of the PostSA, it is simply assumed that the Facility is resaturating (with inflowing water) until fully resaturated, and that no advective flows out of the facility occur during the first 85 y (the resaturation period). The duration of this period was based on resaturation modelling (Arcadis Canada Inc. & Geofirma Ltd., 2023c). Because, during this period, water is inflowing to the facility, the conceptual model assumes that only diffusive releases can occur. Immediately following this period the

facility is assumed to have fully resaturated so the water table is at the same depth within the NPDDF as the surrounding geosphere. In these conditions, groundwater is then assumed to flow through the facility thus permitting a release of contaminants by advection as well as diffusion.

However, as the walls of the structure will themselves be wetted, it is conservatively assumed that diffusion from the facility can occur during the resaturation period. It is the diffusion of tritium that is seen to dominate in the first 100 y, as it can occur from the beginning of the calculations (year zero). In previous iterations, diffusion was only assumed to occur from the resaturated fraction of the facility and, as this was modelled as a linear increase from zero to fully resaturated over the resaturation period, resulting in a gradually increasing diffusion release of tritium, rather than instantaneously being possible from all walls.

The approach taken in this iteration is therefore deliberately cautious and can be expected to overestimate the significance of the tritium release. A more realistic representation is not possible to implement due to the reliance upon the discrete set of calculation cases used in the flow modelling.

By around 100 y the rate of release has decreased from a peak of 3E+09 Bq y^{-1} to 1E+07 Bq y^{-1}. Radionuclides are then released at less than 1E+07 Bq y^{-1} for the remainder of the assessment timeframe. Changes in the profile of releases are seen at 100 y and 1,000 y. The change in releases at 100 y corresponds to the first change in flows through the facility as a result of the failure of the tile drains. A further change in flows occurs at 1,000 y, when the engineered structures of the NPDDF are assumed to have fully degraded, permitting much higher rates of groundwater flow through the wastes. The changes to the releases in the subsequent years (from around 10,000 y on) are as a result of the chemical degradation of the cements. As it degrades, the extent to which key elements are retained in the cement matrix by sorption changes, which can lead to both increases and decreases in the releases of the associated radionuclides. For example, in Figure 5-9 changes can be seen at 12,000 y in the rate of release of Ni59. At this point the sorption coefficient increases from 0.065 to 0.4 m^3 kg^{-1}, in the deeper (below bedrock) parts of the facility (Boiler Room) leading to greater retention of the radionuclide and a decrease in the release rate. The Tc-99 release rate (Figure 5-8) can be seen to drop suddenly at 30,000 y, however this is a result of the end of its release from activated steels, which control the release of this otherwise very mobile radionuclide.

The rate of release of lead is shown in Figure 5-10. The maximum rate of release of lead from the NPDDF is 5E-05 kg y^{-1}.

Figure 5-8 Rate of Release of Radionuclides from the Facility

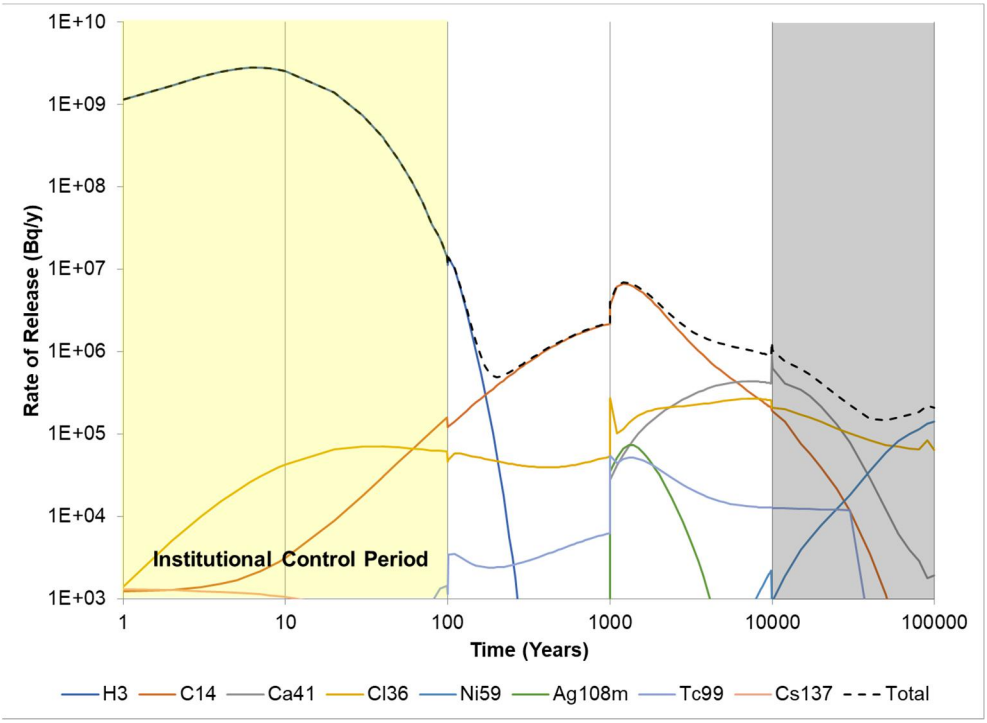


Figure 5-9 Rate of Release of Radionuclides from Reactor Vault

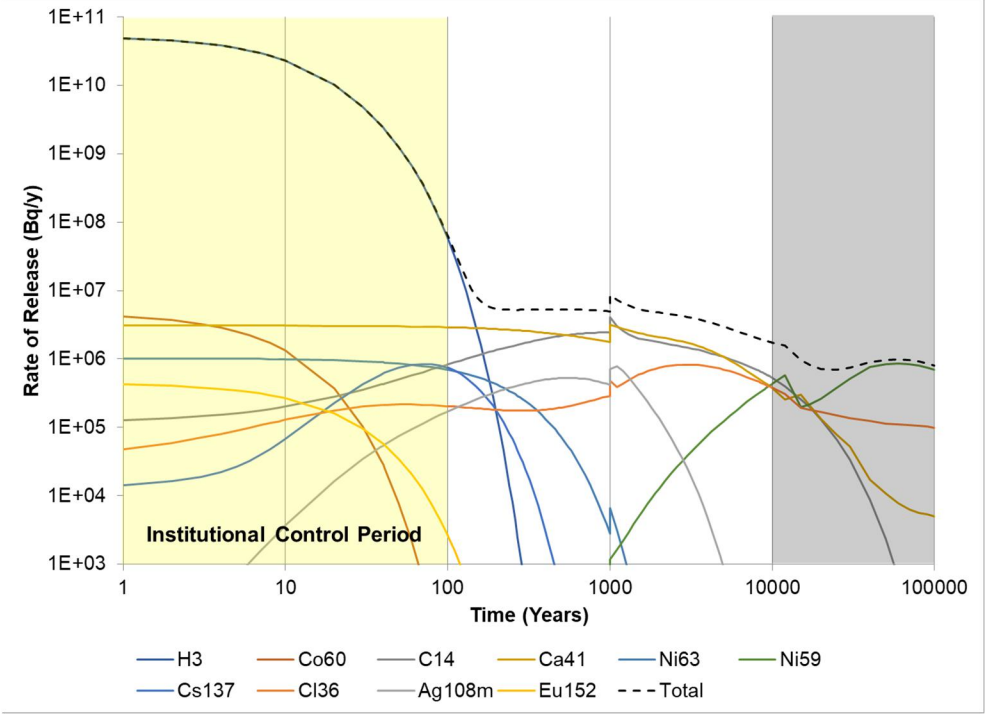
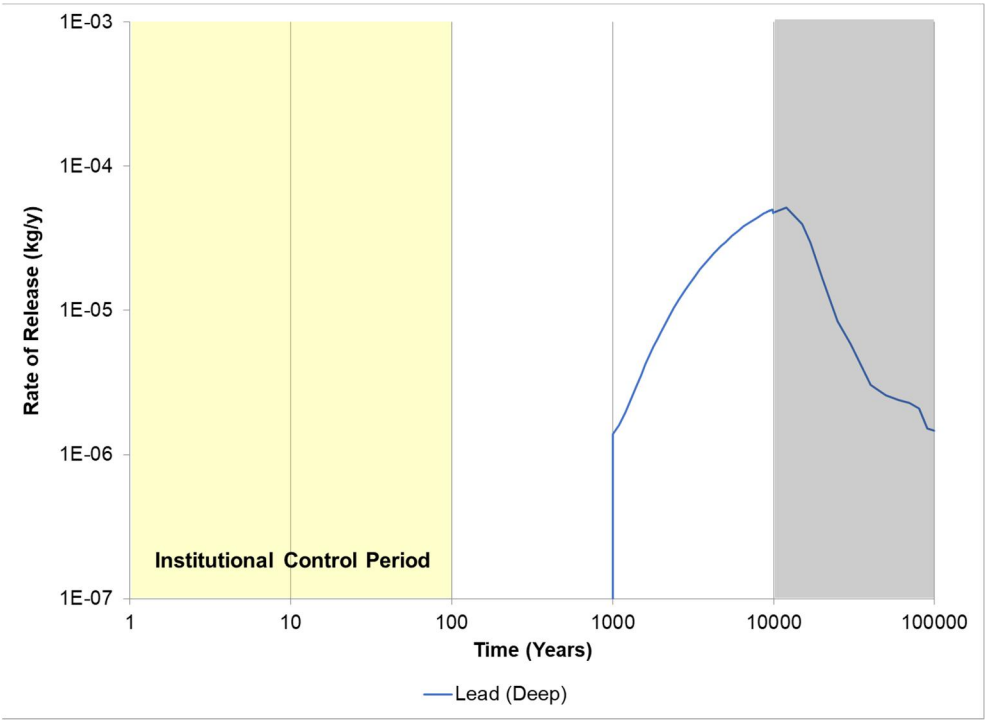


Figure 5-10 Releases of Lead from the Facility



5.1.2 Contaminants in the Environment

5.1.2.1 Contaminant Concentrations in the Geosphere

Radionuclide concentrations in the environment are very much lower than within the Facility. The peak concentration in the overburden groundwater is 0.04 Bq l^{-1} after 90 y (due to tritium). Thereafter, concentrations in the overburden are low, being 1E-03 Bq l^{-1} or less after 130 y. Concentrations in the bedrock groundwater are consistently higher, owing to the inventory of contaminants located in the lower parts of the Facility, and lower volume of water flowing in the bedrock. An initial peak of 3,000 Bq l^{-1} occurs after 7 y due to tritium. Groundwater concentrations remain below 10 Bq l^{-1} after 100 y, with the main peak occurring after 1,300 y, at 7 Bq l^{-1} due to C-14. Profiles of concentration in the geosphere are shown in Figure 5-11. After the initial tritium dominated pulse, radioactivity is dominated by C-14 (180 – 5,500 y) and in the long-term Ca-41 (up to 30,000 y) and thereafter Cl-36 and Ni-59.

Lead concentrations in bedrock groundwater are less than 4E-07 mg l^{-1} (Figure 5-12). This is well below the Environmental Quality Standard (EQS) presented in Appendix A (1.9E-03 mg l^{-1}), and the Ontario Ministry of Environment (MOE) Generic Site Condition Standards for groundwater (0.01 – 0.02 mg l^{-1}). It is also below other guidance such as Health Canada drinking water guidelines (0.01 mg l^{-1}). Thus, no further consideration is required.

Groundwater concentrations for radionuclides are tabulated in Table 5-3; values for non-radioactive contaminants are shown in Table 5-4.

Figure 5-11 Radionuclide Concentrations in the Groundwater Immediately Downstream of the NPDDF

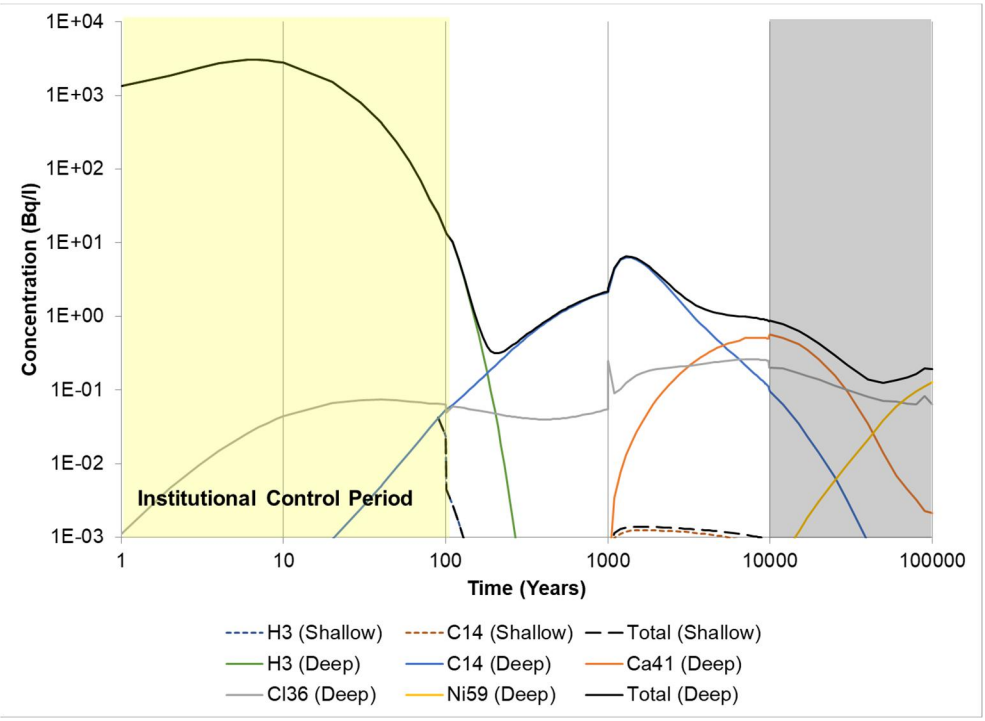


Figure 5-12 Concentrations of Lead in the Groundwater Downstream of the NPDDF

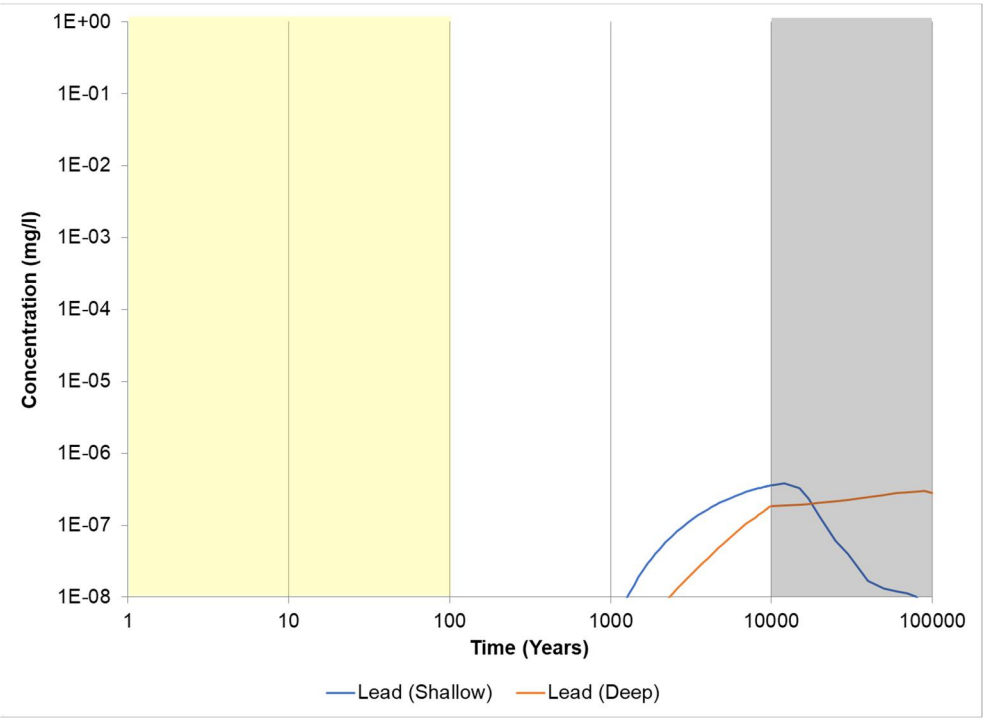


Table 5-3 Radionuclides with the Five Highest Concentrations in Bedrock Groundwater (Bq l^{-1})

Time (y)	H3	C14	Ca41	Cl36	Ni59	Total
100	1E+01	5E-02	2E-07	6E-02	<1E-10	1E+01
300	2E-04	5E-01	8E-06	4E-02	<1E-10	5E-01
1000	<1E-10	2E+00	2E-04	6E-02	<1E-10	2E+00
3000	<1E-10	1E+00	2E-01	2E-01	6E-07	2E+00
10000	<1E-10	1E-01	6E-01	2E-01	4E-04	9E-01
30000	<1E-10	3E-03	1E-01	1E-01	1E-02	2E-01
50000	<1E-10	3E-04	1E-02	7E-02	4E-02	1E-01
Maximum (Bq l^{-1})	3E+03*	6E+00	6E-01	3E-01	4E-02	3E+03
Time of peak (y)	7	1300	10,000	6,500	50,000	7

Note: * The early peak is a result of the rapid diffusion of tritium from NPDDF external walls into groundwater at the beginning of the assessment timeframe.

Table 5-4 Concentrations of Non-radioactive Contaminants in Groundwater (mg l^{-1})

Time (y)	Lead (Overburden)	Lead (Bedrock)
100	<1E-10	<1E-10
300	<1E-10	<1E-10
1000	3E-10	<1E-10
3000	1E-07	2E-08
10000	4E-07	2E-07
30000	4E-08	2E-07
50000	1E-08	3E-07
Maximum (mg l^{-1})	4E-07	3E-07
Time of peak (y)	12,000	90,000

Current background levels (at the NPD site) of radionuclide concentrations, as well as the applicable criteria for such radionuclides are given in Table 5-5. Tritium and C-14 concentrations in the groundwater are above the current background levels at NPD up to 160 y and 15,000 y respectively. However, both values are much lower than the applicable criteria, i.e., by a factor of 2.5 - 3.5 for tritium and by a factor of 16 for C-14.

Table 5-5 Current Background Levels and Applicable Criteria of Radionuclide Concentrations in Groundwater (Bq l^{-1})

Reference	H3	C14	Cl36
Groundwater quality (background levels at NPD)*	7.645	0.038	0.2
Health Canada Drinking Water Guidelines (HC, 2019)	7000	-	-
World Health Organization Drinking Water Guidelines	10,000	100	-

Note: * Arcadis (2023)

5.1.2.2 Concentrations in the Surface Environment

The rate of release of radionuclides out of the Facility (shown in Figure 5-8) indicates that the concentrations in environmental media - such as the river water and sediment – will be much lower than concentrations found within the Facility. Radionuclides released into the Ottawa River would also then be substantially diluted. This is shown in results presented in Figure 5-13.

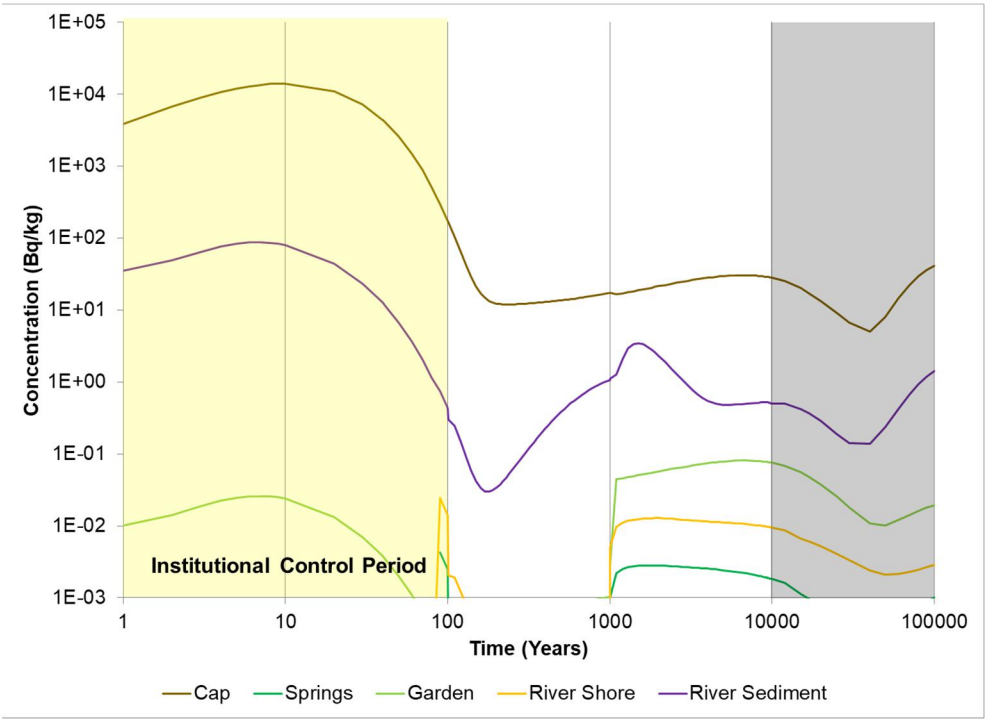
The highest concentrations are found in environmental media closely associated with the assumed points of release of contaminated groundwater. Initially, the highest soil concentration (1E+04 Bq kg^{-1}) occurs in the cap overlying the NPDDF, as a result of tritium diffusion into the concrete cap overlying the facility, and a conservative assumption of some upwards movement of water in the cap. This has decreased substantially to 200 Bq kg^{-1} by the end of institutional control, although the highest concentrations of radionuclides over the entire assessment timeframe are in the region occupied by the cap.

Factors that could result in the upwards migration of contaminated water into the cap (and hence the garden area that is assumed to be used to grow vegetables by the Site Resident exposure group) include capillary action, fluctuations in the water table and the action of biota. Capillary action is a natural phenomenon whereby a liquid can flow in narrow porous spaces in opposition to gravity. It occurs because of intermolecular forces between the liquid and surrounding solid surfaces, specifically the combination of surface tension and adhesive forces between the liquid and the walls of the pore. Short-term fluctuations of the water table could occur after intermittent but heavy precipitation, resulting in a local raising of the water table until the water can drain away. During this time, contaminants in the water and media through which it is flowing will appear to be temporarily transported upwards. Finally, the transpiration stream of rooting plants can act to draw water up through the ground into the plant. In practice, all factors may act to some degree. A sufficiently thick and engineered cap could prevent these processes from occurring; but, conservatively and in order to illustrate the possible significance of the pathway, it has been assumed that upwards flow by these methods occurs at a rate of 10% of the downwards flow (which is driven by infiltration).

The highest concentration in environmental media other than the cap after the institutional control period (but within the assessment timeframe) is 4 Bq kg^{-1} in the river sediments after 1,500 y. River sediment is the main point of discharge for radionuclides in the deep groundwater pathway. The released radioactivity is modelled as being discharged through a small patch of sediment of around 150 m^2, which remains conservative as it is less than the cross-sectional area of the plume in the bedrock. Radionuclides in the shallow pathway discharge in springs and at the shoreline, and concentrations are lower in these media as the concentrations in shallow groundwater are lower than that in the bedrock groundwater (Figure 5-11).

Radionuclides can be transferred to land through four main processes in the Normal Evolution model. River water is assumed to be used for irrigating crops grown in the "Garden" compartment, and groundwater can migrate upward into the cap overlying the NPDDF and, from there, into soils surrounding the engineered cover. River water is also assumed to be drunk by animals who subsequently excrete it into the grazing land (i.e., the forage field). Groundwater may also emerge at the surface in springs occurring near the river. The highest radionuclide concentration in the garden where food is assumed to be grown is only 0.08 Bq kg^{-1}, associated with C-14 after 7,000 y. Radionuclide concentrations in river water (i.e., radionuclides originating from the NPDDF), are very low, owing to the large amount of dilution offered by the river. Initially the river water concentration is 0.006 Bq l^{-1} due to tritium, but after the institutional control period the concentrations of radionuclides are very small, peaking at only 1E-05 Bq l^{-1}.

Figure 5-13 Environmental Concentrations of Radionuclides



The dominant radionuclides consistently include tritium and C-14, with Cl-36, Ca-41, Ni-59 and Pu-239 also notable contributors to environmental concentrations, depending on the medium and timescale. Summary tables of concentrations of key radionuclides and non-radioactive contaminants are presented in Table 5-6 to Table 5-10.

Table 5-6 Radionuclides Present at the Highest Concentration in the NPDDF Cap

Time (y)	Radionuclides (Bq kg^{-1})					
	H3	Ni59	C14	Ca41	Cl36	Total
100	2E+02	3E-08	9E+00	5E-02	9E-01	2E+02
300	2E-03	3E-07	1E+01	4E-01	9E-01	1E+01
1000	<1E-10	4E-06	1E+01	3E+00	9E-01	2E+01
3000	<1E-10	1E-04	2E+01	8E+00	8E-01	3E+01
10000	<1E-10	3E-02	2E+01	9E+00	2E+00	3E+01
30000	<1E-10	8E-01	2E+00	9E-01	1E+00	7E+00
50000	<1E-10	5E+00	3E-01	1E-01	1E+00	8E+00
Maximum (Bq kg^{-1})	1E+04	5E+00	2E+01	1E+01	2E+00	1E+04
Time of Peak (y)	10*	50,000	6,000	6,500	12,000	10

Note: * At times less than 100 y the NPDDF will remain under institutional control and exposures to radionuclides can be controlled, e.g., by land-use restrictions.

Table 5-7 Radionuclides Present at the Highest Concentration in River Shore

Time (y)	Radionuclides (Bq kg^{-1})					
	H3	C14	Pu239	Ni59	Ag108m	Total
100	1E-02	2E-04	6E-09	<1E-10	9E-06	1E-02
300	2E-07	6E-05	5E-06	<1E-10	3E-07	8E-05
1000	2E-07	8E-05	1E-05	<1E-10	1E-05	1E-04
3000	<1E-10	9E-03	2E-03	8E-09	6E-04	1E-02
10000	<1E-10	5E-03	4E-03	3E-06	2E-08	9E-03
30000	<1E-10	4E-04	2E-03	7E-05	<1E-10	3E-03
50000	<1E-10	4E-05	1E-03	4E-04	<1E-10	2E-03
Maximum (Bq kg^{-1})	2E-02	1E-02	4E-03	4E-04	1E-03	2E-02
Time of Peak (y)	90	1,600	12,000	50,000	1,900	90

Note: * At times less than 100 y the NPDDF will remain under institutional control and exposures to radionuclides can be controlled, e.g., by land-use restrictions.

Table 5-8 Radionuclides Present at the Highest Concentrations in River Sediment

Time (y)	Radionuclides (Bq kg^{-1})					
	H3	C14	Ni59	Ca41	Cl36	Total
100	4E-01	5E-04	<1E-10	<1E-10	2E-02	4E-01
300	4E-06	9E-02	<1E-10	3E-10	1E-02	1E-01
1000	<1E-10	1E+00	<1E-10	2E-06	1E-02	1E+00
3000	<1E-10	8E-01	<1E-10	3E-02	5E-02	9E-01
10000	<1E-10	6E-02	2E-05	4E-01	5E-02	5E-01
30000	<1E-10	2E-03	2E-02	9E-02	2E-02	1E-01
50000	<1E-10	2E-04	2E-01	1E-02	2E-02	2E-01
Maximum (Bq kg^{-1})^	9E+01	3E+00	2E-01	4E-01	6E-02	9E+01
Time of Peak (y)	7	1,500	50,000	12,000	6,500	7

Notes: * At times less than 100 y the NPDDF will remain under institutional control and exposures to radionuclides can be controlled e.g. by land-use restrictions.

^ The maximum concentrations are at different times for the different radionuclides. As such, different maxima should not be added because they occur at different times. The value in the maximum row and total column should be read as the maximum value of the total concentration.

Table 5-9 Radionuclides Present at the Highest Concentration in Garden

Time (y)	Radionuclides (Bq kg^{-1})					
	C14	H3	Ni59	Cl36	U238	Total
100	1E-08	1E-04	<1E-10	1E-05	<1E-10	1E-04
300	6E-04	9E-09	<1E-10	7E-05	4E-06	7E-04
1000	9E-04	<1E-10	<1E-10	9E-05	2E-05	1E-03
3000	6E-02	<1E-10	6E-08	4E-03	2E-03	7E-02
10000	6E-02	<1E-10	2E-05	8E-03	2E-03	8E-02
30000	1E-02	<1E-10	5E-04	5E-03	2E-03	2E-02
50000	1E-03	<1E-10	3E-03	4E-03	2E-03	1E-02
Maximum (Bq kg^{-1})	7E-02	3E-02	3E-03	8E-03	2E-03	8E-02
Time of Peak (y)	6000	7	50,000	12,000	9,000	7,000

Note: * At times less than 100 y the NPDDF will remain under institutional control and exposures to radionuclides can be controlled, e.g., by land-use restrictions.

Table 5-10 Radionuclides Present at the Highest Concentration in River Water

Time (y)	Radionuclides (Bq l^{-1})					
	H3	C14	Ca41	Cl36	Ni59	Total
100	3E-05	2E-09	1E-11	1E-07	7E-19	3E-05
300	2E-10	3E-07	6E-12	8E-08	3E-19	4E-07
1000	3E-08	4E-06	6E-11	1E-07	1E-17	4E-06
3000	1E-11	3E-06	7E-08	5E-07	1E-14	4E-06
10000	-3E-16	4E-07	1E-06	4E-07	7E-12	2E-06
30000	-4E-20	2E-08	2E-07	2E-07	3E-09	5E-07
50000	3E-24	2E-09	3E-08	2E-07	3E-08	2E-07
Maximum (Bq l^{-1})	6E-03	1E-05	1E-06	6E-07	3E-08	6E-03
Time of Peak (y)	7	1,500	12,000	6,500	50,000	7

Note: * At times less than 100 y the NPDDF will remain under institutional control and exposures to radionuclides can be controlled, e.g., by land-use restrictions.

Background levels of radionuclide concentrations in different environmental media at the NPD site are given in Table 5-11. Tritium concentrations in the river water are much lower (several orders of magnitude) than the background levels, while tritium concentrations in the river sediment are elevated (one order of magnitude) compared to the background levels. However, the tritium levels in the river are much lower than the guidance levels. C-14 concentrations in the river sediment are one order of magnitude lower than the background concentrations. Both tritium and C-14 concentrations in the garden and the shore are much lower (several orders of magnitude) than the soil background levels.

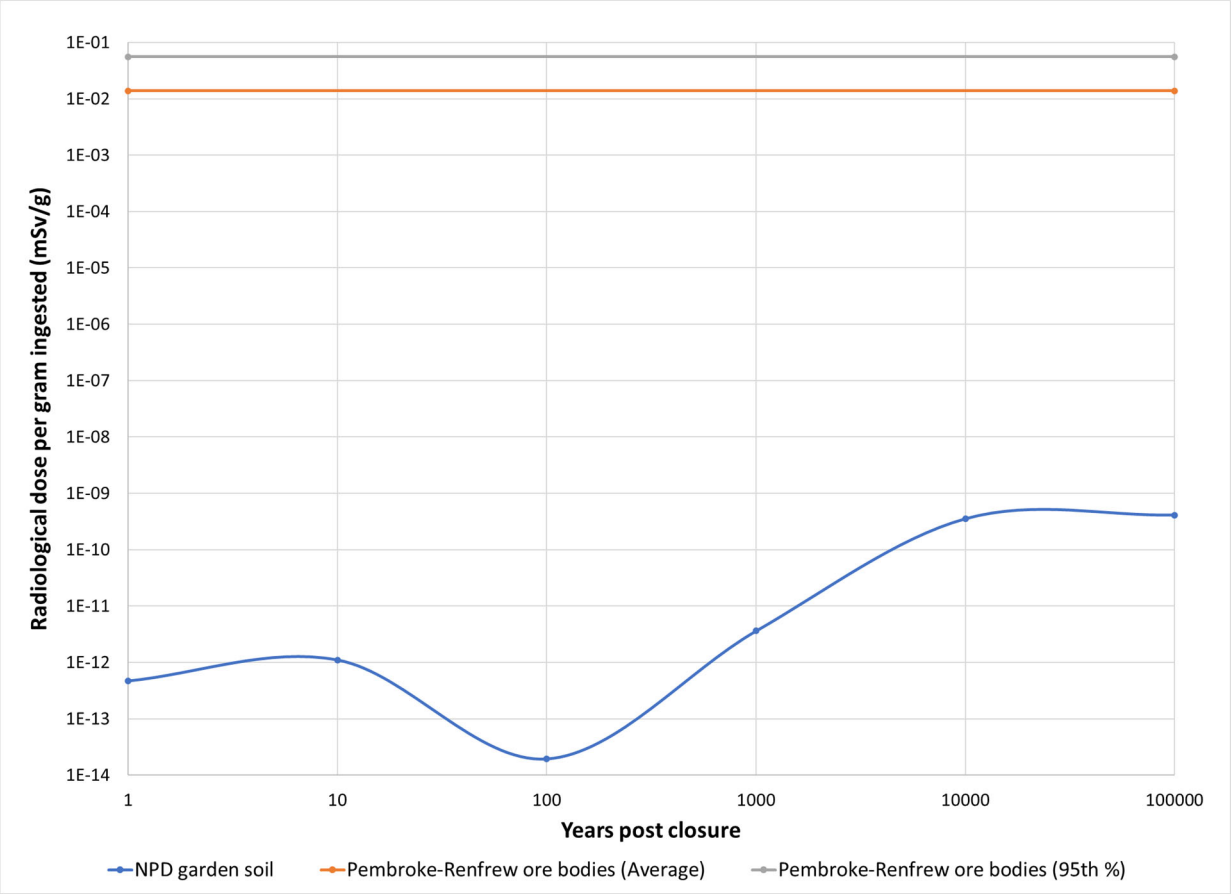
Comparison of radiotoxicity concentrations in garden soil, due to releases from the Facility, to naturally occurring surficial uranium ore deposits in the region, obtained from OGS (1981), is given in Figure 5-14. The NPDDF is located within the same region as these comparison sites (approximately 60 km from Pembroke, and 100 km from Renfrew) and has similar environmental conditions. The comparison shows that concentrations in the soil are more than seven orders of magnitude lower compared to the naturally occurring deposits for the entire duration of the assessment.

Table 5-11 Background Levels of Radionuclide Concentrations at NPD Site

Reference*	H3	C14
Surface Water Quality (Bq l^{-1})		
Surface water quality (obtained from manholes)	< 200	-
Des Joachims	1.65	-
Deep River	1.71	-
Sediment Quality (Bq g^{-1})		
Ottawa River Sediment upstream of NPD	0.003	0.014
Ottawa River Sediment downstream of NPD	0.0024	0.0020
Soil Quality		
Background Reference Areas	0.055	0.017

Note: * Arcadis (2023).

Figure 5-14 Comparison of Radiotoxicity of Contaminated Soil from the Garden at NPD with Naturally Occurring Surficial Uranium Ore Bodies in the Pembroke-Renfrew Area



Concentrations of lead (see Figure 5-15) only accumulate on a long timescale owing to the solubility limitation that restricts the release of the contaminant. The peak concentration of lead in the river is extremely small at 1E-10 mg l^{-1}, compared with the EQS of 0.001 mg l^{-1} (see Appendix A). The highest concentration of lead in soil is 1 mg kg^{-1} in the cap, much lower than the EQS of 45 mg kg^{-1} for soil. Lower concentrations are found in the garden soil (0.04 mg kg^{-1}) and shoreline sediment and springs (4E-05 mg kg^{-1}) on longer timeframes. The EQS for sediment is 31 mg kg^{-1}.

Figure 5-15 Lead Concentrations in the Surface Environment

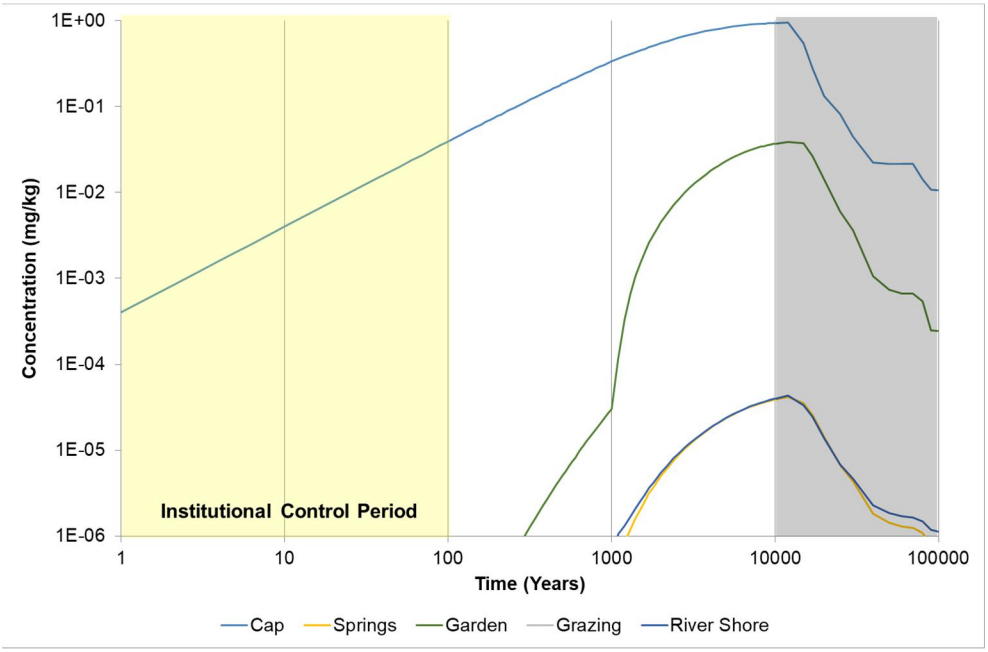


Table 5-12 Lead Concentrations (mg/kg) in the Environment

Time (y)	Cap	Springs	Garden	River Shore	River Water	River Sediment
100	4E-02	6E-10	<1E-10	6E-09	<1E-10	<1E-10
300	1E-01	2E-09	1E-06	3E-09	<1E-10	<1E-10
1000	3E-01	3E-08	3E-05	3E-08	<1E-10	<1E-10
3000	7E-01	1E-05	1E-02	1E-05	<1E-10	<1E-10
10000	9E-01	4E-05	4E-02	4E-05	1E-10	<1E-10
30000	4E-02	4E-06	4E-03	5E-06	1E-11	2E-09
50000	2E-02	1E-06	7E-04	2E-06	5E-12	2E-08
Maximum (mg kg^{-1})	9E-01	4E-05	4E-02	4E-05	1E-10	2E-08
Time of Peak (y)	12,000	12,000	12,000	12,000	12,000	50,000

5.1.2.3 Concentrations in Foodstuffs

A wide variety of foodstuffs have been included in the model in order to maximise the potential exposure of residents. The calculated concentrations are shown in Figure 5-16. As noted in Section 2.2.2, the uptake of non-radioactive contaminants by the food chain is covered by EQS values, therefore non-radioactive contaminants are not included in this subsection. The highest radionuclide concentrations relate to animal feed, potatoes, chicken meat and eggs. For most foodstuffs, the dominant radionuclide is tritium in the first 100 y or so, but institutional controls during this period will prevent people from using the land to grow these foods. In the longer timescale, C-14, Cl-36 and Ca-41 are the most important radionuclides. Most animal foodstuffs (except chickens) are raised on the 'grazing' land which is not irrigated, and only ingest radionuclides by drinking river-water. The dominant radionuclide for this pathway is C-14, which is characterised by a fall in concentrations after about 2000 y, owing to its radioactive decay. For foods derived from the 'garden' (vegetables and chicken meat and eggs) contamination is transferred both by irrigation using river water and by some leakage from the side of the engineered cover. These pathways result in higher concentrations of the long-lived radionuclide Cl-36 which is dominant, and so the concentrations in these foods does not reduce significantly after 1000 y.

Summaries of the calculated concentrations of the five most significant radionuclides are presented in Table 5-13, Table 5-14 and Table 5-15 for potatoes, eggs, and fish, respectively. Figure 5-16 presents the concentrations in all foodstuffs over time.

Figure 5-16 Calculated Concentrations of Radionuclides in Foodstuffs

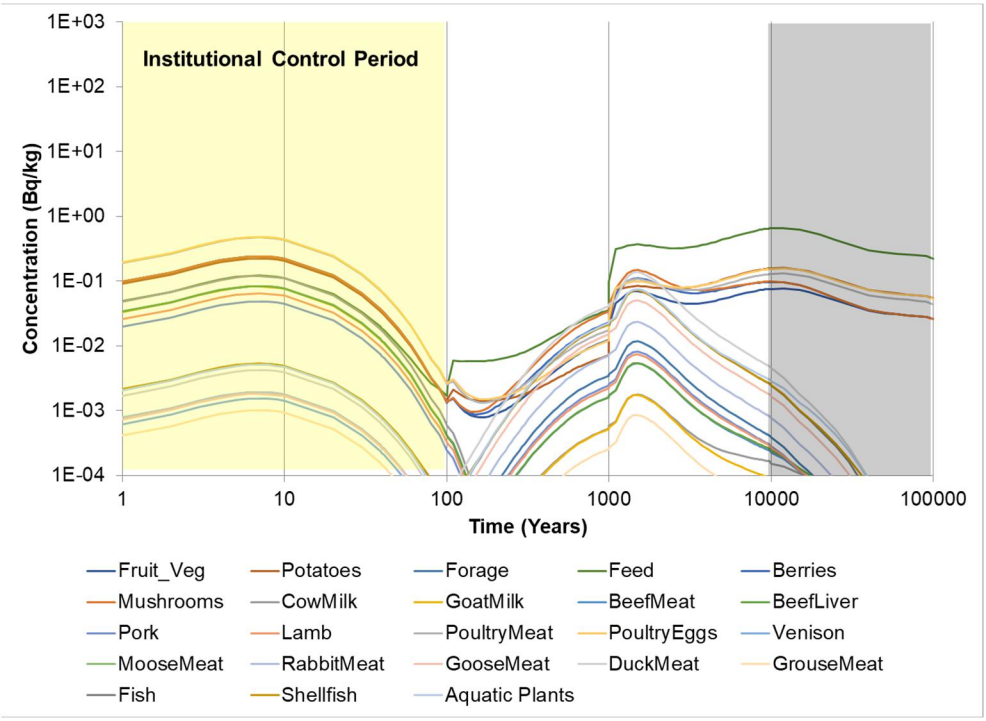


Table 5-13 Radionuclides Present at the Highest Concentrations in Potatoes

Time (y)	Radionuclides (Bq kg^{-1})					
	Cl36	C14	Ca41	Ni59	H3	Total
100	3E-04	3E-06	8E-09	<1E-10	1E-03	1E-03
300	1E-03	5E-04	6E-06	<1E-10	2E-08	2E-03
1000	2E-03	5E-03	5E-05	<1E-10	<1E-10	7E-03
3000	7E-02	5E-03	3E-03	5E-09	<1E-10	8E-02
10000	2E-01	6E-04	5E-03	2E-06	<1E-10	2E-01
30000	9E-02	4E-05	5E-04	5E-05	<1E-10	9E-02
50000	7E-02	3E-06	6E-05	3E-04	<1E-10	7E-02
Maximum (Bq kg^{-1})	2E-01	2E-02	5E-03	3E-04	1E-03	2E-01
Time of Peak (y)	12,000	1,500	8,000	50,000	100	12,000

Note: * At times less than 100 y the NPDDF will remain under institutional control and exposures to radionuclides can be controlled, e.g., by land-use restrictions.

Table 5-14 Radionuclides Present at the Highest Concentrations in Eggs

Time (y)	Radionuclides (Bq kg^{-1})					
	Cl36	C14	H3	Ca41	Ni59	Total
100	3E-04	6E-06	2E-03	2E-09	<1E-10	3E-03
300	1E-03	9E-04	5E-08	1E-06	<1E-10	2E-03
1000	2E-03	1E-02	<1E-10	1E-05	<1E-10	1E-02
3000	7E-02	9E-03	<1E-10	6E-04	1E-09	8E-02
10000	2E-01	1E-03	<1E-10	1E-03	3E-07	2E-01
30000	9E-02	7E-05	<1E-10	1E-04	9E-06	9E-02
50000	7E-02	6E-06	<1E-10	1E-05	5E-05	7E-02
Maximum (Bq kg^{-1})	2E-01	3E-02	2E-03	1E-03	5E-05	2E-01
Time of Peak (y)	12,000	1,500	100	8,000	50,000	12,000

Table 5-15 Radionuclides Present at the Highest Concentrations in Fish

Time (y)	Radionuclides (Bq kg^{-1})					
	C14	Cl36	H3	Ca41	Se79	Total
100	1E-05	6E-06	3E-05	1E-10	<1E-10	4E-05
300	2E-03	4E-06	<1E-10	<1E-10	<1E-10	2E-03
1000	2E-02	5E-06	<1E-10	7E-10	4E-08	2E-02
3000	2E-02	2E-05	<1E-10	8E-07	7E-06	2E-02
10000	2E-03	2E-05	<1E-10	1E-05	7E-06	2E-03
30000	1E-04	1E-05	<1E-10	3E-06	7E-06	2E-04
50000	1E-05	8E-06	<1E-10	4E-07	7E-08	2E-05
Maximum (Bq kg^{-1})	7E-02	3E-05	3E-05	1E-05	7E-06	7E-02
Time of Peak (y)	1,500	6,500	100	12,000	8,250	1,500

Note: * At times less than 100 y the NPDDF will remain under institutional control and exposures to radionuclides can be controlled, e.g., by land-use restrictions.

5.1.3 Doses to Humans

Potential radiation doses to humans have been evaluated for four representative exposure groups. These have been selected to be representative of the most exposed individuals to contaminants released from the Facility:

- The Site Resident represents a small family group that lives on the site of the Facility and obtains all their food from the immediate vicinity. Exposures are maximised by assuming that they obtain water from the river (at the discharge point) and use it to irrigate crops and to drink. They also raise livestock which drink water from the river, fish the river, and use it recreationally, and graze on land adjacent to the river.
- The Hunter exposure group represents recreational activities that could lead to exposure to contaminants. Their exposure pathways include obtaining wild foods from the region of the facility, but they are not assumed to live on-site.
- The Indigenous group with habits based on a new study of the diet and harvest of the AOPFN (Fediuk *et al*., 2021) which shows that, today, their diet is more likely to be supplemented with additional groceries purchased from local shops. This group does not live on the NPD site but uses the land surrounding the facility for some traditional activities (such as fishing, hunting and gathering of wild foods).
- An Offsite Receptor is also considered, living downstream of the NPDDF and using river water to drink and wash with.

An additional 'Self-sufficient Indigenous' exposure group – representing a broadly self-sufficient group of people with conservative assumptions that bound the diet – is assessed as a Sensitivity Case. It is based on the results of lifestyle surveys for an Indigenous community in the area, presented in SENES (2014).

The total radiation dose to these receptors, as a function of time, is presented in Figure 5-17. The highest dose of 8E-05 mSv y^{-1} is received by an infant of the Site Resident group. The dose is dominated by ingestion of food from vegetables grown in the Garden, in which Cl-36 has accumulated (Figure 5-18). The dose is more than 1,000 times lower than the dose criterion of 0.25 mSv y^{-1} and occurs 12,000 y after closure of the Facility. The peak dose rate over the assessment timeframe of 10,000 year is essentially the same as the overall peak dose rate to one significant figure (Figure 5-17). The peak dose to the Hunter exposure group occurs earlier, after 1,500 y, and is 4E-07 mSv y^{-1}. This is due to ingestion of C-14 in animal products (Figure 5-19). The Indigenous (AOPFN) exposure group has habits based on surveys of traditional practices. Their peak dose occurs equally via ingestion of plants and fish. C-14 is the dominant radionuclide and the peak total dose is 7E-06 mSv y^{-1} (Figure 5-20). Finally, the peak dose to the Offsite Receptor, living at Deep River, is only 1E-08 mSv y^{-1} from ingestion of water containing tritium shortly after the closure of the facility (7 y, as institutional controls cannot be applied at offsite locations). For all exposure groups, the doses represent very low levels of radiation exposure and reflect the very low environmental concentrations.

Table 5-16, Table 5-17, Table 5-18 and Table 5-19 provide dose summary information (for the top 5 contributing radionuclides) for the Site Resident, Hunter, Indigenous (AOPFN) and Offsite receptors, respectively.

Figure 5-17 Total Dose to Receptors

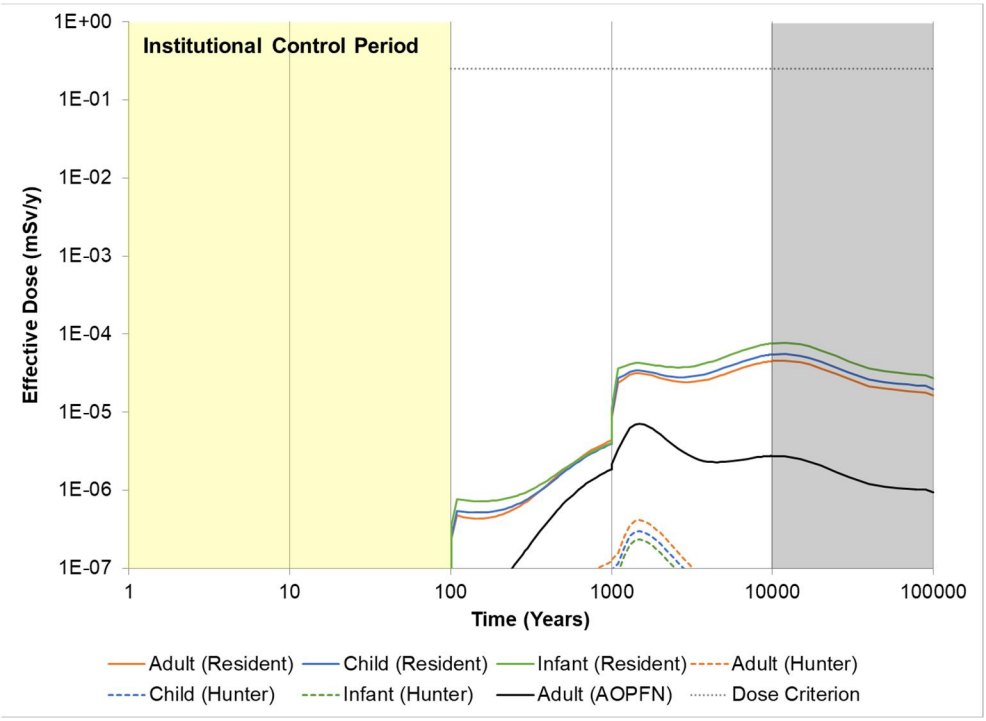
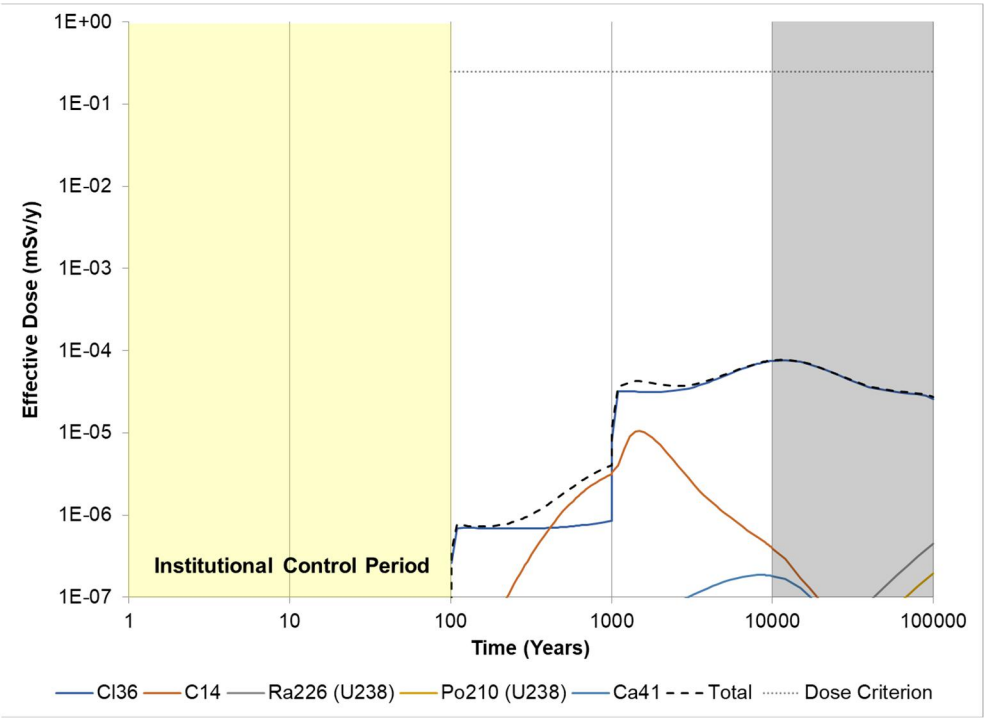


Figure 5-18 Total Dose to the Infant Site Resident (by Radionuclide)



Note: Radionuclides in brackets indicate the parent of the radionuclide that was present in the initial radionuclide inventory of the NPDDF.

Table 5-16 Summary of Dose (in mSv y^{-1}) to the Infant Site Resident for the Five Most Significant Radionuclides

Time (y)	Cl36	C14	Ra226* (U238)	Po210* (U238)	Ca41	Total
100	3E-07	3E-09	<1E-10	<1E-10	<1E-10	4E-07
300	7E-07	3E-07	<1E-10	<1E-10	2E-10	1E-06
1000	8E-07	3E-06	<1E-10	<1E-10	2E-09	4E-06
3000	3E-05	3E-06	1E-10	<1E-10	1E-07	4E-05
10000	8E-05	4E-07	4E-09	2E-09	2E-07	8E-05
30000	4E-05	3E-08	5E-08	2E-08	2E-08	4E-05
50000	3E-05	3E-09	1E-07	6E-08	3E-09	3E-05
Maximum (mSv y^{-1})	8E-05	1E-05	1E-07	6E-08	2E-07	8E-05
Time of Peak (y)	12000	1500	50000	50000	8500	12000

Note: *Ingrown from U-238.

Figure 5-19 Total Dose to an Adult in the Hunter Group (by Radionuclide)

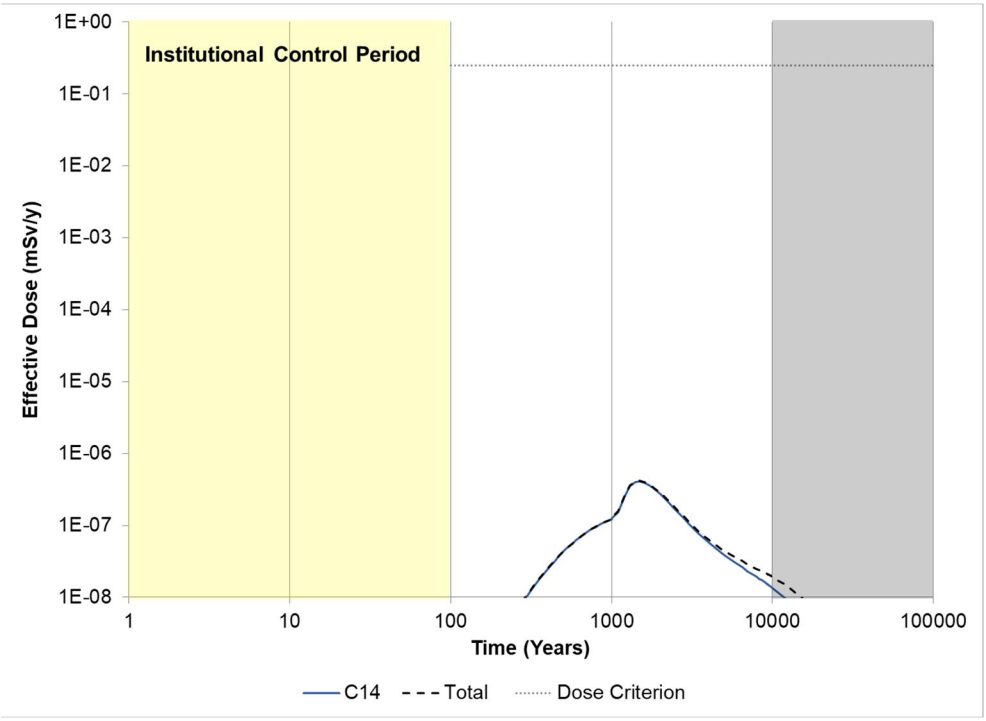


Table 5-17 Summary of Dose (in mSv y^{-1}) to an Adult in the Hunter Group for the Five Most Significant Radionuclides

Time (y)	C14	Ag108m	H3	Ra226* (U238)	Cl36	Total
100	1E-10	1E-10	6E-09	<1E-10	5E-10	7E-09
300	1E-08	<1E-10	<1E-10	<1E-10	4E-10	1E-08
1000	1E-07	<1E-10	<1E-10	<1E-10	5E-10	1E-07
3000	1E-07	<1E-10	<1E-10	<1E-10	2E-09	1E-07
10000	1E-08	<1E-10	<1E-10	<1E-10	2E-09	2E-08
30000	8E-10	<1E-10	<1E-10	3E-10	1E-09	4E-09
50000	7E-11	<1E-10	<1E-10	9E-10	8E-10	3E-09
Maximum (mSv y^{-1})	4E-07	9E-09	6E-09	9E-10	3E-09	4E-07
Time of Peak (y)	1500	1900	101	50000	6500	1500

Note: *Ingrown from U-238.

Figure 5-20 Total Dose to an Adult of the Indigenous (AOPFN) Exposure Group (by Radionuclide)

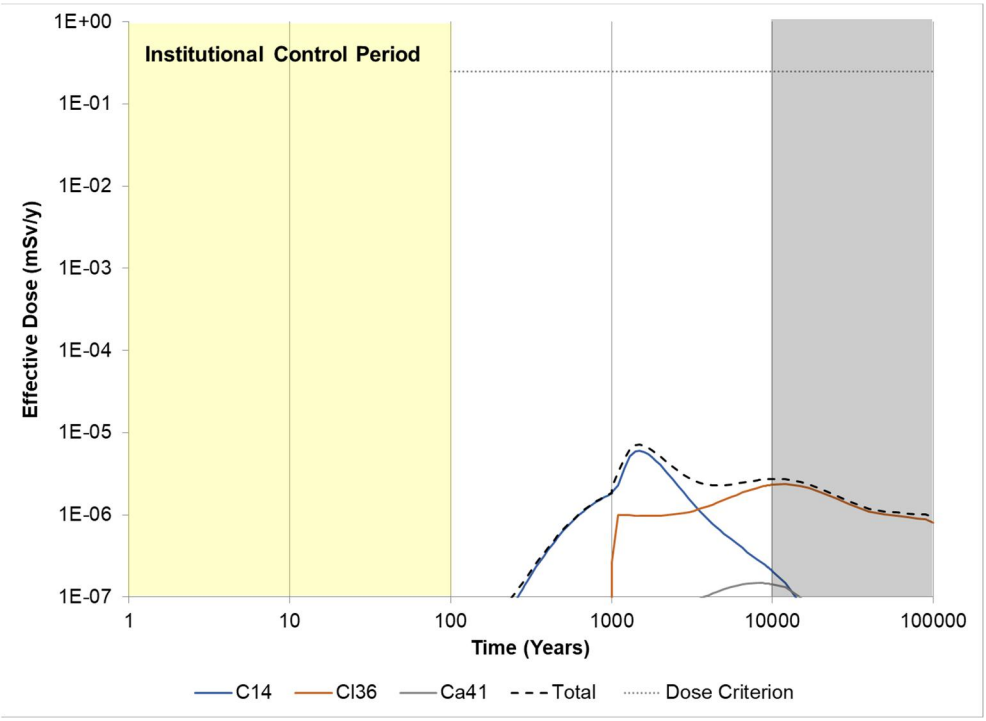


Table 5-18 Summary of Dose (in mSv y^{-1}) to an Adult of the Indigenous (AOPFN) Exposure Group - Five Most Significant Radionuclides

Time (y)	C14	Cl36	Ca41	Ra226* (U238)	H3	Total
100	2E-09	1E-08	<1E-10	<1E-10	6E-08	8E-08
300	2E-07	2E-08	2E-10	<1E-10	<1E-10	2E-07
1000	2E-06	3E-08	2E-09	<1E-10	<1E-10	2E-06
3000	2E-06	1E-06	8E-08	<1E-10	<1E-10	3E-06
10000	2E-07	2E-06	1E-07	5E-10	<1E-10	3E-06
30000	1E-08	1E-06	2E-08	7E-09	<1E-10	1E-06
50000	1E-09	1E-06	2E-09	2E-08	<1E-10	1E-06
Maximum (mSv y^{-1})	6E-06	2E-06	1E-07	2E-08	6E-08	7E-06
Time of Peak (y)	1500	12000	8250	50000	101	1500

Note: *Ingrown from U-238.

Table 5-19 Summary of Dose (in mSv y^{-1}) to an Adult Offsite Receptor for the Five Most Significant Radionuclides

Time (y)	H3	C14	Cl36	Ca41	Tc99	Total
100	<1E-10	<1E-10	<1E-10	<1E-10	<1E-10	<1E-10
300	<1E-10	<1E-10	<1E-10	<1E-10	<1E-10	<1E-10
1000	<1E-10	<1E-10	<1E-10	<1E-10	<1E-10	<1E-10
3000	<1E-10	<1E-10	<1E-10	<1E-10	<1E-10	<1E-10
10000	<1E-10	<1E-10	<1E-10	<1E-10	<1E-10	<1E-10
30000	<1E-10	<1E-10	<1E-10	<1E-10	<1E-10	<1E-10
50000	<1E-10	<1E-10	<1E-10	<1E-10	<1E-10	<1E-10
Maximum (mSv y^{-1})	1E-08	3E-10	2E-11	8E-12	3E-12	1E-08
Time of Peak (y)	7	1500	6500	12000	1400	7

5.2 Sensitivity Cases

5.2.1 Measured Radionuclide Inventory

The reference radionuclide inventory used in the PostSA is based on the estimates that include various conservatisms. In order to gain perspective on the uncertainties in the radionuclide inventory, a sensitivity calculation case has been considered which uses only measured data on radionuclide concentrations where possible, without any uncertainty factors. The calculation case is otherwise the same as the Normal Evolution Scenario.

The activity concentrations in the Reactor Vault of the NPDDF are substantially lower in this calculation case, as shown in Figure 5-21. Initially, the total activity is a factor of six times lower at 4E+06 Bq kg^{-1}, but over time the difference increases to more than a factor of 10. This is due to the lower activity of some longer-lived radionuclides such as Ni-59 and Zr-93 in the inventory derived measurements; some key radionuclides such as Zr-93 can be difficult to measure. The rate of release of radionuclides also differs but less so. As shown in Figure 5-22, the initial tritium release is similar and in the longer term the rate of radionuclide release differs by around factor of 2, mainly because the inventory of the more mobile radionuclides is similar. The dominant radionuclides are H-3 initially, C-14 (190 – 4,250 y) and Ca-41 (after 4,500 y).

Figure 5-21 Radionuclide Inventory in the Reactor Vault (Measured Radionuclide Inventory Case)

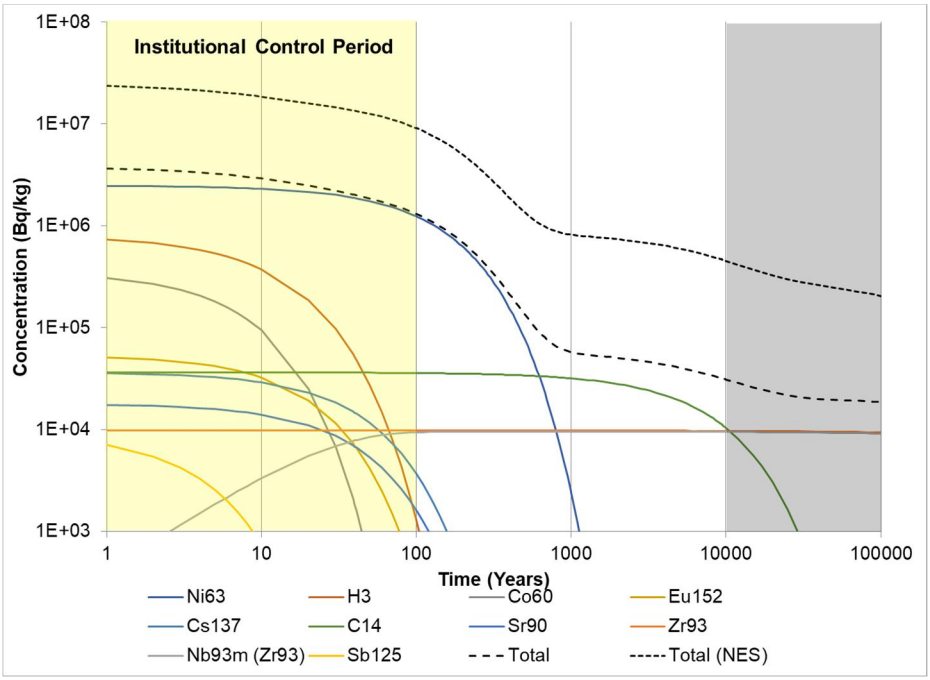
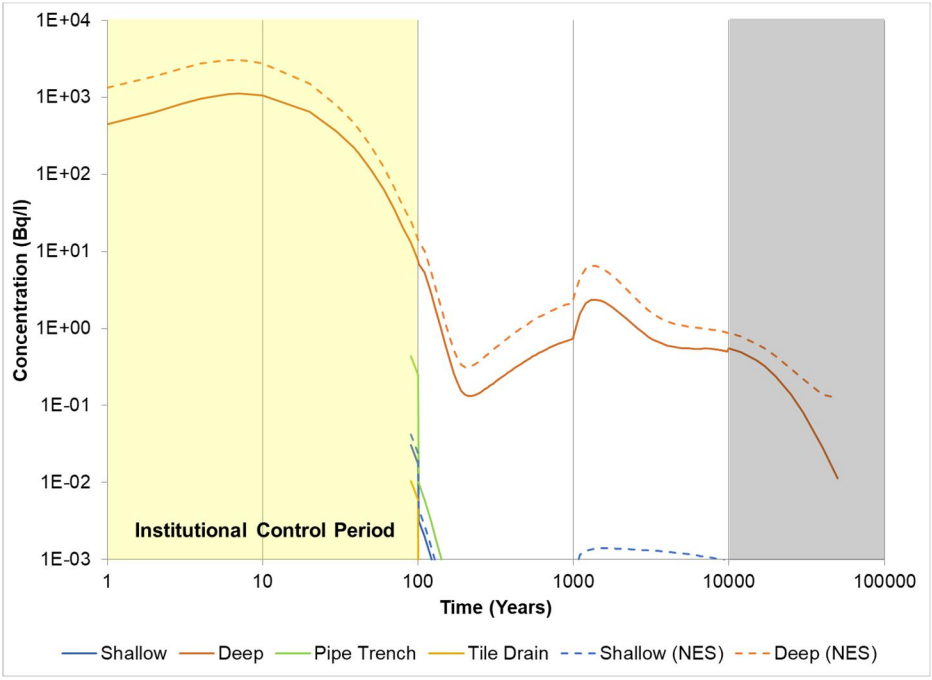
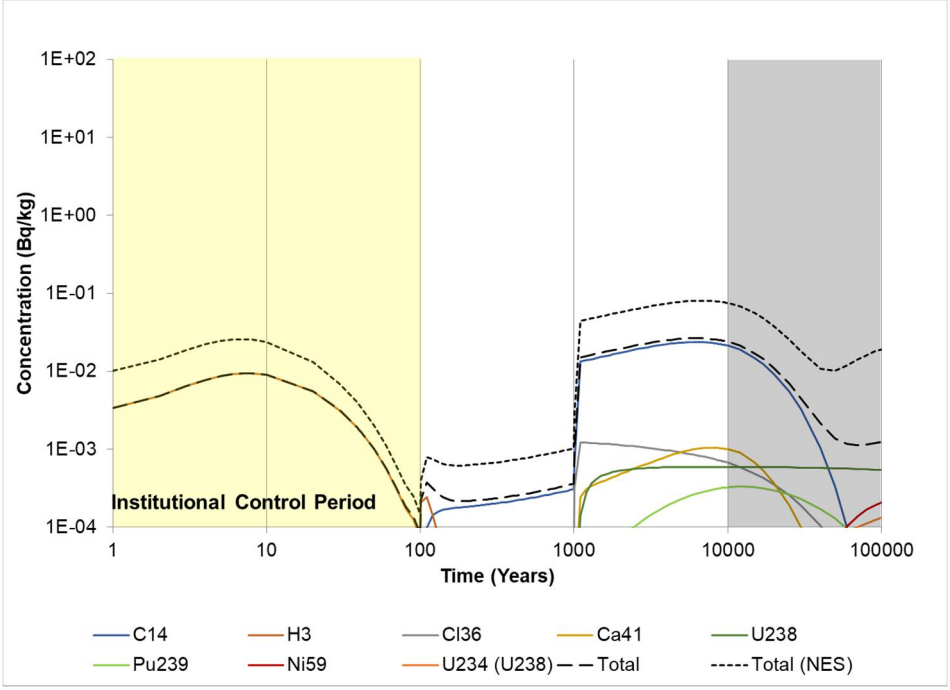


Figure 5-22 Groundwater concentrations of Radionuclides Released from the NPDDF to the Geosphere (Measured Radionuclide Inventory Case)



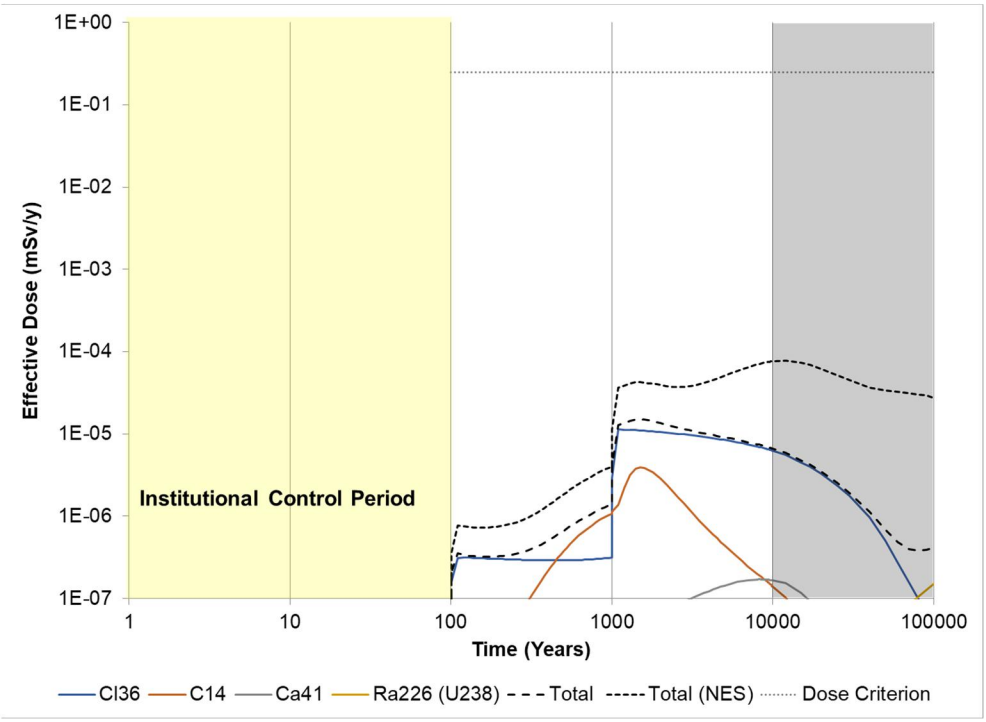
Activity concentrations in groundwater reflect the pattern of releases, but concentrations in surface environmental materials differ significantly. This is because the selective sorption and uptake of certain radionuclides in this environment is a major factor in determining the significance of particular exposure pathways. C-14 is dominant after 120 y to timescales in excess of 10,000 y in the key medium of garden soil (Figure 5-23). The lower inventory of C-14 and other radionuclides important for ingestion pathways, such as Cl-36, means that doses are reduced compared with the Normal Evolution Scenario, with the peak dose being 1E-05 mSv y^{-1} at 1,500 y, resulting from Cl-36 in vegetables grown in the garden (Figure 5-24).

Figure 5-23 Radionuclide Concentrations in Garden Soil (Measured Radionuclide Inventory Case)



Note: Radionuclides in brackets indicate the parent of the radionuclide that was present in the initial radionuclide inventory of the NPDDF.

Figure 5-24 Total Doses to Most Exposed Receptor – Site Resident Infant (Measured Radionuclide Inventory Case)



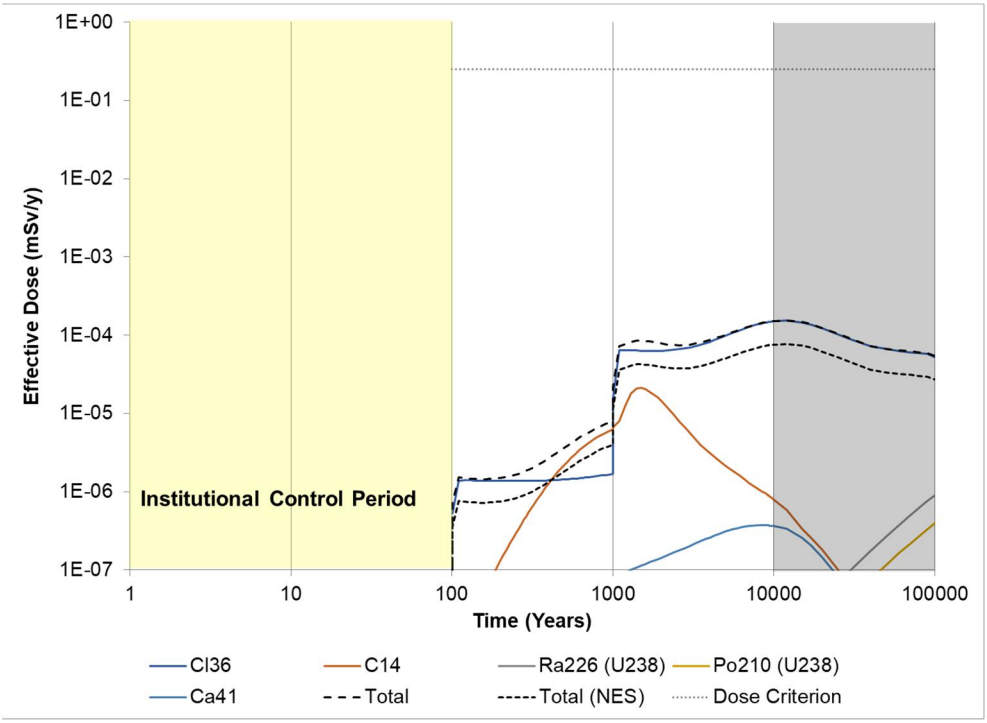
Note: Radionuclides in brackets indicate the parent of the radionuclide that was present in the initial radionuclide inventory of the NPDDF.

5.2.2 Increased Radionuclide Inventory

A conservative higher estimate of the reference inventory has been considered in this sensitivity case. This is simply twice the modelled inventory (considered in the NES).

The results for the most exposed receptor (Site Resident infant) in the increased radionuclide inventory case are shown in Figure 5-25. As shown, the doses follow the same pattern in time when compared with NES (see Section 5.1.3), but are twice as large. This shows that the calculated radiation dose simply scales with the assumed radionuclide inventory. This is because there are no significant non-linear effects in the model: these are generally only apparent for radionuclides that are subject to solubility limitation. This is not the case for the dominant radionuclides (C-14, Cl-36). The peak dose to an infant in the Site Resident exposure group is 2E-04 mSv y^{-1}, 12,000 y after closure of the facility.

Figure 5-25 Total Doses to Receptors (Increased Modelled Radionuclide Inventory Case)



Note: Radionuclides in brackets indicate the parent of the radionuclide that was present in the initial radionuclide inventory of the NPDDF.

5.2.3 Sorption (Reduced in Near-field and/or Far-field)

Sorption coefficients can have significant uncertainty as they depend on characteristics that are specific to the type of material and the characteristics of the groundwater. The values selected for the PostSA are based on well-regarded compilations of data, but retain this uncertainty. Sorption determines the concentrations of radionuclides in water and thus the rate of transport of radionuclides from the NPDDF to the surface environment. One sensitivity case therefore examines the implications of lower sorption coefficients by reducing all of those associated with cement and concrete, the Reduced Near-field Sorption case. Lower limit values from Ochs *et al*. (2016) have been used, where possible. Where no lower limit data were available, the values were reduced by a factor of 10.

To capture the uncertainty in sorption parameters for the overburden and bedrock, all sorption coefficients were reduced by a factor of 10 in an additional sensitivity case, named the Reduced Far-field Sorption case, while keeping the best estimate cement sorption coefficients, as used in the NES.

To provide a transparent analysis of sensitivity and capture the uncertainty in both the near field and far field, the two sensitivity cases described above were also combined and analysed in the third sorption sensitivity case named the Reduced Sorption in Near-field and Far-field.

5.2.3.1 Reduced Near-field Sorption

The reduced sorption on cementitious materials enables contaminants to be released more quickly (except those present in activated metals, such as Ni-59, or solubility limited, such as lead). The consequences of the change are evident in increased concentrations of radionuclides in the groundwater in the Reactor Vault, including key radionuclides such as C-14 and Cl-36 (Figure 5-26). Tritium concentrations are unchanged as this radionuclide is unsorbed (it is entirely present in solution) and is thus unaffected by the changes made in this sensitivity case.

The environmental concentrations are consequently increased in some modelled regions compared with the Normal Evolution Scenario, most notably the garden (the primary source of vegetables) with higher concentrations of radionuclides such as C-14 and Cl-36 (Figure 5-27). The higher concentrations lead to higher doses to humans. Most affected is the Site Resident, whose exposure is dominated by Cl-36 in vegetables (Figure 5-28). The peak dose to the infant in the Site Resident group is increased from 8E-05 mSv y^{-1} in the Normal Evolution scenario to 1E-04 mSv y^{-1} and occurs much earlier, at 2,600 y after closure rather than at 12,000 y in the NES.

Figure 5-26 Radionuclide Concentrations in Water in the Reactor Vault (Reduced Near-field Sorption Case)

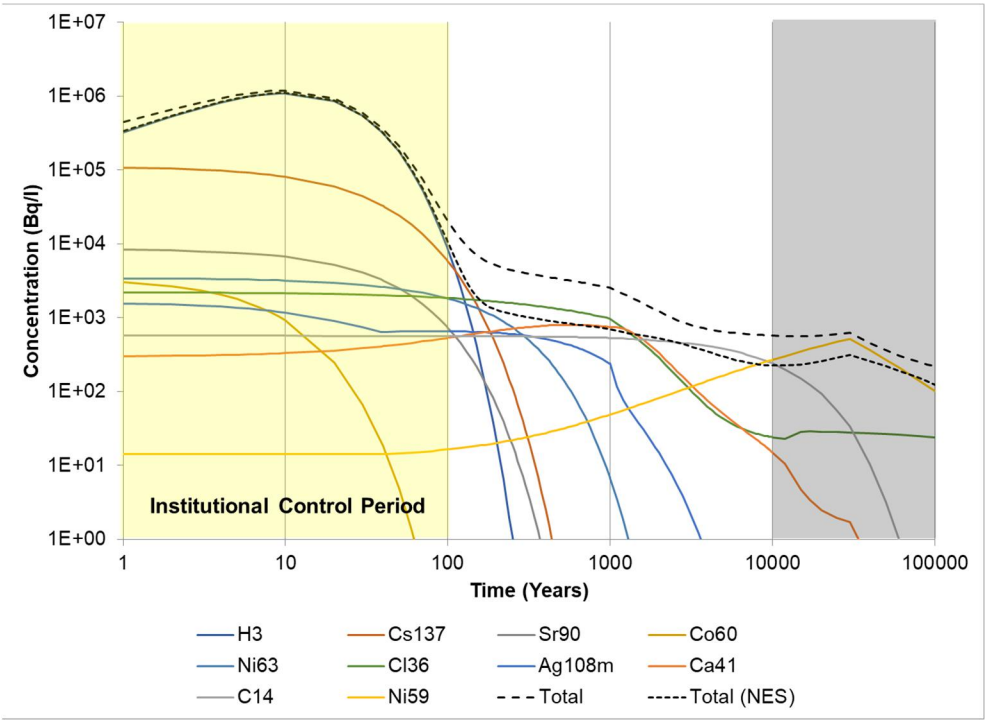
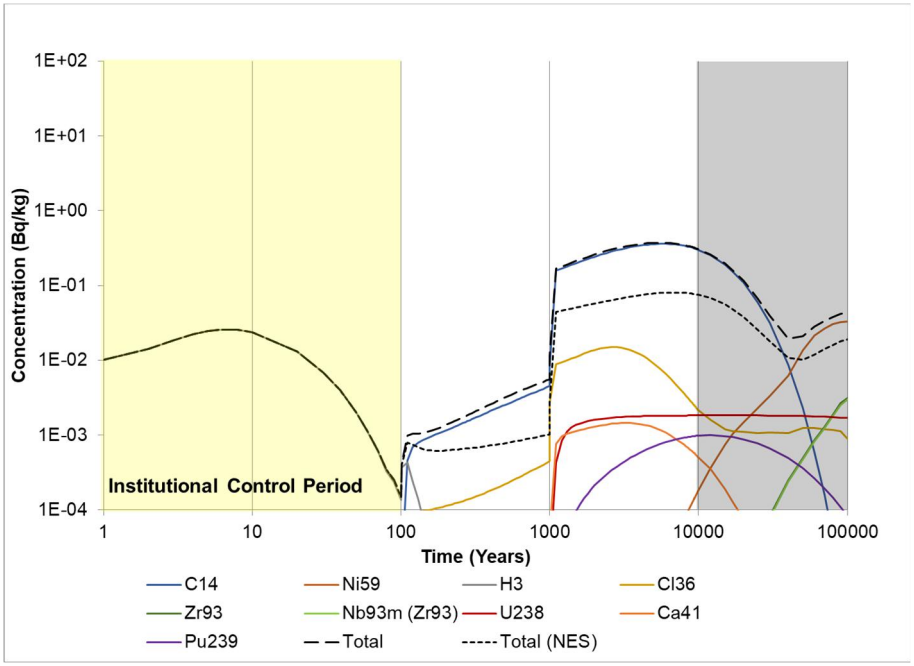
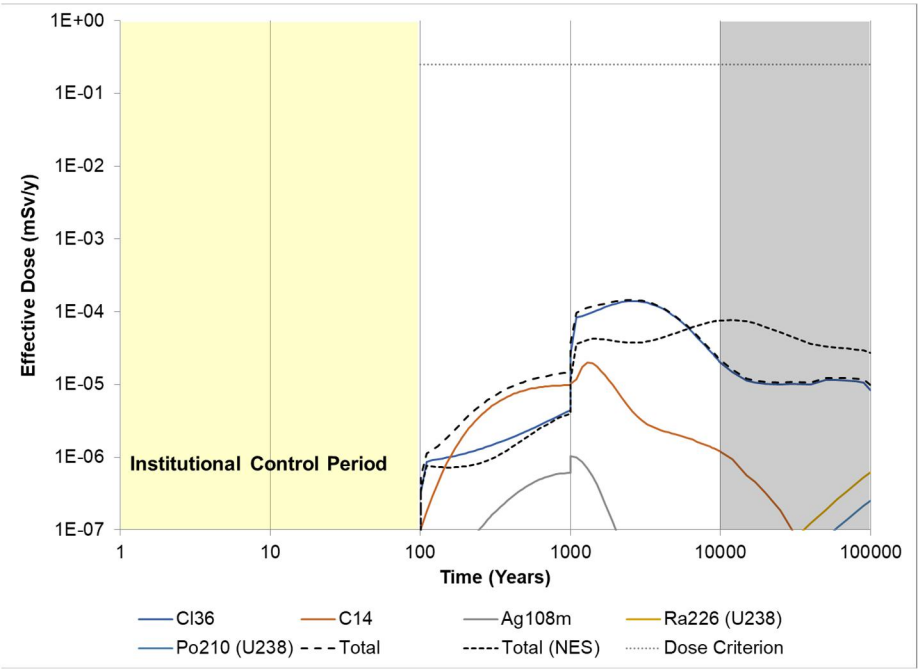


Figure 5-27 Concentrations in the Garden (Reduced Near-field Sorption Case)



Note: Radionuclides in brackets indicate the parent of the radionuclide that was present in the initial radionuclide inventory of the NPDDF.

Figure 5-28 Dose to Infant of the Site Resident Exposure Group (Reduced Near-field Sorption Case)



Note: Radionuclides in brackets indicate the parent of the radionuclide that was present in the initial radionuclide inventory of the NPDDF.

5.2.3.2 Reduced Far-field Sorption

The effect of reduced sorption in the geosphere (the “far-field”) on the transport of contaminants is not very significant, as shown in Figure 5-29; concentrations in the groundwater of both the bedrock and overburden are very similar to those calculated in the NES. This indicates that the dominant factor controlling the concentrations in the groundwater is the retention of contaminants in the NPDDF itself, rather than the geosphere. The environmental concentrations (Figure 5-30) and resulting doses (Figure 5-31) are also very similar to the NES. The highest dose to the infant Site Resident is unchanged at 8E-05 mSv y^{-1}.

Figure 5-29 Radionuclide Concentrations in Groundwater Downstream of the NPDDF (Reduced Far-field Sorption Case)

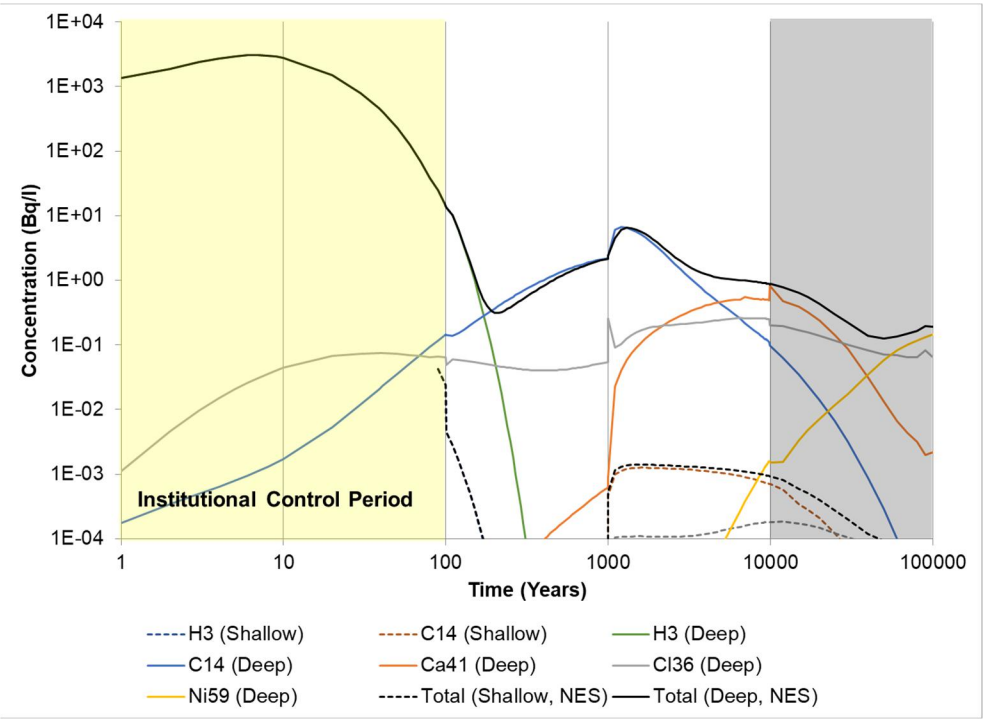


Figure 5-30 Concentrations in the River Water (Reduced Far-field Sorption Case)

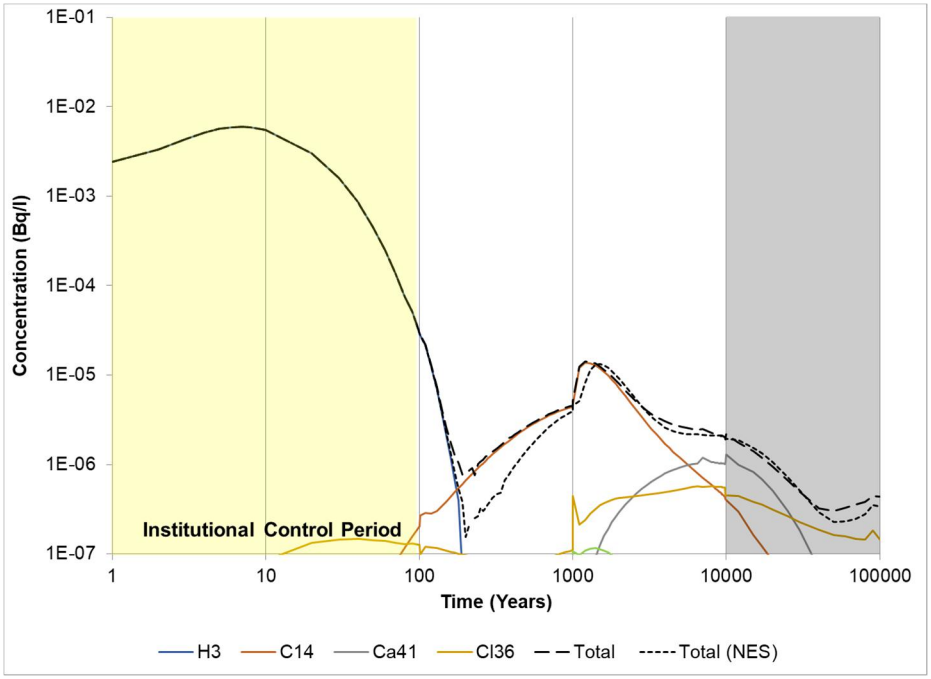
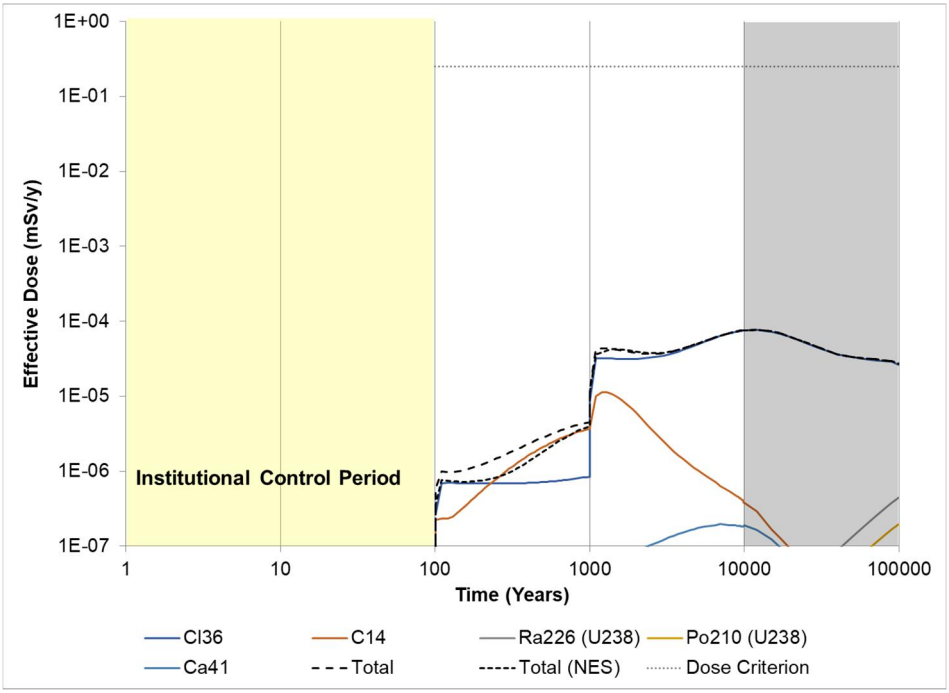


Figure 5-31 Dose to the Most Exposed Group, the Infant Site Resident (Reduced Far-field Sorption Case)



Note: Radionuclides in brackets indicate the parent of the radionuclide that was present in the initial radionuclide inventory of the NPDDF.

5.2.3.3 Reduced Near-field and Far-field Sorption

The effects of reduced sorption in both the near-field and far-field have been explored, and the results are very similar to those obtained in the Reduced Near-field Sorption Case, as near-field sorption is dominant in controlling the environmental concentrations and doses. This is evident in all graphs (Figure 5-32 to Figure 5-34). Figure 5-35 shows the calculated doses from the most exposed members of the three groups for whom radiation doses have been assessed and compares the results from this case, and the cases with Reduced Near-field Sorption only and Reduced Far-field Sorption only, demonstrating that sorption in the near-field is most significant in determining doses to people.

Figure 5-32 Radionuclide Concentrations in Groundwater Downstream of the NPDDF (Reduced Near-field and Far-field Sorption Case)

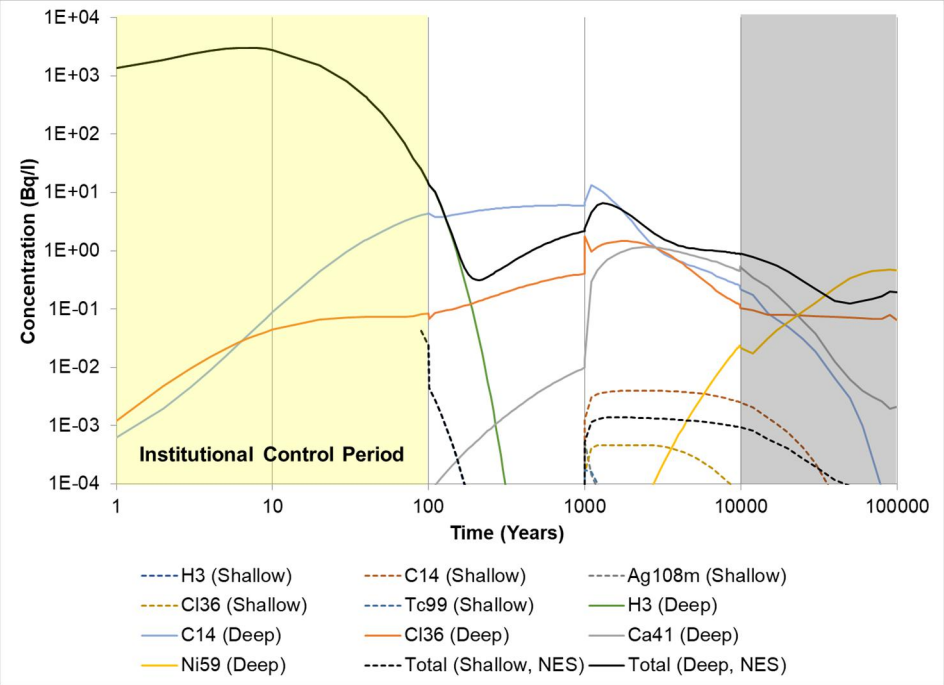


Figure 5-33 Concentrations in the River Water (Reduced Near-field and Far-field Sorption Case)

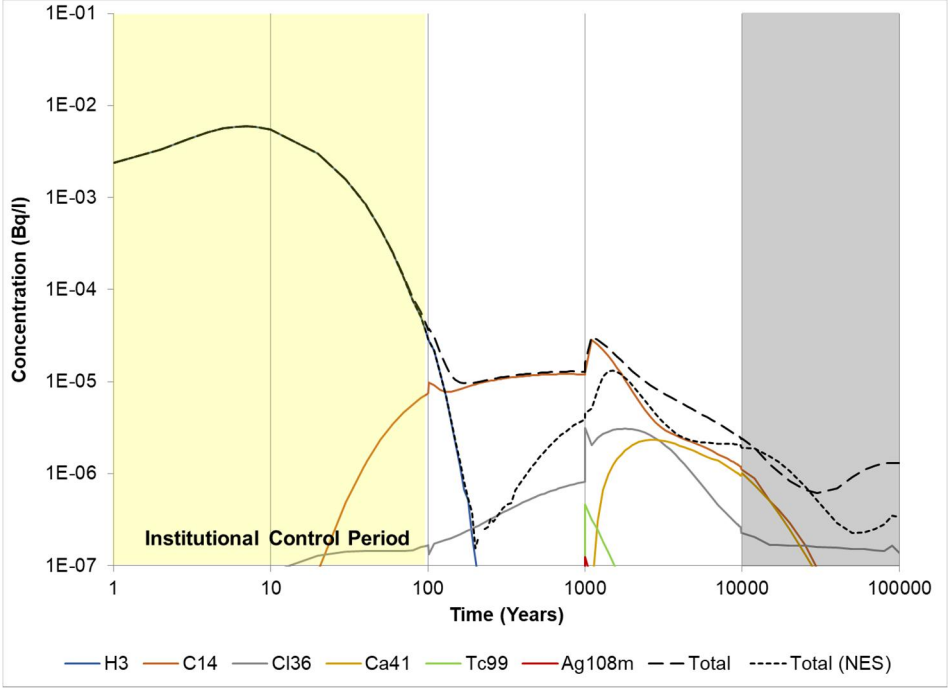
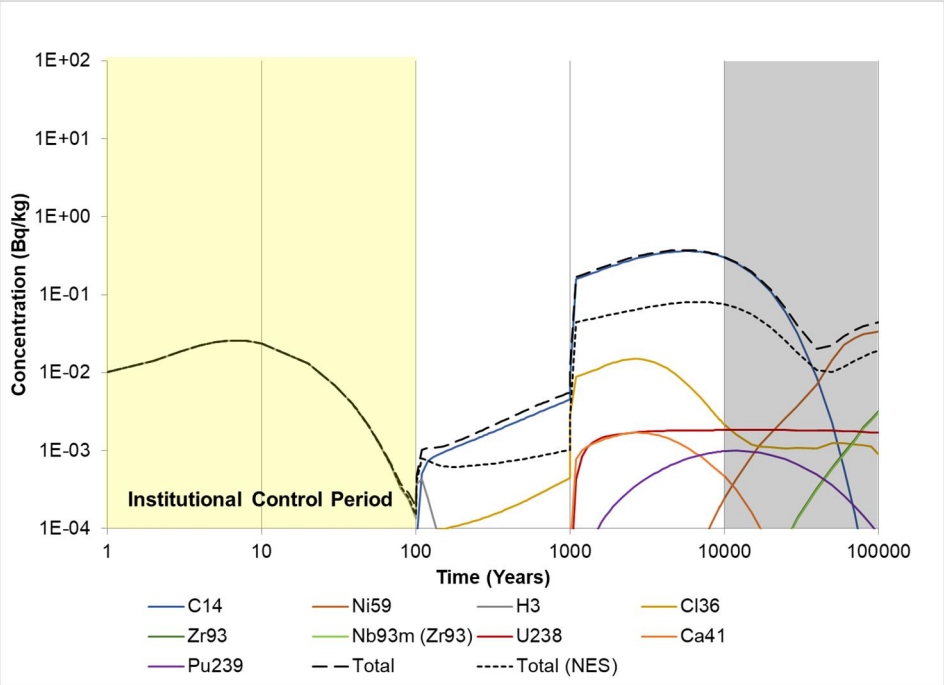
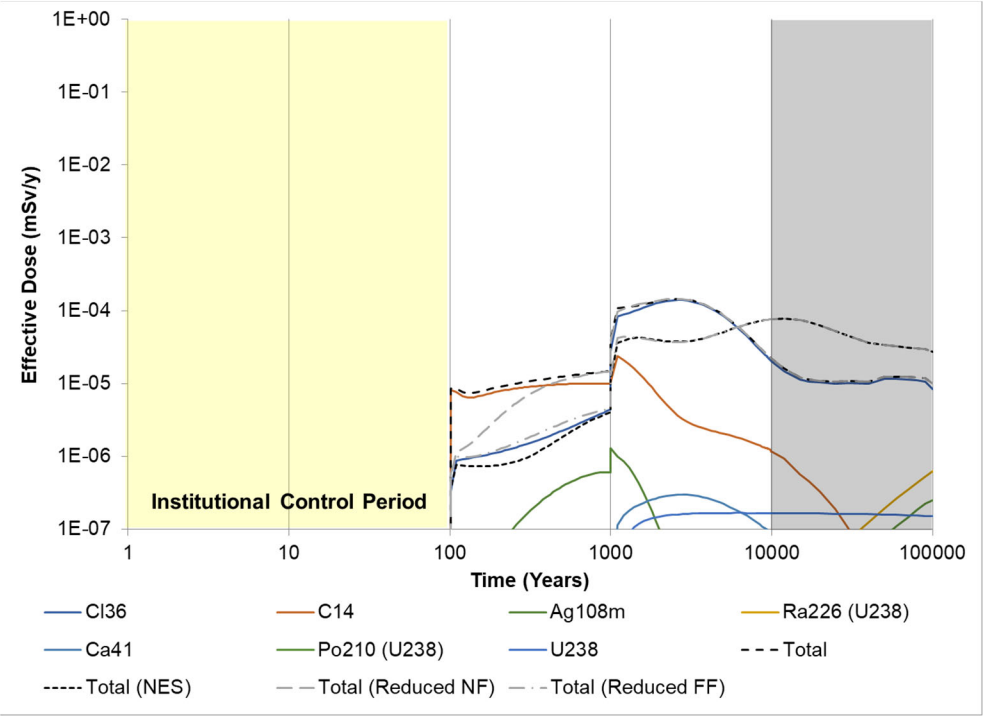


Figure 5-34 Concentrations in the Garden (Reduced Near-field and Far-field Sorption Case)



Note: Radionuclides in brackets indicate the parent of the radionuclide that was present in the initial radionuclide inventory of the NPDDF.

Figure 5-35 Dose to the Infant Site Resident (Reduced Near-field and Far-field Sorption Case) Compared with NES and Reduced Near-field Case and Reduced Far-field Case



The peak doses are compared in Table 5-20 below. As shown, the results between the Reduced Near-field Sorption Case and the Reduced Near-field and Far-field Sorption Case are extremely similar, differing only in a slightly earlier increase in the dose curve from 100 to 1,000 y due to the lower sorption of radionuclides in the geosphere.

Table 5-20 Summary of Peak Dose (mSv y^{-1}) to the Three Exposure Groups for the Normal Evolution Scenario and Reduced Near-field Sorption Case, Reduced Far-field Sorption Case, and Reduced Near-field and Far-field Sorption Case

	Resident Group (Infant)	Hunter Group (Adult)	Offsite Resident(Adult)	AOPFN Group (Adult)
Normal Evolution Scenario	8E-05 (at 12,000 y)	4E-07	3E-10	7E-06
Reduced Near-field Sorption	1E-04 (at 2,600 y)	2E-06	7E-10	2E-05
Reduced Far-field Sorption	8E-05 (at 12,000 y)	4E-07	3E-10	8E-06
Reduced Near-field and Far-field Sorption	1E-04 (at 2,600 y)	3E-06	7E-10	2E-05

5.2.4 Rapid Degradation

The rate of physical degradation of the engineered structures is somewhat uncertain, and an important consideration as it determines the flow rate of water through the Facility. The AMBER model uses different sets of data on groundwater flow through the facility calculated by Arcadis & Geofirma (2023b), which correspond to increased hydraulic conductivity of the grout and concrete expected to result from degradation due to, for example, concrete cracking and seismic activity. This case explores the significance of this aspect by assuming that the engineered structures are instantly in a physically degraded state at the end of the Institutional Control Period (100 y) rather than after 1,000 y. Figure 5-36 shows that immediately after 100 y there is a large increase in the release rate of tritium, and increased releases of other radionuclides including C-14 (dominant after 160 y). From 1,000 y onwards, the releases are similar for both overburden and bedrock groundwater pathways.

The effects on radionuclide concentrations in the surface environment are most important for the garden soils (which are assumed to be irrigated with contaminated river water and contaminated with water migrating upward into the cap and thence into the garden). Figure 5-37 shows much higher concentrations of H-3, C-14 and Cl-36 in the 100 – 1,000 y period for this case; but thereafter the concentrations are the same as the NES. Cl-36 is a key radionuclide from the perspective of exposures of people. As this is released more rapidly, from 100 y onwards, the radiation dose to a Site Resident is increased compared with the NES in the 100 – 1,000 y period. The peak dose, however, occurs much later (at 12,000 y) and is the same as in the NES, at 8E-05 mSv y^{-1} (see Figure 5-38).

Figure 5-36 Groundwater Concentrations of Radionuclides Released from NPDDF to the Geosphere (Rapid Degradation of Engineered Barriers Case)

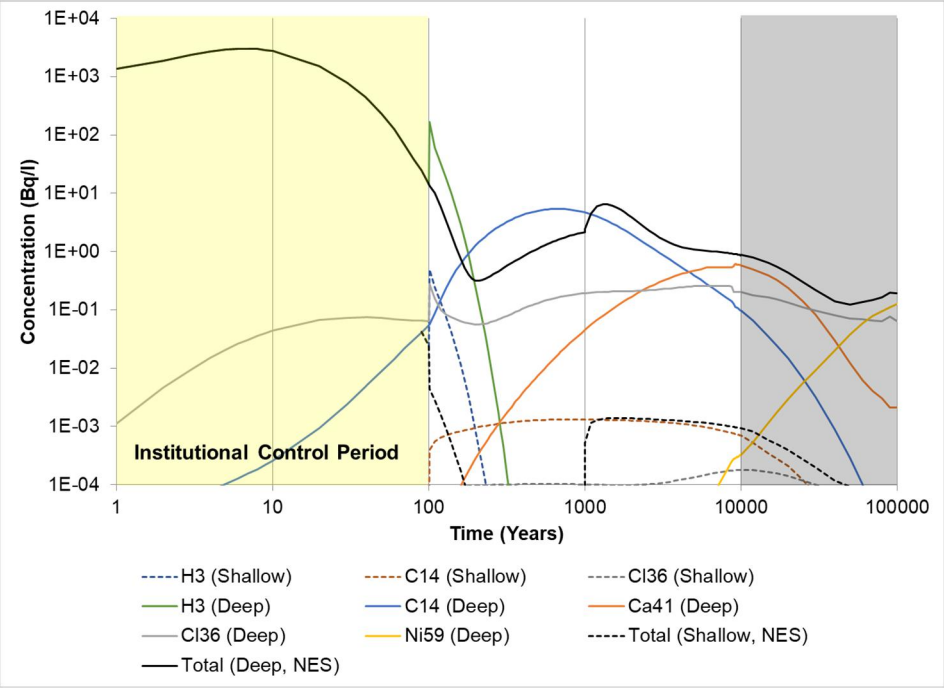
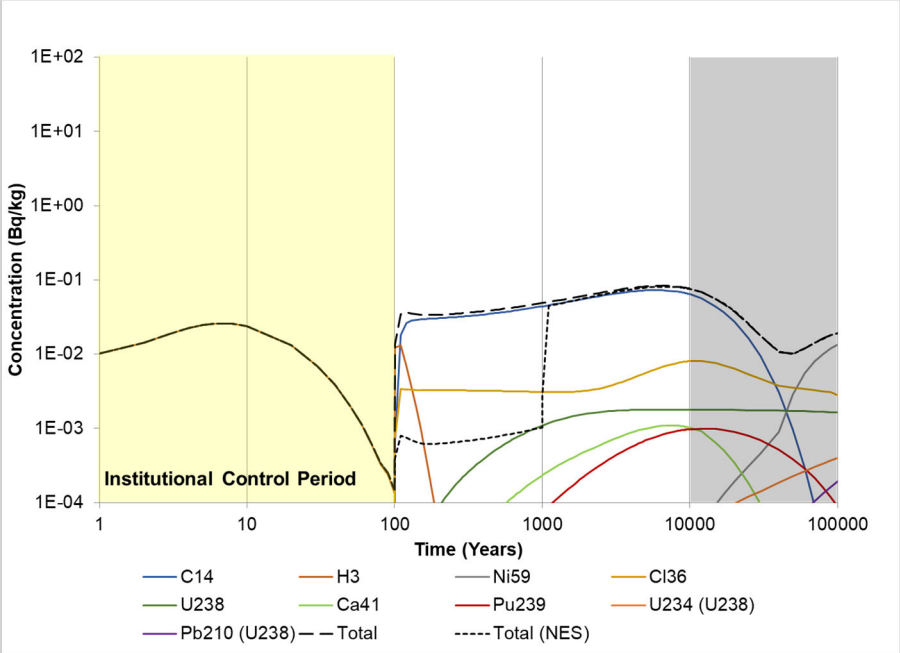
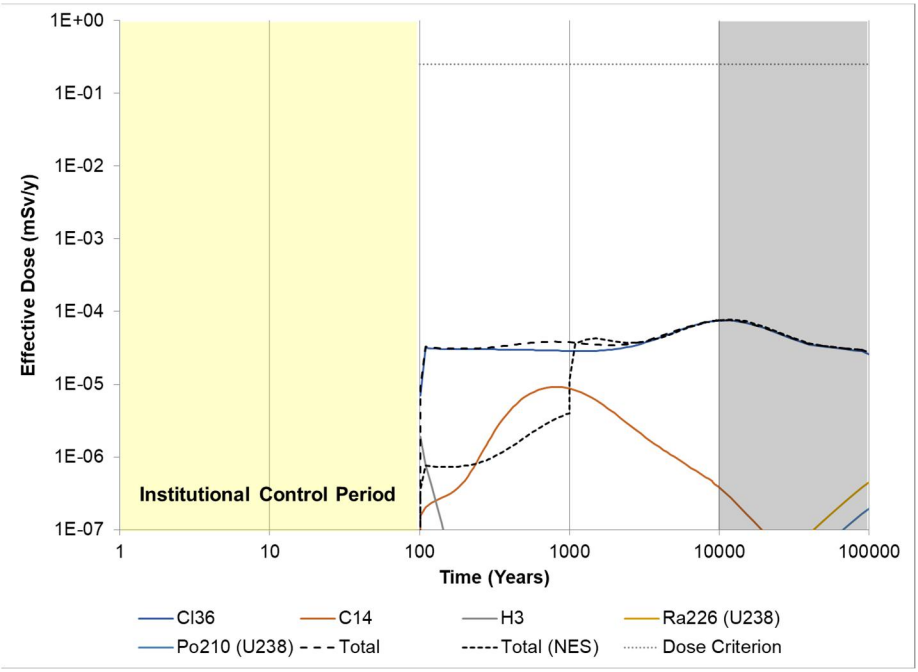


Figure 5-37 Concentration of Radionuclides in Garden Soils (Rapid Degradation of Engineered Barriers Case)



Note: Radionuclides in brackets indicate the parent of the radionuclide that was present in the initial radionuclide inventory of the NPDDF.

Figure 5-38 Dose to Infant Site Resident (Rapid Degradation of Engineered Barriers Case)



Note: Radionuclides in brackets indicate the parent of the radionuclide that was present in the initial radionuclide inventory of the NPDDF.

5.2.5 Increased Hydraulic Conductivity (Bedrock and Overburden)

The regional and site hydrogeological framework for the NPDDF site is described based on historical and 2019 local investigation and site characterization work completed at and in the vicinity of the NPD site and at the CRL site, review of Ministry of Environment, Conservation and Parks (MOECP) water well records, and review of the scientific literature (Arcadis & Geofirma, 2022). The presence and hydrogeological properties of the permeable fluvial sand and gravel layer that subparallels the Ottawa River and extends tile drain capture of overburden groundwater northwest of the NPDWF is identified as an uncertainty in modeling of groundwater flow at the NPDWF site (Arcadis & Geofirma, 2022).

Two alternative calculation cases have therefore been considered to account for the uncertainty in the hydraulic properties of the geosphere. The first case examines increased hydraulic conductivity (and thus flow) in bedrock compared to NES, whereas the second case examines increased hydraulic conductivity (and thus flow) in the overburden fill material between the facility and the river, compared to NES.

5.2.5.1 Geosphere Bedrock Hydraulic Conductivity

This case examines the effect of increased hydraulic conductivity in bedrock compared to Normal Evolution scenario. The change in hydraulic conductivity in bedrock is not represented directly in the AMBER model. Rather, the model uses different sets of data on groundwater flow through the facility, based on detailed modelling undertaken by Arcadis & Geofirma (2023b). The increased flows in the bedrock result in a general lowering of the water table, such that the parts of the NPDDF that sit in the overburden experience no groundwater transport. As a consequence, the only releases that occur are from the rooms that sit within the bedrock. Furthermore, the increased flow rates through the geosphere result in substantially greater dilution of the released contaminants. By way of illustration, the volumetric flows through the bedrock compartment immediately beneath the Turbine Room at closure are increased from 1,000 $m^3\ y^{-1}$ in the NES to 50,000 $m^3\ y^{-1}$ for this sensitivity case.

The radionuclide concentrations in the geosphere are therefore much reduced in the bedrock, and there is no release to the overburden at all. The concentrations in the bedrock are substantially lower (see Figure 5-39) with the peak concentration reducing from 3,000 to 70 Bq l^{-1}. However, the rate of discharge of contaminants to the river is somewhat increased in the period 100 – 1000 y. Consequently, the river water concentrations in this timeframe are increased, as shown in Figure 5-40. This does not, however, affect the doses to the most exposed receptor, the infant Site Resident (Figure 5-42) as the dose is dominated by Cl-36 in the garden soil, which is very much reduced (see Figure 5-41) owing to the lack of releases to the overburden (no pathway from the cap to the adjacent soils due to the lower water table preventing upwelling groundwater from the NPDDF to the cap). Concentrations in the soil are much reduced as there is no pathway for contaminants to reach the soil via the overburden. The peak dose calculated for this case of 3E-05 mSv y^{-1} is three times lower than that in the NES.

Figure 5-39 Groundwater Concentrations of Contaminants Released from the NPDDF to the Geosphere (Geosphere Bedrock Hydraulic Conductivity Case)

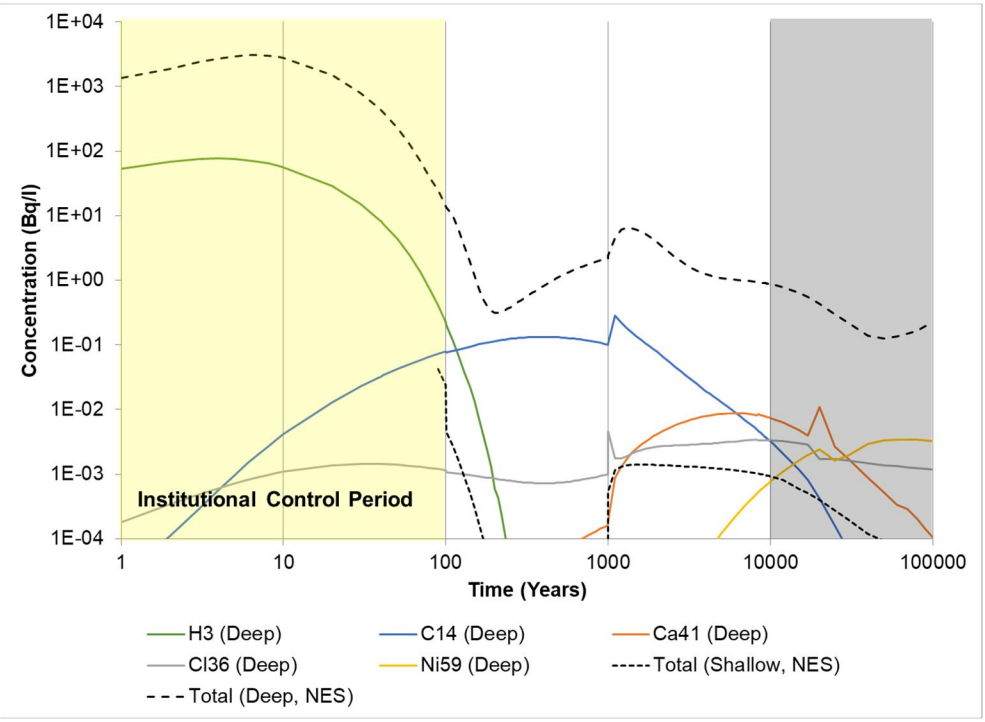


Figure 5-40 Concentrations in the River Water (Geosphere Bedrock Hydraulic Conductivity Case)

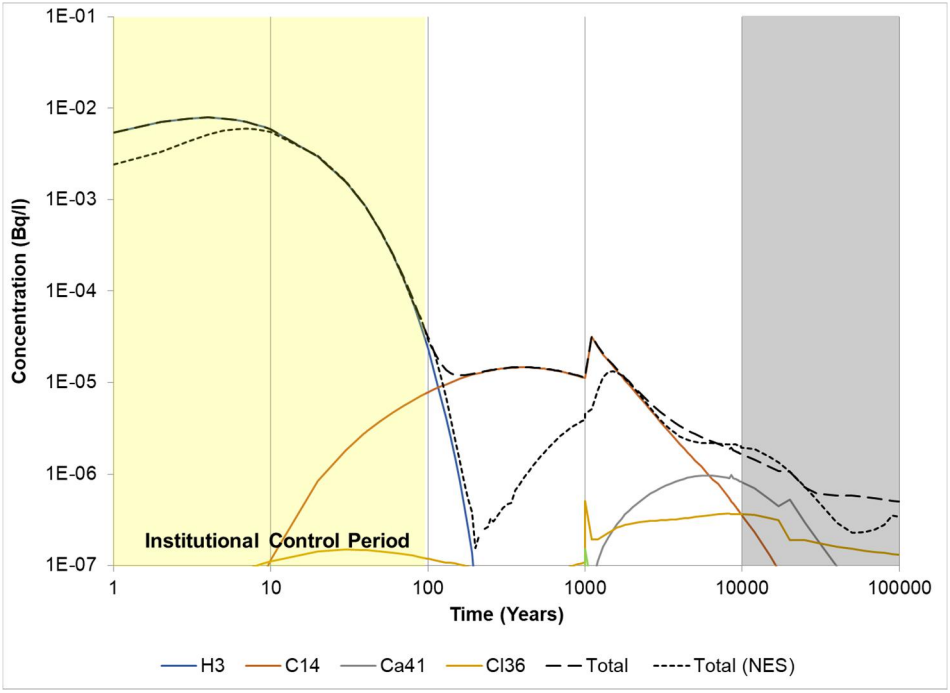


Figure 5-41 Concentrations in the Garden (Bedrock Hydraulic Conductivity Case)

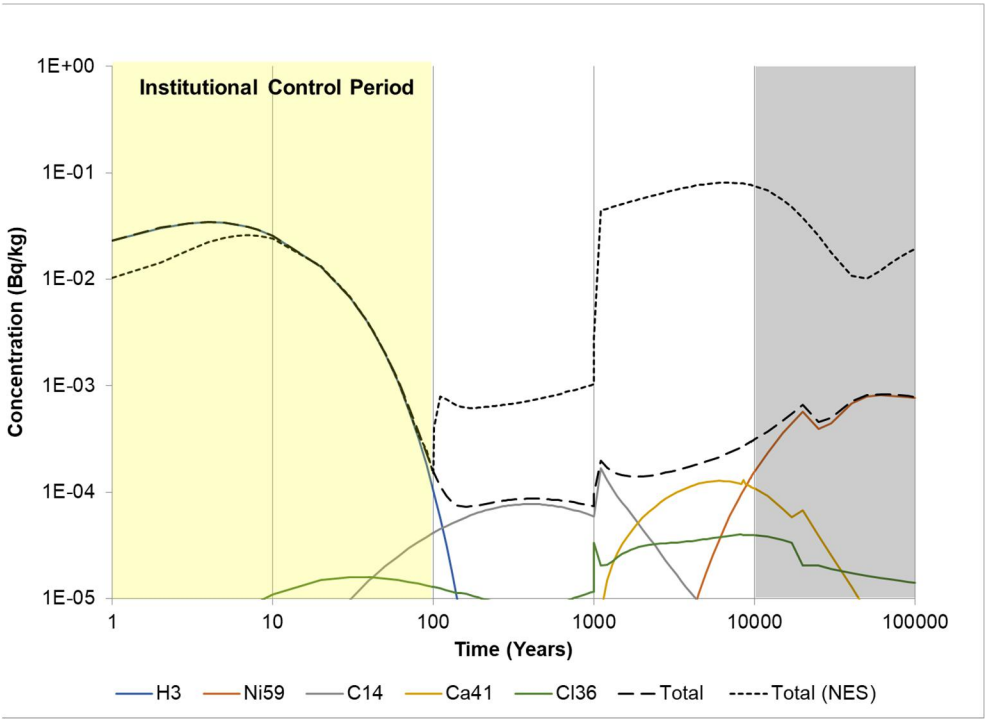
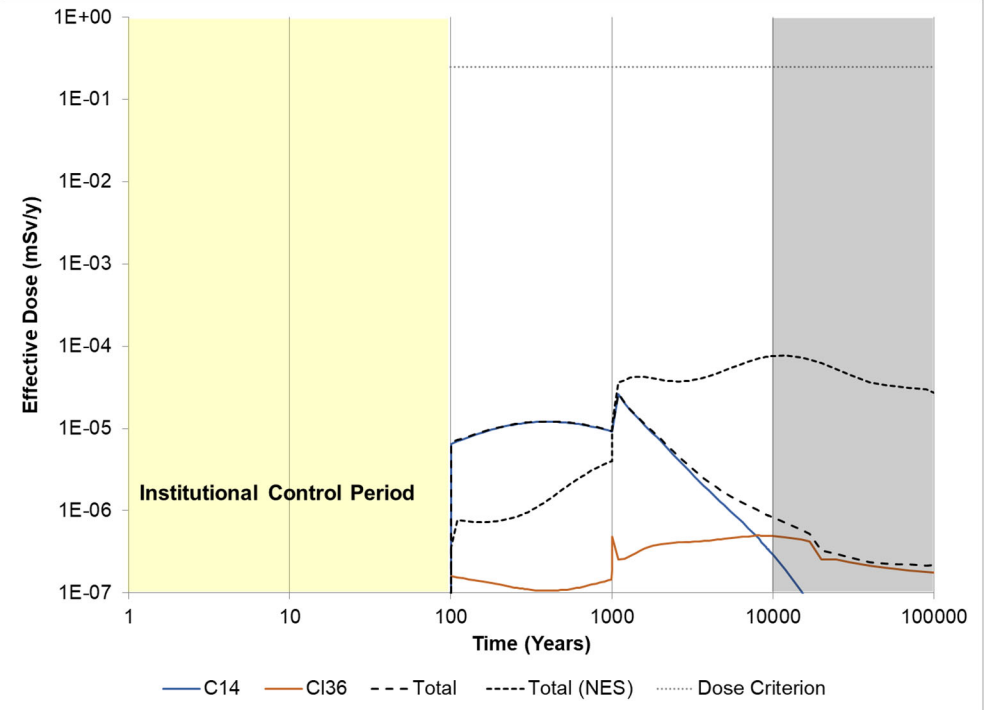


Figure 5-42 Total Dose to the Most Exposed Receptor, Infant Site Resident (Geosphere Bedrock Hydraulic Conductivity Case)



5.2.5.2 Geosphere Overburden Hydraulic Conductivity

In the same manner as in the Geosphere Bedrock Hydraulic Conductivity Case, for this sensitivity case the change in hydraulic conductivity in the overburden (till) is not represented directly in the AMBER model. Rather, the model uses different sets of data on groundwater flow through the facility, based on detailed modelling undertaken by Arcadis & Geofirma (2023b).

Figure 5-43 shows that concentrations of radionuclides in the shallow groundwater are reduced compared with the NES because the higher flow rate increases the dilution of the contaminants. The concentrations in the bedrock pathway are very similar to those for the NES as the flow rate in this part of the geosphere is unchanged. The overburden pathway is the most significant for human exposures as it leads to the release of contaminants (most importantly, Cl-36) to the Garden soil. The dose to the most exposed receptor, the Infant Site Resident is shown in Figure 5-44 and is reduced compared to that calculated for the Normal Evolution scenario. The main difference is that the increased overburden hydraulic conductivity reduces the concentrations of Cl-36. As a consequence, for this case the dominant radionuclide is C-14, and the peak dose is reduced to 1E-05 mSv y^{-1} and occurs as 1400 y after closure.

Figure 5-43 Concentrations in Groundwater Downstream from the NPDDF (Geosphere Overburden Hydraulic Conductivity Case)

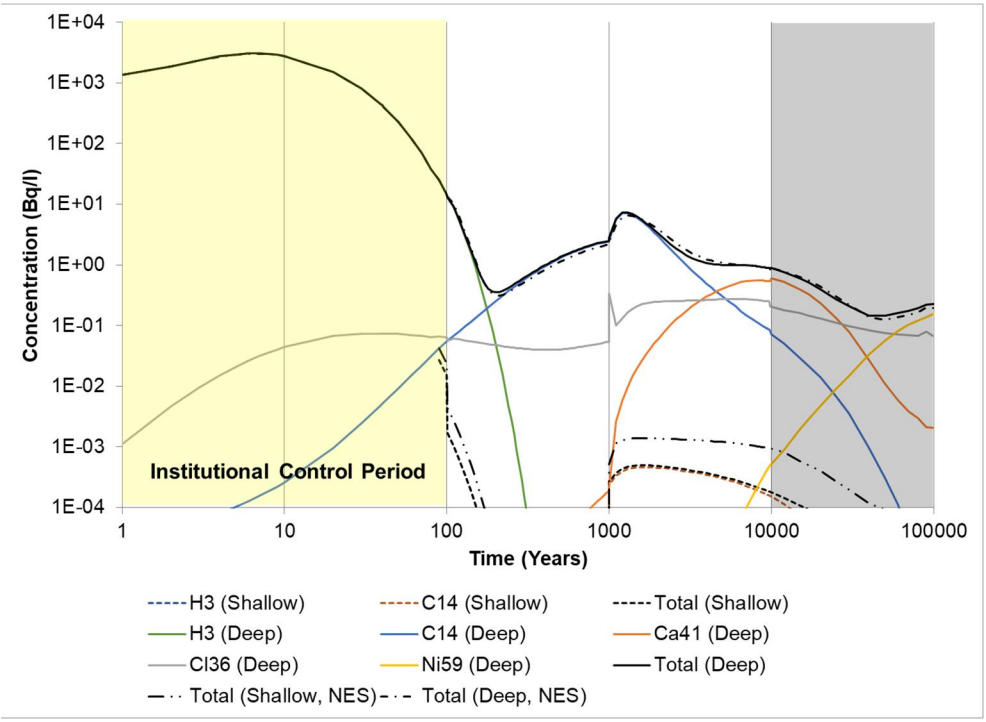
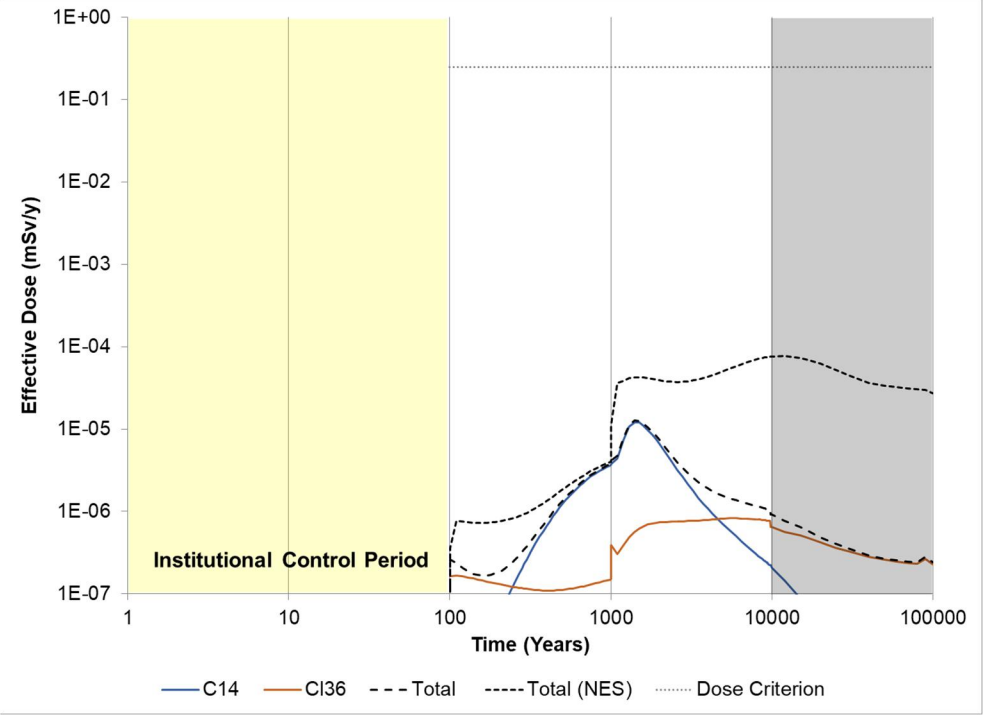


Figure 5-44 Dose to Site Resident Infant (Geosphere Overburden Hydraulic Conductivity Case)



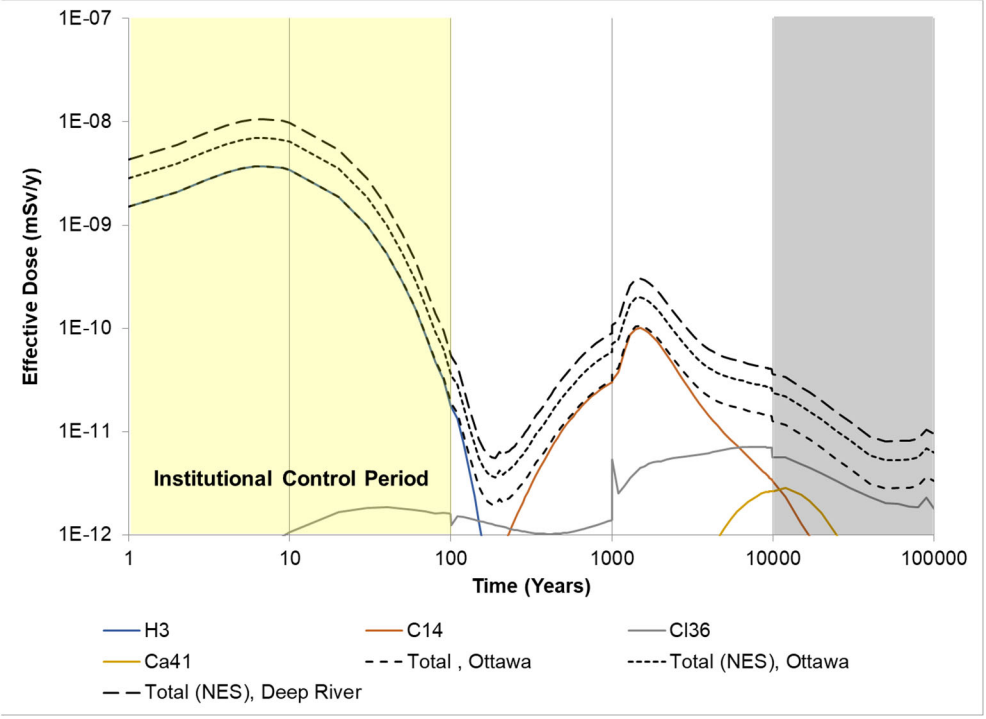
5.2.6 Increased Dilution in the River

Exposure groups have been chosen so as to provide an indication of the potential radiation doses to the most exposed people. The Normal Evolution Scenario included a hypothetical Site Resident, a non-resident group which uses the area for hunting wild foods, and a non-resident Indigenous group which also uses the area for hunting, fishing and gathering wild plants. The Indigenous group supplements its diet with purchased goods, based on a survey of the AOPFN (Fediuk *et al*., 2021). Exposures to these groups will not occur during the institutional control period of 100 y, when the access to the immediate surroundings of the NPDDF will be limited. However, any contamination reaching the river in the institutional control period can be dispersed and travel downstream where other people may be exposed. Doses are therefore calculated for people exposed to river water, i.e., those obtaining all their drinking water from the river and bathing in it for half an hour per day. Exposures via this route are assessed for a resident of Deep River, just downstream of NPDDF, and further downstream at the city of Ottawa.

For the NES the concentrations in river water at Deep River are conservatively assumed to be the same as those at the initial point of discharge of groundwater to the river at NPDDF. The concentrations at Ottawa are determined by the ratio of river flow rate at Des Joachims station (immediately upstream of NPDDF) and the reported flow rate measured at the Ottawa (Britannia) Generating Station just downstream of Gatineau, giving a dilution factor of 0.658.

A sensitivity case considers an alternative dilution factor of 0.35. These dilution factors simply scale the concentrations and hence the doses from the ingestion and external exposure pathways. The results are shown in Figure 5-45. The highest dose calculated at Deep River for the NES is 1E-08 mSv y^{-1} occurring 7 y after closure, through ingestion of water containing tritium. If a dilution factor of 0.658 is applied, then the calculated peak dose at Ottawa is 7E-09 mSv y^{-1}, compared to 4E-09 mSv y^{-1} if a dilution factor of 0.35 is applied instead.

Figure 5-45 Total Dose to People Exposed to Contaminants in River Water at Ottawa, Considering Various Dilution Factors



5.2.7 Indigenous Self-sufficient Receptor

This sensitivity case examines the sensitivity of the lifestyle assumptions for Indigenous communities with an additional exposure group, the Indigenous Self-sufficient Group. This receptor group is assumed to live in the vicinity of the NPDDF and obtain food from that area. It is conservatively-defined and based on Indigenous habits presented in SENES (2014). The dietary intake rates for this receptor are taken from food intake data representing high energy intake rates (SENES, 2014). Their diet consists of deer and moose as well as wildfowl, fish, berries and mushrooms. The Self-sufficient Indigenous group spends less time in the vicinity of the site as a whole than the Site Resident (as they are not living there), but spends longer by the river, fishing.

The peak dose to the Indigenous Self-sufficient exposure group is 4E-05 mSv y^{-1} to an infant, dominated by C-14 at 1,500 y. After 2,200 y Cl-36 is the dominant radionuclide and a second peak dose of

3E-05 mSv y^{-1} is reached after 10,000 y due mainly to Cl-36. As shown, these doses remain lower than the Site Resident (8E-05 mSv y^{-1}) but greater than that to the AOPFN exposure group (7E-06 mSv y^{-1}), as shown in Figure 5-46 and Figure 5-47.

Compared to the AOPFN exposure group, the Indigenous Self-sufficient receptor takes conservative intake rates from a large population survey for each foodstuff, whereas the AOPFN rates are based on targeted dietary surveys and are expected to be more representative. Even when accounting for a local fraction of <1, then intake rates of moose, grouse, duck, fish and berries are significantly higher than for the AOPFN receptor. Foodstuff pathways dominate the doses (Figure 5-48), therefore the AOPFN receptor receives a lower dose.

The summary of dose to an infant in the Indigenous Self-sufficient Group for the five radionuclides contributing most to the dose and the summary of dose to an infant in the Indigenous Self-sufficient for the different pathways through time are given in Table 5-21 and Table 5-22, respectively.

Figure 5-46 Total Dose to the Indigenous Self-sufficient Group, Compared with Exposure Groups Considered in the Normal Evolution Scenario

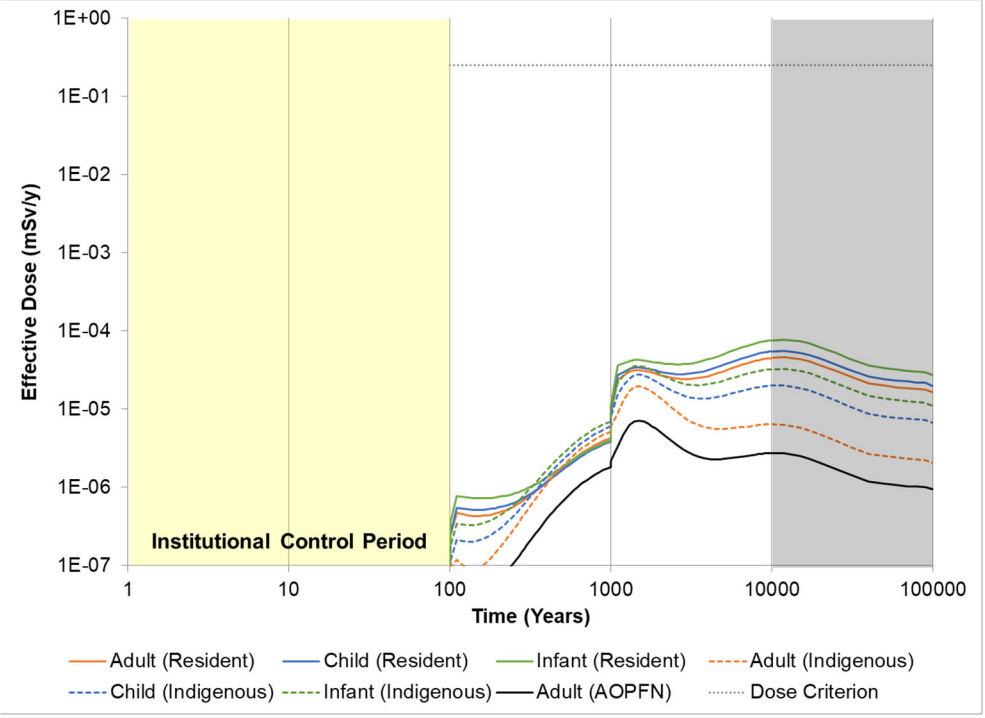


Figure 5-47 Total Dose to an Infant in the Indigenous Self-sufficient Group (by Radionuclide)

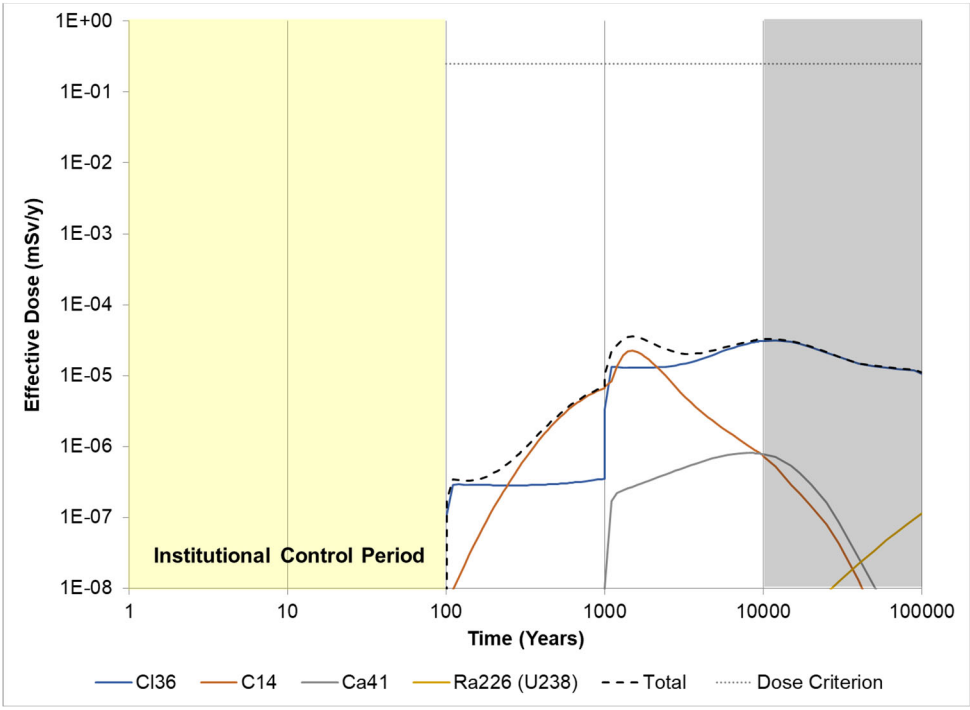


Figure 5-48 Total Dose to an Infant in the Indigenous Self-sufficient Group (by Exposure Pathway)

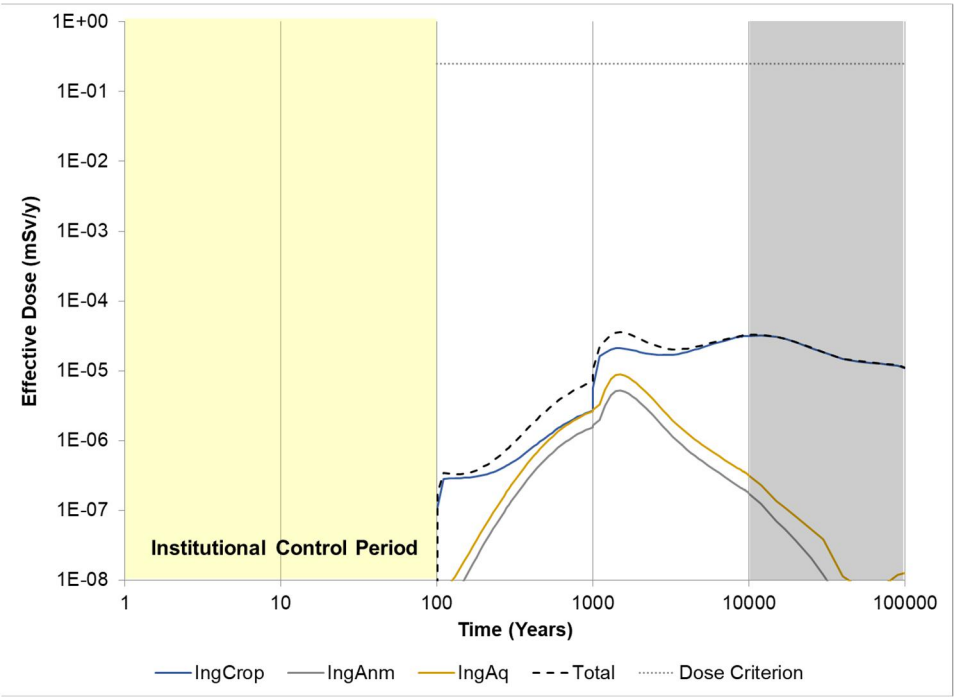


Table 5-21 Summary of Dose (mSv y^{-1}) to an Infant in the Indigenous Self-sufficient Group for the Five Radionuclides Contributing Most to the Dose

Time (y)	Cl36	C14	Ca41	Ra226 (U238)*	Po210 (U238)*	Total
100	1E-07	6E-09	<1E-10	<1E-10	<1E-10	2E-07
300	3E-07	6E-07	1E-09	<1E-10	<1E-10	9E-07
1000	4E-07	7E-06	9E-09	<1E-10	<1E-10	7E-06
3000	1E-05	6E-06	5E-07	<1E-10	<1E-10	2E-05
10000	3E-05	7E-07	8E-07	1E-09	9E-10	3E-05
30000	2E-05	4E-08	9E-08	1E-08	9E-09	2E-05
50000	1E-05	4E-09	1E-08	3E-08	3E-08	1E-05
Maximum (mSv y^{-1})	3E-05	2E-05	8E-07	3E-08	3E-08	4E-05
Time of Peak (y)	12000	1500	8000	50000	50000	1500

Note: * Radionuclide is a daughter not present at closure that has ingrown from its parent, U-238.

Table 5-22 Summary of Dose (mSv y^{-1}) to an Infant in the Indigenous Self-sufficient Group for the Different Pathways Through Time

Time (y)	Ingestion of Crops	Ingestion of Honey	Ingestion of Animals	Ingestion of Fish	Ingestion of Water	Inhalation of Gas	Total
100	1E-07	1E-09	2E-09	5E-09	6E-08	<1E-10	2E-07
300	5E-07	7E-09	1E-07	2E-07	1E-08	<1E-10	9E-07
1000	6E-06	9E-08	2E-06	3E-06	1E-07	<1E-10	1E-05
3000	2E-05	1E-07	1E-06	2E-06	1E-07	<1E-10	2E-05
10000	3E-05	2E-07	2E-07	3E-07	6E-08	<1E-10	3E-05
30000	2E-05	1E-07	1E-08	4E-08	2E-08	<1E-10	2E-05
50000	1E-05	7E-08	3E-09	8E-09	2E-08	<1E-10	1E-05
Max. (mSv y^{-1})	3E-05	3E-07	5E-06	9E-06	3E-07	4E-13	4E-05
Time of Peak (y)	12000	1500	1500	1500	1500	1500	1500

5.3 Disruptive Event Scenarios

5.3.1 Site Investigation

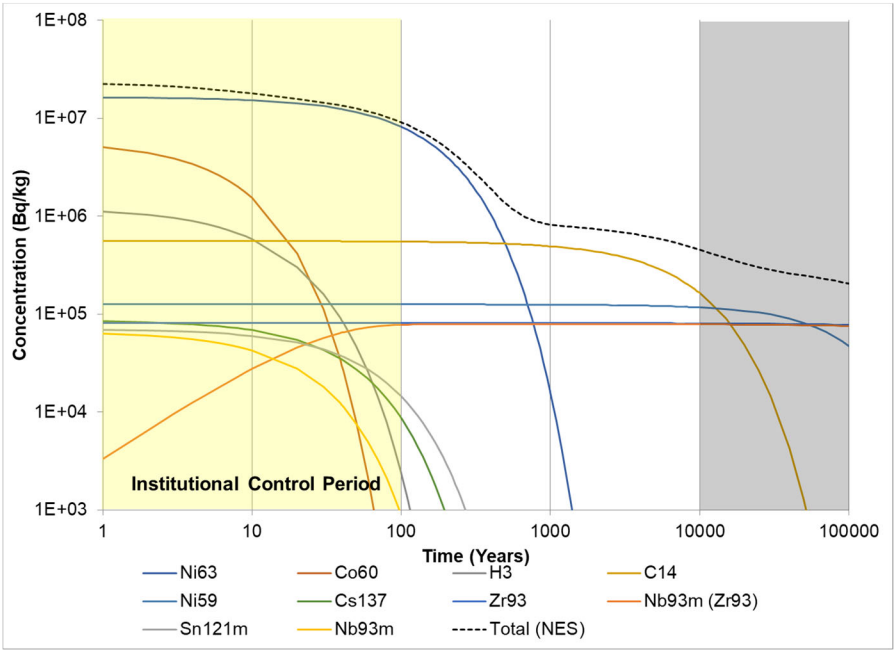
Site investigation is a Disruptive Event scenario that represents the possible consequences of people, in the future, locating and investigating the NPDDF without knowledge of its contents. Even if it were located, the monolithic nature of the Facility at closure means that inadvertent disruption by humans is difficult and unlikely to occur without a significant degree of careful investigation. Barriers to human intrusion will include a concrete cap with an engineered cover, and beneath the concrete cap the rooms in the nuclear area will be filled with grout. Access to the NPDDF rooms would require machinery and facilities usually deployed for geological excavations. This would in turn be expected to reveal the nature of the facility. Nevertheless, the persistent nature of the contaminants in the Facility mean that such events cannot be discounted in the far future.

The scenario considers the possibility of people drilling a borehole into the NPDDF at some point after the Institutional Control period. The investigation is assumed to retrieve a 5 kg sample of material, which is a factor of 10 more conservative than would be expected. The duration of the exposure to contaminated material is 12 hours (for further details, the reader is referred to Appendix E). In order to examine subsequent exposures, the contaminated material retrieved to the surface is subsequently assumed to be discarded and become mixed with the “Garden” soil. Radiation doses to the Site Resident exposure group are therefore also calculated, taking account of the additional radioactivity within the garden soil. Cautiously, the additional contamination is assumed not to be leached from the soil.

For the purposes of the dose assessment, the average concentration in the Reactor Vault is taken (Figure 5-49). The peak dose rate from external radiation, after 100y, is 0.04 μSv h^{-1}, initially dominated by Ag-108m (Figure 5-50). The half-life of Ag-108m means that a substantial decrease does not occur until more than 1,000 y after closure of the NPDDF. The radionuclide has a half-life of 418 y and is dominant due to its presence as an activation product and strong gamma emission. After 1,200 y the dominant radionuclide is Nb-94, present in activated metal reactor components.

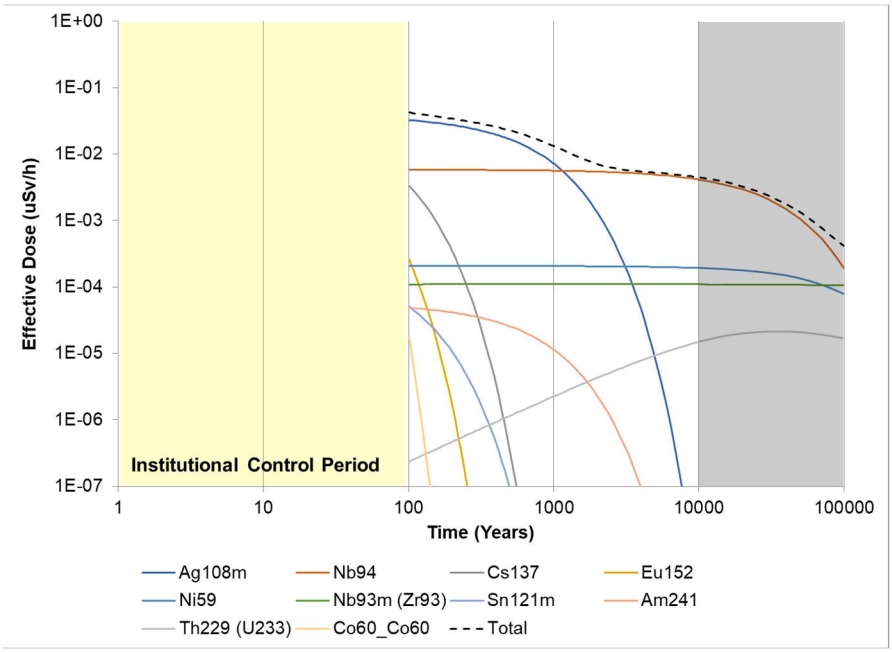
Radiation doses to the Borehole Driller and to the Site Resident group following intrusion are shown in Figure 5-51, compared with calculated exposures for the Normal Evolution scenario. The highest doses are if the intrusion were to occur immediately after the end of Institutional control at 100 y after closure and are 5E-04 mSv y^{-1} to the Borehole Driller and 4E-04 mSv y^{-1} to the Infant Site Resident (following intrusion). The dominant exposure pathway for the Borehole Driller is external irradiation by Ag-108m and Nb-94 in the retrieved drill core (Figure 5-52). Food chain pathways dominate the dose to the Site Resident living on land contaminated with the retrieved contaminants (Figure 5-53). Cl-36 is the dominant radionuclide owing to its high uptake factor for terrestrial biota (Figure 5-54).

Figure 5-49 Average Concentration of Radionuclides in the Reactor Vault (Note: Total and Total NES are identical here)



Note: Radionuclides in brackets indicate the parent of the radionuclide that was present in the initial radionuclide inventory of the NPDDF.

Figure 5-50 Dose Rate at 1 m from the 5 kg Core at Average Concentration in the Reactor Vault (Site Investigation Scenario)



Note: Radionuclides in brackets indicate the parent of the radionuclide that was present in the initial radionuclide inventory of the NPDDF.

Figure 5-51 Dose to Exposure Groups (Site Investigation Case)

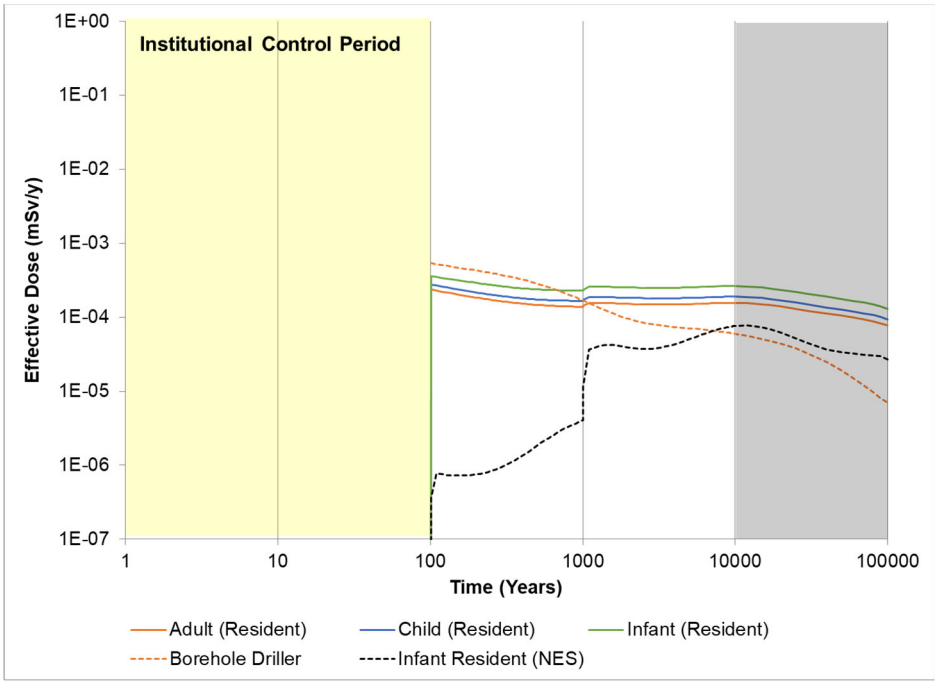


Figure 5-52 Dose to Borehole Driller, by Radionuclide (Site Investigation Case)

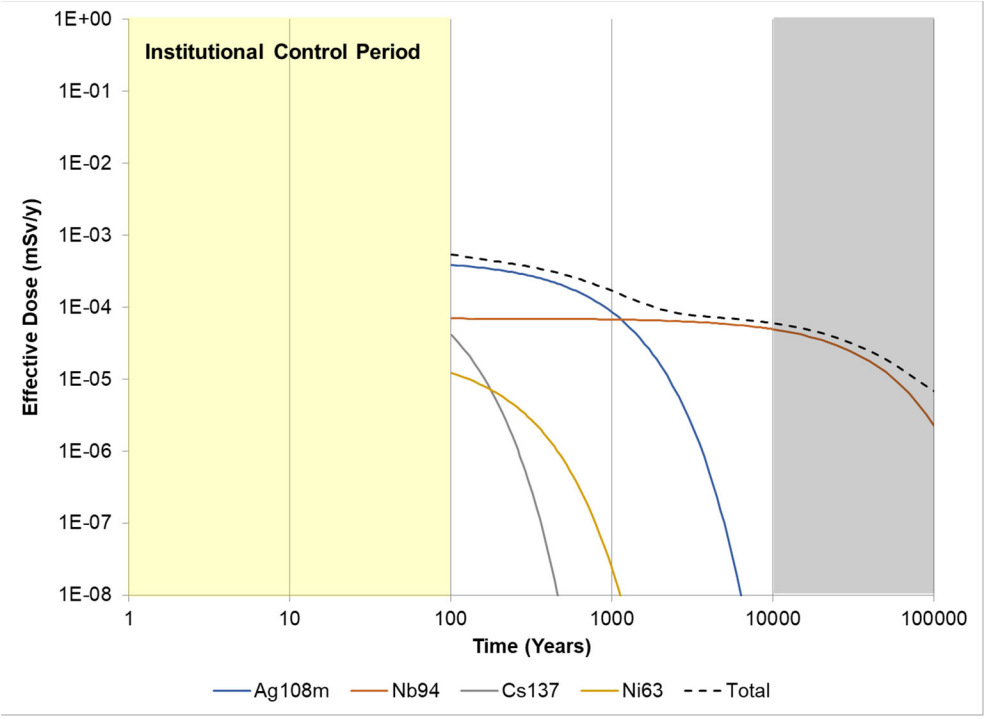


Figure 5-53 Dose to Infant Site Resident on Contaminated Ground, by Pathway (Site Investigation Case)

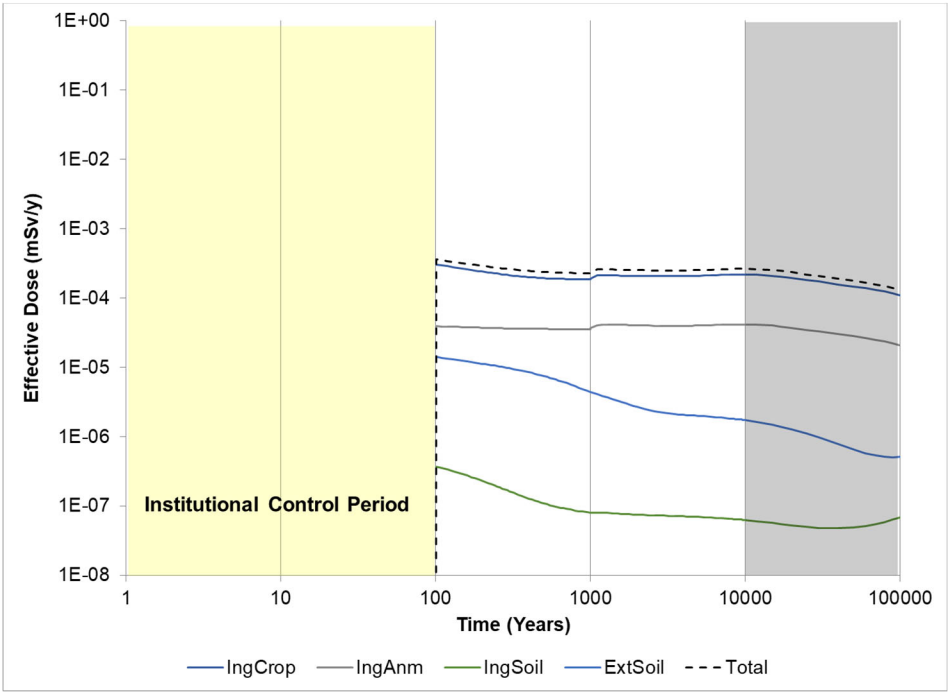
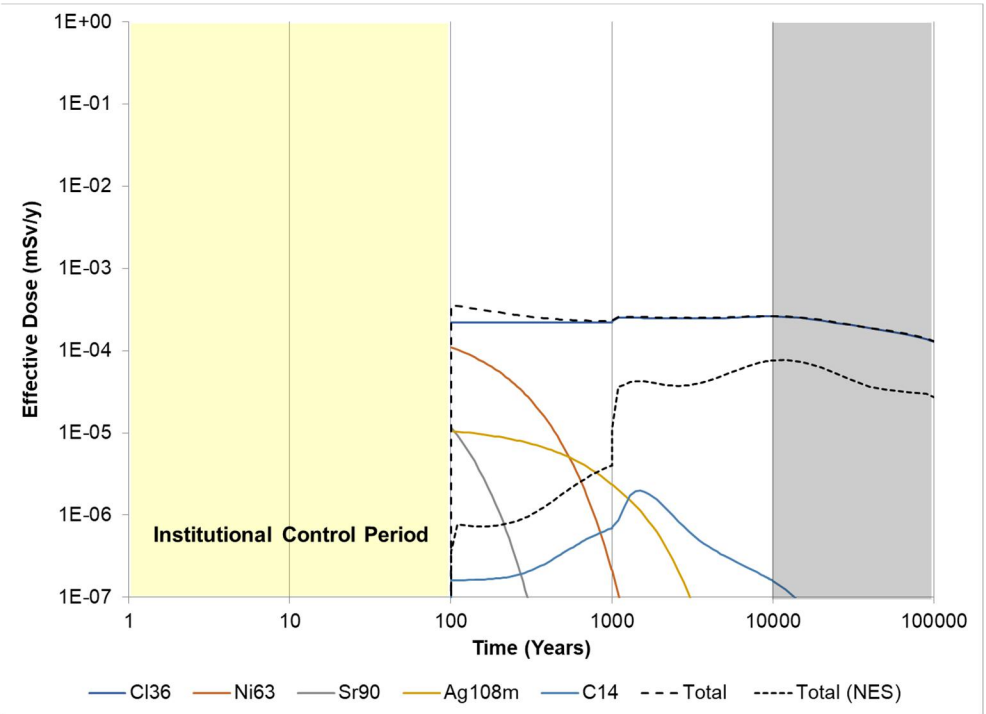


Figure 5-54 Dose to Infant Site Resident on Contaminated Ground, by Radionuclide (Site Investigation Case)



5.3.2 Surface Erosion

This case assumes that a flood or erosion event occurs after 100 y and scours the surface and leads to people being directly exposed to the rock that has been contaminated by groundwater. It is modelled by assuming that the "Garden" is relocated onto the contaminated part of the geosphere. The radionuclide concentrations in the Garden are set equal to those in the overburden through which the contaminated groundwater has flowed. There are no other changes to the model compared with the NES.

As can be seen in Figure 5-55, there is immediately an increase in concentrations in the part of the garden soil with tritium peaking at 2 Bq kg^{-1} at 100 y. Subsequently, after the degradation of the engineered structure of the NPDDF at 1,000 y, radionuclides are released at greater rates. Thereafter, the dominant radionuclide is C-14 out to 4,000 y with a peak concentration of 26 Bq kg^{-1} after 1,300 y. In the very far future, the concentration in the Garden could reach 39 Bq kg^{-1} with Ni-59 dominating.

The radionuclide concentrations in certain foodstuffs (vegetables and poultry) are much increased as they are assumed to come from this area of contaminated ground (e.g., see Figure 5-56). In practice, growing vegetables on the small area of ground downslope of the NPDDF would not be feasible in the Surface Erosion case because the material is rock, not soil, the area of the ground contaminated by groundwater is small (around 100 m by a few 10's of m), and it is steeply sloping.

Figure 5-55 Concentration Assumed in Garden (Surface Erosion Case)

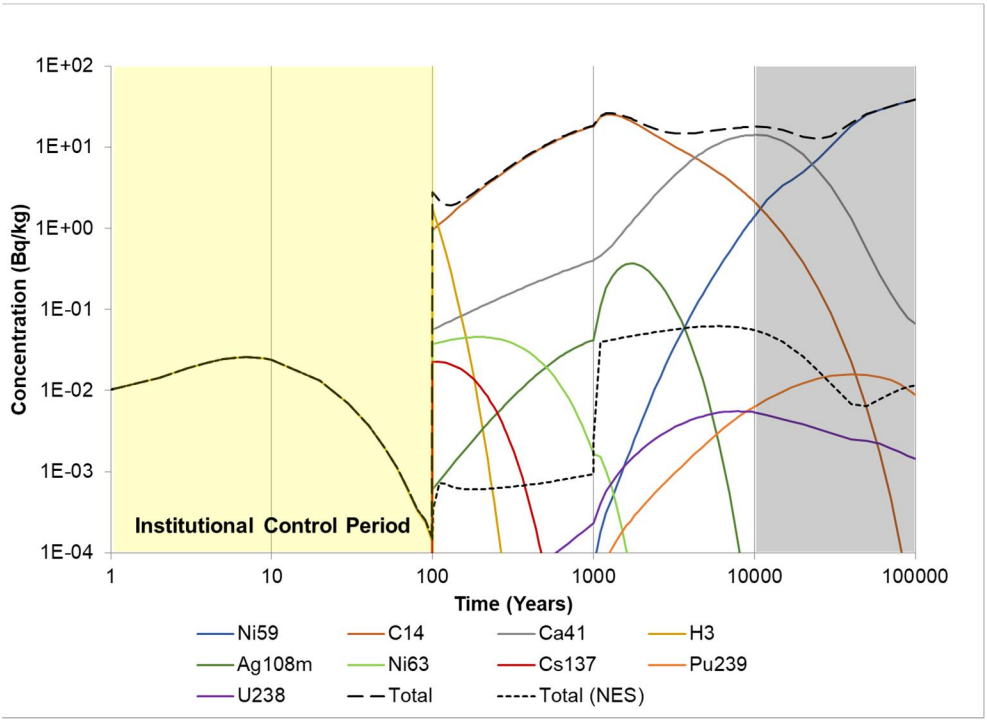
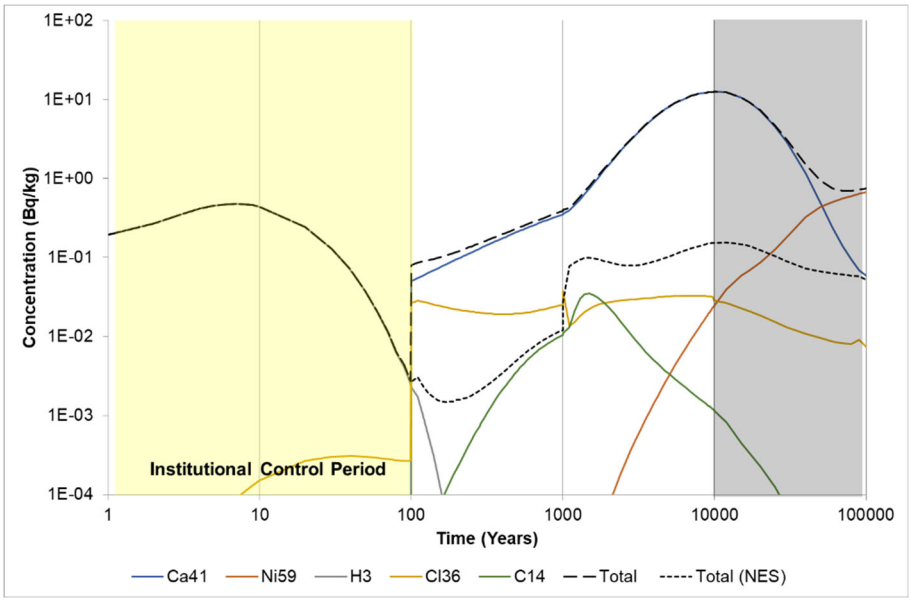
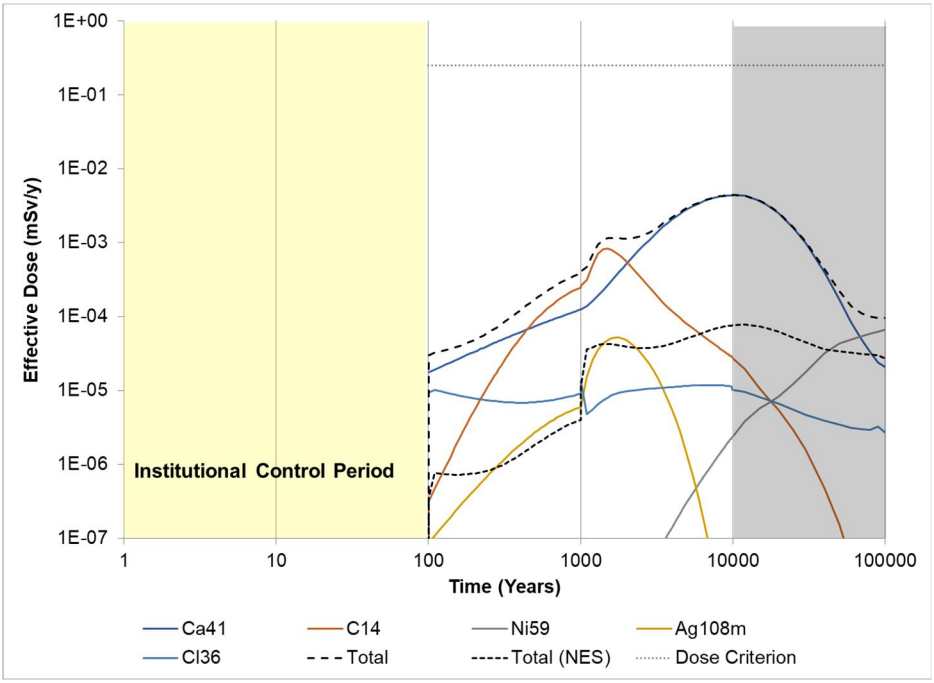


Figure 5-56 Concentration in Eggs from Chickens Kept in the Garden (Surface Erosion Case)



All receptors are assumed to consume vegetables and/or wild foods sourced from this area, and thus doses are increased to all. The highest dose of 4E-03 mSv y^{-1} is to a child in the Resident receptor group (compared with 8E-05 mSv y^{-1} to the Infant Resident in the NES) (Figure 5-57). Doses are dominated by Ca-41 and peak at 10,000 y.

Figure 5-57 Dose to the Most Exposed Receptor – Child Site Resident, by Radionuclide (Surface Erosion Case)



5.3.3 Extreme Degradation

The structure of the NPDDF, and the grout planned to be added, both physically limit water flow through the wastes, and also provide chemical conditions that limit the release of radionuclides. This scenario examines the consequences of the extreme degradation of these barriers. The engineered barriers are assumed to become degraded after 1,000 y, for example due to a severe seismic event. To represent this, the hydraulic conductivity of the above bedrock concrete and grout was increased to 1E-06 m s^{-1}. The portion of the NPDDF that sits within the bedrock is protected by the bedrock and so is less degraded (represented with a hydraulic conductivity of 1E-08 m s^{-1}).

The very much higher hydraulic conductivity of the above-bedrock barriers allows much more water flow through the above-bedrock parts of the Facility. This in turn increases the rate of release of contaminants. Importantly, it also reduces the duration that the chemical effects of the cement persist, which reduces the period in which high-pH conditions lead to increased sorption of key radionuclides. Table 5-23 and Table 5-24 present the times at which the different concrete and grout degradation stages begin in this case. Comparing the times presented in Table 5-23 and Table 5-24 to those of the NES (shown earlier in Figure 5-7) shows that the duration of the key concrete and grout degradation stages in the above-bedrock parts of the facility are much shorter than those calculated for the NES whereas the below-bedrock parts are similar. For example, in the NES, concrete in the turbine room experiences stage 1 degradation for approximately the first 15,000 years, then stage 2 onward. Whereas in this extreme degradation case, concrete in the turbine room experiences stage 1 degradation for only the first 2,200 years, then stage 2 from year 2,200 to 15,000, stage 3 from year 15,000 to 90,000, and stage 4 from year 90,000 and onward.

Table 5-23 Time at Which Concrete Degradation Stages Begin – Extreme Degradation Case

Room	Stage 1	Stage 2	Stage 3	Stage 4
Above Bedrock				
Fuel Storage Room	0	1,900	9,700	70,000
Fueling Room	0	1,700	8,000	60,000
Boiler Room	0	1,600	6,500	40,000
Turbine Room	0	2,200	15,000	90,000
Below Bedrock				
Fuel Storage Room	0	12,000	>100,000	>100,000
Reactor Vault	0	12,000	>100,000	>100,000
East of Reactor Vault	0	3,000	25,000	>100,000
West of Reactor Vault	0	8,000	70,000	>100,000
Dump Tank Pipe Room	0	8,000	70,000	>100,000
Boiler Room	0	8,500	80,000	>100,000
Boiler Room (deep)	0	7,000	70,000	>100,000

Note: Greyed-out cells are after the main assessment timeframe of 10,000 y.

Table 5-24 Time at Which Grout Degradation Stages Begin – Extreme Degradation Case

Room	Stage A	Stage B	Stage C	Stage D	Stage E	Stage F
Above Bedrock						
Fuel Storage Room	0	2,000	3,000	7,000	20,000	50,000
Fueling Room	0	1,700	2,600	5,500	15,000	40,000
Boiler Room	0	1,600	2,200	4,250	12,000	25,000
Turbine Room	0	2,400	3,750	8,500	25,000	60,000
Below Bedrock						
Fuel Storage Room	0	15,000	30,000	80,000	>100,000	>100,000
Reactor Vault	0	12,000	25,000	70,000	>100,000	>100,000
East of Reactor Vault	0	3,250	5,500	15,000	40,000	100,000
West of Reactor Vault	0	8,000	17,000	50,000	>100,000	>100,000
Dump Tank Pipe Room	0	8,000	17,000	50,000	>100,000	>100,000
Boiler Room	0	9,000	20,000	50,000	>100,000	>100,000
Boiler Room (deep)	0	8,000	15,000	40,000	>100,000	>100,000

Note: Greyed-out cells are after the main assessment timeframe of 10,000 y.

The effect of higher flows and the more rapid chemical degradation of the cementitious structures is seen in Figure 5-58 in which the greater release of radionuclides is most noticeable in the overburden. Concentrations in the bedrock are similar to the NES. The more significant physical degradation can be seen in a sharp increase in concentrations at 1,000 y and the more rapid chemical degradation in the "lumpy" nature of the releases after 10,000 y. The latter reflects a sequence of transitions in sorption coefficient, as the chemical degradation of the cementitious materials moves through successive stages of reduced pH. As flows through each room are different, these transitions occur at different times. In the overburden the peak concentration increases 20 times from 0.001 Bq kg^{-1} to 0.02 Bq l^{-1}. Particularly notable is the sudden increase in the Cl-36 concentrations in overburden groundwater at 12,000 – 15,000 y, when grout degradation transitions from Stage D to E in the Boiler Room and Fuelling Room, and the sorption of Cl changes from 0.02 m^3 kg^{-1} to 0 m^3 kg^{-1} (unsorbed).

The key environmental media are river water (Figure 5-59) and the garden soil (Figure 5-60). The primary source of contamination in the river is the bedrock pathway and so the peak concentrations are only modestly increased by a factor of 3 from the NES, to 3E-05 Bq l^{-1}. The source of radionuclides to the Garden is dominated by the overburden pathway and so the increase is greater amount, from 6E-02 Bq kg^{-1} to 1 Bq kg^{-1}. The peak dose (to an infant Site Resident, see Figure 5-61) is increased to 3E-04 mSv y^{-1} due to higher concentrations of Cl-36 in foodstuffs. The spike in the dose at 12,000 y, resulting from the reduction in Cl-36 sorption in the boiler room as the grout transitions from Stage D to Stage E is particularly noticeable.

Figure 5-58 Release of Radionuclides from the NPDDF to the Geosphere (Extreme Degradation of Engineered Barriers Case)

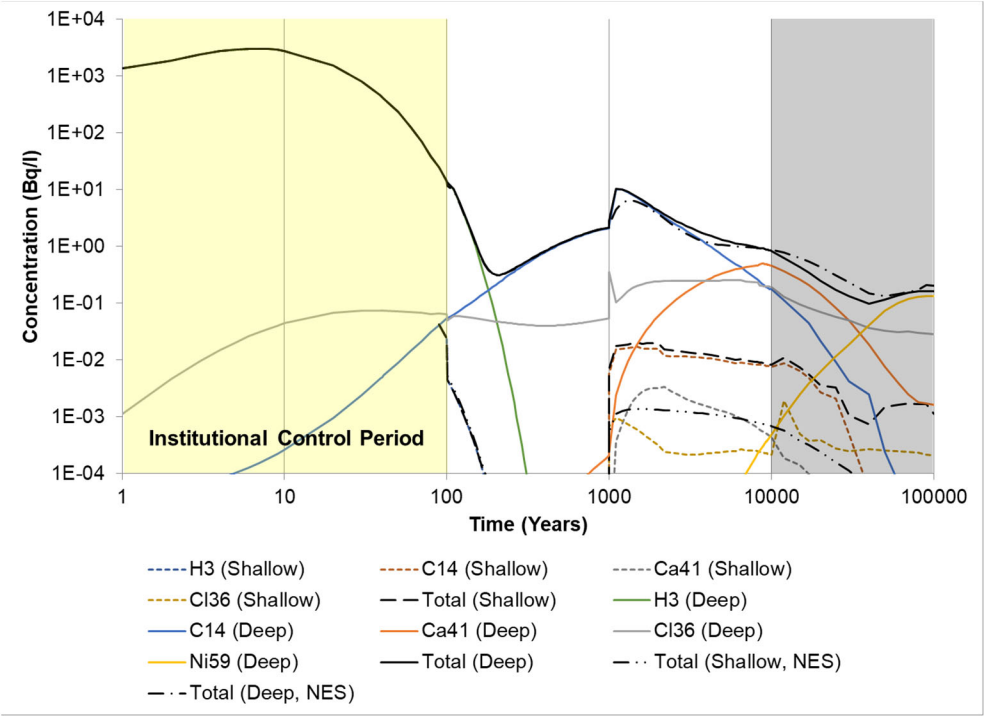


Figure 5-59 Concentrations of Radionuclides in River Water (Extreme Degradation of Engineered Barriers Case)

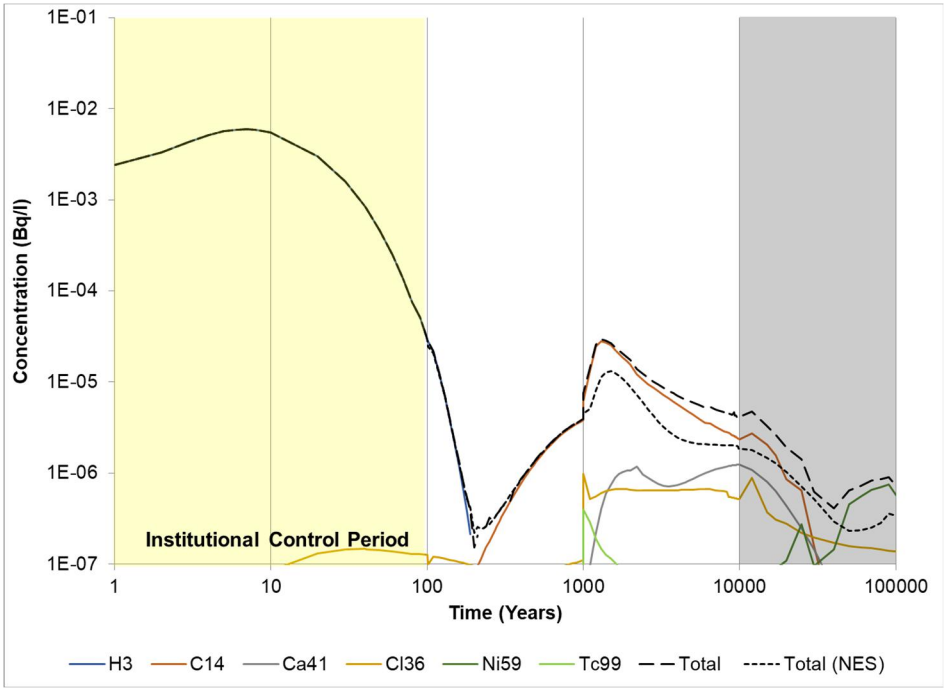


Figure 5-60 Concentrations of Radionuclides in the Garden (Extreme Degradation of Engineered Barriers Case)

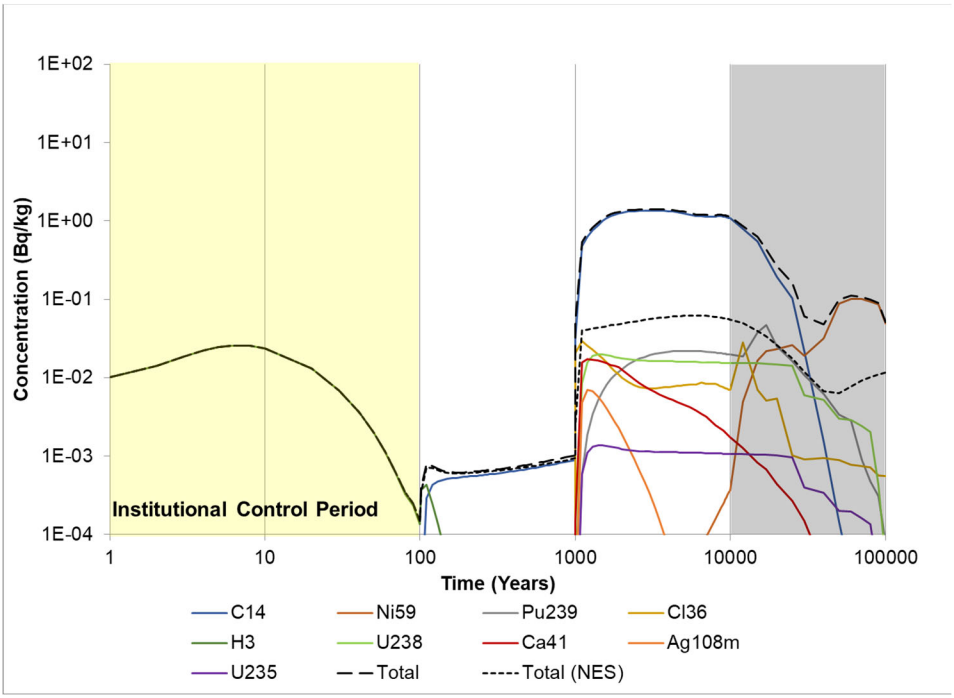
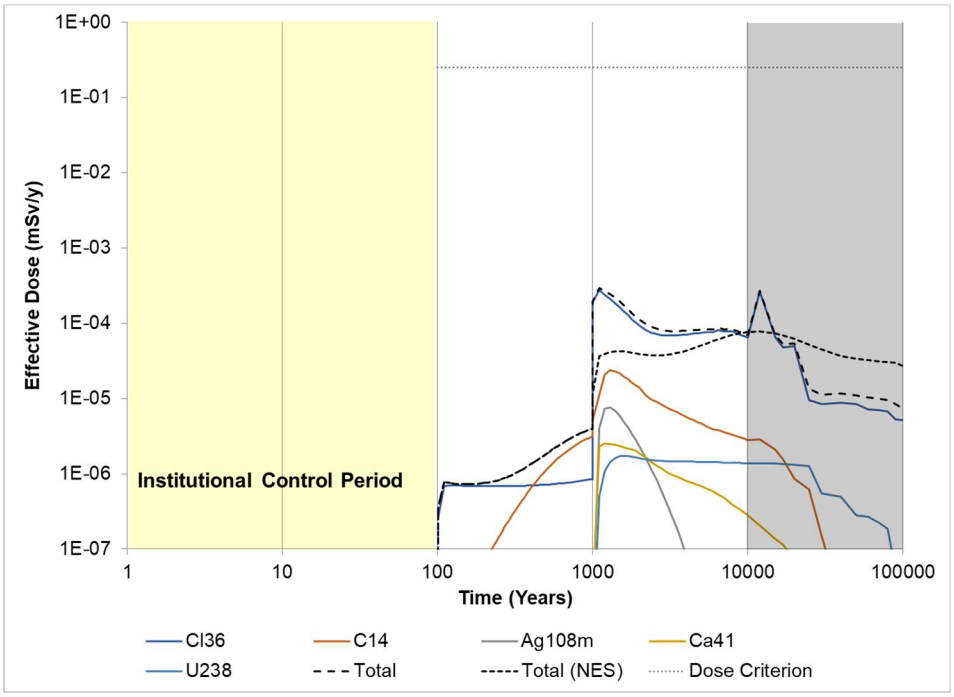


Figure 5-61 Dose to Most Exposed Receptor - Infant Site Resident, by Radionuclide (Extreme Degradation of Engineered Barriers Case)



5.3.4 Fault Zone Activation

Seismic events of even greater magnitudes than assumed in the NES (such as a 1-in-50,000-y event) could potentially induce a fault zone of higher conductivity in the geosphere as well as cause extreme degradation of engineered barriers. This Disruptive Event case builds on the assumptions made in the Extreme Degradation case to represent even more comprehensive damage to the NPDDF as well as higher conductivity in the bedrock due to a fault zone.

The seismic event is assumed to occur at 1,000 y. At this point, the entire Facility structure is assumed to be extremely degraded with hydraulic conductivity increased to 1E-06 m s^{-1} in concrete and grout throughout the NPDDF. The fault zone is represented using a higher hydraulic conductivity in the bedrock between the facility and the river compared to the NES leading to increased flows through the bedrock (Geofirma & Arcadis, 2023a,b). These lead to much more rapid chemical degradation with the below-bedrock parts of the NPDDF entirely losing the chemical effects of the cements by 15,000 y, and the degradation well advanced in the above bedrock parts by 10,000 y (see Table 5-25 and Table 5-26).

Table 5-25 Time at Which Concrete Degradation Stages Begin – Fault Zone Activation Case

Room	Stage 1	Stage 2	Stage 3	Stage 4
Above Bedrock				
Fuel Storage Room	0	1,400	4,250	25,000
Fueling Room	0	1,200	3,000	17,000
Boiler Room	0	1,700	8,000	50,000
Turbine Room	0	1,300	3,500	20,000
Below Bedrock				
Fuel Storage Room	0	1,200	2,800	15,000
Reactor Vault	0	1,200	2,800	15,000
East of Reactor Vault	0	1,100	1,500	4,250
West of Reactor Vault	0	1,100	2,000	8,000
Dump Tank Pipe Room	0	1,200	2,200	9,000
Boiler Room	0	1,200	2,600	15,000
Boiler Room (deep)	0	1,100	2,000	8,000

Note: Greyed-out cells are after the main assessment timeframe of 10,000 y.

Table 5-26 Time at Which Grout Degradation Stages Begin – Fault Zone Activation Case

Room	Stage A	Stage B	Stage C	Stage D	Stage E	Stage F
Above Bedrock						
Fuel Storage Room	0	1,400	1,700	3,000	8,000	17,000
Fueling Room	0	1,300	1,500	2,400	5,000	12,000
Boiler Room	0	1,700	2,600	5,500	15,000	40,000
Turbine Room	0	1,300	1,600	2,600	6,000	15,000
Below Bedrock						
Fuel Storage Room	0	1,200	1,400	2,200	4,500	9,200
Reactor Vault	0	1,200	1,400	2,200	4,500	9,100
East of Reactor Vault	0	-*	1,100	1,300	1,900	3,000
West of Reactor Vault	0	1,100	1,300	1,600	3,000	5,500
Dump Tank Pipe Room	0	1,200	1,300	1,700	3,250	6,000
Boiler Room	0	1,200	1,400	2,000	4,000	8,250
Boiler Room (deep)	0	1,100	1,300	1,700	3,000	5,500

Note: Greyed-out cells are after the main assessment timeframe of 10,000 y.

*Transition through Stage B is not resolved in the model output as it occurs between timesteps at 1,001 y and 1,100 y

In the first 1000 y the results are the same as the NES as there is no difference with the scenario, therefore this period is not discussed further. After degradation occurs, however, the higher conductivity of the Facility and the bedrock groundwater path leads to very different pattern of releases than the NES and indeed the Extreme Degradation case (Section 5.3.3). Because the entire facility is assumed to be extremely degraded, rather than just the above bedrock portion, there is a greater flux of water through the structure and grout. This leads to more rapid chemical degradation of these materials, resulting in 'spikes' as there are transitions that involve changes to the sorption of key radionuclides like C-14. However, the higher flow rates also increase the dilution of the radionuclides that have been released from the NPDDF into the bedrock meaning that the peak concentrations are similar in this period (albeit peaking at 8,000 y rather than 1,300 y). This is illustrated in Figure 5-62 where the peak concentration in the bedrock after degradation has occurred is 8 Bq l^{-1}, similar to the peak of 6 Bq l^{-1} for the NES and 10 Bq l^{-1} for the Extreme Degradation case. The overall greater releases of contaminants induced by the higher bedrock flow rates do, however, result in an increased peak concentration in the overburden of 0.1 Bq l^{-1} compared with 0.001 Bq l^{-1} in the NES and 0.02 Bq l^{-1} for the Extreme Degradation case.

The total flux of radionuclide releases is increased, resulting in higher concentrations in the river (Figure 5-63). Particularly notable is the very 'spiky' releases of C-14, in particular the peak at 8,000 y which corresponds to a transition in the chemical regime in the deep Boiler Room and rooms surrounding the Reactor Vault. The peak concentration in river water, occurring at 8,000 y, is $5x10^{-4}$ Bq l^{-1}, compared with the $1x10^{-5}$ Bq l^{-1} in the NES and $3x10^{-5}$ Bq l^{-1} in the Extreme Degradation case.

The resulting doses are similar to those calculated for the Extreme Degradation case (see Figure 5-64) although slightly higher resulting from the more rapid release induced by the higher bedrock flow rates. In addition, the key radionuclide and time of peak differs. In this case the dose is dominated by C-14 rather than Cl-36 and occurs significantly later, owing to the different pattern of chemical degradation, particularly

in the below bedrock rooms such as the deep Boiler Room and Reactor Vault. The peak dose, shown in Figure 5-64, is $5x10^{-4}$ mSv y^{-1} after 8,000 y to an adult Site Resident, dominated by C-14 via ingestion of vegetables.

Figure 5-62 Release of Radionuclides from the NPDDF to the Geosphere (Fault Zone Activation Case)

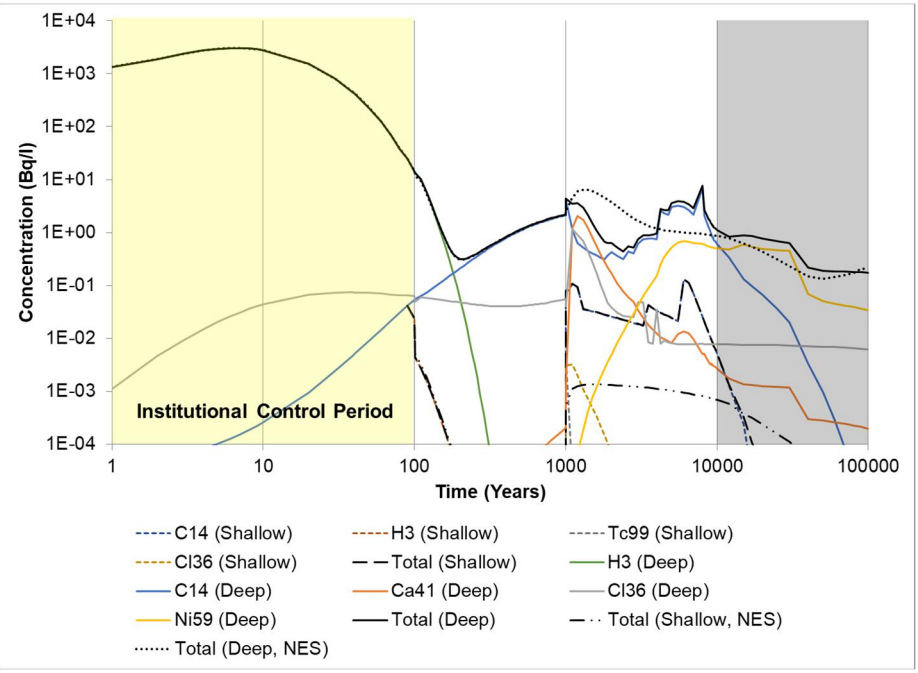


Figure 5-63 Concentrations of Radionuclides in River Water (Fault Zone Activation)

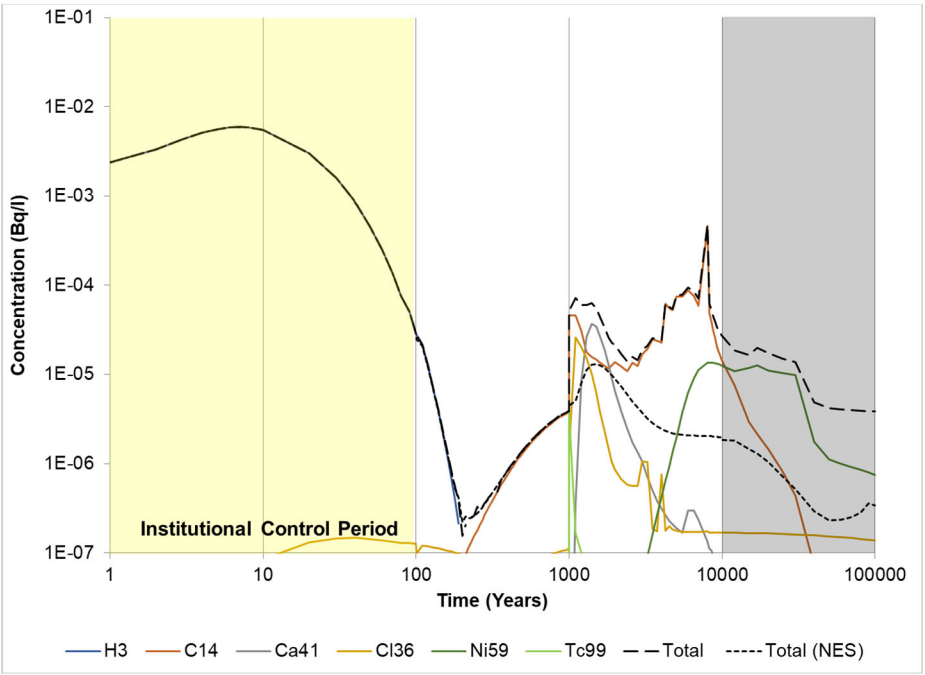
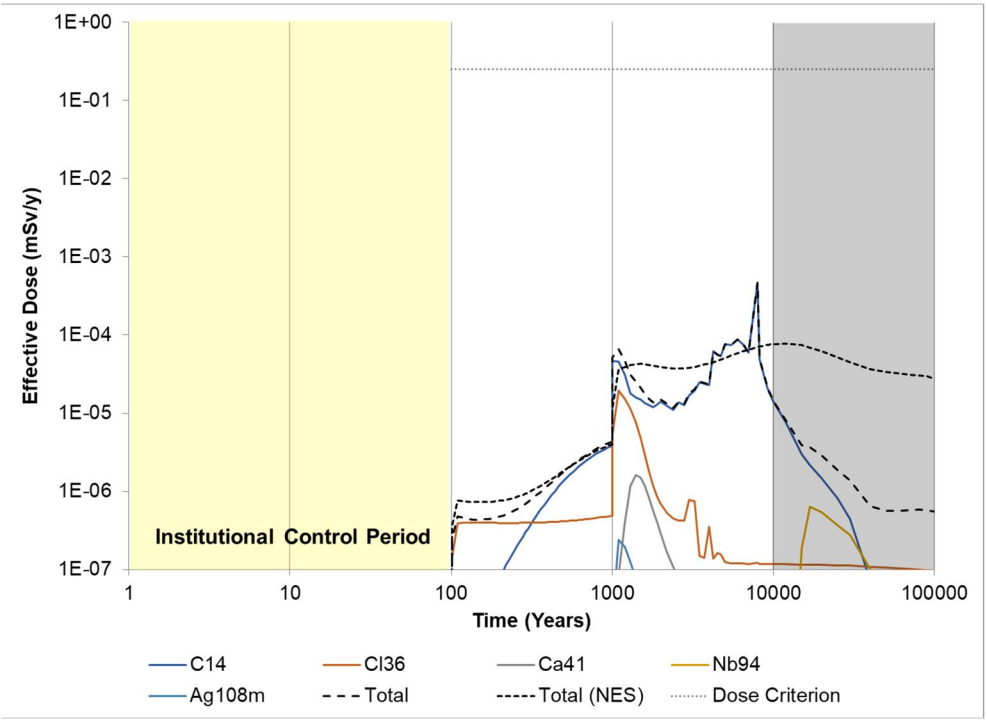


Figure 5-64 Dose to Most Exposed Receptor - Adult Site Resident, by Radionuclide (Fault Zone Activation Case)



5.3.5 Excavation of Above-Bedrock Facility

The mass excavation of the entire Facility is too unlikely to be considered to be a plausible Disruptive Event Scenario because the concrete structure would retain sufficient structural integrity to preclude it. In addition to the existing structure, it will be backfilled with grout and a concrete cap will be placed over the nuclear area as well as an engineered barrier over the entire facility. More limited examination (as considered in the Site Investigation Case) would be sufficient to reveal the characteristics of the Facility and deter any more large-scale disruption. Nevertheless, the consequences of the partial disruption and excavation of the NPDDF is examined in this case. This Disruptive Event scenario examines the impacts of the above-bedrock portion of the facility being excavated. The assumption is that a house is built adjacent to (but not inside) the excavated hole and the garden contains the excavated waste mixed with soil (at a ratio of 1:10 grout and concrete to soil). Only the resident receptor is assumed to be exposed.

The concentrations of radionuclides in the soil which is assumed to be used for growing crops is much higher than in the NES, owing to its contamination with excavated material. As shown in Figure 5-65, the peak concentration is 600 Bq kg^{-1} compared with 0.06 Bq kg^{-1} for the NES. Furthermore, the soil concentrations would be above 100 Bq kg^{-1} if the excavation took place at any time between 100 and 10,000 y, dominated by C-14. The doses are, however, dominated by the long-lived radionuclide Cl-36, and peak at 0.01 mSv y^{-1} at 10,000 y to the Infant Site Resident (see Figure 5-66), via ingestion of plants. Despite the conservative assumptions, the dose remains below the general dose criterion of 0.25 mSv y^{-1} and is well below the criterion which applies to human intrusion situations.

Figure 5-65 Concentrations of Radionuclides in the Garden Soil (Excavation of Above-Bedrock Facility Case)

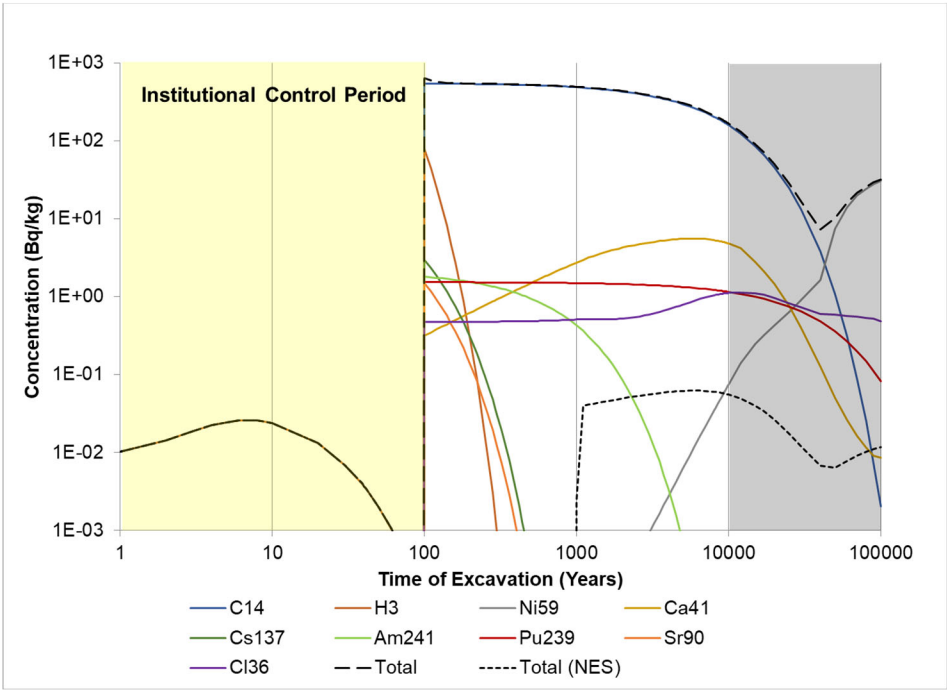
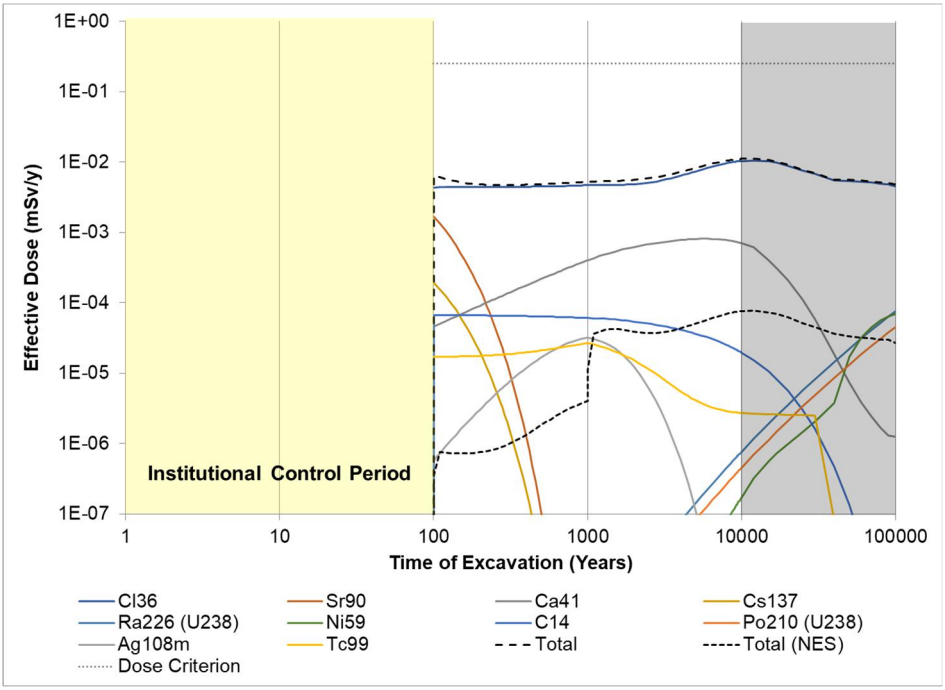


Figure 5-66 Dose to Infant Site Resident, by Radionuclide (Excavation of Above-Bedrock Facility Case)



Note: Radionuclides in brackets indicate the parent of the radionuclide that was present in the initial radionuclide inventory of the NPDDF.

5.3.6 Well

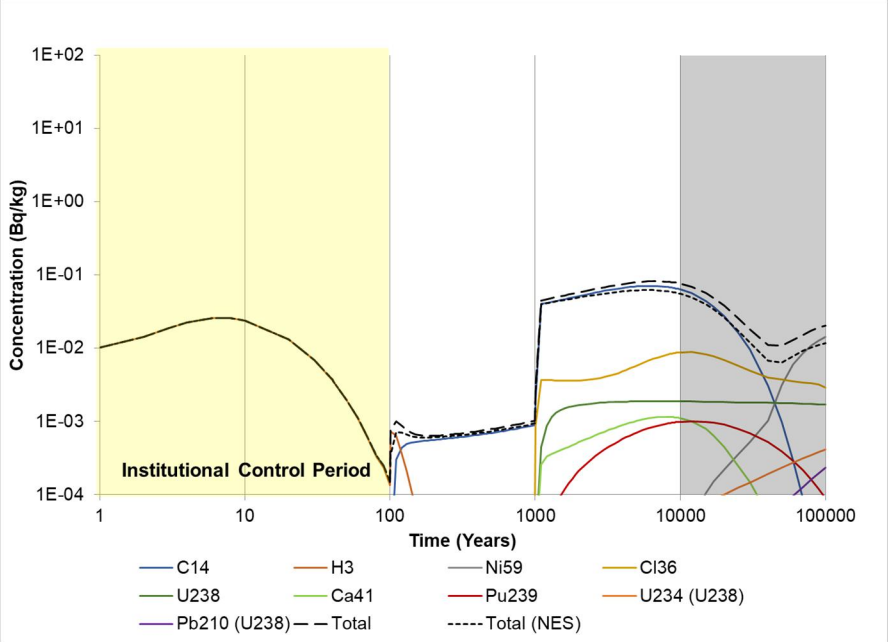
A well provides a route by which radionuclides in groundwater can be ingested in drinking water and also used to irrigate soil that is used for farming. Wells are used by people living in the region, but they are typically into deeper aquifers than those which could be affected by the NPDDF. Furthermore, the likely plume from the Facility is expected to be no more than a few tens of meters wide and around 100 m in length, as demonstrated by Arcadis & Geofirma (2023a,b). It is also beneath relatively steeply sloping ground, and close to the river, so it is highly unlikely to be a location in which a well would be installed. Nevertheless, an analysis (Arcadis & Geofirma, 2023a,b) has examined a hypothetical overburden well located within the pipe trench area between the facility and the slope, and a hypothetical bedrock well located to the east side of the building so as to coincide with the modelled release path. The analysis (Arcadis & Geofirma, 2021b) found that a hypothetical well, located in the overburden along the release path, is only viable if the tile drains have failed and if the overburden well is located within the fill of the pipe trench. The analysis (Arcadis & Geofirma, 2021b) found that a hypothetical well located in the bedrock along the release path could be viable. One additional limitation that must be accounted for is the plan to grout-fill the pipes within the pipe trench. This further reduces the potential locations of a well that both intersects the release path and is also viable. For this reason, the possibility of a well is treated as a very unlikely Disruptive Event case.

5.3.6.1 Overburden Well

This case examines the impacts of the resident receptor using an overburden well intersecting water in the pipe trench.

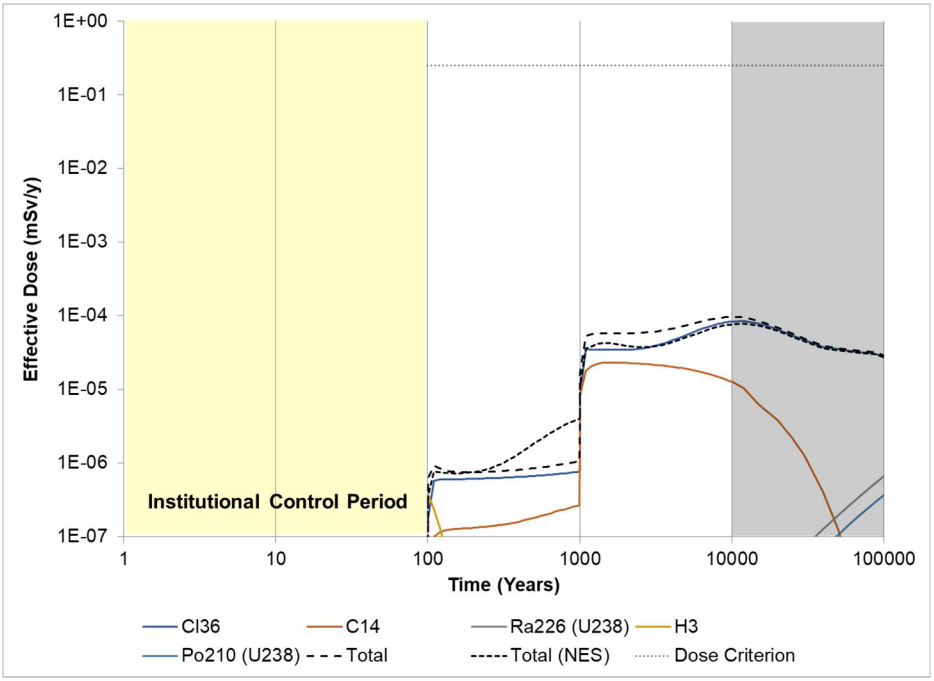
The concentration of radionuclides in irrigated garden soil is shown in Figure 5-67. The garden soil is dominantly affected by contamination released from the NPDDF to the soil via the overburden, rather than the irrigation water, so radionuclide concentrations are not substantially increased (the peak activity in soil increases from 0.06 to 0.08 Bq kg^{-1} from C-14 at 7,000 y). The increase in concentrations in the water used by people and animals for drinking does nevertheless lead to a slightly increased dose. This is principally because the livestock raised by the Site Resident is assumed to consume well water rather than river water, and as a result become more contaminated. The peak dose to the Infant Site Resident is increased from 8E-05 to 1E-04 mSv y^{-1}, peaking at 10,000 y (see Figure 5-68).

Figure 5-67 Concentration of Radionuclides in Garden Soil Irrigated with Groundwater (Overburden Well Case)



Note: Radionuclides in brackets indicate the parent of the radionuclide that was present in the initial radionuclide inventory of the NPDDF.

Figure 5-68 Radiation Dose to Infant Site Resident, by Pathway (Overburden Well Case)



Note: Radionuclides in brackets indicate the parent of the radionuclide that was present in the initial radionuclide inventory of the NPDDF.

5.3.6.2 Bedrock Well

This case examines the impacts of the resident receptor using a bedrock well intersecting the bedrock release plume between the facility and the river. As with the overburden well case, it is assumed that the extracted water is used for irrigation, and consumption by animals and humans.

Radionuclide concentrations in the well water from the bedrock far exceed those in the river, as can be seen from Figure 5-69, owing to the very high dilution offered by the river. The volumes of water flowing through the bedrock are very much smaller, to the extent that it would be difficult to abstract sufficient quantities for use. The peak concentration in the bedrock groundwater after the period of institutional control is 14 Bq l^{-1}, almost entirely due to tritium. A later peak of 3 Bq l^{-1} occurs after 1,300 y due to C-14. These compare with a peak concentration in the river water of 0.006 Bq l^{-1} (this is within the institutional control period; after that time the highest concentration in the river is 1E-05 Bq l^{-1} at 1,500 y). As a consequence, the concentration of radionuclides in soil in the Garden are substantially increased, as illustrated in Figure 5-70. As sorption dictates the extent to which contaminants accumulate in the soil, the mix of radionuclides differs, with the peak concentration being 0.9 Bq kg^{-1}, dominated by Ca-41 in the period up to 10,000 y. In the far future the highest concentration to occur is 4 Bq kg^{-1} from Pu-239.

The high concentrations in the well-water significantly increase the dose to a Site Resident, peaking at 0.03 mSv y^{-1} for an infant (Figure 5-71). The main exposure pathway is ingestion of irrigated crops, and the dose is dominated by C-14. While this is more than 20 times greater than the highest dose in the Normal Evolution scenario it remains nearly an order of magnitude below the dose criterion applied in that scenario.

Figure 5-69 Concentration of Radionuclides in Well Water Compared with the River Water Concentration in the NES (Bedrock Well Case)

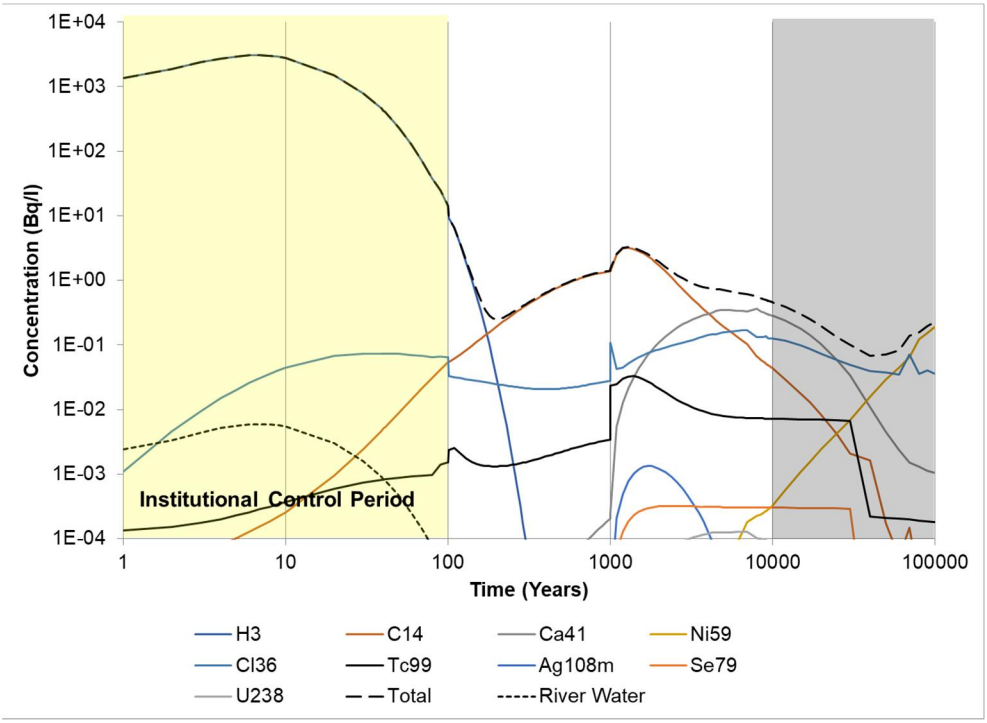


Figure 5-70 Radionuclides in Garden Soil Irrigated with Groundwater (Bedrock Well Case)

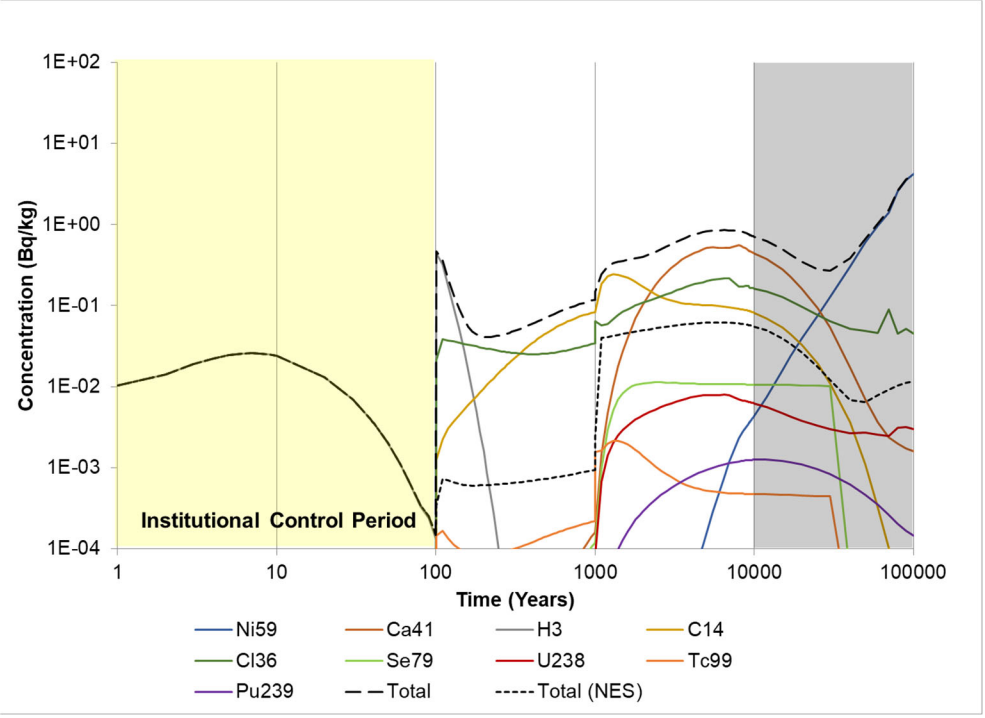
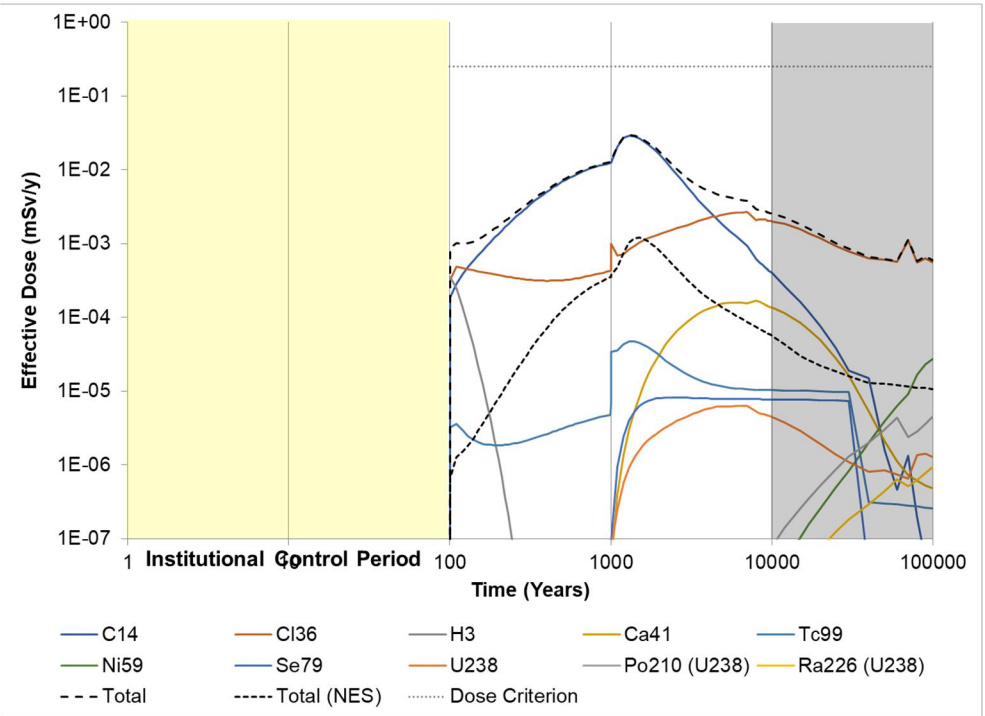


Figure 5-71 Radiation Dose to Infant Site Resident, by Pathway (Bedrock Well Case)



5.4 Defence-in-Depth Cases

5.4.1 Role of Existing Facility Structure

The concrete structure of the NPDDF is also a barrier to the release of radionuclides. This case seeks to quantify its importance by assigning the properties of fully degraded concrete in all the model compartments that represent the NPDDF walls in the Normal Evolution scenario. The grouted rooms, however, remain. The flow rates through the fully degraded Facility structure are described by the modelling results of Arcadis & Geofirma (2023b).

The effect of the increased rates of release due to the degraded structure are most evident in the 100 – 1,000 y period. Groundwater concentrations are significantly higher in both the bedrock and overburden (Figure 5-72). The peak concentration in the bedrock is 40 Bq l^{-1} compared with 6 Bq l^{-1} in the Normal Evolution scenario, and it also occurs much earlier after only 170 y. Even more markedly, the peak concentration in the overburden is 2 Bq l^{-1} immediately after institutional control ends, compared with 0.001 Bq l^{-1} in the NES.

The effect of the increased rates of release in the 100 – 1,000 y period are evident when considering the environmental concentrations (e.g., concentrations in the garden soil, Figure 5-73). The peak concentration in the soil is 2 Bq kg^{-1} from C-14 at 1,100 y compared with 0.06 Bq kg^{-1} at 6,000 y in the Normal Evolution scenario. The highest doses in this case are received by the Indigenous (AOPFN) receptor immediately after the end of Institutional Control. The peak dose is 0.004 mSv y^{-1}, dominantly from external irradiation by Cs-137 and Ag-108m in soil (Figure 5-74). After about 130 y, these radionuclides have decayed and migrated, and the highest doses are to Site Residents via C-14 in crops (see Figure 5-75).

Figure 5-72 Groundwater Concentrations of Contaminants Released from the NPDDF to the Geosphere (Role of Existing Facility Structure Case)

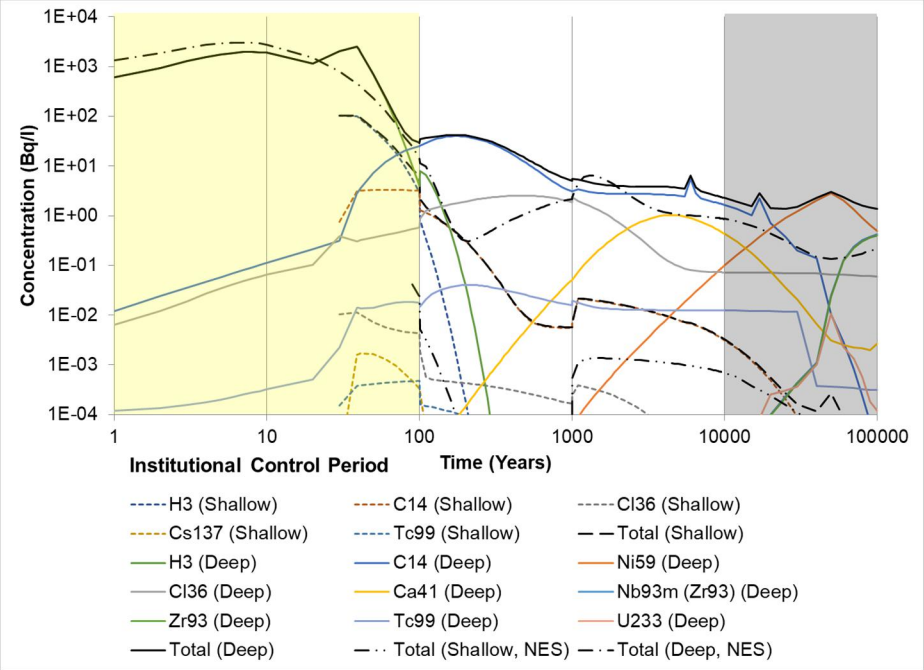
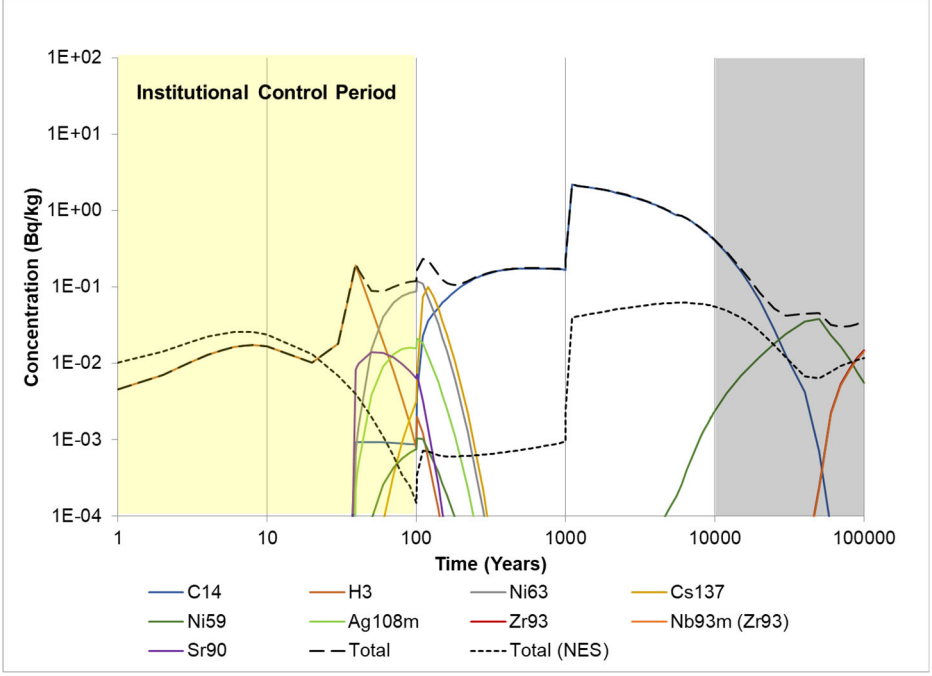
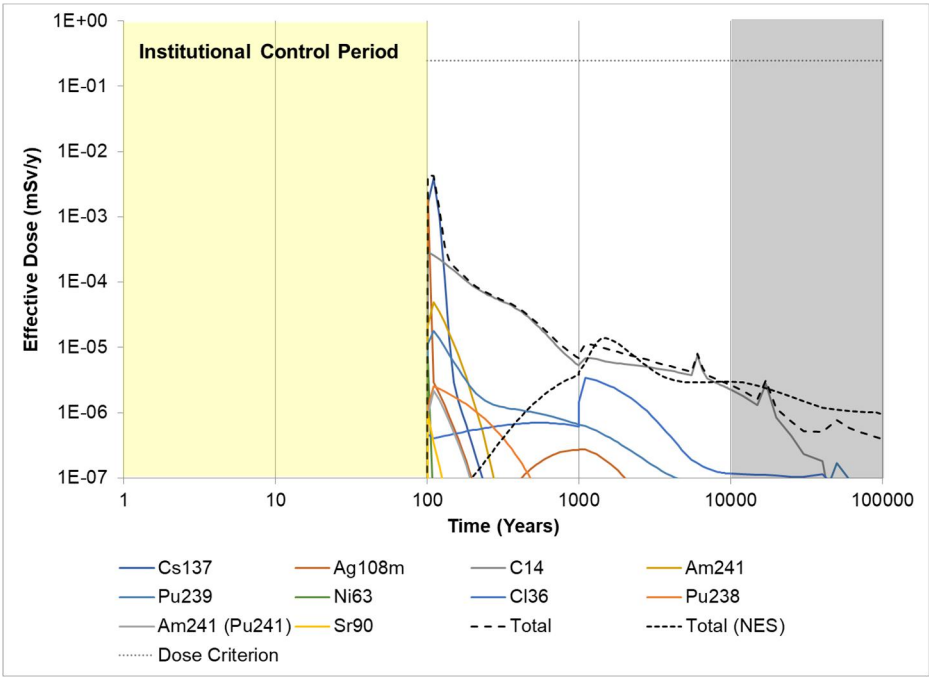


Figure 5-73 Concentrations in the Garden Soil (Role of Structure Case)



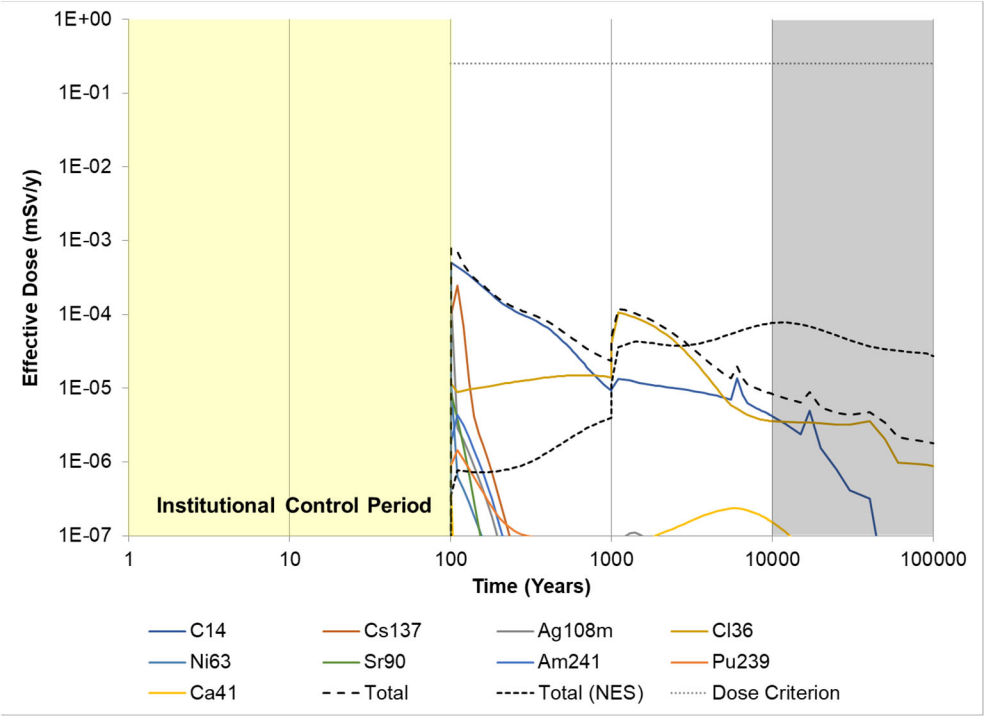
Note: Radionuclides in brackets indicate the parent of the radionuclide that was present in the initial radionuclide inventory of the NPDDF.

Figure 5-74 Dose to an Adult Indigenous (AOPFN) Receptor (Role of Structure Case)



Note: Radionuclides in brackets indicate the parent of the radionuclide that was present in the initial radionuclide inventory of the NPDDF.

Figure 5-75 Dose to an Infant Site Resident (Role of Structure Case)



5.4.2 Role of Grout

This calculation case illustrates the role of grout within the NPDDF as a barrier to the release of radionuclides. Using the same method as the investigation of the role of the existing facility structure (Section 5.4.1), the Role of Grout case is modelled by assigning the properties of fully degraded grout in all the model compartments that are represented as grout in the NES, with the properties of the structure being unchanged.

Figure 5-76 shows the resulting concentrations of radionuclides from the NPDDF in the geosphere. These are initially similar in the bedrock, dominated by tritium and then C-14 in the first 1,000 y. At this point, the concrete structure is assumed to degrade, exposing the degraded grout to higher water flows. The result is increased concentrations in bedrock groundwater, from a peak of 6 Bq l^{-1} in the Normal Evolution scenario to 50 Bq l^{-1} in this case. The concentrations in the overburden groundwater are also increased, peaking at 0.09 Bq l^{-1} just after 1000 y, compared with 1E-03 Bq l^{-1} in the Normal Evolution scenario.

The environmental concentrations reflect the higher groundwater concentrations in both pathways. The concentrations in garden soil (see Figure 5-77) increase from 0.06 Bq kg^{-1} in the NES to more than 10 Bq kg^{-1} in this case. The highest doses are to the infant Site Resident and the key pathway is the ingestion of vegetables, with Cl-36 being the most significant radionuclide (see Figure 5-78). The peak dose is more than 10 times that in the NES at 9E-04 mSv y^{-1} at 1,000y.

Figure 5-76 Concentrations of Contaminants from the NPDDF in the Geosphere (Role of Grout Case)

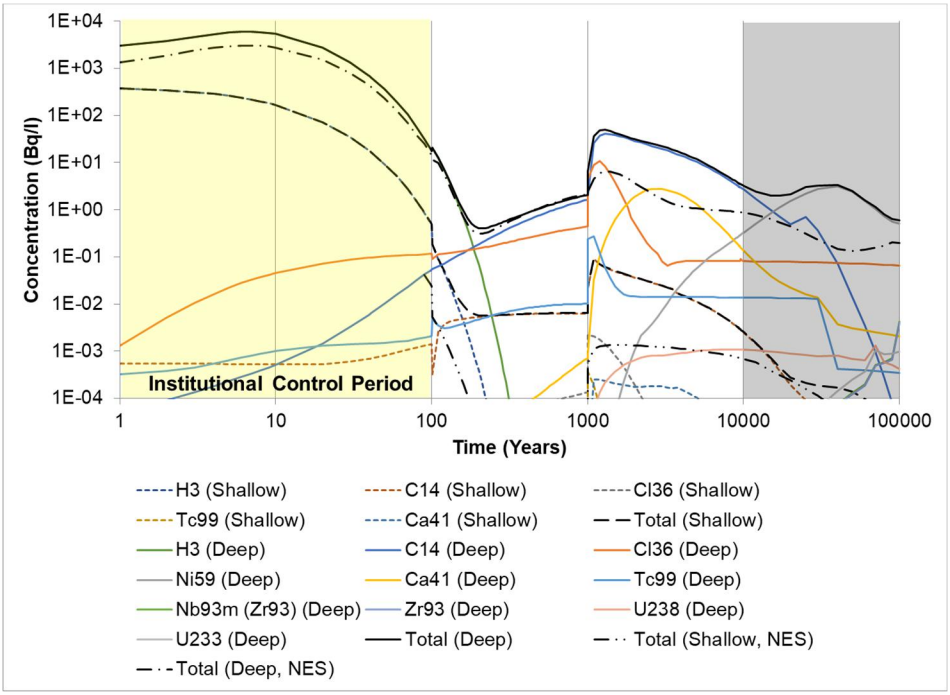


Figure 5-77 Concentrations in the Garden Soil (Role of Grout Case)

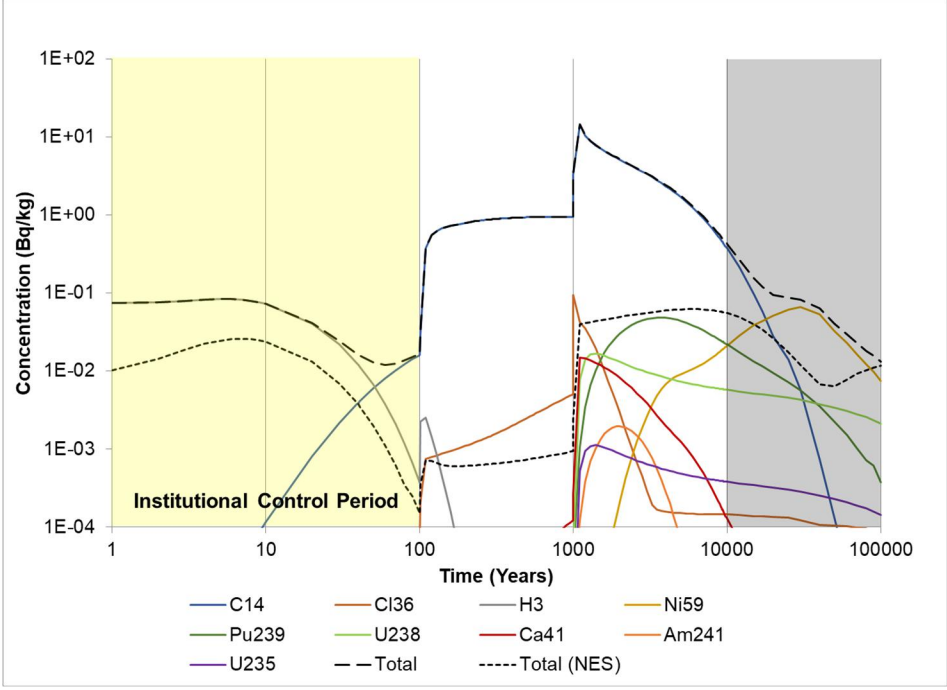
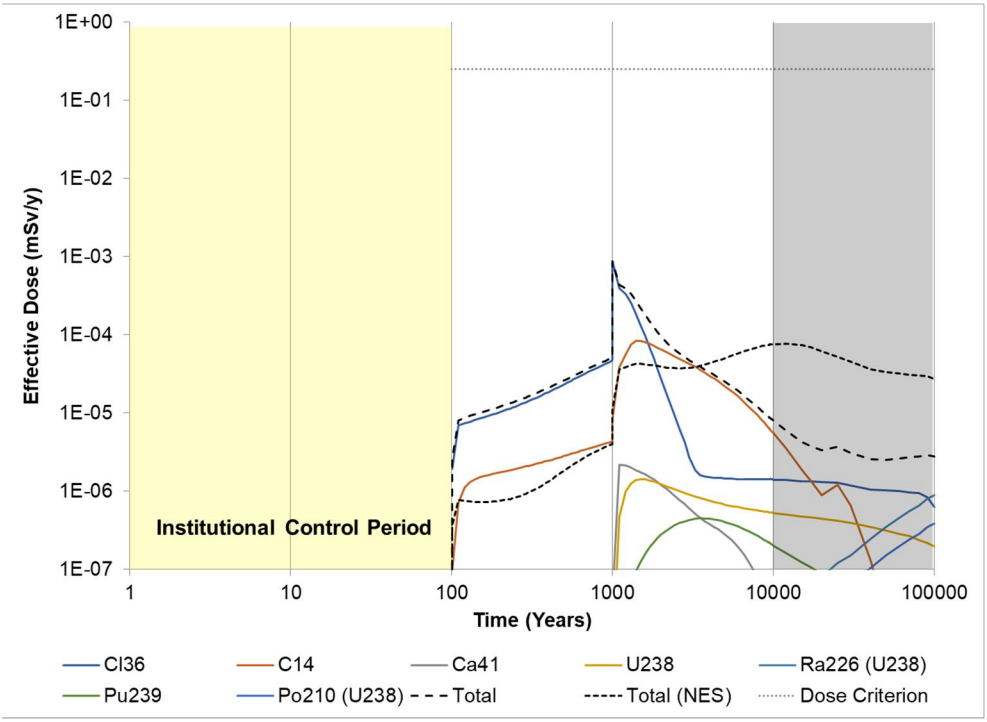


Figure 5-78 Dose to an Infant Site Resident (Role of Grout Case)



5.5 What-if Cases

5.5.1 Mass Excavation

This calculation case examines the potential effects of the most extreme disruption that could occur to the NPDDF. It provides an indication of the upper limit to the dose that could occur due to such a situation. The case assumes that at some time after 100 y, the entire Facility is excavated and its entire contents, including all radionuclides, are dispersed in a small patch of surface soils. The radioactive inventory of the NPDDF is assumed to be with the “Garden” soil, at a 10% loading of waste. Very conservatively, a person is assumed to live on and cultivate the contaminated soil.

The peak concentration in soil of 9E+04 Bq kg^{-1} (see Figure 5-79) is much higher than in the NES, owing to the presence of waste material from, primarily, the Reactor Vault. This compares with just 0.06 Bq kg^{-1} for the NES. Because radionuclides in the wastes are transferred directly into soil, rather than via groundwater, the dominant radionuclides differ from previous cases. Ni-63 is most significant until 500 y, thereafter C-14 until 15,000 y, then Ni-59, Zr-93 and Nb-93m. The resulting dose to the Infant Site Resident is just over 1 mSv y^{-1} (Figure 5-80) with the dose dominated by Cl-36 in crops. The dose is not compared with any criteria as the case is extremely conservative, but does provide an indication of the likely maximum level of dose.

Figure 5-79 Radionuclide Concentrations in the Garden Soil (Mass Excavation Case, no Leaching of Soil)

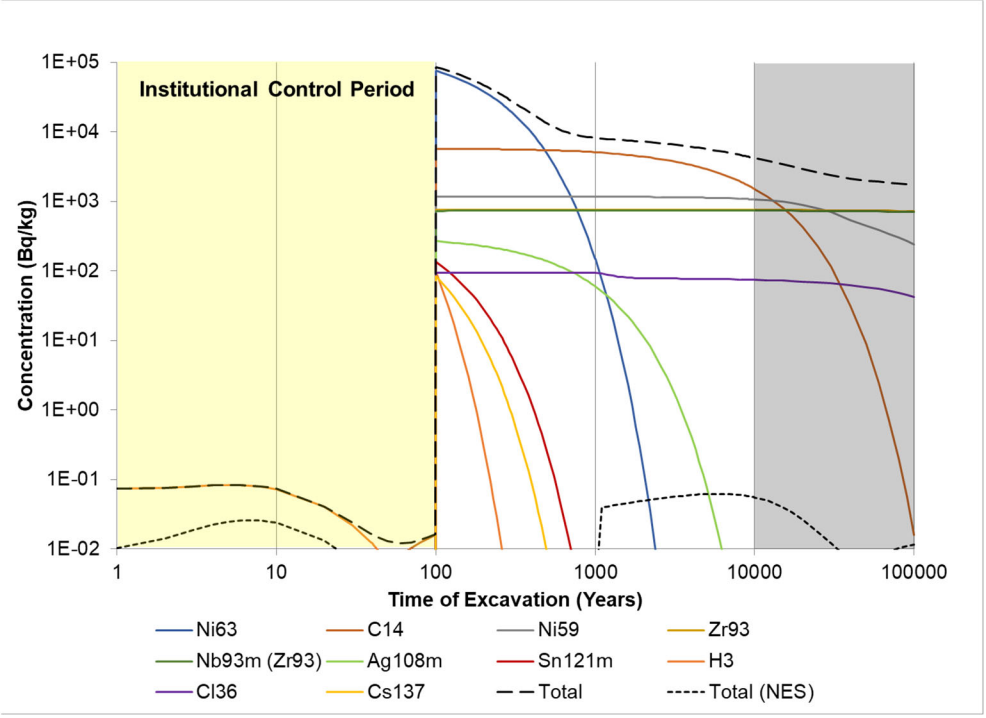
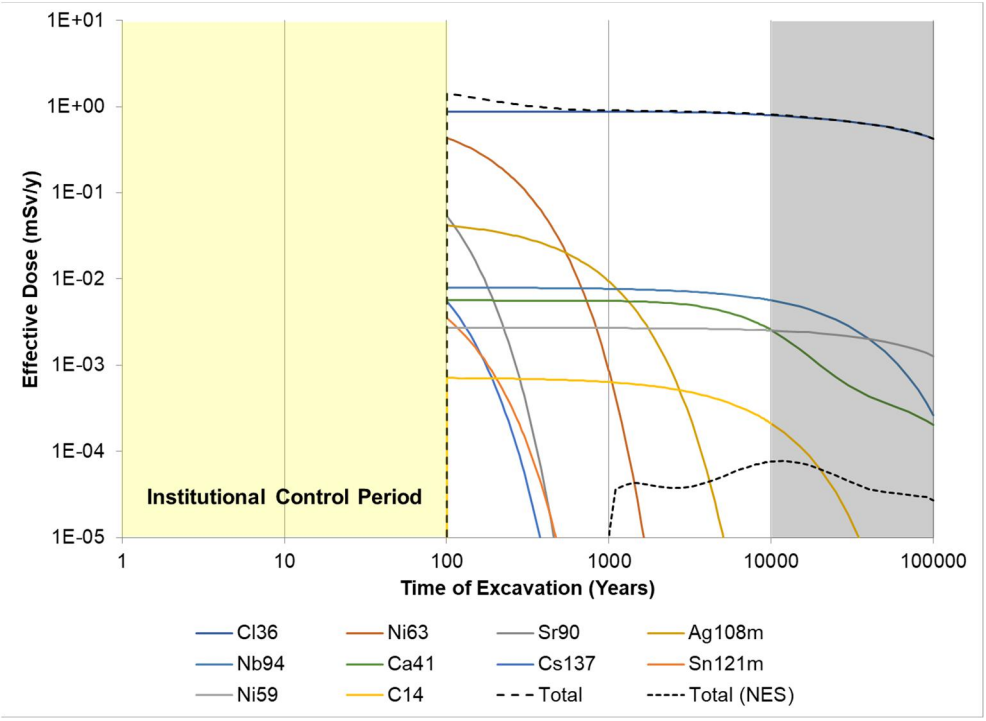


Figure 5-80 Dose to an Infant Site Resident, by Radionuclides (Mass Excavation Case, no Leaching of Garden Soil)

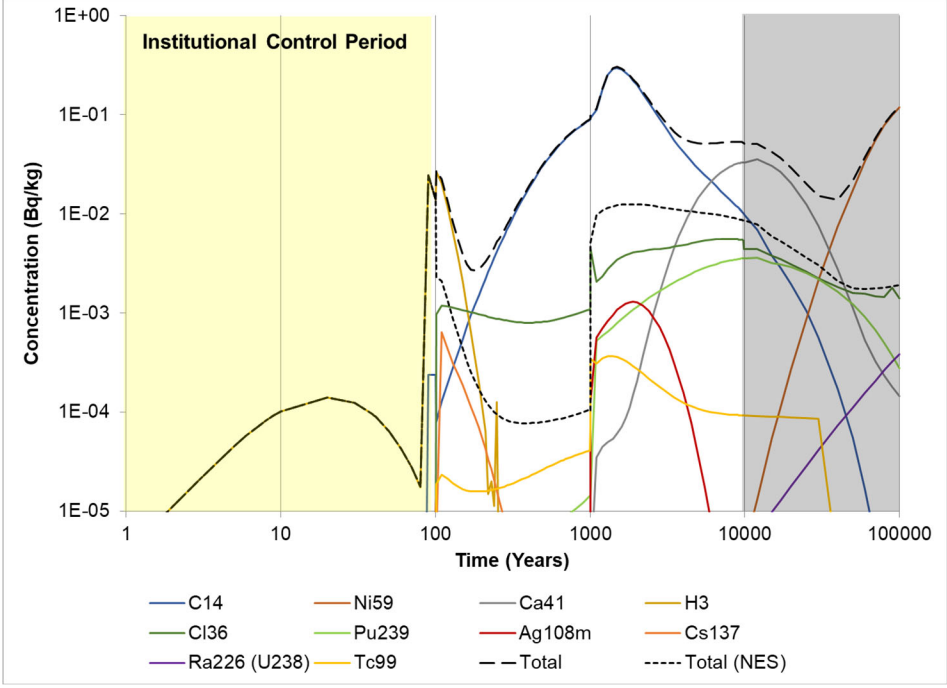


5.5.2 River Level Fall

This “What If” calculation case examines the possibility of a significant change to the location and nature of contaminated groundwater releases to the surface environment. The reference assumption is that groundwater from the overburden is released via springs while groundwater in the bedrock discharges directly to the river. However, an extreme environmental change, leading to much reduced precipitation over a wide area (e.g., due to the onset of a glaciation) could reduce the river level. In such a situation, the groundwater from the bedrock might be released onto the banks of the river.

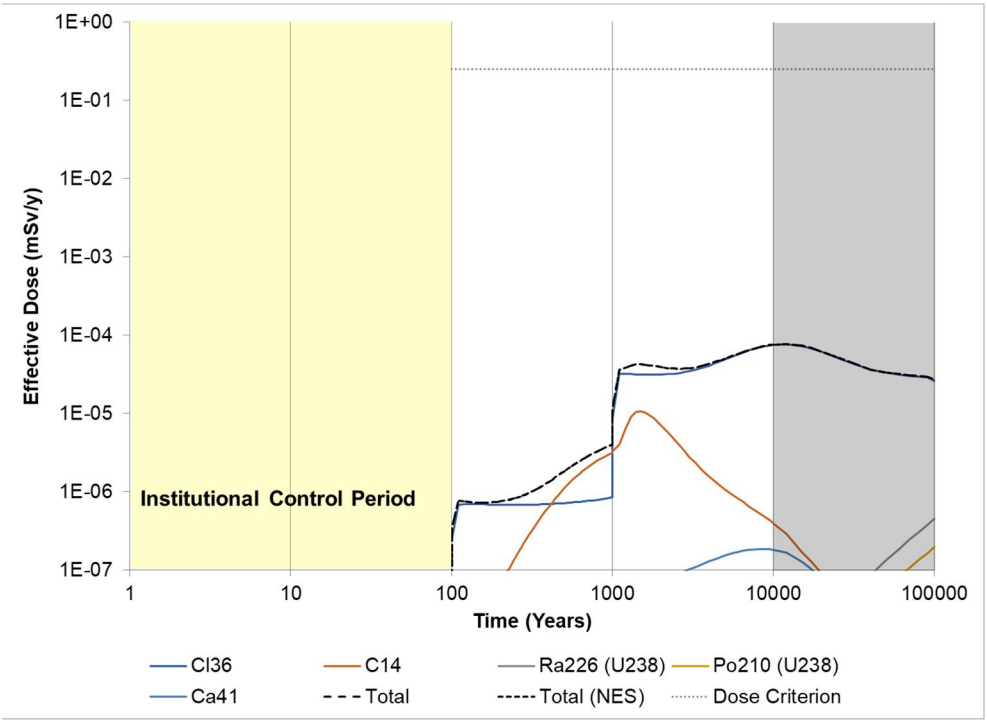
The model of the NPDDF and the geosphere is exactly the same as the NES, with the only difference being that the bedrock pathway releases to the shoreline after 100 y. The concentrations calculated in the shoreline sediments for this case are presented in Figure 5-81. The peak concentration in these sediments is increased from 0.01 in the NES to 0.3 Bq kg^{-1}, dominated by C-14 at 1,500 y. Although this is a significant increase, other parts of the surface environment are unaffected, and the shoreline sediments are not a significant contributor to dose. The peak dose (to a Site Resident Infant) is therefore unchanged from the NES (see Figure 5-82).

Figure 5-81 Concentration of Radionuclides in the Shore Sediments (River Level Fall Case)



Note: Radionuclides in brackets indicate the parent of the radionuclide that was present in the initial radionuclide inventory of the NPDDF.

Figure 5-82 Radiation Doses to Site Resident Infant (River Level Fall Case)

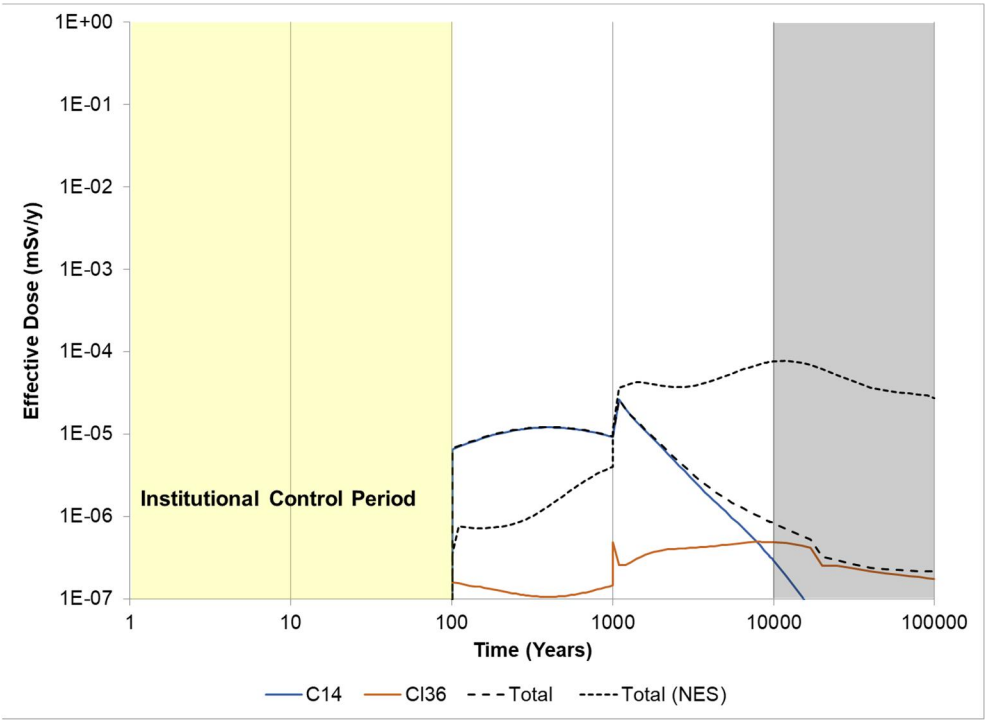


5.5.3 Undetected Fracture Zone

The natural or man-made features within the geosphere that may not be detected during the site investigation (e.g., fracture zones, faults, brine pockets, old mine workings, and boreholes) could play a role in the transport of groundwater to and from the Facility and the associated migration of contaminants. Some physical features of the geological environment may remain undetected during site surveys. The nature of the geological environment will indicate the likelihood that certain types of undetected features may be present, and the site investigation may be able to place bounds on the maximum size or minimum proximity to such features. Hence, this case examines the impact of an undetected fracture zone being present. This is represented by applying the higher hydraulic conductivity to all bedrock downgradient of the facility. This is a conservative approach, rather than limiting the higher bedrock conductivity to a defined area. Practically, the combination of conditions considered in this “What If” case is the same as modelled in the Sensitivity Case that assesses the impact of higher geosphere bedrock hydraulic conductivity (see Section 5.2.5.1).

These conditions lead to greater dilution of the released contaminants and consequently, radionuclide concentrations in groundwater are lower than in the NES. However, the rate of discharge of contaminants to the river is notably higher in the period 100 – 1000 y but the time taken for contaminants to migrate from the facility to the river is also lower. As a result, the concentrations in the long-term are decreased. The peak dose of 3E-05 mSv y^{-1} is three times lower than that in the NES and occurs just after 1,100 y (see Figure 5-83).

Figure 5-83 Radiation Dose to Site Resident Infant (Undetected Fracture Zone)



6.0 CONCLUSIONS

6.1 Objectives of the Study

The objectives of this iteration of the PostSA for the NPDDF are:

- To undertake a quantitative assessment of the postclosure radiological and non-radiological safety of the proposed in-situ disposal of the former Nuclear Power Demonstration Facility according to CNL's reference ISD strategy, following a recognized credible methodology;
- To identify those uncertainties that have the greatest potential impact on the long-term performance of the NPDDF and determine their significance;
- To address the requirements of relevant Canadian regulations and legislation and provide necessary information to support an Environmental Impact Statement which will address the requirements of the *Canadian Environmental Assessment Act (CEAA)*, 2012. The NPD Closure Project was initiated in 2016 under the CEAA 2012 regulatory framework, thus the CEAA 2012 framework remains applicable to this project though a newer regulatory framework now exists; and,
- To form part of CNL's licensing submission to the CNSC, seeking approval for a licence amendment to allow in-situ disposal to occur.

This report addresses each of these objectives as follows:

- The study has undertaken a quantitative assessment of the postclosure radiological and non-radiological safety of the NPDDF. This has involved applying CNSC and international guidance (e.g., IAEA ISAM approach) to:
    - Define the scope, context, key criteria and assumptions necessary to undertake the assessment;
    - Characterise the NPDDF and surrounding environment according to the best available information;
    - Systematically develop scenarios, calculation cases, models and data to represent the NPDDF and its environment over timescales necessary to consider in the assessment;
    - Calculate environmental concentrations and radiation doses for the range of scenarios and calculation cases considered, and compare them with established criteria;
    - Determine important uncertainties and their significance; and
    - Iterate the assessment to account for new information as it becomes available, and to refine assumptions made in the assessment.
- The analysis has identified those uncertainties that have the greatest potential impact on the long-term performance of the NPDDF. These primarily relate to the inventory of contaminants, mechanisms for their release from the environment of the NPDDF, the evolution of the vault (resaturation and chemistry) and potential mechanisms that might disturb or disrupt the NPDDF and surrounding environment (such as seismic activity or erosion).

- The PostSA presents considerable detail in terms of the current understanding of the NPDDF and its environment, and how these may evolve, to support the EIS. Analysis of a wide range of scenarios and presentation of a wide range of results provides a robust basis for the EIS.

Subsections 6.1 to 6.8 present more detailed discussion of key outcomes of the work.

Assessment Timeframe:

Note that a timeframe of 10,000 years was selected *a-priori* based on the arguments in Appendix A. One of the main considerations was the time of the peak doses found in the previous iteration of the PostSA, where peak doses occurred relatively early at less than 5,000 years post-closure. However, in the 4th iteration, changes were made to the C-14 dose model for animals in order to remove overly conservative assumptions (i.e., C-14 concentrations in animal products were previously determined mainly by the C-14 concentrations in animal drinking water). Due to this change, peak doses appear at about 12,000 years for the Normal Evolution Scenario (NES), because the lower C-14 dose rates make Cl-36 the dominant dose contributor in the NES. However, given the similarity in dose at 10,000 and 12,000 years and the similarity between the selected timeframe and the time of the peak dose in the NES, the assessment timeframe of 10,000 years was not changed. Furthermore, dose rates are calculated for times up to 100,000 years in the PostSA. It should be noted that for less conservative scenarios and sensitivity cases, calculated peak doses occur at much earlier times than in the NES (at about 2,500 years). Finally, the effects of seismic events are assumed to occur at 1000 years.

6.2 Containment of Radioactivity

A fundamental objective of the in-situ disposal strategy is to contain and isolate the residual contaminants in the NPDDF for a sufficiently long time to ensure that postclosure doses and environmental concentrations are not of concern. The PostSA analysis shows that the NPDDF can be expected to contain the dominant radionuclides effectively.

For the assessed period after the end of institutional control the releases from the Facility are less than 7E+06 Bq y^{-1}, a small fraction of the typical level of permitted discharges to air and water from nuclear facilities. Even after 10,000 y more than 99% of the remaining radioactivity is contained in the NPDDF.

The main feature containing the radionuclides is the waste form; the majority of the radioactivity is present within the matrix of steels and Zircaloy that will corrode very slowly in the chemical environment of the NPDDF. The concrete structure and grout backfill also contribute to containment and isolation. Initially, there is a release of tritium, which is highly mobile, but of relatively low radiotoxicity. Environmental concentrations are less than 10 Bq l^{-1} in groundwater for the whole period after institutional control, and less than 3 Bq kg^{-1} in all soils and sediments except the soil directly overlying the facility that declines from a maximum of 160 Bq kg^{-1} immediately after the institutional control period. The result is that, for the Normal Evolution scenario, the peak dose to a person is 8E-05 mSv y^{-1}, occurring around 12,000 y in the future. (Note that the peak dose rate within the assessment timeframe of 10,000 years is essentially the same as the overall peak dose rate, as shown in Figure 5-17). This is more than three orders of magnitude below the dose criterion of 0.25 mSv y^{-1} for Normal Evolution used in this study.

6.3 Isolation of Radioactivity

The isolation of radionuclides is achieved by filling much of the NPDDF with grout and placing a reinforced concrete cap over the footprint of parts of the nuclear area. This creates a structure that would be extremely difficult to excavate without heavy equipment such as that used for geological investigations. Users of such equipment can be expected to scientifically examine the structure with the likelihood that its nature would be revealed, enabling them to take suitable precautions should they encounter any radioactive material.

IAEA SSR-5 (IAEA, 2011) provides guidance for determining when inadvertent human intrusion preventions are warranted. Specifically, Clause 2.15 (c) states: "*In relation to the effects of inadvertent human intrusion after closure, if such intrusion is expected to lead to an annual dose of less than 1 mSv to those living around the site, then efforts to reduce the probability of intrusion or limit its consequences are not warranted"*. Given the low estimated doses (see Sections 5.1, 5.2 and 5.3 above), following this guidance leads to such prevention measures being unwarranted. Therefore, although unnecessary based on IAEA SSR-5 (IAEA, 2011), the concrete cap can be considered an additional means for reducing the probability of inadvertent human intrusion..

The PostSA study has nevertheless examined the possible radiological consequences of inadvertent intrusion without knowledge of the hazard present in the Facility. Assuming that institutional control is retained for 100 y, the highest dose rate from any material recovered from the Facility would be from stainless steel components of the Calandria. The dose rate from a representative average of all of the material in the Reactor Vault is 0.04 μSv h^{-1}, dominated by Ag-108m.

6.4 Radiation Doses

The radiation doses to potentially exposed groups of people are summarised in Table 6-1. All doses lie well below the dose criterion of 0.25 mSv y^{-1}. The “What If” cases that examine the consequences of excavating the entire backfilled structure, contaminated discharges to the shore, or a possibility of undetected fracture zone, should not be compared with the dose criterion as they adopt deliberately extreme assumptions. In other plausible cases, the calculated dose is at least 10 times lower than the relevant dose criterion, despite conservative assumptions in many cases.

The very low doses are calculated because:

- the system provides effective containment of radioactivity within the Facility, for a very long time, due to the slow corrosion-controlled releases of key radionuclides and large volume of grout and concrete which both constrains water flow into the Facility and also limits the mobility of key radionuclides;
- the very slow releases of radioactivity to the environment that migrate into the river will be substantially diluted and dispersed before pathways to people are encountered, and even if there were a direct release to the surface, the area contaminated would be only a few tens of square meters;
- in the unlikely event that the Facility was disrupted, either by people or a natural event, the difficulty in accessing the rooms containing contaminants would mean that either very little radioactive material would be recovered, or the contaminants would become diluted with a very large amount of uncontaminated material that would need to be excavated to reach the vault.

Table 6-1 Summary of the Peak Dose for each Scenario and Calculation Case

Scenario	Peak Dose (mSv y^{-1})	Time of Peak (y)	Dominant Radionuclide	Exposure Group
Normal Evolution	**8E-05**	**12,000**	**Cl36**	**Resident (Infant)**
Sensitivity Cases				
Measured Radionuclide Inventory	1E-05	1,500	Cl36	Resident (Infant)
Increased Modelled Radionuclide Inventory	2E-04	12,000	Cl36	Resident (Infant)
Reduced Near-field Sorption	1E-04	2,600	Cl36	Resident (Infant)
Reduced Far-field Sorption	8E-05	12,000	Cl36	Resident (Infant)
Reduced Sorption in Near-field and Far-field	1E-04	2,600	Cl36	Resident (Infant)
Rapid Degradation	8E-05	12,000	Cl36	Resident (Infant)
Increased Geosphere Bedrock Hydraulic Conductivity	3E-05	1,100	C14	Resident (Adult)
Increased Geosphere Overburden Hydraulic Conductivity	2E-05	1,400	C14	Resident (Adult)
Increased Dilution in the River	8E-05	12,000	Cl36	Resident (Infant)
Self-sufficient Indigenous Receptor	4E-05	1,500	C-14	Self-sufficient Indigenous (Infant)
Disruptive Event Cases				
Site Investigation (Inadvertent Human Intrusion)	5E-04	100 y	Ag108m	Borehole driller
Surface Erosion	4E-03	10,000 y	Ca41	Resident (Child)
Extreme Degradation	3E-4	1,100 y	Cl36	Resident (Infant)
Fault Zone Activation	5E-4	8,000 y	C14	Resident (Adult)
Excavation of Above-Bedrock Facility	1E-02	12,000 y	Cl36	Resident (Infant)
Overburden Well	1E-04	10,000 y	Cl36	Resident (Infant)
Bedrock Well	4E-02	1,300 y	C14	Resident (Adult)
Defence-in-Depth Cases				
Role of Existing Facility Concrete Structure	4E-03	100 y	Cs137	Indigenous (AOPFN)
Role of Grout	9E-04	1,000 y	Cl36	Resident (Infant)
“What If” Cases				
Facility Mass Excavation	1E+00	100 y	Cl36	Resident (Infant)
River Level Fall	8E-05	12,000	Cl36	Resident (Infant)
Undetected Fracture Zone	3E-05	1,100	C14	Resident (Infant)

Note: * The institutional control period would prevent on-site receptors from establishing themselves before 100 y after closure.

The average natural background dose rate in Ottawa (CNSC, 2013) is 1.6 mSv y^{-1}. In all but one of the cases considered, the peak dose is several orders of magnitude lower than this natural background dose rate. The only exception is the deliberately extreme "What If" case for mass excavation of the facility which results in a dose rate of similar size to the natural background dose.

Four conservatively defined exposure groups have been assessed for most scenarios: a family living on the site and obtaining all their food from irrigated soil, as well as using river water; an Indigenous receptor with modified (less conservative) lifestyle compared to the Self-sufficient Indigenous receptor (considered as a Sensitivity Case); a Hunter; and an off-site resident group which use water from the Ottawa River downstream from the NPDDF. The site resident receives the largest dose for all scenarios except the 'Defence-in-Depth case in which the entire NPDDF structure is assumed to be extremely degraded, for which the highest doses are to the Indigenous (AOPFN) group immediately after the end of institutional control. The most important pathways for the site resident are related to food grown on soil that is assumed to receive groundwater discharges from the Facility (via leakage to soil of groundwater upwelling into the cap) and to be irrigated with contaminated water. The dominant radionuclides include C-14, Cl-36 and Ca-41. The dose to an offsite resident group is dominated by the early release of tritium via ingestion of drinking water from the river.

It is important to note that the calculated peak doses in Table 6-1 for Normal Evolution, Disruptive Events, and Defence-in-Depth cases are all below their corresponding dose criteria (see Section 2.2.2). "What if" scenarios are used to exhibit the robustness and performance of various natural and engineered barriers under extreme conditions. They involve parameter values or other properties that cause the system to be influenced in an exaggerated manner. For example, to show that such exaggerated conditions are impractical, do not negatively impact safety, or can be avoided by design. Thus, "What If" dose results are not compared to dose criteria.

Even if an extreme situation were considered, in which the entire inventory was excavated after 100 y and dispersed on the surface, the peak dose to a person living permanently on the material and growing food in soil contaminated by the excavated concrete would be just over 1 mSv y^{-1}.

6.5 Environmental Effects

Environmental concentrations calculated in the model are consistently low, at levels that would in many cases be challenging to detect (see for example Table 6-2 and Table 6-3). Apart from an initial release of tritium in the first few decades (during institutional control), groundwater concentrations of radionuclides are 10 Bq l^{-1} or lower in the Normal Evolution scenario after the period of institutional control.

Naturally occurring surficial uranium/thorium deposits in Canada have an activity concentration range between 2E+03 and 9E+04 Bq kg^{-1} at the Trout Lake Graben and between 4E+05 and 3E+06 Bq kg^{-1} in the Pembroke-Renfrew area (see Appendix A). Background activity levels at Chalk River are 6E+02 Bq kg^{-1}. Concentrations calculated in all the surface environmental media (shore sediment and garden) are less than those at Chalk River and are more than ten times smaller than the naturally occurring surface deposits for all cases except the deliberately extreme Mass Excavation "What If" case.

In the NES, the only non-radioactive contaminant that is released to the environment to any degree was lead, for which the peak groundwater concentration was 4E-07 mg l^{-1}. This is far less than the corresponding EQS used for the study (0.0019 mg l^{-1}). The peak concentration of lead in river water is extremely small at 1E-10 mg l^{-1}, compared with the EQS of 0.001 mg l^{-1} (see Appendix A) and the peak concentration in spring water is 4E-05 mg l^{-1}. The highest concentration of lead in soil is 0.9 mg kg^{-1} in the cap, much lower than the EQS of 45 mg kg^{-1} for soil. This is despite the very conservative assumption that upwards transport of contaminants in groundwater would occur through the cap, since the cap is expected to be designed in such a manner so as to avoid becoming saturated. It has been conservatively assumed that water can migrate against gravity with 10% of the rate that infiltrating water percolates downwards to the water table, e.g., 0.04 m y^{-1} compared with the infiltration rate of 0.4 m y^{-1}. Over even longer periods of time (i.e., up to 100,000 y, well outside of the assessment timeframe) the peak concentration found in garden soil is 0.04 mg kg^{-1} and in river shore sediment it is 4E-05 mg kg^{-1}. The EQS for sediment is 31 mg kg^{-1}. Thus, concentrations of lead in all of these environmental media are far less than corresponding environmental standards.

Table 6-4 presents peak lead concentrations in environmental media (up to 100,000 years past closure) for each calculation case, along with corresponding EQSs. No EQSs are exceeded for the NES or its sensitivity cases. The only two (2) exceedances occur for the Excavation of Above-Bedrock Facility and the Mass Excavation cases (**bold** and shaded in Table 6-4 below), but for these cases it can be argued that large pieces of lead will not be mixed into the garden.

Table 6-2 Summary of the Peak Concentrations in Groundwater & Surface Water for each Calculation Case, Within the 10,000 y Assessment Timeframe

Scenario	Groundwater				River water*			
	Radionuclide (Bq l^{-1})		Chemical (mg l^{-1})		Radionuclide (Bq l^{-1})		Chemical (mg l^{-1})	
Normal Evolution	3E+03	H3 (Deep)	4E-07	Pb	6E-03	H3	1E-10	Pb
Sensitivity Cases								
Measured Radionuclide Inventory	1E+03	H3 (Deep)	4E-07	Pb	2E-03	H3	1E-10	Pb
Increased Modelled Radionuclide Inventory	6E+03	H3 (Deep)	4E-07	Pb	1E-02	H3	1E-10	Pb
Reduced Near-field Sorption	3E+03	H3 (Deep)	4E-06	Pb	6E-03	H3	5E-10	Pb
Reduced Far-field Sorption	3E+03	H3 (Deep)	1E-06	Pb	6E-03	H3	1E-10	Pb
Reduced Sorption in Near-field and Far-field	3E+03	H3 (Deep)	3E-05	Pb	6E-03	H3	5E-10	Pb
Rapid Degradation	3E+03	H3 (Deep)	4E-07	Pb	6E-03	H3	1E-10	Pb
Increased Geosphere Bedrock Hydraulic Conductivity	8E+01	H3 (Deep)	5E-08	Pb	8E-03	H3	2E-12	Pb
Increased Geosphere Overburden Hydraulic Conductivity	3E+03	H3 (Deep)	1E-07	Pb	6E-03	H3	2E-11	Pb
Increased Dilution in the River^	3E+03	H3 (Deep)	4E-07	Pb	6E-03	H3	1E-10	Pb
Self-Sufficient Indigenous Receptor	3E+03	H3 (Deep)	4E-07	Pb	6E-03	H3	1E-10	Pb
Disruptive Events								
Site Investigation (Inadvertent Human Intrusion)	3E+03	H3 (Deep)	4E-07	Pb	6E-03	H3	1E-10	Pb
Surface Erosion	3E+03	H3 (Deep)	4E-07	Pb	6E-03	H3	1E-10	Pb
Extreme Degradation	3E+03	H3 (Deep)	1E-06	Pb	6E-03	H3	3E-10	Pb
Fault Zone Activation	3E+03	H3 (Deep)	3E-06	Pb	6E-03	H3	3E-10	Pb
Excavation of Above-Bedrock Facility	3E+03	H3 (Deep)	4E-07	Pb	6E-03	H3	1E-10	Pb
Overburden Well	3E+03	H3 (Deep)	3E-07	Pb	6E-03	H3	1E-10	Pb
Bedrock Well	3E+03	H3	4E-07	Pb	6E-03	H3	1E-10	Pb
Defence-in-Depth Cases								
Role of Existing Facility Structure	3E+03	H3 (Deep)	3E-07	Pb	4E-02	H3	6E-07	Pb
Role of Grout	6E+03	H3 (Deep)	4E-06	Pb	2E-02	H3	3E-08	Pb
"What-If" Cases								
Mass Excavation	3E+03	H3 (Deep)	4E-07	Pb	6E-03	H3	1E-10	Pb
River Level Fall	3E+03	H3 (Deep)	4E-07	Pb	6E-03	H3	1E-10	Pb
Undetected Fracture Zone	8E+01	H3 (Deep)	5E-08	Pb	8E-03	H3	2E-12	Pb

Note: * Note this is the concentration in river water at the groundwater discharge point; the increased dilution only affects concentrations downstream.

Table 6-3 Summary of the Peak Concentrations in Soil and Sediment for each Calculation Case, Within the 10,000 y Assessment Timeframe

Scenario	Shore Sediment				Garden			
	Radionuclide (Bq kg^{-1})		Chemical (mg kg^{-1})		Radionuclide (Bq kg^{-1})		Chemical (mg kg^{-1})	
Normal Evolution	2E-02	H3	4E-05	Pb	8E-02	C14	4E-02	Pb
Sensitivity Cases								
Measured Radionuclide Inventory	2E-02	H3	4E-05	Pb	3E-02	C14	4E-02	Pb
Increased Modelled Radionuclide Inventory	5E-02	H3	4E-05	Pb	2E-01	C14	4E-02	Pb
Reduced Near-field Sorption	2E-01	Ag108m	2E-04	Pb	4E-01	C14	4E-02	Pb
Reduced Far-field Sorption	2E-02	H3	4E-05	Pb	8E-02	C14	4E-02	Pb
Reduced Sorption in Near-field and Far-field	3E-01	Ag108m	2E-04	Pb	4E-01	C14	4E-02	Pb
Rapid Degradation	2E-01	H3	4E-05	Pb	8E-02	C14	4E-02	Pb
Increased Geosphere Bedrock Hydraulic Conductivity	2E-04	H3	1E-11	Pb	3E-02	H3	2E-08	Pb
Increased Geosphere Overburden Hydraulic Conductivity	2E-02	H3	5E-06	Pb	3E-02	H3	1E-05	Pb
Increased Dilution in the River^	2E-02	H3	4E-05	Pb	8E-02	C14	4E-02	Pb
Self-Sufficient Indigenous Receptor	2E-02	H3	4E-05	Pb	8E-02	C14	4E-02	Pb
Disruptive Events								
Site Investigation (Inadvertent Human Intrusion)	2E-02	H3	4E-05	Pb	2E+01	Ni63	6E-02	Pb
Surface Erosion	2E-02	H3	4E-05	Pb	3E+01	C14	1E-04	Pb
Extreme Degradation	4E-01	Ag108m	1E-04	Pb	1E+00	C14	2E-01	Pb
Fault Zone Activation	7E-01	C14	2E-04	Pb	2E-01	C14	1E-03	Pb
Excavation of Above-Bedrock Facility	2E-02	H3	4E-05	Pb	6E+02	C14	8E+02	Pb
Overburden Well	2E-02	H3	4E-05	Pb	8E-02	C14	4E-02	Pb
Bedrock Well	2E-02	H3	5E-05	Pb	9E-01	Ca41	5E-02	Pb
Defence-in-Depth Cases								
Role of Existing Facility Structure	1E+03	Cs137	4E-01	Pb	2E+00	C14	3E-02	Pb
Role of Grout	1E+02	H3	2E-02	Pb	1E+01	C14	9E-02	Pb
"What-If" Cases								
Mass Excavation	2E-02	H3	4E-05	Pb	9E+04	Ni63	7E+02	Pb
River Level Fall	3E-01	C14	4E-05	Pb	8E-02	C14	4E-02	Pb
Undetected Fracture Zone	2E-04	H3	1E-11	Pb	3E-02	H3	2E-08	Pb

Table 6-4 Summary of the Peak Concentrations (mg/kg) for Lead in Different Environmental Media for each Calculation Case and Comparison with EQS, Within the 100,000 y past closure

Scenario		Groundwater	River	Cap	Springs	Garden	Grazing	River Shore	River Sediment
Scenario	EQS	0.0019 mg l-1	0.001 mg l^{-1}	45 mg kg^{-1}	0.001 mg l^{-1}	45 mg kg^{-1}	45 mg kg^{-1}	31 mg kg^{-1}	31 mg kg^{-1}
Normal Evolution	Peak	4E-07	1E-10	9E-01	4E-05	4E-02	1E-09	4E-05	3E-07
	Time	12000	12000	12000	12000	12000	12000	12000	100000
Sensitivity Cases									
Measured Radionuclide Inventory	Peak	4E-07	1E-10	9E-01	4E-05	4E-02	1E-09	4E-05	3E-07
	Time	12000	12000	12000	12000	12000	12000	12000	100000
Increased Modelled Radionuclide Inventory	Peak	4E-07	1E-10	9E-01	4E-05	4E-02	1E-09	4E-05	3E-07
	Time	12000	12000	12000	12000	12000	12000	12000	100000
Reduced Near-field Sorption	Peak	7E-06	5E-10	1E+00	2E-04	4E-02	5E-09	2E-04	7E-06
	Time	100000	12000	12000	12000	12000	12000	12000	100000
Reduced Far-field Sorption	Peak	1E-06	1E-10	9E-01	4E-05	4E-02	1E-09	4E-05	8E-06
	Time	9800	12000	12000	12000	12000	12000	12000	30000
Reduced Sorption in Near-field and Far-field	Peak	3E-05	5E-10	1E+00	2E-04	4E-02	5E-09	2E-04	2E-04
	Time	9800	12000	12000	12000	12000	12000	12000	30000
Rapid Degradation	Peak	4E-07	1E-10	9E-01	4E-05	4E-02	1E-09	4E-05	3E-07
	Time	10000	10000	12000	10000	12000	12000	10000	100000
Increased Geosphere Bedrock Hydraulic Conductivity	Peak	9E-08	8E-12	1E+00	0E+00	9E-08	8E-11	9E-10	2E-06
	Time	20000	25000	60000	0	25000	25000	100000	25000
Increased Geosphere Overburden Hydraulic Conductivity	Peak	3E-07	3E-11	9E-01	5E-06	2E-05	3E-10	8E-06	2E-07
	Time	90000	17000	15000	17000	15000	17000	17000	100000
Increased Dilution in the River	Peak	4E-07	1E-10	9E-01	4E-05	4E-02	1E-09	4E-05	3E-07
	Time	12000	12000	12000	12000	12000	12000	12000	100000
Self-Sufficient Indigenous Receptor	Peak	4E-07	1E-10	9E-01	4E-05	4E-02	1E-09	4E-05	3E-07
	Time	12000	12000	12000	12000	12000	12000	12000	100000

Scenario		Groundwater	River	Cap	Springs	Garden	Grazing	River Shore	River Sediment
Disruptive Events									
Site Investigation (Inadvertent Human Intrusion)	Peak	4E-07	1E-10	9E-01	4E-05	4E-02	1E-09	4E-05	3E-07
	Time	12000	12000	12000	12000	12000	12000	12000	100000
Surface Erosion	Peak	4E-07	1E-10	9E-01	4E-05	4E-02	1E-09	4E-05	3E-07
	Time	12000	12000	12000	12000	12000	12000	12000	100000
Extreme Degradation	Peak	2E-06	7E-10	4E-01	3E-04	2E-01	7E-09	3E-04	3E-07
	Time	100000	100000	1700	100000	3250	100000	100000	100000
Fault Zone Activation	Peak	6E-04	2E-09	3E-01	7E-04	1E-03	2E-08	1E-03	6E-05
	Time	100000	100000	1000	100000	2200	100000	100000	100000
Excavation of Above-Bedrock Facility	Peak	4E-07	1E-10	9E-01	4E-05	**8E+02**	1E-09	4E-05	3E-07
	Time	12000	12000	12000	12000	100	12000	12000	100000
Overburden Well	Peak	4E-07	1E-10	9E-01	4E-05	4E-02	9E-08	5E-05	3E-07
	Time	12000	12000	12000	12000	12000	12000	12000	100000
Bedrock Well	Peak	4E-07	1E-10	9E-01	5E-05	5E-02	2E-08	5E-05	4E-08
	Time	9300	9300	9800	9300	10000	80000	9300	100000
Defence-in-Depth Cases									
Role of Existing Facility Structure	Peak	2E-06	6E-07	7E-01	3E-05	3E-02	3E-07	4E-01	3E-07
	Time	100000	101	2800	4750	4750	110	100	100000
Role of Grout	Peak	3E-05	3E-08	1E-01	3E-04	1E-01	2E-08	2E-02	7E-06
	Time	100000	101	90000	3500	90000	110	90	100000
"What-If" Cases									
Mass Excavation	Peak	4E-07	1E-10	9E-01	4E-05	**7E+02**	1E-09	4E-05	3E-07
	Time	12000	12000	12000	12000	100	12000	12000	100000
River Level Fall	Peak	4E-07	1E-10	9E-01	4E-05	4E-02	1E-09	4E-05	7E-10
	Time	12000	12000	12000	12000	12000	12000	12000	100000
Undetected Fracture Zone	Peak	9E-08	8E-12	1E+00	0E+00	9E-08	8E-11	9E-10	2E-06
	Time	20000	25000	60000	0	25000	25000	100000	25000

Note: **Bold** & Shading: Exceedance of corresponding EQS.

6.6 Uncertainties in Key Parameters

The scenarios and calculation cases discussed in preceding sections explore uncertainties related to model assumptions for the PostSA of the NPDDF. In addition, some targeted sensitivity calculations were undertaken to explore aspects of the model that were either recognised as being significantly uncertain, or, to explore how the performance of the system responds to extreme conditions (i.e., "What If" calculations). In the latter case, the results are not suitable for comparison with dose criteria, because the calculations are intentionally extreme and at the limits of plausibility. Instead, they are performance indicators which illustrate the sensitivity of the model to important factors.

Three "What If" calculations were undertaken to examine hypothetical situations which could lead to high concentrations in the accessible environment:

- Mass excavation examined the potential excavation of the entire Facility and its distribution in surface soils, subsequently lived upon and farmed. As noted in Section 6.4, even under such conditions, the highest dose that occurs is 1 mSv y^{-1}.

- Also examined are the potential surface environment impacts that could arise if environmental changes led to the river level falling significantly. This could result in the discharge of contaminated groundwater to a patch of dry land on the shoreline, rather than into the river. The concentrations in the shoreline sediments are increased and peak at 0.3 Bq kg^{-1} after 1,500 y, 30 times greater than the NES. As only a small area is contaminated, there is limited potential for human exposure to these shoreline sediments and the peak assessed dose to a person is the same as for the NES.

- Finally, the impact of an undetected fracture zone being present was assessed. The results are the same as in the Sensitivity Case "Geosphere Bedrock Hydraulic Conductivity", which shows that doses were reduced compared with the NES, being 3E-05 mSv y^{-1}. This is because the higher flow rates mean the radionuclides released from the NPDDF are dispersed in the environment more rapidly and therefore do not accumulate to the same concentrations as in the NES.

The sensitivity of the system to uncertainties in inventory, sorption coefficients, structure degradation times, hydraulic conductivity, river dilution, and lifestyle of an Indigenous Self-sufficient receptor was examined.

Using a more realistic inventory has a significant effect on the results, since it is a key driver of environmental concentrations and subsequent doses. The more realistic, "measured", inventory produces a peak dose that is around a factor of eight lower than that of the NES. Thus, inventory is an aspect that the model is indeed sensitive to, and the use of a conservative inventory in the NES ensures a conservative estimate of the dose. The dominant radionuclide also changes to C-14 because Cl-36, which dominates when the modelled inventory is used, is difficult to measure in practice, but its presence can be calculated relatively reliably through neutron activation modelling. An additional sensitivity case was run in which the NES inventory was increased by a factor of two. This correspondingly increased the calculated doses by a factor of two compared to NES.

Sorption coefficients are uncertain and so the sensitivity of calculated dose to the assigned values for grout and concrete was examined. The NES uses best-estimate values from an international compilation (Ochs

et al., 2016). Reducing the sorption coefficients in the near-field (i.e., the grout and concrete) to the lower limit values from Ochs *et al*. (2016) (where possible) or by a factor of 10, increased the peak concentrations in the garden by a factor of 5, although the resulting doses increased by only about a factor of 2 (this is because the sorption coefficients for different radionuclides change by differing amounts, according to the values presented by Ochs *et al.,* (2016), and peak soil concentrations are dominated by C-14 whereas peak doses are dominated by Cl-36). Sorption also affects the transport of contaminants in the geosphere (the "far-field"). However, reducing the sorption coefficients by a factor of 10 (representative of the typical uncertainty in such values) did not significantly affect environmental concentrations or doses, indicating that sorption within the NPDDF is far more important. To confirm this, the effects of reduced sorption in both the near-field and far-field, by combining the lower sorption values in the near-field and the reduced values in the far-field from the abovementioned cases, were investigated. The results are similar to those obtained for the case where only lower sorption values in the near-field are considered.

Sensitivity to less than anticipated physical performance of the NPDDF structure and grout has been examined by assuming an instantaneous increase in the hydraulic conductivity of the concrete and grout materials to a "degraded" value (resulting in higher flows of water through the Facility) immediately after the end of institutional control period. The results suggest that it is primarily the concrete structure that is important, rather than the grout. When the structure is assumed to be instantly degraded there is a much more rapid release of contaminants, leading to a dose 50 times higher than the NES, from Cs-137 immediately after the period of control to an Indigenous (AOPFN) receptor. However, when the grout is assumed to be degraded there is very little difference from the NES results.

The presence and hydrogeological properties of the permeable fluvial sand and gravel layer that subparallels the Ottawa River and extends tile drain capture of overburden groundwater northwest of the NPDWF is identified as an uncertainty in modeling of groundwater flow at the NPDWF site (Arcadis & Geofirma, 2022). Two alternative calculation cases have therefore been considered to account for the uncertainty in the hydraulic properties of the geosphere. The first case examines increased hydraulic conductivity (and thus flow) in bedrock compared to NES, whereas the second case examines increased hydraulic conductivity (and thus flow) in the overburden fill material between the facility and the river, compared to NES. The results show that in both cases concentrations in the key environmental media are reduced, as are doses to receptors. In the case of the higher bedrock hydraulic conductivity, this is because the water table becomes lower, preventing radionuclides from reaching the garden via a pathway in the overburden. When the overburden hydraulic conductivity is increased, the concentrations are reduced because more water flows through it, increasing dilution.

A sensitivity calculation was also conducted to assess the effect of increased dilution in the river Ottawa, which simply linearly scales the concentrations and hence the doses from water ingestion and external exposure pathways.

Finally, using a more conservative lifestyle for the Indigenous Self-sufficient receptor compared to the AOPFN Indigenous receptor used in NES showed that there is an increase in peak doses by around a factor of six to the Indigenous Self-sufficient group, but such doses remained lower than for the site resident. This reflects the importance to the site resident of exposure to vegetables grown in the garden area, adjacent to the NPDDF. By contrast, the Indigenous Self-sufficient exposure group obtains wild food from a wider range which includes land that is not contaminated by irrigation.

6.7 Confidence in the Assessment

Regulatory and international guidance recognizes that the process of postclosure safety assessment inherently involves uncertainties, such that absolute measures of safety cannot readily be applied. Consequently, there is an emphasis on building confidence in safety through a variety of methods which, together, provide a robust case that the Facility under consideration will be safe in the future. The following are recognised as key contributors to confidence, and the way in which they have been addressed in the PostSA is discussed.

- Process – A systematic, transparent and auditable process for developing and analysing models to evaluate postclosure safety is an essential element to building confidence in the assessment. This is because the process demonstrates that the scenarios, models and data have been carefully selected making the best use of available information, and recognising the uncertainties present. This study has rigorously applied best practice in its assessment approach to develop scenarios, models and data that are specifically designed to address the safety performance of the Facility.
- Comparison with criteria – regulatory safety criteria and constraints derived from them are set so as to prevent an unacceptable level of harm or risk to people or the environment. The PostSA shows that the expected levels of radiation dose will be well below these criteria in all circumstances that have been assessed, even with conservative assumptions. For non-radioactive contaminants (i.e., lead), the calculated peak environmental concentrations are below their EQSs for groundwater, surface water, soil, and sediment.
- Range of Performance Measures – the main endpoint for the PostSA is radiation dose (to humans and other species). The calculated doses have been presented alongside other measures of performance to give additional context and address the issue that there may be uncertainties in the nature of exposures to species.
    - Calculations of the total amount of contaminants and their location in the modelled system, for example, illustrate the effectiveness of the Facility in containing the contaminants for long periods of time. Specific “Defence in Depth” calculations have been undertaken to show the performance of multiple engineered barriers.
    - Rates of release also provide an indication of the containment function of the Facility, and although it is not appropriate to compare these results with authorised discharges of contaminants, they can be seen to be small in comparison with the inventory present; the peak rate of release from the Facility is a million times lower than the initial inventory.
    - Environmental concentrations also give a measure of performance and can be compared with accepted measurements of radioactivity at the site and elsewhere. Typically, concentrations are extremely small (of the order of 1 Bq kg^{-1} or less). Such levels are challenging to measure, and a factor of ten or more lower than natural radionuclide concentrations.
- Range of calculations – a suitably developed assessment model can provide the capability to explore and evaluate alternative assumptions with a range of calculation cases. This enables uncertainties to be explored (e.g., by adopting alternative parameter values and examining the difference in results). The range of results calculated with the ensemble of calculation cases and scenarios is also a very valuable confidence-building measure, as it demonstrates that even under a range of different assumptions and conditions, the safety criteria are not exceeded. This

illustrates the intrinsic robustness of the system that comes from a range of barriers (waste form, grout, Facility structure) and a range of safety functions (containment, isolation, and ultimately release to a highly dispersive environmental receptor).

- Comparison with other work – CNL performed an alternative calculation on the first iteration of the PostSA using RESRAD-OFFSITE Version 3.1 to provide confidence in the NPD post-closure safety analysis (CNL, 2017). RESRAD-OFFSITE and AMBER are both computer programs that meet the requirements of CNL's Code Management Program and have been validated in accordance with CNL's *Guideline for Application of Quality Assurance for Analytical, Scientific, and Design Computer Programs* (CNL, 2019c). Even though both computer programs have been previously validated and approved for use by CNL's Code Management Panel it was considered that additional confidence in the results from the first iteration AMBER model would be obtained by comparison with RESRAD-OFFSITE. The aim of the verification (CNL, 2017), against the AMBER output was to show that the peak dose was within an order of magnitude of the peak dose from the peak dose in the first iteration AMBER model. CNL (2019c) suggests that an acceptance criterion would be whether the calculated parameters show similar trends and magnitudes as the measurements. The results of this assessment were verified against the long-term radiological dose consequence acceptance criteria of 0.25 mSv y^{-1} and analyzed post-closure normal evolution scenario. The RESRAD-OFFSITE analysis peak dose was 2.3E-04 mSv y^{-1} to the agricultural land use receptor, which is less than the 0.25 mSv y^{-1} limit. The peak dose to the agricultural land use receptor and parkland receptor were both within an order of magnitude of the peak doses in the PostSA using the AMBER code. It was concluded that the RESRAD results were able to verify the AMBER analysis results, and that the dose consequences between the two models vary within a set margin and are well below the 0.25 mSv y^{-1} limit. The order of magnitude is therefore the set margin referred to and provides a purely qualitative comparison of the results.

6.8 Comparison with Previous Iterations

This is the 4th iteration of the PostSA. The main developments to the modelling approach since the 3rd iteration include:

- A major revision to the geometry used to represent the NPDDF structure, to move from the simplified "2.5D" representation of the facility and its major rooms to a fully 3D realization derived from the as-built structure and which aligns directly with that used in detailed groundwater model;
- Additional pathways in the geosphere model, to explicitly represent the tile drains and pipe trench;
- Inclusion of updated groundwater flow modelling results;
- Revised material properties for infill and bedrock materials;
- Updated assumptions for exposure groups, including the assessment of doses to a person representative of the indigenous community, based on a dietary survey of the AOPFN;
- Inclusion of updated inventory based on Porter (2022) and a revised screening approach;

- Change to the C-14 model in relation to the contamination of (terrestrial) animal produce due to ingestion of water, from the C-14 specific activity model for aquatic organisms to the C-14 model used for other radionuclides for ingestion of water by animals (based on CSA, 2022).

These modifications, particularly those relating to the representation of the NPDDF structure and water flows through it, result in some changes to the calculated results. A comparison of a number of cases is presented in Table 6-5 below. The reasons for the differences are primarily related to revisions to the pattern of groundwater flow through the NPDDF and to the transfer of C-14 in river water to animal produce through ingestion of water (which was modelled in the 3rd iteration). In the 4th iteration, the former results in a more rapid release of some key contaminants and leading to a greater significance of Cl-36 in terms of doses to receptors. The latter, given that C-14 in drinking water has negligible effect on C-14 concentrations in animals relative to that via food (according to CSA, 2022), results in the dominant pathway changing from ingestion of animal produce to ingestion of crops (with Cl-36 becoming the dominant radionuclide). The difference between the two approaches is summarised in Quintessa (2023). The other key factor is the assumptions concerning the sorption of Ag-108m in the geosphere and biosphere. In the 3rd Iteration, this had been cautiously assumed to be low in the geosphere and very high in sediments, based on limited data. More information has been gathered, and with more realistic assumptions this radionuclide is not now calculated to accumulate to very high concentrations in sediments, very considerably reducing its significance.

Table 6-5 Comparison of Doses to for the 3rd and 4th Iteration PostSA

Scenario*	3rd Iteration			4th Iteration		
	Peak Dose (mSv y^{-1})	Time of Peak (y)	Dominant Radionuclide	Peak Dose (mSv y^{-1})	Time of Peak (y)	Dominant Radionuclide
Reference Inventory	**3E-04**	**1100**	**C14**	**8E-05**	**12,000**	**Cl36**
Site Resident Adult	3E-04	1100	C14	5E-05	12,000	Cl36
Site Resident Child	2E-04	1100	C14	6E-05	12,000	Cl36
Site Resident Infant	3E-04	1100	C14	8E-05	12,000	Cl36
Hunter Adult	2E-04	1100	Ag108m	4E-07	1,500	C14
Hunter Child	8E-05	1100	Ag108m	3E-07	1,500	C14
Hunter Infant	2E-07	1300	C14	2E-07	1,500	C14
AOPFN Indigenous Adult	Not calculated			7E-06	1,500	C14
Off-site Adult	1E-05	1	H3	1E-08	7	H3
Off-site Child	9E-06	1	H3	6E-09	7	H3
Off-site Infant	1E-05	1	H3	8E-09	7	H3
Measurement Inventory						
Site Resident Adult	2E-06	101	Cs137	1E-05	1,500	Cl36
Site Resident Child	1E-06	101	Cs137	1E-05	1,500	Cl36
Site Resident Infant	8E-07	101	Cs137	1E-05	1,500	Cl36
Hunter Adult	5E-07	110	Cs137	1E-07	1,500	C14
Hunter Child	3E-07	1700	Pu239	1E-07	1,500	C14
Hunter Infant	1E-08	101	H3	9E-08	1,500	C14
AOPFN Indigenous Adult	Not calculated			3E-06	1,500	C14
Off-site Adult	3E-05	1	H3	4E-09	8	H3
Off-site Child	2E-05	1	H3	2E-09	8	H3
Off-site Infant	2E-05	1	H3	3E-09	8	H3

Note: *Other than the inventory assumptions, both have the same assumptions for the rest of the model, which reflect the NES in each respective iteration.

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APPENDIX A: APPROACH AND ASSESSMENT CONTEXT

APPENDIX A - APPROACH AND ASSESSMENT CONTEXT

A 1 INTRODUCTION

Canadian Nuclear Laboratories (CNL, acting on behalf of Atomic Energy of Canada Limited, AECL) is proposing in-situ disposal of the Nuclear Power Demonstration Waste Facility (NPDWF), thereafter referred to as the Nuclear Power Demonstration Disposal Facility (NPDDF). This 4th Iteration Postclosure Safety Assessment (PostSA) will support the final Environmental Impact Statement (EIS) submission.

This 4th Iteration PostSA has been undertaken using international best practice, specifically the International Atomic Energy Agency's (IAEA's) Improving Safety Assessment Methodologies (ISAM) guidance (IAEA, 2004). This is a systematic, stepwise approach, the main stages of which are illustrated in Figure A-1. This PostSA has been documented in a way that corresponds to the ISAM approach, with a main report describing the key elements of the assessment and its outcomes.

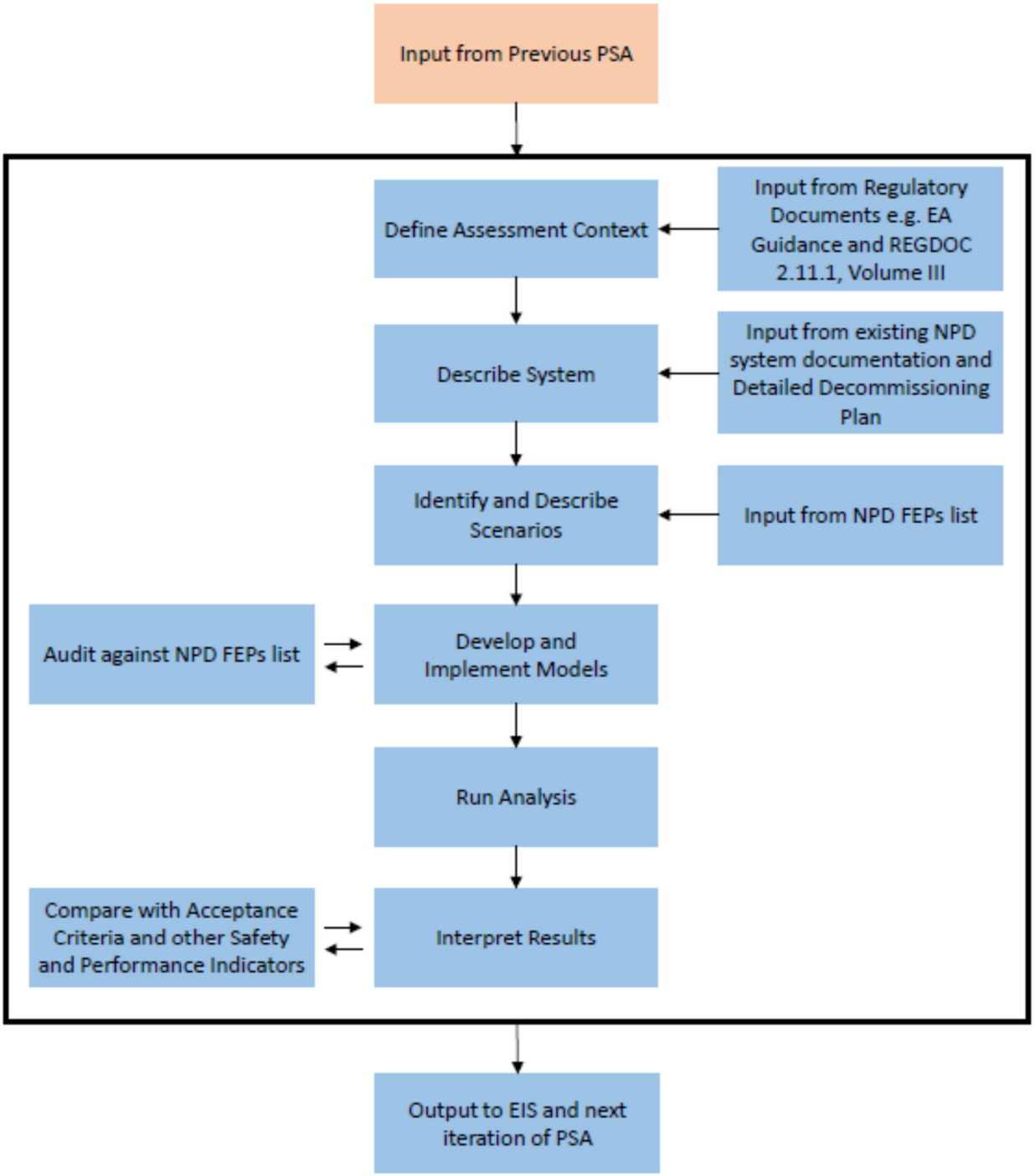
This appendix introduces the overall approach to the assessment, which reflects the ISAM approach and relevant regulatory guidance. It then addresses the first step of the approach by documenting the context within which the assessment is being undertaken, dealing with questions such as the specific regulatory requirements and criteria, the assessment timeframe, and calculation end points.

The purpose of the structured approach, and clearly defined context, is to establish clearly the framework and scope within which the more detailed technical aspects of the PostSA are developed.

The appendix is organized as follows:

- Section A 2 describes the main steps of the approach;
- The assessment context, the first step in the approach, is then developed and documented in Section A 3; and
- This is followed in Section A 4 by a description of quality assurance aspects.

Figure A-1 Approach Used in the Postclosure Safety Assessment (Adapted from ISAM (IAEA, 2004))



A 2 APPROACH

The CNSC has issued a regulatory document (REGDOC 2.11.1, Volume III, Version 2) on the safety case for the disposal of radioactive waste (CNSC, 2021a) which describes its expectations in relation to the assessment of postclosure safety. The CNSC expects a well-structured, transparent and traceable approach to analysing the long-term performance of the radioactive waste disposal system. The approach should: facilitate comparison of results with regulatory requirements; enable uncertainties to be identified and analysed; provide clear links to other aspects of the Environmental Impact Statement and decommissioning programme; demonstrate use of appropriate quality assurance; be amenable to review; and provide a basis for future iterations. REGDOC 2.11.1, Volume III, Version 2 specifies the information that should be included in the documentation of a safety assessment, which maps onto the approach used for the PostSA (Figure A-1):

- A selection of an appropriate methodology;
- The assessment context ("Define Assessment Context" in Figure A-1);
- The system description ("Describe System" in Figure A-1);
- The assessment timeframes (part of "Define Assessment Context" in Figure A-1);
- The assessment scenarios and calculation cases ("Identify and Define Scenarios" in Figure A-1);
- The development and use of assessment models ("Develop and Implement Models" and "Run Analyses" in Figure A-1); and
- The interpretation of results ("Interpret Results" in Figure A-1).

The methodology for the safety assessment is based on international best practice, as embodied in the safety standards on the safety case and safety assessment for radioactive waste disposal from the International Atomic Energy Agency (IAEA) (IAEA, 2012) and the recommendations of the IAEA ISAM programme (IAEA, 2004).

As IAEA (2012) notes, the safety assessment will ultimately become part of a broader safety case. The PostSA comprises the main scientific evidence basis for the long-term performance of the facility. It highlights the safety functions and addresses uncertainties in long-term assessment. The overall Safety Case, including in particular the integration of safety arguments, is outlined in CNL (2020a).

The approach used for the PostSA comprises the following steps, shown in Figure A-1.

- The context of the assessment is defined, documenting the high-level assumptions, the constraints (reflecting the regulatory requirements), and the assessment's purpose, end points, treatment of uncertainties, and timeframes.
- The current information on the waste, repository, geological setting and surface environment relevant to postclosure safety is reported.
- A range of internally consistent potential future evolutions of the system (scenarios) is systematically identified, together with a suite of calculation cases that examine the performance

of the disposal system under other conditions of interest and explore its sensitivity to key uncertainties.

- Conceptual and mathematical models and data are developed for the scenarios; and a range of calculation cases, which explore key areas of uncertainty, are identified and implemented in an appropriate software tool.
- The results are analysed, interpreted and discussed to inform on the performance of the system, its overall robustness, and the nature and role of key uncertainties. Particular emphasis is given to the comparison of the results for the identified safety and performance indicators against the relevant reference levels which have been derived from guidance by CNSC (2021a).

Further details of each step are presented in the main sections and corresponding appendices of this report which correspond to the main steps in the ISAM approach.

A 3 ASSESSMENT CONTEXT

A 3.1 Regulatory Requirements and Guidance

The NPD Waste Facility (NPDWF) is presently in the Storage with Surveillance (SWS) phase of decommissioning. The next step, which is being considered, is in-situ disposal. This would leave a radiological inventory encased within the NPDWF structure, creating a disposal facility hereafter referred to as the NPD Disposal Facility (NPDDF). The focus of the PostSA is to evaluate the potential long-term impact of this inventory on the health and safety of humans and the environment. This includes considering the potential for radionuclide releases to groundwater from the NPDDF and radionuclide migration to the Ottawa River. It is also necessary to assess the possible consequences of any unlikely situations that could lead to the disturbance and disruption of the Facility, after controls over it cease. For all these situations, the potential effects on people and the environment of any significant accumulations of non-radioactive hazardous materials remaining in-situ are also evaluated.

Generic guidance on assessing long-term safety of radioactive waste management is set out in the regulatory guide REGDOC-2.11.1, Volume III, Version 2 (CNSC, 2021a). This provides guidance on performing long-term assessments and interpreting the results. Key requirements and recommendations are summarized in Table A-1. This table also provides a mapping to the parts of the PostSA documentation where the requirements have been addressed.

Table A-1 Requirements of CNSC REGDOC-2.11.1, Volume III, Version 2 on Safety Case for the Disposal of Radioactive Waste

Section	Requirements (Quoted from REGDOC-2.11.1, Volume III, Version 2 (2021a))	Section of this Report	Appendix Material
[7.4.1.3] Post-closure safety Assessment	*"The licensee or applicant shall perform a post-closure safety assessment. The post-closure safety assessment forms the core of the safety assessment for a disposal facility. It involves an analysis of the expected normal evolution of the disposal system, possible disruptive events, and the potential radiological and non-radiological impacts on people and the environment, as well as the interpretation of results. Scenarios are used to describe possible evolutions of the disposal system and its environment as well as the impacts.* *The impacts are determined quantitatively by means of mathematical models. This includes an analysis of the potential migration of radioactive and hazardous substances from the disposal facility, their movement in the environment and resulting impacts. Requirements and guidance on how to perform a post-closure safety assessment can be found in section 8 of this document."*	All	All

CNL – Postclosure Safety Assessment

Section	Requirements (Quoted from REGDOC-2.11.1, Volume III, Version 2 (2021a))	Section of this Report	Appendix Material
[8] Post-Closure Safety Assessment	*"The licensee or applicant shall ensure that the post-closure safety assessment for a disposal system includes a systematic quantitative analysis of the evolution of the disposal system and its environment, possible disruptive events, and the potential resulting radiological and non-radiological impacts on people and the environment. The interpretation of the quantitative results should be clear."*	All	All
[8] Post-Closure Safety Assessment [8.1.3] Post-Closure Safety Assessment Scenarios and Time Frames	*"The licensee or applicant shall develop and use scenarios to describe possible evolutions of the facility and its environment as well as the potential impact of the identified FEPs on safety."*	4.1	Appendix C Appendix D
[8] Post-Closure Safety Assessment	*The licensee or applicant should apply models to each given scenario to assess:* • *evolution of the waste form and associated contaminant activity/concentrations over time* • *contaminant release rates* • *evolution of the engineered barriers* • *evolution of the natural barriers* • *contaminant transport through the engineered barriers, the geosphere and the biosphere* • *receptor exposure* • *potential effects resulting from the exposure*	4 5	Appendix E Appendix F Appendix G
[8] Post-Closure Safety Assessment	*"The licensee or applicant shall ensure that the post-closure safety assessment demonstrates their understanding of the disposal system through a well-structured, transparent and traceable methodology."*	2.1	Appendix A
[8] Post-Closure Safety Assessment	*"The post-closure safety assessment documentation should provide a clear and complete record of the decisions made and the assumptions adopted in developing the model of the disposal system. The parameters and variables used to run the model and to arrive at a given set of results should be reported and justified. This input data should be obtained from site-specific studies and research results."*	4	Appendix E Appendix F

Section	Requirements (Quoted from REGDOC-2.11.1, Volume III, Version 2 (2021a))	Section of this Report	Appendix Material
[8] Post-Closure Safety Assessment	*"The assumptions and data of the post-closure safety assessment shall be supported by an assessment of the current and future conditions of the disposal system."*	4	Appendix E Appendix F
[8.1] Components of the post-closure safety assessment	*"The licensee or applicant should use a structured approach to perform the post-closure safety assessment of a disposal system that includes the following components:* • *Post-closure safety assessment context* • *Disposal system description* • *Post-closure safety assessment scenarios and time frames* • *Development and use of safety assessment models* • *Interpretation of results"*	2.1	Appendix A
[8.1.1] Post-closure Safety Assessment Context	*"The licensee or applicant shall ensure that the safety assessment context:* • *Defines the scope and purpose* • *States the assessment criteria used in the assessment* • *Outlines the approach adopted to demonstrate safety* • *States the end points for the assessment (i.e. the modelling output that needs to be compared to the acceptance criteria; see section 8.1.1.1)"*	2	Appendix A
[8.1.1.1] Acceptance Criteria used in the Assessment	*"The licensee or applicant shall ensure that the safety assessment context contains the criteria by which the safety assessment results will be deemed acceptable. These criteria shall be based on regulatory requirements and/or derived from other scientifically justifiable benchmarks or safety indicators that indicate system performance. The licensee should establish explicit criteria for the level of safety to be achieved."*	2.2.2	Appendix A
[8.1.1.1] Acceptance Criteria used in the Assessment	*The post-closure safety assessment of a disposal facility shall provide reasonable assurance that the regulatory radiological dose limit for public exposure (currently 1 mSv/year) will not be exceeded for the normal evolution scenario. To account for the possibility of exposure to multiple sources, and their potential cumulative effects, and to help ensure that doses resulting from the disposal system are as low as reasonably achievable (ALARA), a dose constraint should be established as a fraction of the regulatory dose limit. The dose constraint is not a limit, but rather a design tool in the optimization process."*	2.2.2	Appendix A

Section	Requirements (Quoted from REGDOC-2.11.1, Volume III, Version 2 (2021a))	Section of this Report	Appendix Material
[8.1.1.1] Acceptance Criteria used in the Assessment	*"Benchmark values for protection from hazardous substances can be found in federal and provincial environmental objectives and guidelines. Where available, the Canadian Environmental Quality Guidelines [10], established by the Canadian Council of Ministers of the Environment (CCME) for protection of human health, should be used for benchmark or toxicological reference values. Where the CCME's human health guidelines are not available, human health-based federal or provincial guidelines should be used. If none are available, benchmarks can be derived from the toxicity literature or other regulatory agencies, or from CCME protocols for the derivation of criteria."*	2.2.2	Appendix A
[8.1.1.1] Acceptance Criteria used in the Assessment	*"For the protection of non-human biota from radiation exposure, the primary concern is the total radiation dose to the organisms resulting in deterministic effects. Radiation dose benchmarks for a quantitative effects analysis should follow the guidance of the United Nations Scientific Committee on the Effects of Atomic Radiation [11]. For species identified to be in need of special protection (e.g., those named on the Government of Canada's List of Wildlife Species at Risk), a more conservative screening dose rate criterion [8] should be considered. Other benchmark values for mean radiation doses to non-human biota have been derived for various types of organisms [12, 13, 14, 15, 16, 17]. Development of criteria for ensuring radiological protection of the environment should follow the protocols established for hazardous substances, as discussed below."*	2.2.2	Appendix A

Section	Requirements (Quoted from REGDOC-2.11.1, Volume III, Version 2 (2021a))	Section of this Report	Appendix Material
[8.1.1.1] Acceptance Criteria used in the Assessment	*"Non-radiological acceptance criteria for protection of the environment can include concentration or flux of hazardous substances. The Canadian Environmental Quality Guidelines [10] for water, sediment and soil are appropriate benchmarks for conservative safety analyses. Provincial guidelines can be used, where appropriate, for substances for which federal guidelines have not been established.* *Alternatively, benchmarks for hazardous substances can be derived from toxicity literature, or other regulatory agencies (e.g., the U.S. Environmental Protection Agency). The CCME provides protocols for the derivation of air, soil and water quality criteria. The protocols for developing criteria for the protection of the environment include determining critical toxicity values –such as an effects concentration for a 10% or 20% response, lowest observable adverse effects level, or no observable adverse effects level –from studies of chronic exposure to the most sensitive species. The assessment of risks of hazardous substances to non-human biota is done at the population level, but for species identified to be in need of special protection (e.g., those identified under the Species at Risk Act), the assessment should focus on protection at an individual level."*	2.2.2	Appendix A
[8.1.1.2] Approach Adopted to Demonstrate Safety	*"A licensee or applicant should use risk-informed approaches to estimate the release and dispersal of contaminants and resulting concentrations in water, sediment, soil and air based on waste characteristics, release mechanisms and rates, and contaminant transport rates. This may be a combination of modelling supported by monitoring data."* *"The licensee or applicant should discuss and justify the choice of approach in the documentation demonstrating post-closure safety. It is expected that the purpose of the safety assessment will also justify the assessment model used (section 8.1.5) and the level of confidence that is needed in the results."*	2.1	Appendix A

Section	Requirements (Quoted from REGDOC-2.11.1, Volume III, Version 2 (2021a))	Section of this Report	Appendix Material
[8.1.1.2] Approach Adopted to Demonstrate Safety	*"A licensee or applicant should assess post-closure safety using a number of quantitative approaches, including, without being limited to:* • *a scoping assessment to illustrate the factors that are important to post-closure safety and a bounding assessment to show the limits of potential impact* • *calculations that give a realistic best estimate of the performance of the disposal facility or system, or conservative calculations that intentionally over-estimate potential impact* • *deterministic or probabilistic calculations, appropriate for the purpose of the safety assessment, to reflect data uncertainty"* *"The licensee or applicant may use any combination of these or other appropriate assessment strategies in a complementary manner to increase confidence in the demonstration of the safety of the facility."*	2.1 4.1	Appendix A Appendix D
[8.1.1.2] Approach Adopted to Demonstrate Safety	*The licensee or applicant should use real site and as-built facility data, site-specific scenarios and accurate models of the processes being simulated in the realistic estimate."*	4	Appendix E
[8.1.1.2] Approach Adopted to Demonstrate Safety	*"A conservative approach should be used when developing computer codes and models. Assumptions and simplifications of processes should not result in underestimation of the potential risks or impacts. It may not be necessary for every assumption to be conservative; however, the net effect of all assumptions should be a conservative representation of long-term impact and risk"*	4	Appendix E Appendix F
[8.1.1.3] Assessment End Points	*"The licensee or applicant shall demonstrate that the selected assessment end points are consistent with the purpose of the assessment and with relevant regulatory requirements, such as requirements related to radiological dose."*	2.2.3	Appendix A

Section	Requirements (Quoted from REGDOC-2.11.1, Volume III, Version 2 (2021a))	Section of this Report	Appendix Material
[8.1.1.3] Assessment End Points	*"Other safety indicators, complementary safety indicators, such as those that reflect containment barrier effectiveness or impacts on non-human species, can also be presented to illustrate the long-term performance of a disposal system."* *"The licensee or applicant should derive and justify the acceptance criteria by which these complementary safety indicators are to be judged from the relationship between the complementary safety indicator and the more direct assessment end-points."*	2.2.3	Appendix A
[7.3] Disposal System Description	*"The licensee or applicant shall describe the disposal system in the safety case. The disposal system is defined as the integrated collection of properties of the site for a disposal facility; design of the disposal system; physical structures and items; procedures for control; and characteristics of the waste and other elements that contribute in different ways and over different time frames to the fulfilment of safety functions for disposal."* *"Following a graded approach to safety, the level of rigour and completeness in the description of the system and its components should be commensurate with the hazards imposed by the waste, and with the development and licensing stage of the facility."* *"The licensee or applicant shall identify the safety functions of both the overall disposal system and the individual SSCs* [Systems, Structures and Components] *and assess the safety performance in terms of their ability to fulfill the safety functions. The safety case and its supporting safety assessment should explain and justify the safety functions of the overall disposal system and of each individual barrier."*	3	Appendix B
[8.1.2] Disposal System Description	*"The licensee shall include the disposal system description, a component of the overall safety case, which should be reiterated to show that the features are relevant to the safety assessment."*	3	Appendix B
[8.1.2] Disposal System Description	*"The disposal system description should present both the characteristics of the site and the design of the SSCs important to safety, as well as a description of the waste to be managed."*	3.1	Appendix B

Section	Requirements (Quoted from REGDOC-2.11.1, Volume III, Version 2 (2021a))	Section of this Report	Appendix Material

[7.3]
Disposal System Description
	"The description should also include both quantitative and qualitative information. As applicable, the following shall be included:
	• *specific understanding of features, events and processes (FEPs) associated with the site and the disposal facility*
	• *waste information (e.g., quantities and properties of the waste and the radionuclide inventory)*
	• *waste acceptance criteria at the disposal facility*
	• *description of the biosphere including human and non-human biota and the surface environment*
	• *site characteristics including, as applicable, the deep and near-surface geological units at the site, including:*
	  ○ *the description of surface and subsurface characteristics (e.g. geology, hydrogeology, hydrology, geochemistry, tectonics, seismicity, geomorphology, climate, ecology)*
	  ○ *current and foreseeable land use*
	  ○ *the identification and description of expected natural evolution and disruptive events*
	• *the design and assumptions upon which the design is based*
	• *description of the structure, systems and components (SSCs) of the disposal system, which includes the engineered and natural barriers, their safety functions, interfaces, associated uncertainties and performance as a function of time*
	• *radiological, thermal, hydraulic, mechanical, chemical and biological processes that may affect the disposal system and its components as well as the possible interaction among those components"*
		FEPs:
		4.1.1
		
		Waste:
		3.1, 4.2.2, 4.3.1
		
		Characterisation:
		3, 4.1, 4.2
		
		Disposal System:
		3.1, 4.2
		
		Uncertainty:
		2.2.5, 6.6
		
		Processes:
		4.1
			Appendix C
			
			Appendix B
			Appendix E
			
			Appendix B
			Appendix D
			
			Appendix A
			Appendix B
			Appendix E
			
			Appendix B
			Appendix E

Section	Requirements (Quoted from REGDOC-2.11.1, Volume III, Version 2 (2021a))	Section of this Report	Appendix Material
[8.1.2.1] Site Characterization	*"The licensee or applicant shall include site characterization data in the safety assessment."* *"The licensee or applicant should ensure that the site characteristics are sufficiently defined to support an accurate description of the current site conditions and a credible projection of their future evolution."* *"Guidance on the site characterization of a deep geological repository is found in REGDOC-1.2.1, Guidance on Deep Geological Repository Site Characterization."*	3.2 4.2, 4.3	Appendix B Appendix E
[7.3.1] Site Characterizations	*"Site characteristics must be sufficiently defined to produce an accurately descriptive model."*	3	Appendix B
[8.1.3.3] Assessment Time Frames	*"The licensee or applicant shall ensure that future impact that may arise from the radioactive waste Includes the period of time during which the maximum impact is predicted to occur."*	2.2.4	Appendix A
[8.1.3.3] Assessment Time Frames	*"A rationale for the time frame associated with the safety assessment shall be given. The approach taken to determine respective periods of time used in the safety assessment should take into account the following elements:* • *Hazardous lifetime of the contaminants associated with the waste* • *Duration of the operational period (before the facility reaches its end state)* • *Design life of engineered barriers* • *Duration of both active and passive institutional controls* • *Frequency of natural events and human-induced environmental changes (e.g., seismic occurrence, flood, drought, glaciation, climate change)* • *The degree of protection and isolation required against inadvertent intrusion over the long term"* *"The licensee or applicant should document and justify the assumed performance time frames of engineered barriers and the evolution of their safety functions over time. Depending on the purpose of the assessment, it might be convenient to divide the overall time frame into several shorter time windows for modelling or presentational reasons. Different end points can also be used for different time windows."*	2.2.4	Appendix A

Section	Requirements (Quoted from REGDOC-2.11.1, Volume III, Version 2 (2021a))	Section of this Report	Appendix Material
[8.1.3] Post-closure Safety Assessment Scenarios and Time Frames	*"The licensee or applicant shall ensure that assessment scenarios are sufficiently comprehensive to account for all of the present and potential future states of the site and the biosphere.* *The safety assessment shall include a base case scenario of the normal, expected or anticipated evolution of the site and the disposal system over time, and additional scenarios that examine the potential impact of disruptive events with a low probability of occurrence."*	4.1	Appendix C Appendix D
[8.1.3] Post-closure Safety Assessment Scenarios and Time Frames	*"Each scenario presented in a safety assessment should include specific information about:* • *The timeframe on which the assessment is based* • *The length of time (start to finish) that institutional controls are relied upon as a safety feature* • *The identity and characteristics of the assumed receptors and critical groups."*	Scenarios, Models, Data: 4.1, 4.2, 4.3	Appendix C Appendix D Appendix E
[8.1.3] Post-closure Safety Assessment Scenarios and Time Frames	*"A safety assessment should present and justify the techniques and criteria used to develop the scenarios that are analyzed."*	Scenarios: 4.1 Model: 4.2	Appendix C Appendix D
[8.1.3] Post-closure Safety Assessment Scenarios and Time Frames	*"Scenarios should be developed in a systematic, transparent, and traceable manner through a structured analysis of relevant FEPs that are based on current and predicted future conditions of site characteristics, waste properties, and receptor characteristics and their lifestyles."*	Scenarios: 4.1 Model: 4.2	Appendix C Appendix D
[8.1.3] Post-closure Safety Assessment Scenarios and Time Frames	*"The approach to scenario development should be consistent with the rigour of the safety assessment, taking into consideration the purpose of the assessment, the hazards of the waste, and the nature of the decision for which the assessment is being undertaken."*	Scenarios: 4.1 Model: 4.2	Appendix C Appendix D
[8.1.3] Post-closure Safety Assessment Scenarios and Time Frames	*"For the demonstration of the robustness of a disposal system, the assessment should consider disruptive event scenarios in which the total or partial failure of one or several barriers or safety functions is assumed. These disruptive event scenarios should show that the safety of the overall disposal system is still valid."*	Scenarios: 4.1 Model: 4.2	Appendix C Appendix D

Section	Requirements (Quoted from REGDOC-2.11.1, Volume III, Version 2 (2021a))	Section of this Report	Appendix Material
[8.1.3] Post-closure Safety Assessment Scenarios and Time Frames	*""What if" scenarios should be used to exhibit the robustness and performance of various natural and engineered barriers under extreme conditions. It can be instructive to assign parameter values or other properties to parts of the barrier system such that the barrier under consideration is influenced in an exaggerated way. This may show that such exaggerated conditions are impractical, do not negatively impact safety or that they can be avoided by design."*	Scenarios: 4.1 Model: 4.2	Appendix C Appendix D
[8.1.3] Post-closure Safety Assessment Scenarios and Time Frames	*"The safety assessment should demonstrate that the set of scenarios developed is credible and comprehensive"* *"The approach and screening criteria used to exclude or include scenarios should be justified and well documented."*	Scenarios: 4.1 Model: 4.2	Appendix C Appendix D
[8.1.3.1] Normal Evolution Scenario	*"The licensee or applicant shall present a normal evolution scenario in the post-closure safety assessment. The normal evolution scenario should be based on reasonable extrapolation of current site features and receptor lifestyles. It should include expected evolution of the site and the degradation of the 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 post-closure safety assessment."*	Scenarios: 4.1 Model: 4.2	Appendix C Appendix D
[8.1.3.1] Normal Evolution Scenario	*"Depending on site-specific conditions and the time frame for the safety assessment, a normal evolution scenario should include expected conditions or events such as, earthquakes, climate shifts or the onset of glaciation. Similarly, periodic natural events such as floods or forest fires, if they are expected to occur during the time frame, should be part of the normal evolution scenario. These scenarios may be analyzed separately as variants of the normal evolution scenario.* *The decision about which natural events should be included is based on the assessment of FEPs and the probability of their occurrence within the time frame of the safety assessment."*	Scenarios: 4.1 Model: 4.2	Appendix C Appendix D
[8.1.3.1] Normal Evolution Scenario	*"Normal evolution scenarios should also take into account the failure modes of the containment and isolation systems."*	Scenarios: 4.1 Model: 4.2	Appendix C Appendix D

Section	Requirements (Quoted from REGDOC-2.11.1, Volume III, Version 2 (2021a))	Section of this Report	Appendix Material
[8.1.3.2] Disruptive Event Scenarios, Including Human Intrusion	*"The licensee or applicant shall postulate disruptive event scenarios leading to possible penetration of barriers and abnormal loss of containment."*	Scenarios: 4.1 Model: 4.2	Appendix C Appendix D
[8.1.3.2] Disruptive Event Scenarios, Including Human Intrusion	*"Assessments of human intrusion therefore needs to estimate the exposure of persons and the environment that would result from waste redistribution."*	Scenarios: 4.1 Model: 4.2	Appendix C Appendix D
[8.1.3.2] Disruptive Event Scenarios, Including Human Intrusion	*"Scenarios of inadvertent intrusion, where the intruder is not aware of the hazards of the waste, should estimate the exposure of the intruder. However, intentional human intrusion, where the intruder is assumed to be aware of the hazard of the waste, need not be considered."*	Scenarios: 4.1 Model: 4.2	Appendix C Appendix D
[8.1.3.2] Disruptive Event Scenarios, Including Human Intrusion	*"Scenarios for inadvertent intrusion should be case-specific, based on the class of waste and the design of the disposal system, and should consider both the probability of intrusion and its associated consequences."* *"Reasonable efforts should be made to limit the dose from a high-consequence intrusion scenario and to reduce the probability of the intrusion."*	Scenarios: 4.1 Model: 4.2	Appendix C Appendix D
[8.1.3.2] Disruptive Event Scenarios, Including Human Intrusion	*"For deep geological repositories – where the site characteristics, and the depth and the design of the facility have already been optimized to reduce the likelihood of the intrusion – the assessment results of human intrusion scenarios should be used for illustrative purposes. Scenarios concerning inadvertent human intrusion into such repositories could estimate doses that are greater than the regulatory limit. Such results should be interpreted in light of the degree of uncertainty associated with the assessment, the conservatism in the dose limit, and the likelihood of the intrusion. Both the likelihood and the consequences from the intrusion should therefore be reported."*	Scenarios: 4.1 Model: 4.2	Appendix C Appendix D
[8.1.3.2] Disruptive Event Scenarios, Including Human Intrusion	*"Reasonable efforts should be made to limit the dose from a high-consequence intrusion scenario and to reduce the probability of the intrusion."*	5.3	Appendix G

Section	Requirements (Quoted from REGDOC-2.11.1, Volume III, Version 2 (2021a))	Section of this Report	Appendix Material
[8.1.3.2] Disruptive Event Scenarios, Including Human Intrusion	*"Design modifications to reduce the likelihood of inadvertent intrusion should be undertaken."*	3.1 5.3	Appendix B Appendix G
[7.9] Institutional Controls	*"The licensee or applicant shall identify the role that institutional controls play in disposal facility safety, and how that role is taken into account in the safety case and its supporting safety assessment."*	Scenarios, Models, Data: 4.1, 4.2, 4.3 Results: 5	Appendix C Appendix D Appendix E Appendix G
[7.9] Institutional Controls	*"While long-term safety of the disposal facility should not be dependent on institutional controls, these should be used to the extent practicable to confirm that the disposal system is performing as designed."* *"Given the uncertainties associated with future human activities and the evolution and stability of societies, licensees or applicants should limit reliance on institutional control as a safety feature to a few hundred years."* *"Reliance on such longer-term institutional control (beyond a few hundred years) should be justified in the safety case through an optimization process taking into account technical and socio-economic factors."*	Scenarios, Models, Data: 4.1, 4.2, 4.3 Results: 5	Appendix C Appendix D Appendix E Appendix G
[8.1.1.3] Assessment End Points	*"The licensee or applicant shall develop scenarios to include the identification of human and environmental receptors that may be exposed to radioactive and hazardous substances."*	4.1 & 4.2 *For Non-Human Biota (NHB), see Arcadis, 2020b*	Appendix C Appendix D Appendix E.2 *For NHB, see Arcadis, 2020b*
[8.1.1.3] Assessment End Points	*"Human and environmental receptors should be identified based on the guidance of CSA N288.1, Guidelines for Calculating Derived Release Limits for Radioactive Material in Airborne and Liquid Effluents for Normal Operations, and CSA N288.6, Environmental Risk Assessment for Class I Facilities and Uranium Mines and Mills."*	4.1, 4.2, 4.3	Appendix D Appendix E

Section	Requirements (Quoted from REGDOC-2.11.1, Volume III, Version 2 (2021a))	Section of this Report	Appendix Material
[8.1.1.3] Assessment End Points	*"The exposures of persons and the various receptor organisms can occur by different pathways and will be judged by different acceptance criteria even when all receptors are present in the same environment at the same time."* *"IAEA-TECDOC-1077, Critical Groups and Biospheres in the Context of Radioactive Waste Disposal, provides guidance for assessing exposures to critical groups throughout the time frame of the normal evolution scenario. For long time frames, the proponent may elect to use a reference biosphere for the critical group. Additional guidance on the use of reference biospheres can be found in the 2003 IAEA's BIOMASS-6, Reference Biospheres for Solid Radioactive Waste Disposal."*	*For NHB, see Arcadis, 2020b* *For human receptors, 2.2*	*For NHB, see Arcadis, 2020b* *For human receptors, Appendix A*
[8.1.3.1] Normal Evolution Scenario	*"The safety assessment should model the biosphere, which will be the receiving environment for the contaminants, based as much as possible on the site-specific information in the system description. Alternatively, when-site specific information is not adequate to make reasonable or conservative extrapolations from the characteristics of the current biosphere, a stylized approach to defining the biosphere may meet the purpose of the safety assessment."*	4.1 & 4.2	Appendix D Appendix E
[8.1.4] Development and Use of Assessment Models	*"The licensee or applicant should develop a conceptual model, which is a representation of the behaviour of the disposal system that includes the description of the components of the system and the interactions between these components. It should also include a set of assumptions concerning the geometry of the system and the chemical, physical, biological, mechanical and geological behavior of the facility or activity, consistent with the information and knowledge available."*	4.2 & 4.3	Appendix E
[8.1.4] Development and Use of Assessment Models	*"The level of accuracy needed in the post-closure safety assessment models, and the degree of conservatism desired in the results, are determined by:* • *The purpose of the safety assessment* • *The importance of the model results with respect to indicating expected performance and safety"*	4.2 & 4.3	Appendix E Appendix F

Section	Requirements (Quoted from REGDOC-2.11.1, Volume III, Version 2 (2021a))	Section of this Report	Appendix Material
[8.1.2] Disposal System Description	*"As licensing progresses through the facility's lifecycle, as-built information and operational data are acquired. Both of these sources of information will enhance the understanding of the site characteristics. It is expected that safety assessments that are made later in the facility's lifecycle will be based on updated and refined models and data. There should be less reliance on default, generic or assumed information, resulting in more reliable model results."*	4.2 & 4.3	Appendix E Appendix F
[8.1.4] Development and Use of Assessment Models	*"In developing assessment models, the licensee or applicant should employ a variety of computational tools (conceptual and mathematical models) to predict future conditions for comparison to acceptance criteria."* *"The conceptual models of the site and the disposal system often need to be simplified to correspond to the limitations of the mathematical equations and the capabilities of computer models. A mathematical model is a representation of the features and processes included in the conceptual model in the form of mathematical equations."*	4.1, 4.2, 4.3, 4.4	Appendix E Appendix F
[8.1.4.2] Confidence in Computing Tools	*"The licensee or applicant should ensure that computer programs are suitable for the given assessment; these may include commercially available software packages or software specifically developed for the assessment in question."* *"The computer software used for assessment calculations should be qualified in accordance with applicable standards."*	2.3	Appendix F
[8.1.4.2] Confidence in Computing Tools	*"Calibration of computer models and verification and validation of software are the main processes involved in software quality assurance."*	QA: 2.3	Appendix E (data QA) Appendix F (equations QA)
[8.1.4.2] Confidence in Computing Tools	*"The licensee or applicant should verify and validate all computer software used for the safety assessment or provide reference to existing validation."*	2.3	Appendix E (data QA) Appendix F (equations QA)

Section	Requirements (Quoted from REGDOC-2.11.1, Volume III, Version 2 (2021a))	Section of this Report	Appendix Material
[8.1.4.1] Confidence in Safety Assessment Models	*"The licensee or applicant should ensure that safety assessment models are fit for purpose. The input parameters, the scenarios analyzed, and the results should be shown to be consistent with the assumptions and limitations of the model."* *"The licensee or applicant should keep records of how site-specific and system-specific characterization data have been used to derive input parameters."*	2.3 (ISO Certified)	Appendix E (data QA) Appendix F (equations QA)
[8.1.4.1] Confidence in Safety Assessment Models	*"The safety assessment model evaluation process should concentrate on identifying and understanding the key radiological, physical, chemical and biological processes that are important to safety at the various spatial and temporal scales of concern in the safety assessment."*	2.3 2.2.5 (multi-variate sensitivity analyses) 5	Appendix E (data QA) Appendix F (equations QA) Appendix G (results and sensitivity analyses)
[8.1.4.1] Confidence in Safety Assessment Models	*"Model evaluation should include sensitivity analyses to show whether the model output responds as expected to variations in the model input parameter. Model evaluation should also include uncertainty and importance analyses to show which parameters control the variability in model output. These analyses should demonstrate how well the model replicates what is known and understood about the processes being simulated. The results obtained from these analyses should be shown to conform to the limitations and restrictions of the assumptions in the safety assessment model."*	2.2.5 (multi-variate sensitivity analyses) 5	Appendix G (results and sensitivity analyses)
[8.1.4.1] Confidence in Safety Assessment Models	*"The need to evaluate the uncertainty in the safety assessment models is determined by the level of confidence needed in the modelling results. The acceptable level of confidence is governed by the purpose of the safety assessment, the safety factor built into the acceptance criteria for safety indicators, and the importance of the safety assessment model results to the safety case."*	4.2	Appendix F

Section	Requirements (Quoted from REGDOC-2.11.1, Volume III, Version 2 (2021a))	Section of this Report	Appendix Material
[8.1.5] Interpretation of Results	*"When interpreting the safety assessment results, the applicant should demonstrate a thorough understanding of the underlying science and engineering principles that are controlling the safety assessment results. Interpretation should include evaluation of compliance with the acceptance criteria and analysis of the uncertainties associated with the safety assessment."*	5, 6	Appendix G
[8.1.5] Interpretation of Results	*"The results of the safety assessment should also be analyzed to show consistency with system performance expectations and with the complete set of assumptions and simplifications used in developing the models and scenarios. Any unexpected results or discrepancies should be documented, investigated and explained."*	5, 6	Appendix G
[8.1.5.1] Comparing Safety Assessment Results with Acceptance Criteria	*"Comparison of the safety assessment results with acceptance criteria should include discussion of the conservatism of the model results, and the conservatism built into the acceptance criteria for the assessment end points."* *"If the safety assessment results do not demonstrate compliance with the acceptance criteria, the safety assessment shall be revised. Sufficient detail should be provided to enable the CNSC to verify the results."*	5, 6	Appendix G
[8.1.5.2] Analyzing Uncertainties	*"It is expected that the comparison between the safety assessment end points and the acceptance criteria will explicitly take the uncertainty in the safety assessment into account, as follows:* *1. For deterministic assessments, the range of uncertainty in the calculated result as determined by a sensitivity analysis (or importance analysis) is expected to be explicitly included in the comparison* *2. For probabilistic assessments, the likelihood of exceeding the acceptance criteria should be determined from the calculated results distribution; if the range of safety assessment results from deterministic uncertainty analysis or from the probabilistic results distribution shows that part of the results may exceed the acceptance criteria, the applicant should demonstrate that these results will not represent unreasonable risk to the environment or to the health and safety of persons, taking into account the conservatism built into the safety assessment calculations and the likelihood of the circumstances leading to these results."*	5, 6 2.2.5 (multi-variate sensitivity analyses)	Appendix G

Section	Requirements (Quoted from REGDOC-2.11.1, Volume III, Version 2 (2021a))	Section of this Report	Appendix Material
[8.1.5.2] Analyzing Uncertainties	*"An uncertainty analysis of the assessment results should be performed to identify the sources and significance of uncertainty. This analysis should distinguish between uncertainties arising from:* • *Input data or parameters* • *Scenario assumptions* • *The imprecision in the mathematical model* • *The conceptual models"*	4.1, 4.3, 5 2.2.5 (multi-variate sensitivity analyses)	Appendix D Appendix E (uncertainty discussions for models and all parameters) Appendix G (results of sensitivity analyses)

A 3.2 Acceptance Criteria

Radionuclides

Acceptance criteria are derived from current regulatory limits, standards, objectives, and benchmarks, where appropriate applying an additional margin of safety, such as a dose criterion. In light of the Canadian regulatory requirements and guidance and international standards and guidance from organizations such as the International Commission on Radiological Protection (ICRP), specific criteria have been proposed for:

- The radiation exposure of people that may arise from the expected evolution of the NPDDF and its environment, referred to as the Normal Evolution scenario;
- The radiation exposure of people that may arise as a result of events with uncertain or low probability which could disrupt the NPDDF, Disruptive Event scenarios;
- The radiation effects on non-human biota; and
- The effects of non-radioactive contaminants.

In addition to Normal Evolution and Disruptive Event scenarios, illustrative calculations are also made for a range of other cases that are used to explore the performance of the NPDDF in the light of underlying uncertainties. One category of calculations, "What If" cases, make deliberately extreme assumptions so as to understand the limits of safety performance. These are not compared with any criteria because they are extremely unlikely, and in some cases implausible.

Human health criteria have been defined according to CNSC REGDOC-2.11.1, Volume III, Version 2 (CNSC, 2021a) which requires reasonable assurance that:

- the regulatory radiological dose limit for public exposure (1 mSv y^{-1}) will not be exceeded;
- the possibility of exposure to multiple sources is allowed for; and
- doses are As Low as Reasonably Achievable (ALARA).

The criteria used in the safety assessment are based on those presented in the Project Description (CNL, 2016) and are consistent the ICRP's 2007 recommendations (ICRP, 2007) and with specific guidance on radioactive waste disposal (ICRP, 2013; IAEA, 2014; IAEA, 2011). They also draw on those proposed in relation to Ontario Power Generation's proposed Deep Geological Repository for low and intermediate level radioactive waste (Quintessa *et al.*, 2011).

- The criterion used for public radiological exposure as a result of the Normal Evolution scenario is that the dose to the public and to workers will be ALARA and subject to a dose constraint of 0.25 mSv y^{-1}.
- A tiered approach is adopted for Disruptive Event scenarios, recognising their speculative nature. The probability of exposure is considered during the scenario definition process; very low probability provides a basis for screening scenarios from detailed assessment. A dose criterion of 1 mSv y^{-1} is then used for radiation exposure of humans for unlikely but credible scenarios. If calculated dose exceeds 1 mSv y^{-1}, the scenario is examined on a case-by-case basis, taking into

account the likelihood and nature of the exposure, conservatism and uncertainty in the assessment, and conservatism in the dose rate criterion. If the probability of exposure can be quantified, a reference health risk criterion of $\leq 10^{-5}$ y^{-1} (ICRP, 2013; IAEA, 2011) can be used.

Site Investigation (Inadvertent human intrusion) and Excavation of Above-Bedrock Facility are special cases of Disruptive Event scenarios that are assessed separately. Reasonable efforts should be made to limit the dose from a high-consequence intrusion scenario and to reduce the probability of the intrusion occurring (NSC, 2021a). In this respect, the in-situ disposal concept would encase all parts of the NPDDF within concrete and cover the nuclear area footprint with a reinforced concrete cap. This provides a substantial deterrent and limits the range of situations that could lead to intrusion. An engineered barrier will then be placed over the entire grouted Facility to minimize infiltration.

The PostSA also considers the potential impacts on non-human species to ensure these are within acceptable limits; though potential radiological impacts on non-human biota are assessed in a separate Ecological Risk Assessment report (Arcadis, 2020b), drawing on guidance and recommendations from CSA N288.6 and CSA N288.1 standards. The radiation dose rate criterion for terrestrial biota is 100 µGy h^{-1} (2.4 mGy/d) and for aquatic biota is 400 µGy h^{-1} (9.6 mGy/d). These benchmarks were adjusted by a factor of 1/10 for terrestrial and aquatic species at risk.

Non-Radiological Contaminants

Potential impacts from non-radioactive elements or chemical species are assessed for environmental media that are relevant to human health and environmental protection. The environmental quality standard criteria for soil, sediment and water are designed to protect against adverse effects due to exposure by food chain and/or other pathways. The criteria for non-radioactive elements or chemical species are based on federal and provincial guideline concentrations for groundwater, surface water, soil and sediment and are presented in Table A-2. As noted in the main report (Sections 4.3 and 6.5), only lead (Pb) is of potential concern for the NPDDF PostSA.

A tiered approach is applied to the assessment of non-radioactive contaminants. Contaminants are screened first based on a comparison with the criteria given above. If any criteria are exceeded under the Normal Evolution Scenario, these species will be assessed further using more realistic models. If any concentrations exceed the criteria under Disruptive Event scenarios, then the acceptability is judged on a case-by-case basis taking into account the likelihood and nature of the exposure, uncertainty in the assessment, and conservatism in the criteria.

Table A-2 Criteria for Non-Radiological Contaminants

Species	Groundwater (µg/L)	Ref.	Soil (µg/g)	Ref.	Surface Water (µg/L)	Ref.	Sediment (µg/g)	Note
Pb	1.9	A	45	A	1	**B**	31	A

A ‘Full depth background site condition standard’ (Table 1) for Ontario from MOE (2011); soil standard for agricultural land use.

B Lowest Provincial Water Quality Objective (PWQO)/Interim PWQO conservatively adopted from OMOEE (1994).

A 3.3 End Points

Assessment end points are the calculation results used to assess the impact of the radiological and non-radiological releases. In order to demonstrate that the postclosure acceptance criteria can be achieved, the following end points are calculated:

- Peak radiation dose rate to adults, children and infants in the critical group and to non-human biota;
- Peak environmental concentrations of radionuclides; and
- Peak environmental concentrations of non-radioactive hazardous substances.

“Radiation dose rate” includes the contribution of external irradiation and the committed effective dose rate equivalent from intakes of radionuclides by ingestion and inhalation. Dermal absorption is also considered in the special case of immersion in water containing tritium.

The focus is on the parts of the environment that are expected to receive the highest concentrations of contaminants released from the Facility, i.e., within a few hundred metres of it. Potential effects beyond this will be substantially lower as contaminants are diluted and dispersed.

In addition, the various results are useful performance indicators which can help to show the way in which the system is behaving. These include:

- Contaminant amounts within various media (e.g., the NPDDF structure, the surrounding rock, surface media) on various timescales; and
- Fluxes of contaminants at various points in the NPDDF and surrounding materials.

To demonstrate barrier robustness and the performance of the facility during the post-closure period, additional facility endpoints are derived:

- Comparison of radiotoxicity concentrations in the environment, due to releases from the facility, to natural background radiotoxicity concentrations at the NPD site;
- Comparison of radiotoxicity concentrations in soil, due to releases from the facility, to naturally occurring surficial uranium ore deposits in the region;
- Comparison of radionuclide concentration in the environment, due to releases from the facility, to environmental limits where available (e.g. tritium); and
- Comparison of concentrations of mobile radionuclides (e.g., Cl-36, tritium, C-14) to background levels, where data are available from the NPD EIS (Arcadis, 2020a).

A 3.4 Assessment Timeframe

According to REGDOC 2.11.1, Volume III, Version 2 (CNSC, 2021a):

> "*The licensee or applicant shall ensure that future impact that may arise from the radioactive waste includes the period of time during which the maximum impact is predicted to occur."*

This period is referred to as the assessment timeframe. This sub-section of the report develops the assessment timeframe based on:

- Peak dose rate results from the first three (3) iterations of the PostSA; and
- Additional considerations from REGDOC 2.11.1, Volume III, Version 2 (CNSC, 2021a).

A.3.4.1 Peak Dose Rate & Prior PostSA Iterations

1st Iteration PostSA

The 1st Iteration PostSA (Arcadis & Quintessa, 2017a) selected its assessment timeframe based on the anticipated timing of the next glacial event. This provided an upper limit on the period that the PostSA can reasonably cover because the NPDDF and its environment would be substantially disturbed by the resulting ice-sheet, in a way that means subsequent dose calculations are highly uncertain. Based on information such as that presented by Ganopolski *et al*. (2016) the next ice age was estimated not to occur for 100,000 y as a result of anthropogenic climate change. Therefore, 100,000 y was used as the assessment timeframe for the 1st iteration PostSA (Arcadis & Quintessa, 2017a). The results of the 1st Iteration PostSA (Arcadis & Quintessa, 2017a) showed that the estimated peak dose rate for the Normal Evolution Scenario (NES) was 0.0001 mSv/y, to the adult site resident, occurring at approximately 13,000 y past closure.

2nd Iteration PostSA

The 2nd Iteration PostSA (Arcadis & Quintessa, 2017b) selected its assessment timeframe by accounting for:

- the dose rate results of the 1st iteration (Arcadis & Quintessa, 2017a); the timing of the next ice age (100,000 y, based on Ganopolski *et al*. (2016));
- the timeframes considered for postclosure assessments of near-surface disposal facilities (between 10,000 and 100,000 y, based on Hoorelbeke & Thabet (2016)); and,
- findings from the 1st iteration PostSA (Arcadis & Quintessa, 2017a) regarding the performance of the engineered barriers (indicating a range from tens-of-thousands of years to beyond 100,000 y).

Overall, the 2nd iteration PostSA (Arcadis & Quintessa, 2017b) selected an assessment timeframe of 50,000 y though results were calculated out to 100,000 y to demonstrate that the peak dose rate had in fact been captured.

The 2nd Iteration PostSA (Arcadis & Quintessa, 2017b) also included several refinements to the model and its parameter values. The results of the 2nd Iteration PostSA (Arcadis & Quintessa, 2017b) showed that the estimated peak dose rate for the NES was 0.0001 mSv/y, occurring very early at approximately 1,200 y past closure.

3rd Iteration PostSA

The 3rd Iteration PostSA (Arcadis & Quintessa, 2020b) selected its assessment timeframe by accounting for:

- peak dose results, and the time(s) of these peak doses, from the 1st and 2nd iteration PostSAs (Arcadis & Quintessa, 2017a); and,
- the additional considerations outlined in CNSC REGDOC 2.11.1 Volume III (CNSC, 2018), i.e., hazardous lifetime of contaminants in the waste; duration of operational period; design life of engineered barriers; the planned duration of institutional controls; and the frequency of natural events and human-induced environmental changes.

Accounting for these factors, the 3rd Iteration PostSA (Arcadis & Quintessa, 2020b) selected an assessment timeframe of the first 10,000 y post-closure. The 3rd Iteration PostSA's (Arcadis & Quintessa, 2020b) NES results indicated a peak dose of 0.0003 mSv/y, to the site resident receptor, occurring at 1,100 y post-closure.

4th Iteration PostSA

This 4th iteration of the PostSA similarly selects the assessment timeframe by accounting for the results of previous iterations and by considering the topics outlined in CNSC REGDOC 2.11.1 Volume III, Version 2 (CNSC, 2021a).

For all scenarios, peak doses in the 3rd iteration PostSA (Arcadis & Quintessa, 2020b) occur within the first 10,000 y post-closure. Many occur within even the first 1,100 y post-closure. The 3rd Iteration PostSA's (Arcadis & Quintessa, 2020b) estimated peak dose rate for the NES (0.0003 mSv/y) is much less than the dose rate criterion (0.25 mSv/y). Therefore, based on the results of previous iterations, an assessment timeframe focusing on the first 10,000 y post-closure continues to be a reasonable choice for the 4th Iteration PostSA.

After the 4th iteration PostSA was completed, it became clear that the peak dose of the Normal Evolution Scenario in the 4th iteration occurs around 12,000 years. However, the assessment timeframe of 10,000 years was not changed in the 4th iteration for the reasons given below.

The timeframe of 10,000 years was selected *a-priori* largely based on the results of the 3rd iteration PostSA, where peak doses occurred relatively early at less than 5,000 years post-closure. However, in the 4th iteration, changes were made to the C-14 dose model for animals in order to remove overly conservative assumptions (i.e., C-14 concentrations in animal products were previously determined mainly by the C-14 concentrations in animal drinking water). Due to this change, peak dose appears at about 12,000 years for the Normal Evolution Scenario (NES), because the lower C-14 dose rates make Cl-36 the dominant dose contributor in the NES. However, given the similarity in dose at 10,000 and 12,000 years and the similarity between the selected timeframe and the time of the peak dose in the NES, the assessment timeframe of 10,000 years was not changed. Furthermore, dose rates are calculated for times up to 100,000 years in the PostSA. It should also be noted that for less conservative scenarios and sensitivity cases, calculated peak doses occur at much earlier times than in the NES (at about 2,500 years). Finally, the effects of seismic events are assumed to occur at 1000 years.

Consideration of other factors outlined in CNSC REGDOC 2.11.1 Volume III, Version 2 (CNSC, 2021a) are discussed below.

A.3.4.2 Additional Considerations from REGDOC-2.11.1, Volume III, Version 2 (CNSC, 2021a)

For the 3rd Iteration PostSA (Arcadis & Quintessa, 2020b), the assessment timeframe was selected to be 10,000 y, informed not only by peak dose rate and information from prior iterations (as discussed above), but also by additional guidance from REGDOC 2.11.1, Volume III (CNSC, 2018). This 4th Iteration PostSA is consistent with the most recent guidance in REGDOC 2.11.1 Vol III, Version 2 (CNSC, 2021a). As outlined in REGDOC 2.11.1, Volume III, Version 2 (CNSC, 2021a):

> *"A rationale for the timeframe associated with the safety assessment shall be given. The approach taken to determine respective periods of time used in the safety assessment should take into account the following elements:*
>
> 1. *Hazardous lifetime of the contaminants associated with the waste;*
> 2. *Duration of the operational period (before the disposal facility reaches its end state);*
> 3. *Design life of engineered barriers;*
> 4. *Duration of both active and passive institutional controls;*
> 5. *Frequency of natural events and human-induced environmental changes (e.g., seismic occurrence, flood, drought, glaciation, climate change); and*
> 6. *The degree of protection and isolation required against inadvertent intrusion over the long term."*

For this 4th Iteration PostSA, the same assessment timeframe is selected, informed by the same information from prior iterations and the additional guidance from REGDOC 2.11.1, Volume III, Version 2 (CNSC, 2021a).

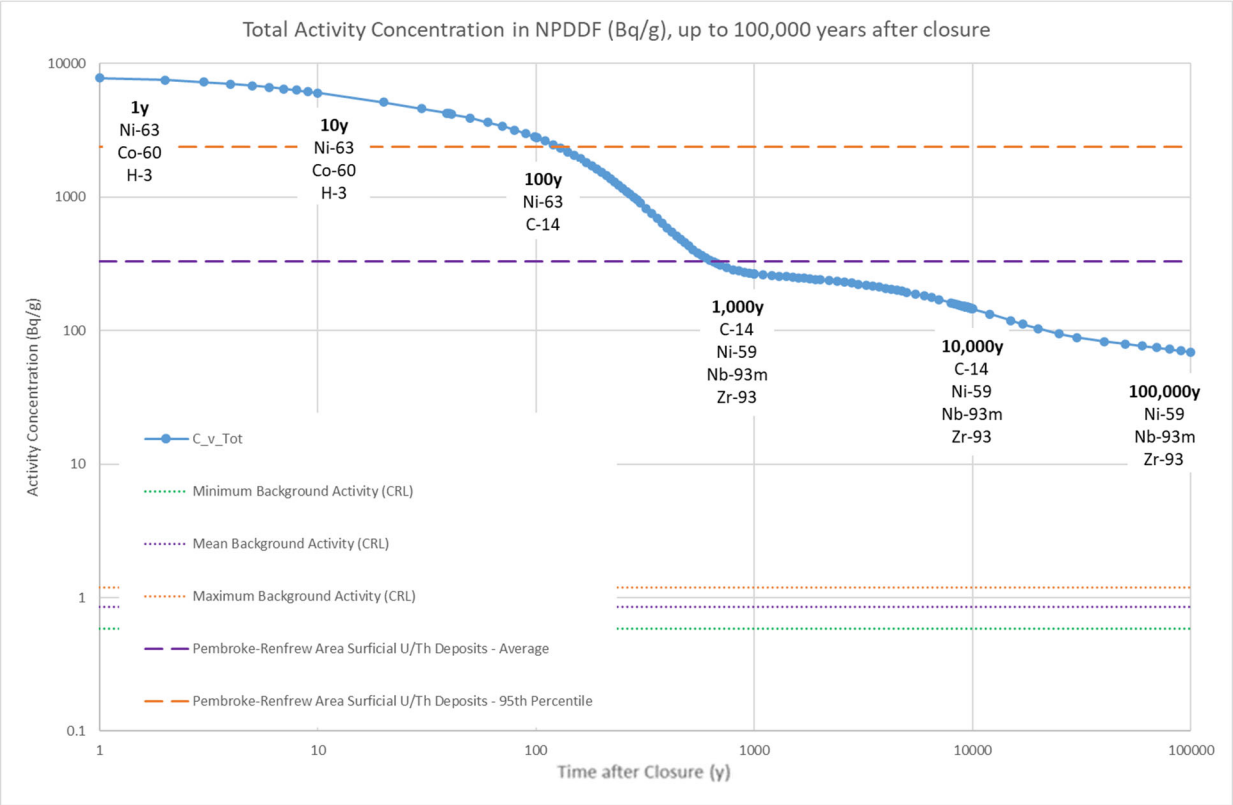
Each of these aspects are discussed below in regard to the assessment timeframe.

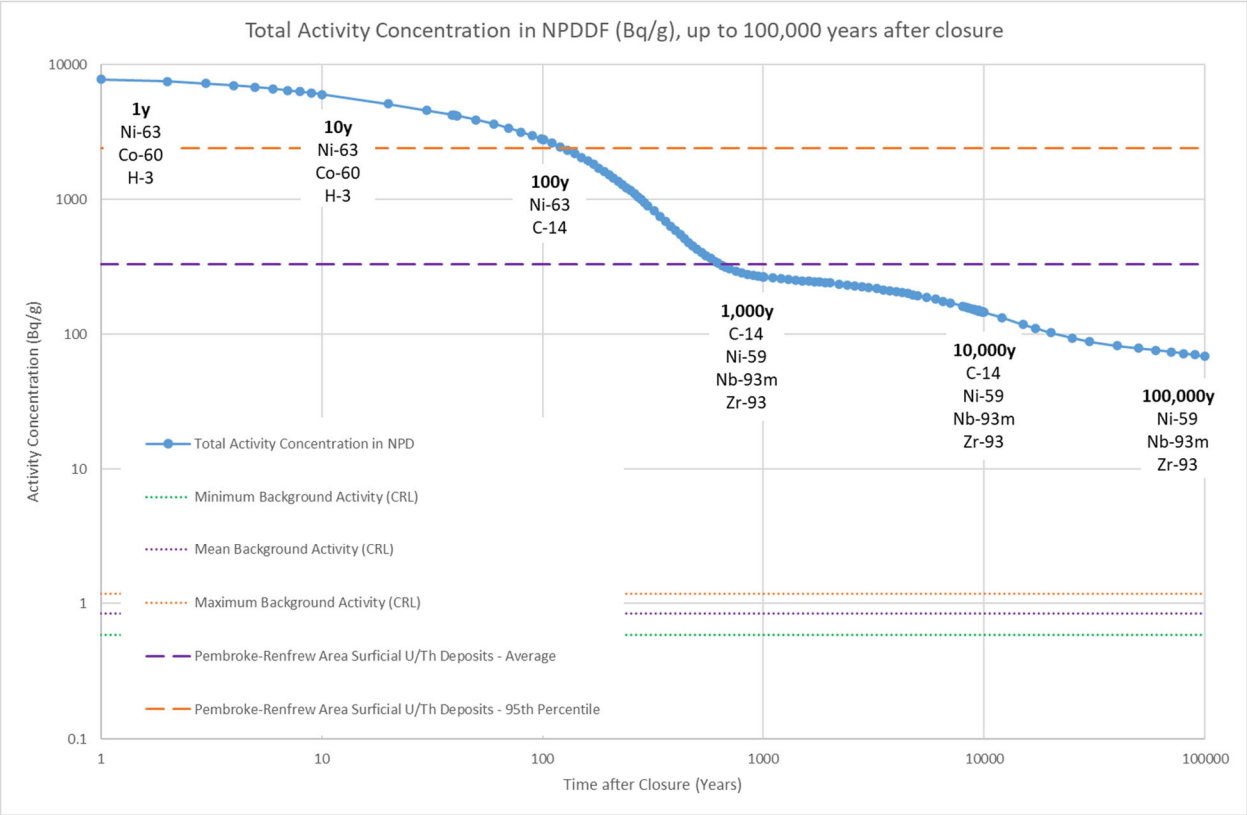
- **1st Aspect: Hazardous lifetime of the contaminants associated with the waste**

Radioactive Contaminants

Most radionuclides within the NPDDF will decay and decrease with time. Some have radioactive progeny that will increase in time due to ingrowth, but this is a small portion of the inventory. Figure A-2 below, provides a comparison of the total activity concentration of NPDDF to background levels at CRL (CNL, 2017a) and to local mineral deposits (average and 95th percentile of values in OGS (1981)). The NPDDF is located within the same region as these comparison sites (approximately 30 km from Chalk River, 60 km from Pembroke, and 100 km from Renfrew) and has similar environmental conditions. Details on the radionuclide inventory are available in Appendix E.

Figure A-2 Total Activity Concentration in NPD Compared to CRL Background Levels (CNL, 2017a) and Local Mineral Deposits (OGS, 1981)



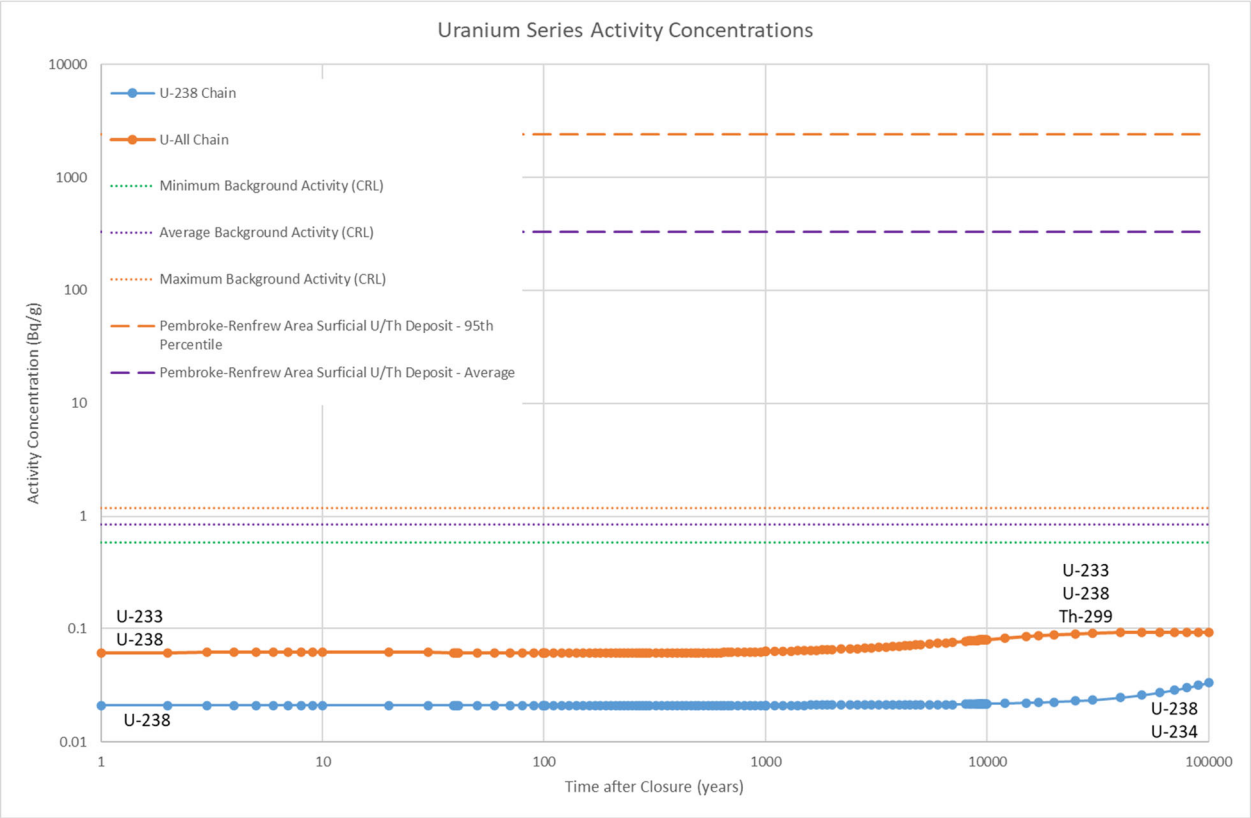


Notes:
Pembroke-Renfrew area surficial deposits concentrations are derived from (OGS, 1981).
Activity of surficial deposit assumes that U-238 is in equilibrium with U-234 and Ra-226.
CRL background activities are obtained from CNL (2017a).
Radionuclides listed represent the radionuclides contributing more than 10% of the total activity at that time.
See Appendix E for further details on the radionuclide inventory.

Figure A-2 shows that the total activity concentrations of the NPDDF is less than the 95th percentile of values characteristic of local uranium mineral deposits (OGS, 1981) 150 y after closure of the facility. The comparison also shows that within approximately 1000 y the total activity concentration of the NPDDF will decay to be comparable to the average activity concentration recorded at local uranium mineral deposits (OPG, 1981).

It is acknowledged that comparing the facility inventory to these surficial uranium bodies is not in-and-of-itself a complete assessment, due to important differences in the radionuclides present, and due to the fact that activity alone is not the resulting hazard. However, it does form part of the rationale because the comparison does provide important perspective on the NPDDF inventory. So, for perspective, Figure A-3 uses the same time period but presents the total activity of uranium isotopes and their decay products in the NPDDF inventory.

Figure A-3 Activity Concentration of Uranium Isotopes (and decay products) in NPD Compared to CRL Background Levels (CNL, 2017a) and Local Mineral Deposits (OGS, 1981)



For additional perspective, Arcadis & Quintessa (2020a) performed a dose comparison between the NPD facility inventory and an inventory equivalent to that of the Pembroke-Renfrew near-surface uranium ore bodies. Arcadis & Quintessa (2020a) found that the peak dose from the NPD facility inventory was far less than the peak dose associated with the near-surface uranium ore bodies inventory. Whilst total concentrations of radionuclides in the biosphere are of a similar order of magnitude for the shallow and surface uranium ore deposits and their corresponding cases for the NPDDF, the radionuclides in the biosphere are different. For the uranium ore cases, radionuclides in the biosphere have dose coefficients up to 3 orders of magnitude higher than the radionuclides which lead to doses for the NPDDF. This is the main reason for higher doses in the uranium ore calculations. For details, the reader is referred to Arcadis & Quintessa (2020a).

Finally, in order to gain a more complete understanding, dose rate and the time of peak dose rate were examined as indicators of the hazardous lifetime of the facility (see earlier discussions for details). As mentioned earlier, the 3rd Iteration PostSA (Arcadis & Quintessa, 2020b) calculated dose rates over time and showed that peak dose rate for Normal Evolution (0.0003 mSv/y) occurs very early, within the first 1,100 y.

Non-Radioactive Contaminants

For this 4th iteration PostSA, the non-radiological hazardous contaminants include lead (Pb), as was the case for the 3rd Iteration. Polychlorinated biphenyls (PCBs) were included in first two iterations but now will be removed from the facility before or during decommissioning. Therefore, since PCBs will no longer be present at closure, they do not warrant inclusion in this assessment.

Mercury was assessed in the 2nd Iteration PostSA (Arcadis & Quintessa, 2017b), which concluded that mercury is contained within the NPDDF for the whole assessment timeframe, and, that mercury shows negligible releases and environmental concentrations (less than 10^{-10} mg/L (Arcadis & Quintessa, 2017b)). For that reason, the 3rd Iteration PostSA (Arcadis & Quintessa, 2020b) did not consider mercury. The same approach is followed in this 4th Iteration PostSA.

Lead was also assessed in the 2nd Iteration PostSA (Arcadis & Quintessa, 2017b), which concluded that lead would be released from the facility to groundwater, over time. Within the assessment timeframe of the 2nd iteration PostSA (Arcadis & Quintessa, 2017b), the peak lead concentration in groundwater was calculated to be 0.0009 mg/L, occurring very early at 850 y past closure. This is less than the benchmark values from Health Canada for potable groundwater (i.e., 0.005 mg/L; HC, 2019). Beyond the assessment timeframe of the 2nd iteration PostSA (Arcadis & Quintessa, 2017b), peak lead concentrations in groundwater were calculated to be 0.005 mg/L, occurring in the far future (approximately 100,000 y past closure). However, it is important to note that estimates for such a long time period are subject to great uncertainties. Furthermore, the model used was very conservative and did not fully reflect the actual storage conditions. Following the refinements to the model a Human Health Risk Assessment would have been produced if the lead concentrations remained high enough to warrant further assessment.

The 3rd iteration PostSA included additional refinements to model and control the release of lead, which are retained for the 4th iteration PostSA. More detailed information on the quantity, location, form, and geometry of lead has been incorporated. Lead solubility was also taken into account, along with any encapsulation and related corrosion-dependent releases. It was shown that there is very little transport of non-radioactive lead because of the high sorption of the contaminant, and its very limited solubility within the BFS/PC grout. Lead concentrations in the geosphere groundwater were less than 3.4×10^{-6} mg l^{-1}. This is well below the Environmental Quality Standard (EQS) (0.0019 mg l^{-1}), and the Ontario Ministry of Environment (MOE) Generic Site Condition Standards for groundwater (0.01 – 0.02 mg l^{-1}). It is also below other guidance such as Health Canada drinking water guidelines (0.01 mg l^{-1}). The peak concentration of lead in surface water (river) was extremely small at 7×10^{-11} mg l^{-1}, compared with the EQS of 0.001 mg l^{-1}. The highest concentration of lead in soil was 0.04 mg kg^{-1} in the cap, much lower than the EQS of 45 mg kg^{-1} for soil. Similar concentrations are also found in the garden soil (0.008 mg kg^{-1}) and river sediment (0.0002 mg kg^{-1}) on longer timeframes. The EQS for sediment is 31 mg kg^{-1}.

The same applies for this 4th iteration PostSA.

Therefore:

Peak Dose:

Peak dose rate results from the 2nd and 3rd Iterations PostSA are 0.0001 mSv/y and 0.0003 mSv/y, occurring at 1,200 and 1,100 y past closure (Arcadis & Quintessa, 2017b, 2020b), respectively. Based on this, the assessment timeframe should extend at least 1,200 y past closure so as to encompass the time of peak dose rate.

Radionuclides:

Based on the decrease of the hazard with time, an assessment timeframe of 10,000 y encompasses the time required for the NPDDF to experience total activity decay to well below the activity concentrations associated with the Pembroke-Renfrew uranium surface deposits.

Non-Radiological Contaminants

Results of the 2nd and 3rd Iterations PostSA (Arcadis & Quintessa, 2017b; 2020b) indicate that the groundwater concentrations of released non-radioactive contaminants (lead and mercury) were less than their corresponding benchmarks, within the assessment timeframe.

- **2nd Aspect: Duration of the operational period (before the facility reaches its end state);**

The NPD Facility was constructed between 1956 and 1961. It began operation in 1962 and was permanently shut down in 1987. It then entered a three-phase decommissioning plan.

Phase I was complete in the early 1990's, which brought the facility to a safe and sustainable shutdown state referred to as Storage with Surveillance (SwS). This included for example: draining the primary heat transport and moderator systems of heavy water and de-fueling the reactor, with the resulting materials being transferred off-site; removal of the demineralizer system equipment and other nuclear process systems from the site; shutdown and draining of all redundant process systems and disconnecting of all services with the exception of those required for the SwS state; and, decontamination of structures, systems and equipment when required (Arcadis & Quintessa, 2020b).

Phase II followed, in which the facility remained in the established Storage with Surveillance State from the early 1990's until now (the facility presently continues to exist in its SwS state as it is being prepared for Phase III final decommissioning). Overall, the facility has undergone approximately 30 y of storage and surveillance, and much information relevant to post-closure performance has been obtained on the system during this time, such as measurements of water ingress to the building structure.

This 4th Iteration PostSA is to support CNL's licence application for the NPDDF to enter the final Phase III of its decommissioning. Within Phase III the facility is anticipated to be in an active decommissioning state (operations) for 1 to 2 y, which is assumed in approximately 2026. Following this, the facility will be fully closed (assumed to be in approximately 2028) and will then enter an institutional control period of at least 100 y (this is discussed further as part of the 4th Aspect).

Therefore: The decommissioning (operation) period is small, spanning only 1 to 2 y compared to approximately 30 y of post-shutdown storage and surveillance and a planned institutional control period of at least 100 y. The Postclosure time period will begin approximately at the year 2028.

- **3rd Aspect: Design life of engineered barriers;**

  The engineered barriers in the system are:

  - The waste form;
  - The concrete cap and earthen cover;
  - The existing facility structure (concrete); and,
  - The grout backfill.

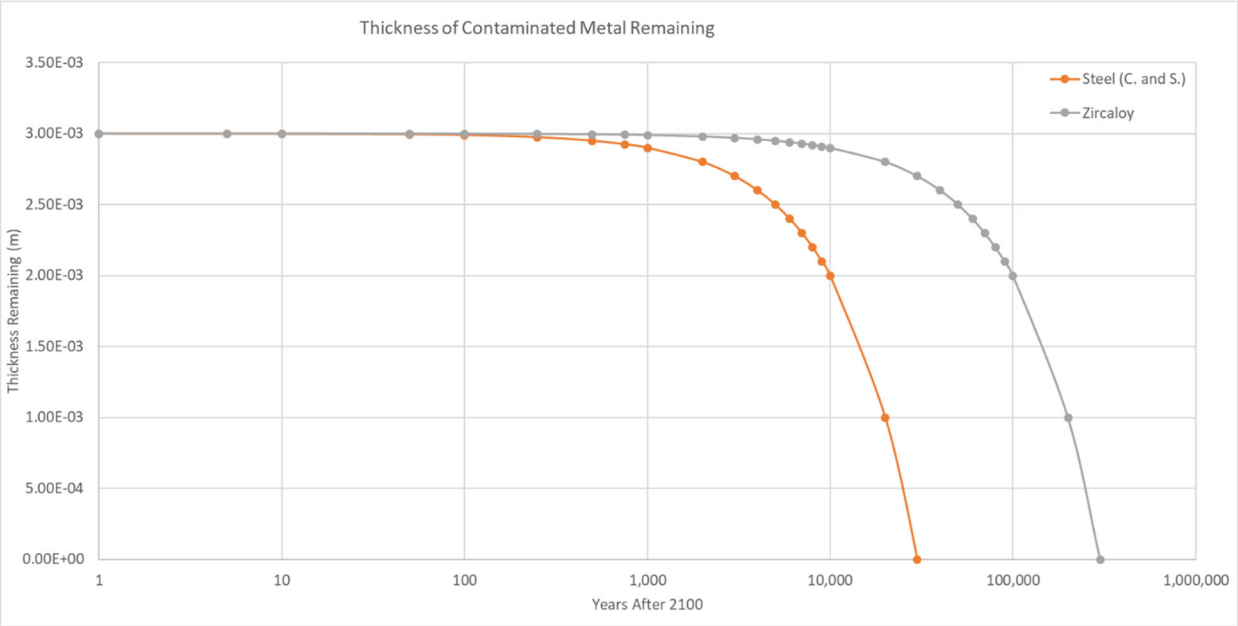
  Each of these are discussed below.

Waste Form (Corrosion):

In addition to the cover slowing water ingress into the facility, a major factor in the release of contaminants is that the metal components contain the majority of the radioactivity. This is a key barrier in the protection of the public and environment. Radionuclides are primarily in the form of activation products, and as such are distributed throughout the whole volume of the metals. This means that the release of these contaminants will be controlled by the corrosion of the containing metal. Figure A-4 shows the thickness of the remaining metal for three key metals, using the corrosion rates, and initial metal thicknesses as discussed in Appendix E, and assuming aerobic, high pH conditions. Aluminum is not shown because it is conservatively assumed to all corrode within the first year. It can be seen that the steels (carbon steel and stainless steel) take approximately 30,000 y to fully corrode, and that Zircaloy still retains the majority of its thickness even after 100,000 y. Zircaloy requires approximately 300,000 y to fully corrode. This would ensure that the contaminants in these materials remained in place, unable to travel, and therefore unable to cause impact to the public, for a very long period of time. By comparison, after 30,000 y the activity concentration of the facility has significantly reduced through radioactive decay (see earlier Figure A-2).

A review of the expected corrosion behaviour of various metallic waste forms included in the PostSA is given in the Waste Form Synthesis Report (CNL, 2021b), which concludes that none of the various factors that could lead to an enhanced rate of radionuclide release under disposal conditions have a significant impact on the release rate. Only once the concrete grout has been degraded and the pore-water pH decreases (perhaps after 100,000 y) is there a possibility of an increased rate of carbon steel corrosion when compared with either stainless steel or zirconium alloys.

Figure A-4 Thickness of Metals in the Reactor Vault



Note: Zircaloy and stainless steel corrosion rates remain the same under neutral and high-pH conditions (see Appendix E).

Concrete Cap and Earthen Cover:

The facility includes a concrete cap and earthen cover to limit water infiltration. The concrete cap and earthen cover have a design life of 100 y. This value has been chosen to be very conservative; the expected lifetime of the cap is much greater. The cap is assumed to function as-designed during this 100-year period and to limit water infiltration. Upon reaching the end of its design life (at 100 y past closure), the cap is assumed to gradually degrade until it provides no barrier to flow. This was assumed to occur at 1,000 y past closure based on information on cover performance from other radioactive waste disposal sites (see discussions in Arcadis & Quintessa, 2020b).

Existing Facility Structure (Concrete):

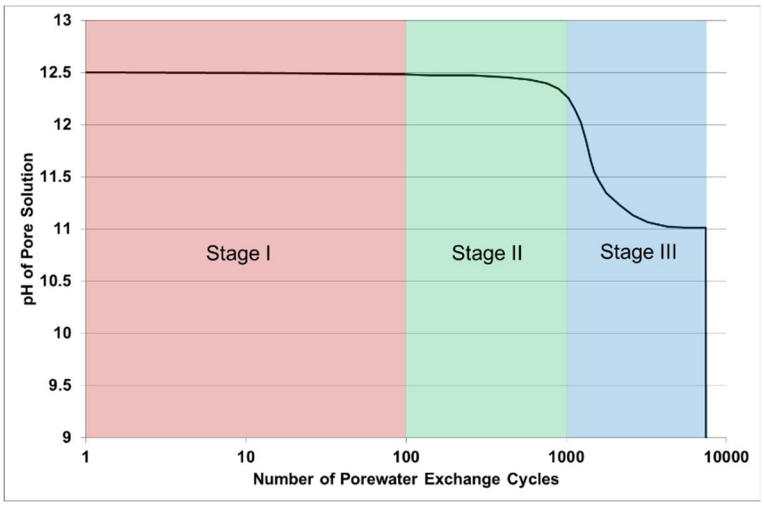
The existing facility concrete structure acts as a barrier to releases. Concrete will degrade over time; this is an important process and it is accounted for in this 4th iteration PostSA as well as in prior iterations.

The expansion of reinforcing bars and other processes, such as ground movement and thermal stresses, will cause the concrete to crack, reducing its effectiveness as a barrier to water flow. The physical lifetime of the concrete structure of the NPDDF is based on the estimated performance of the concrete engineering of the low-level waste repository (LLWR) near-surface disposal facility in the UK (LLWR, 2011). This is assumed to have completely degraded physically by 1000 y after decommissioning is complete.

In general, three characteristic phases are recognized for the chemical degradation of Portland-cement-based cementitious materials (Arcadis & Quintessa, 2017b; Berner, 1992) (shown in Figure A-5):

- Stage I – 'fresh' cementitious material with pH 12.5-13;
- Stage II – partially degraded cements, with portlandite partially removed by leaching;
- Stage III – portlandite removed, with properties controlled by calcium-silica-hydrate (CSH) gel (pH < 12); and
- Stage IV – pH returns to background value.

Figure A-5 Characteristic Phases of Cement Degradation (Arcadis & Quintessa, 2017b; Berner, 1992)



These phases are related to the integrated flow of water through the cement. These degradation phases were most recently examined for the NPDDF in the 2nd and 3rd Iterations PostSA (Arcadis & Quintessa, 2017b, Arcadis & Quintessa, 2020b) and were found to be as follows:

- Stage I ends after approximately 100 flushes of the porespace [as early as ~15,000 y past closure for rooms above bedrock, and as early as ~3,250 y past closure for rooms below bedrock];
- Stage II ends after approximately 1,000 flushes [beyond 100,000 y past closure for rooms above bedrock, and as early as ~25,000 y past closure for rooms below bedrock]; and
- Stage III ends after approximately 7,500 flushes [beyond 100,000 y].

The physical characteristics of concrete will change as it degrades. The density and porosity of concrete are modelled as changing over time according to the 3-stage degradation phases. The values used for the various concrete degradation phases are shown in Table A-3 below (see the Models & Data Section of this report for details regarding their derivation and references). Although the hydraulic conductivity of concrete also changes as it degrades, this is not explicitly modelled in the PostSA AMBER model. Instead, flow regimes through the structure assuming various degrees

of degradation based on the near-field groundwater modelling (Arcadis & Geofirma, 2023) are implemented in the AMBER model (see Appendix E for more information).

Table A-3 Physical Parameters for Concrete – Changes Over Time

(see Models & Data Section for References and Derivation Details)

Parameter	Units	Concrete Degradation Stage		
		Stage I	Stage II	Stage III
Density	kg/m^3	2100	2100	1800
Porosity	-	0.125	0.125	0.25

***Note**: See Models & Data Section for references and derivation details.*

Grout Backfill:

The below grade structure will be filled with grout. The grout will be flowable such that it fills all voids as well as possible.

The 3-stage degradation scheme discussed earlier applies only to typical Portland-cement-based materials, whereas the grout used at the NPDDF will be comprised of a much higher proportion of blast furnace slag (BFS). Therefore, additional modelling was conducted in order to understand the degradation of this particular BFS grout formulation. Grout modelling results (Arcadis & Quintessa, 2020c) for this BFS formula indicate that:

- Stage I does not occur, because there are no alkali (Na and K) species present to be leached;
- Stage II also does not occur, because there is no portlandite;
- Stage III, which is controlled by C-S-H gel, does occur and lasts until C-S-H gel is depleted at approximately flush number 1978;
- "Stage IV" (cement leaching, as in Ochs *et al*., 2016) follows, during which the system becomes buffered by calcite solubility until calcite has dissolved away at approximately flush number 4386;
- The pH then returns to that of the groundwater.

In order to provide a suitable representation of the effects of pH evolution on solubility, the earlier phases of grout degradation can be subdivided, as follows:

- Stage A: 0 - 106 flushes, pH = 11.9
- Stage B: 106 – 227 flushes, pH = 11.5
- Stage C: 228 - 643 flushes, pH = 11.2
- Stage D: 644 – 1978 flushes, pH = 10.2
- Stage E: 1979 - 4386 flushes, pH = 8.2
- Stage F: 4386 - onwards flushes, near neutral pH

Here, Stages A – D correspond with Stages I-III, Stage E corresponds to Stage IV, and Stage F corresponds to background conditions.

Grout “Stage D” ends (i.e., grout “Stage E” begins) as early as 40,000 y post-closure for above-bedrock rooms, and as early as 80,000 y post-closure for below-bedrock rooms.

Grout “Stage E” ends (i.e., grout “Stage F” begins) as early as 80,000 y post-closure for above-bedrock rooms, and beyond 100,000 y post-closure for below-bedrock rooms.

Therefore:

The BFS grout will begin at an equivalent Stage III state and will gradually degrade. The grout will reach the end of “Stage D” as early as 40,000 y post-closure (the earliest estimate, for rooms above-bedrock). At approximately 80,000 y past closure (the earliest estimate, for rooms above-bedrock) the grout will cease being buffered by calcite solubility (i.e., reach the end of “Stage IV”, grout “Stage E”), and the pH will return to that of groundwater.

The existing concrete structure will gradually degrade. The existing concrete structure will begin its Stage III degraded state by approximately 17,000 y post-closure (the earliest estimate, for rooms above-bedrock), and will begin its final Stage IV degraded state beyond 100,000 y past closure (for above-bedrock and below-bedrock rooms).

The waste form is a primary barrier and it includes aluminum, steel (carbon-and-stainless steels) and Zircaloy metals. All aluminum is assumed to be corroded within the first year. Steel takes approximately 30,000 y to fully corrode, and Zircaloy will retain the majority of its thickness even after 100,000 y. By comparison, after 30,000 y the activity concentration of the facility has significantly reduced through radioactive decay (see earlier Figure A-2). The waste form containment barrier will therefore continue to function well beyond an assessment timeframe of 10,000 y.

The engineered cover has a minimum design life of 100 y. After 100 y past closure, the cover will gradually degrade (allowing for increasing recharge rates) until it provides no barrier to flow (estimated to occur at approximately 1000 y past closure – see earlier discussion for details). This degradation is accounted for in the PostSA.

Overall Selection:

Based on the above, an assessment timeframe of 10,000 y would therefore encompass the timeframe of degradation of *some* engineered barriers.

- **4th Aspect: Duration of both active and passive institutional controls**

  Following the short 1-to-2-year decommissioning period, the facility will be closed and a period of institutional control (IC) will take effect for at least 100 y. This institutional control period will include long term care and maintenance, as well as monitoring of the facility, and will ensure that members of the public are not present at the NPDDF.

  The 2nd Iteration PostSA (Arcadis & Quintessa, 2017b) also included an alternate strategy case investigating the effects of a longer institutional control period. Because the PostSA only represents the period of institutional control in terms of preventing human intrusion, the dose implications of having a longer IC period were evaluated by examining the extent to which the dose rate to an intruder was reduced if human intrusion were to be prevented for a longer period (i.e., from 100 y past closure to 300 y past closure). Ultimately, the results indicated that extending the period of institutional control from 100 y to 300 y did not substantially reduce the dose rate to the inadvertent intruder.

  Therefore: Closure of the facility will be followed by an institutional control period of at least 100 y.

- **5th Aspect: Frequency of natural events and human-induced environmental changes (e.g., seismic occurrence, flood, drought, glaciation, climate change, etc.).**

  Another consideration in the development of assessment timeframes is the frequency of natural events and human-induced environmental changes (e.g., seismic occurrence, flood, drought, glaciation, climate change, etc.) that could affect the performance of the NPDDF. However, although the assessment timeframe should be informed by the frequencies of natural events, it should not necessarily be *driven* by them; rather, the assessment timeframe should be developed first, then the assessment must account for the natural events that are expected to occur within that period.

  Seismic Occurrences:

  In the 2nd Iteration PostSA (Arcadis & Quintessa, 2017b) seismic effects were assessed through a set of conservative disruptive event scenarios which included accelerated engineered barrier degradation and localized fast pathways (the “Degradation of Engineered Barriers” Scenario).

  Following the completion of the 2nd Iteration PostSA (Arcadis & Quintessa, 2017b) additional PostSA calculations were performed in Arcadis & Quintessa (2018) to better understand the effects of a seismic event on the system. The calculations in Arcadis & Quintessa (2018) included two particular seismic events: a design-basis event (DBE) of a 1-in-2,250 year event, and, a 1-in-10,000 year event (as determined in CNL, 2018). The effects of these events on the facility (e.g., structure and grout) were examined in CNL (CNL, 2018), and those effects were represented in the assessment model using a fracture model approach and using an equivalent-porous-medium (EPM) approach to allow for comparison. The results of Arcadis & Quintessa (2018) show that, by taking the effects of these seismic events into account, the peak dose rate associated with the NES increases by up to a factor of three. The dose rate is still lower than that calculated for the “Degradation of Engineered Barriers” scenario which was already assessed in the 2nd Iteration PostSA (Arcadis & Quintessa, 2017b) and

was intended to encompass damage caused by a seismic event. Arcadis & Quintessa (2018) concluded that:

- seismic damage to the NPDDF will not lead to significantly greater dose rates, with calculated dose rates remaining *several* orders of magnitude below the dose rate criterion; and,
- the dose rates calculated for the "Degradation of Engineered Barriers" scenario of the 2nd Iteration PostSA (Arcadis & Quintessa, 2017b) were in fact encompassing of the dose rates associated with these events (as assessed using both the fracture approach and the EPM approach) – as they were intended.

Following completion of the Arcadis & Quintessa (2018) seismic calculations, CNL initiated further work to examine the effects of a 1-in-50,000 year seismic event on the facility. As this event is only relevant on timescales considerably outside of the institutional control period, such a seismic event is assumed to occur 1000 y past closure. After this period in time, the facility enters an extremely degraded state – an order of magnitude more severe than the most degraded stage in the NES. The results were incorporated into the 3rd Iteration PostSA (Arcadis & Quintessa, 2020b) through the chosen scenarios, more specifically:

- Seismic effects within the NES;
- A Disruptive Event scenario involving extreme damage to the facility; and,
- A Sensitivity Case examining rapid degradation of engineered barriers.

The radiation dose in the Sensitivity Case to the site resident was slightly lower than the peak dose in the NES, as the release of C-14 was more protracted. However, in the Disruptive Event Case, the peak dose increased by a factor of 3 as a result of the more rapid degradation of the cementitious barriers in the facility, resulting in a reduction in the retention of C-14 and thus higher environmental concentrations.

This 4th Iteration of the PostSA relies on CNL's updated 2021 Seismic Assessment (CNL, 2021a), which has been updated based on regulatory feedback. It is important to note that the overall conclusions of the 2021 CNL seismic assessment (CNL, 2021a) remain the same: that the below-bedrock portion of the facility will experience no cracking, whereas the above-bedrock portion of the facility will experience considerable cracking (for both the 1-in-10,000 and 1-in-50,000 year events).

- *Flooding:*

The 2nd and the 3rd Iterations PostSA (Arcadis & Quintessa, 2017b; 2020b) considered the potential effects of a flood on the facility (based on information in OPG, 1999) and accounted for these using a "Surface Erosion" scenario. The scenario assumes that: a flood scours the surface and exposes contaminated overburden and rock through which groundwater flows; and, a person subsequently lives next to, and uses, the contaminated area in the same way as a site resident is assumed to in the Normal Evolution scenario. However, it is important to note that the frequency of such a flood is less than one in ten million years (Arcadis *et al*., 2017b), which is less than the probability screening criterion.

Results for this scenario in the 2nd Iteration PostSA showed that estimated peak dose rate was less than 0.003 mSv/y, occurring shortly after 1,000 y past closure. In the 3rd Iteration PostSA, the estimated peak dose rate was 0.009 mSv/y, occurring at 4,500 y past closure.

Drought:

In the 2nd Iteration PostSA (Arcadis & Quintessa, 2017b) and in the 3rd Iteration PostSA (Arcadis & Quintessa, 2020b), drought conditions and their effect on the system were considered as part of the systematic FEPs screening process that is used to define the assessment's scenarios and what they entail.

FEPs that involved climate considerations such as drought include:

- FEP #1.3.6 (Warm Climate Effects);
- FEP #5.1.11 (Climate and Weather); and,
- FEP #5.1.12 (Hydrological Regime and Water Balance) (Arcadis & Quintessa, 2017b; 2020b).

FEP #1.3.6 was screened *out* because the development of a warm tropical or desert climate at the site is not considered to be plausible over the timescales of concern, and so, this FEP is not relevant for the site geographical setting. Additional details can be found in the FEPs Appendix of Arcadis & Quintessa (2017b; 2020b) and in Appendix C of this 4th Iteration PostSA.

FEP #5.1.11 was screened *in* because the climate and weather do affect the system and surrounding land. The climate of the area (classified as humid continental, with warm summers, cold winters, and no distinct dry season) is expected to remain largely as such in the future, although climate change effects might result in some modest warming. Because the FEP is relevant, it was therefore deemed appropriate to represent such a climate state as part of the NES. Additional details can be found in the FEPs section of Arcadis & Quintessa (2017b; 2020b) and in Appendix C of this 4th Iteration PostSA.

FEP #5.1.12 was screened *in* because the hydrological regime and water balance do affect the system and the evolution of the NPDDF. Because the FEP is relevant, it was therefore deemed appropriate to represent the existing hydrological regime and to account for water balance within the assessment model. As such, these aspects were included for all scenarios.

The 2nd Iteration PostSA (Arcadis & Quintessa, 2017b) and the 3rd Iteration PostSA (Arcadis & Quintessa, 2020b) also included a "River Level Fall" Scenario which examined the effects of a significant change to the environment resulting in decreased river water levels, e.g., as a result of much reduced precipitation over a wide area, or due to periglacial conditions north of the site in the run up to glaciation (i.e., 100,000 y) reducing the flow to the river in its more northerly catchments. The main effect of the drop in river level was the release of groundwater directly to the surface rather than through river sediments, with an estimated peak dose rate of 0.004 mSv/y occurring at 1,200 y past closure in the 2nd Iteration PostSA (Arcadis & Quintessa, 2017b). In the 3rd Iteration PostSA, the peak dose was unchanged from the NES.

For the 3rd Iteration PostSA and subsequently this 4th Iteration PostSA, additional information was available from CNL (2017a) and IPCC (2013) which predicts warmer and wetter conditions. Based on these predictions, drought conditions are unlikely - see Appendix C (FEPs) for further discussion.

Glaciation:

As outlined in the 2nd Iteration PostSA (Arcadis & Quintessa, 2017b), while glaciation at the site is certain to occur at some point in the future, it is not expected to occur for more than 100,000 y due to climate change effects (Ganopolski *et al*., 2016). Nevertheless, there are substantial uncertainties in the future evolution of the climate, and it is possible that such an event could occur earlier than this. For this reason, the 2nd Iteration PostSA (Arcadis & Quintessa, 2017b) included an "Early Glaciation" Scenario occurring at around 60,000 y (i.e., the approximate timescale for the next major glaciation if anthropogenic global warming had not occurred). Further details about the modelling of this scenario and its results can be found in the 2nd iteration PostSA (Arcadis & Quintessa, 2017b).

For the 3rd and this 4th Iteration PostSA, because glaciation is not expected to occur for over 100,000 y (due to climate change effects (Ganopolski *et al*., 2016)), it is not credible over a 10,000 year assessment timeframe and is screened out (see Appendix C (FEPs)).

Climate Change:

In the 2nd Iteration PostSA (Arcadis & Quintessa, 2017b), climate change was accounted for through specific scenarios, including the river level fall/discharge to shore case, and the erosion case to represent floods. In the 3rd iteration of the PostSA (Arcadis & Quintessa, 2020b) and this 4th iteration of the PostSA, current climate change information is explicitly accounted for in the NES and in all scenarios through increased precipitation (CNL, 2017b; IPCC, 2013) (the small increase in temperature is not expected to affect other parameters).

Therefore:

Seismic effects, other natural events (such flooding), and global warming are included in (or encompassed by) the 4th Iteration PostSA model, as discussed above (and many of these were already encompassed by scenarios in the prior 2nd Iteration PostSA (Arcadis & Quintessa, 2017b)) and 3rd Iteration PostSA (Arcadis & Quintessa, 2020b).

Glaciation is not expected to occur for 100,000 y as a result of anthropogenic climate change (Ganopolski *et al.,* 2016), and is therefore not credible over a 10,000-year assessment timeframe.

By accounting for these events using a range of scenarios that occur *early* in the assessment timeframe, when the inventory is larger and has not decayed, the results of later events are bounded.

- **6th Aspect: The degree of protection and isolation required against inadvertent intrusion over the long term**

Another consideration in the development of assessment timeframes is the degree of protection and isolation required against inadvertent intrusion over the long term.

In relation to the Facility, the most important aspect to consider is the resilience offered by the NPDDF structure. This will be covered with a robust concrete cap and engineered barrier once the facility has been decommissioned. Such a construction would be highly robust and would require specialist engineering to intrude into it. Specifically, until such a time that the concrete cap, engineered barrier and Facility structure becomes substantially degraded, a plausible method of intrusion that would reach the wastes themselves would be to drill and core the Facility. This type of activity is, however, not uncommon as a method for investigating an unusual feature, which the Facility could readily be established as. The intrusion could, for example, be motivated by archaeological interests without knowledge of the nature of the Facility and its contents. However, it seems equally likely that intrusion from future development of the river shoreline including road construction and blasting or the construction of a home(s) on the site could also result in an excavation of the monolith and represent a more conservative human intrusion scenario. Intrusion into the Facility with prior knowledge of its content is excluded from the scope of the postclosure safety assessment.

The mass excavation of the entire Facility is too unlikely to be considered to be a plausible scenario because the concrete structure would retain sufficient structural integrity to preclude it. In addition to the existing structure, it will be backfilled with grout and a concrete cap will be placed over the nuclear area as well as an engineered barrier over the entire facility. Nevertheless, the persistent nature of the contaminants in the Facility mean that such events cannot be discounted in the far future and the scenario requires analysis as it can provide an indication of the likely maximum level of dose.

In the 3rd Iteration PostSA (Arcadis & Quintessa, 2020b), human intrusion was assessed as a Disruptive Event scenario (Site Investigation), and as a What If Mass Excavation case. Although the What If Mass Excavation was a highly conservative scenario, due to its “what if” nature it was not compared to the relevant dose criteria.

Therefore: At some time after 100 y, the 4th iteration PostSA model considers the possibility of Site Investigation (Disruptive Event), Excavation of Above-Bedrock Facility (Disruptive Event), and Mass Excavation (What If Scenario).

Overall Selection:

Based on the above, an assessment timeframe of 10,000 y would therefore encompass the possibility of human intrusion.

- **Final Selection of Assessment Timeframe**

  A final assessment timeframe of 10,000 y is selected, based on the above considerations of the peak dose (from prior iterations), hazard lifetime, duration of operational (decommissioning) period, design life of the engineered barriers, planned institutional control period, frequency of natural events, and the potential of inadvertent intrusion over the long term. The focus of assessment calculations is therefore on the first 10,000 y, and the emphasis in the PostSA is on interpreting the potential consequences within this timeframe. A 10,000 year assessment timeframe also compares well with safety assessment studies for other near-surface disposal facilities which also typically consider timeframes of 10,000 to 100,000 y as common practice.

  As discussed earlier, the 1st Iteration PostSA (Arcadis & Quintessa, 2017a) explored an assessment timeframe of 100,000 y, and NES results identified the time of peak dose to be approximately 13,000 y past closure. The 2nd Iteration PostSA (Arcadis & Quintessa, 2017b) explored an assessment timeframe of 50,000 y, and NES results identified the time of peak dose to be approximately 1,200 y past closure.

  The 3rd Iteration PostSA (Arcadis & Quintessa, 2020b) explored an assessment timeframe of 10,000 y, and NES results identified the time of peak does to be approximately 1,100 y past closure. The calculated peak doses for Normal Evolution, Disruptive Events and Defence-in-Depth cases were all below their corresponding dose criteria, while the What-if dose results were not compared to dose criteria as they involved parameter values or other properties such that the system is influenced in an exaggerated way. Nevertheless, the times of peak doses for the What-if scenarios all occurred before 1,100 y past closure.

  The results of these prior iterations give an indication that peak dose will be captured within an assessment timeframe of 10,000 y. The results of these prior iterations also give useful perspective on timeframes beyond 10,000 y; however, it is important to note that estimates for such a long time period are subject to greater uncertainties.

  For context, historical events occurring during an equivalent period of time to the assessment timeframe are shown in Table A-4.

  It is important to recognize that the reliability of quantitative predictions diminishes with increasing time. Therefore, the long-term quantitative estimates of impacts, such as dose rate, presented in this report should be seen as indicators rather than absolute measures of impact.

Table A-4 Timeline of Historical Events Covering the Same Timeframe as the PostSA

Time	Historical Event
100,000 y ago	Humans begin to move beyond Africa
70,000 y ago	Severe Ice Age results from an eruption in Sumatra, humans almost extinct as a result
50,000 y ago	Transient agriculture begins in temperate regions
50,000 y - 17,000 y ago	Wisconsin Glaciation, with the last glacial maximum 20,000 y ago
10,000 y ago	Settled agriculture established in suitable climates; Hunter-gatherers in Canada
9,000 - 7,000 y ago	Domestication of animals for food
3,000 y ago	Bronze Age
2,000 y ago	Woodland settlements in Ontario
1500 y ago	Aboriginal river settlements in Canada
500 y ago	Colonization of North America by Europeans
150 y ago	Colonies of Canada, Nova Scotia, and New Brunswick united as the Dominion of Canada
100 y ago	First World War

A 3.5 Dealing with Uncertainties

The treatment of uncertainty is a key issue in safety assessment because of the range and nature of uncertainties over the typical assessment timescale. The uncertainties can be categorized into three types (Marivoet *et al*., 2008).

- Future or scenario uncertainty: uncertainty in the evolution of the system and human behaviour over the timescales of interest;
- Model uncertainty: uncertainty in the models used to simulate the system (especially any approximations and simplifications); and
- Data uncertainty: uncertainty in the data and parameters used in the modelling.

These uncertainties are managed in the current assessment in the following way:

- The assessment of a range of scenarios, models and data with a suite of calculation cases; and
- The adoption of conservative scenarios, models and data.

It should be noted that care is needed as the net effect of an aggregation of many conservative assumptions can be an unrealistic estimate of impacts. Furthermore, some analyses (e.g., optimisation studies) can be meaningless if the assessment is dominated by conservative assumptions. Where possible, scientifically informed, physically realistic assumptions are made for processes that are understood and can be justified on the basis of the results of research and/or site investigation. Where there are high levels of uncertainty associated with processes and data, conservative assumptions are adopted to allow uncertainties to be bounded.

In this study, uncertainty in the future evolution of the site is addressed by the consideration of a range of scenarios that encompass its expected futures. Key conceptual and mathematical model uncertainties are assessed in a similar way, through a series of alternative calculation cases, identified via a structured model development process making use of a FEPs analysis. Discrete alternative calculations can be easier to interpret than probabilistic analyses.

Multi-Variate Sensitivity Analyses

In order to better understand data uncertainties and their influence on their results, multivariate sensitivity analyses were performed using the results of the 2nd iteration PostSA (Arcadis & Quintessa, 2017b), in Arcadis & Quintessa (2018). The multivariate sensitivity analyses in Arcadis & Quintessa (2018) encompassed several parameters: inventory, corrosion rates, number of pore flushes/degradation time, sorption coefficients, solubility limits, river flow rate, and transfer factors. Results from Arcadis & Quintessa (2018) indicated that the parameters whose uncertainties have the most influence on the results of the assessment are:

- Corrosion rates;
- Inventory; and,
- Cement sorption coefficients.

For corrosion rates and inventory, Arcadis & Quintessa (2018) found that radiation dose varies linearly, since these parameters directly define the rate of release of key contaminants from the wastes. Increasing either parameter by an order of magnitude will increase the rate of release of key radionuclides (e.g., C-14 and Cl-36) and subsequently the dose from exposure to the contaminant.

For cement sorption coefficients, dose was seen to vary by a factor of approximately 50 times over the range of Kd values for cement. However, the range of cement sorption coefficient values covers several orders of magnitude for some radionuclides, larger than the range considered for the inventory and corrosion rate (which was varied by a factor of a hundred). In addition, Arcadis & Quintessa (2018) found that increasing the cement Kd values to more than 80% of their range does not further change the dose. This indicates that, beyond this point, the dose is solely controlled by very long-lived radionuclides. These are not sensitive to cement Kd value as they will ultimately be released whatever Kd value is selected due to the long half-life. A similar relationship is seen with the chemical degradation timescale, although it has a far smaller influence on dose. (Arcadis & Quintessa, 2018)

Another important overall finding of the Arcadis & Quintessa (2018) multivariate calculations was that the highest calculated dose for any possible combination of parameter values was less than 0.1 mSv y^{-1}. This value was the result of the most extreme combination of values from the sampled parameter distributions. Despite the parameter distributions being defined conservatively (using wide ranges and adopting a uniform distribution function that overestimates the likelihood of extreme values) even this result is more than a factor of two below the dose criterion. When account is taken of the conservative nature of the sensitivity analysis this represents a very considerable safety margin, as it shows that even using a combination of extreme assumptions the dose remains below the criterion. (Arcadis & Quintessa, 2018)

A 4 QUALITY ASSURANCE

The regulatory guidance prepared by CNSC (2021) emphasizes the importance of Quality Assurance (QA) within safety assessment studies. This subsection summarizes the QA status of the work, which has been undertaken under a quality management system accredited to ISO 9001:2015.

A 4.1 Models and Data

All data used in the model are verified and, where possible, validated. The following steps are applied to all the models and data used in the PostSA.

1. The basis (rationale) for selected data is checked independently by a safety assessment specialist to ensure it is reasonable, consistent with the assessment context, and adopts an appropriate degree of conservatism.
2. All data presented are checked back to the stated source document (except where an assumption has been made, in which case the appropriateness of the data is checked in Step 1).
3. The correct transcription of the data into reports and the assessment code is checked.

Records for the checking of data are included in the data forms presented in Appendix E. Parameters are assigned the same name in the models as given in the documentation to facilitate checking.

In addition, all equations used in the model, documented in Appendix F, are checked for dimensional consistency and, where possible, related to the underlying science. All equations are independently checked for their validity by a safety assessment specialist.

Due to the nature of long-term modelling, there is relatively limited scope to validate the model's behaviour as suitable observations and points of comparison are not available. This is addressed by basing models on well-established physical and chemical processes, as documented in in Appendices E and F, and / or models and relationships developed independently of the PostSA and that have been used or recommended for use in safety assessment studies (e.g., CSA (2022), IAEA (2010)). Furthermore, where possible, models and data, such as soil-plant transfer factors, are based on validated models and datasets, themselves based on observations. To reduce uncertainty in the NPDDF long-term models, comparison with natural analogues, archaeological artifacts and other complementary safety indicators has also been made (for example, naturally occurring surficial uranium ore deposits in the region, obtained from OGS (1981)).

A 4.2 Software

The models and data are implemented in the general-purpose modelling software tool AMBER. AMBER is managed and developed under an ISO 9001:2015 registered QA system that incorporates the requirements of TickIT software quality system (www.TickIt.org). Each release is extensively tested against a broad set of verification and validation tests (Quintessa, 2021a). AMBER's capabilities are fully described in a Reference Manual (Quintessa, 2021b) and a User Guide (Quintessa, 2021c). AMBER has been verified to ensure that models are solved correctly in accordance with what has been specified. This involves implementation and analysis of set of test cases specifically developed to check the correct functioning of the code. Every application of AMBER builds confidence in the tool itself. This is particularly true when intercomparisons with other codes are performed and when checks against analytic solutions are made. In addition to the ongoing use of the tool, a set of test cases have been specifically developed to check the correct functioning of the code. The tests are as follows.

- Some simple cases with known solutions that have been used throughout AMBER's development;
- A simple biosphere model, which checks the deterministic and probabilistic functioning of AMBER against documented results from a Nuclear Energy Authority (NEA) study;
- A comparison with a solubility-limited source term model, developed by AEA Technology for Nirex;
- A comparison with analytical and spreadsheet calculations for cases involving Langmuir Availability schemes;
- A case using all the probability distributions available in AMBER to check that sensible values are generated;
- The results of cases used to test that sampling is properly random and that correlations are appropriately generated when specified;
- Some tests that check the correct calculation of spatial properties in AMBER;

- The results of 'pressure testing' of the code and solvers to determine some of the practical limits for aspects including transfer rates, number handling, contaminants and transfers.

AMBER meets the requirements of CNL's Code Management Program and has also been validated in accordance with CNL's management system document, *Guideline for Application of Quality Assurance for Analytical, Scientific, and Design Computer Programs* (CNL, 2019).

The results calculated by the code have also been compared with those calculated by other similar tools. For example, the deterministic and probabilistic functioning of AMBER has been compared against the documented results from a number of participant members of the Nuclear Energy Agency (NEA) PSAG group for their "PSAG Level 1B exercise" (NEA, 1993).

In addition to these formal mathematical tests, the software has a proven track record for performance assessment of radioactive waste disposal facilities and a strong quality assurance status (e.g., see Medri (2015), Thomson *et al*. (2008), Walke *et al*. (2011)). AMBER also has features that facilitate the quality assurance of specific models. For example, equations and data are defined in AMBER parameters which are saved in text-based case files which allow easy checking of the model. AMBER also automatically checks the dimensionality of equations on the basis of the units assigned to parameters. The code generates Microsoft Excel® compatible output files, which are time-stamped and include model filenames, minimising the amount of post-processing of data that is required.

A specific validation activity was also performed using RESRAD-OFFSITE Version 3.1 in CNL (2017c), to provide confidence in the model developed in the first iteration of the NPD post-closure safety analysis. The results of this assessment were verified against the long term radiological dose consequence acceptance criteria of 0.25 mSv y^{-1} and analyzed post-closure normal evolution scenarios. The normal evolution scenario modeled were:

- Adult Receptor Agricultural Land Use Scenario; and
- Adult Receptor Parkland Use Scenario.

The CNL (2017c) RESRAD-OFFSITE analysis peak dose was 2.34×10^{-4} mSv y^{-1} to the agricultural land use receptor, which is less than the 0.25 mSv y^{-1} limit. The dose to the parkland receptor was estimated to be 1.55×10^{-5} mSv y^{-1}. The peak dose to the agricultural land use receptor and parkland receptor were both within an order of magnitude to the peak doses in the 1st iteration PostSA calculated using the AMBER code. It was concluded that the RESRAD results were able to verify the AMBER analysis results, and that the dose consequences between the two models vary within a set margin and are well below the 0.25 mSv y^{-1} limit.

For further details on AMBER's verification and validation, the reader is referred to AMBER 6.5.1 Verification and Validation Summary document (Quintessa, 2021a).

A 4.3 Documentation

The documentation of the PostSA is intended to be sufficiently comprehensive to enable the models and data to be implemented independently and has been reviewed to ensure that it is clear, accurate and comprehensive.

All documents are subject to at least one round of internal review by a specialist member of the project team who is not the main author of the report. The review considers the technical details from the perspective of their appropriateness to the scope of work and the associated justification. This also includes checking that the work addresses the relevant regulatory standards (CNSC, 2021) and applies national and international best practice guidance.

Documents are also reviewed by CNL prior to finalisation. Comments and suggestions from CNL are considered before finalising the document. Formal records of the comments and how they have been addressed are maintained.

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APPENDIX B: SYSTEM DESCRIPTION

APPENDIX B - SYSTEM DESCRIPTION

B 1 INTRODUCTION

Canadian Nuclear Laboratories (CNL, acting on behalf of Atomic Energy of Canada Limited, AECL) is proposing in-situ disposal of the Nuclear Power Demonstration Waste Facility (NPDWF), thereafter referred to as the Nuclear Power Demonstration Disposal Facility (NPDDF). This 4th Iteration Postclosure Safety Assessment (PostSA) will support the EIS submission.

This 4th Iteration PostSA has been undertaken using international best practice, specifically the International Atomic Energy Agency's (IAEA's) Improving Safety Assessment Methodologies (ISAM) guidance (IAEA, 2004). This is a systematic, stepwise approach, the main stages of which are illustrated in Figure B-1. This PostSA has been documented in a way that corresponds to the ISAM approach, with a main report describing the key elements of the assessment and its outcomes.

This appendix provides additional details of the second stage of the process, the description of the "system" being assessed. The system comprises the NPDWF buildings and the radioactive and non-radioactive hazardous contamination that remains within these buildings. Upon closure this will constitute a disposal facility hereafter referred to as the NPD Disposal Facility (NPDDF). The system also includes the geological setting and the surface environment within which contaminants may subsequently migrate.

This appendix therefore presents current information on the reactor site, inventory, geosphere and biosphere systems that is relevant to postclosure safety, along with identified areas of uncertainty. It does not present the data used in the PostSA models, as this will be selected to accord with scenario and modelling decisions that are taken in subsequent steps of the ISAM approach. It does, however, provide a narrative description of the system and provide details of what is known and where there are uncertainties.

The main data sources for this appendix are:

- Smith (1988), Trottier & Edwards (2012), Kinectrics (2015), Edwards (2017), NMNTI (2017), McVeigh (2018a,b), Edwards & Adams (2019), McVeigh (2019a,b), McVeigh (2020), Psotka (2021), Porter (2022) – radiological inventory information;
- Schruder & Vickerd (2017), Arcadis & Quintessa (2019), Arcadis (2021) – non-radiological inventory information;
- Athauda-Arachchige (2015) - Safety Analysis Report for the NPDWF;
- Arcadis & Geofirma (2023a,b,c; and 2022) – Groundwater, Near-Field, Resaturation, and Geosynthesis;
- Arcadis & Geofirma (2021d) – Slope Stability Study;
- CNL (2021) – Underground Structure Seismic Assessment;
- Arcadis & Quintessa (2019) – Grout Geochemical Modelling Study;

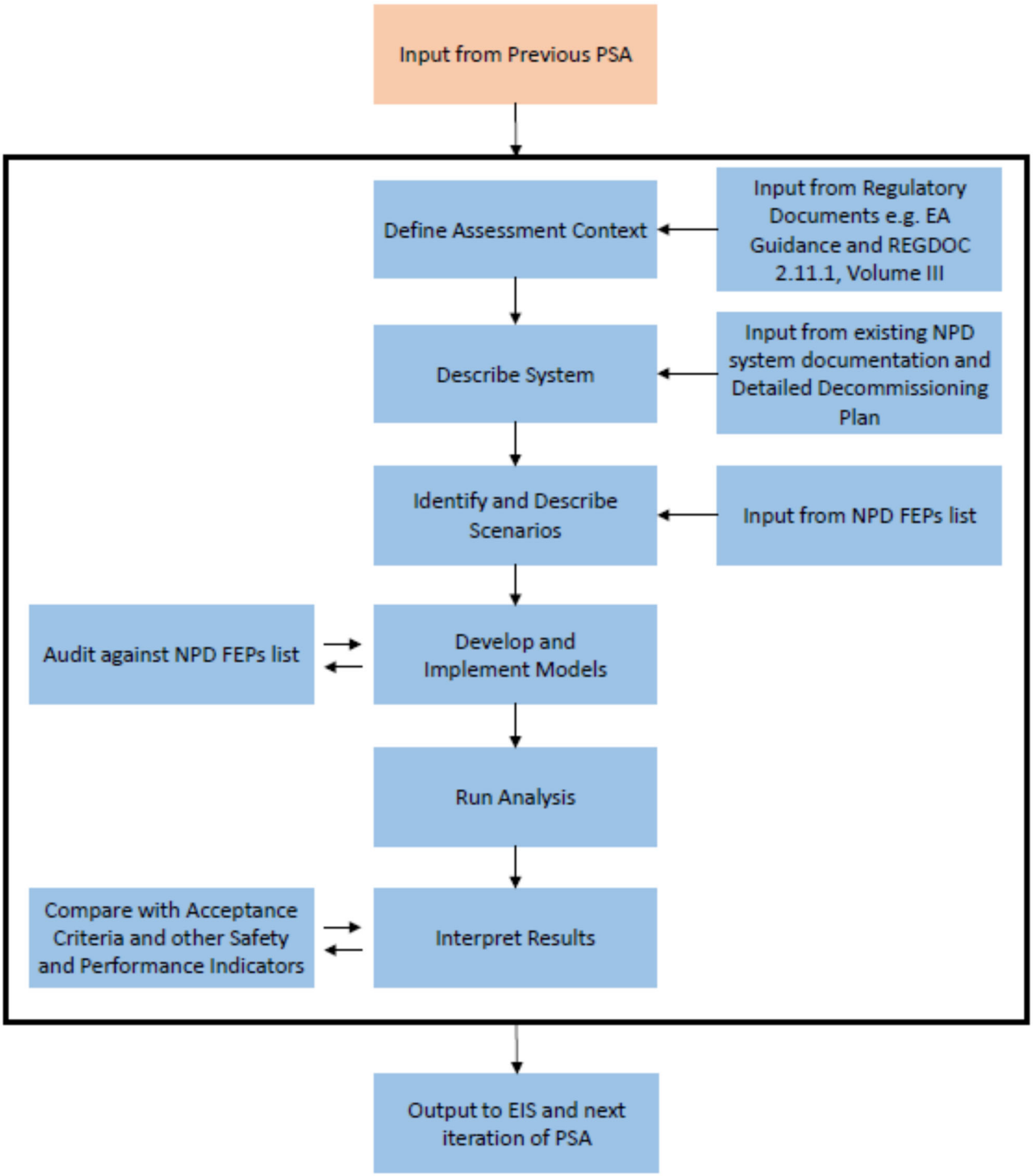
- Arcadis & Quintessa (2020a) – Grout Flushing Models; and,
- Wills (2013) – environmental baseline conditions of the site.

Other, specific documents are signposted throughout the report.

The appendix is structured according to the main components of the system:

- Section B 2 describes the NPDDF itself, its history and context;
- Section B 3 describes the inventory of radionuclides and non-radioactive contaminants;
- Section 0 describes the subsurface environment relevant to the NPDDF;
- Section 0 describes the surface environment surrounding the facility;
- Section B 6 describes the appropriateness of the facility and its location for radioactive waste disposal; and
- Section B 7 outlines the references.

Figure B-1 Approach to Postclosure Safety Assessment, adapted from ISAM (IAEA, 2004)

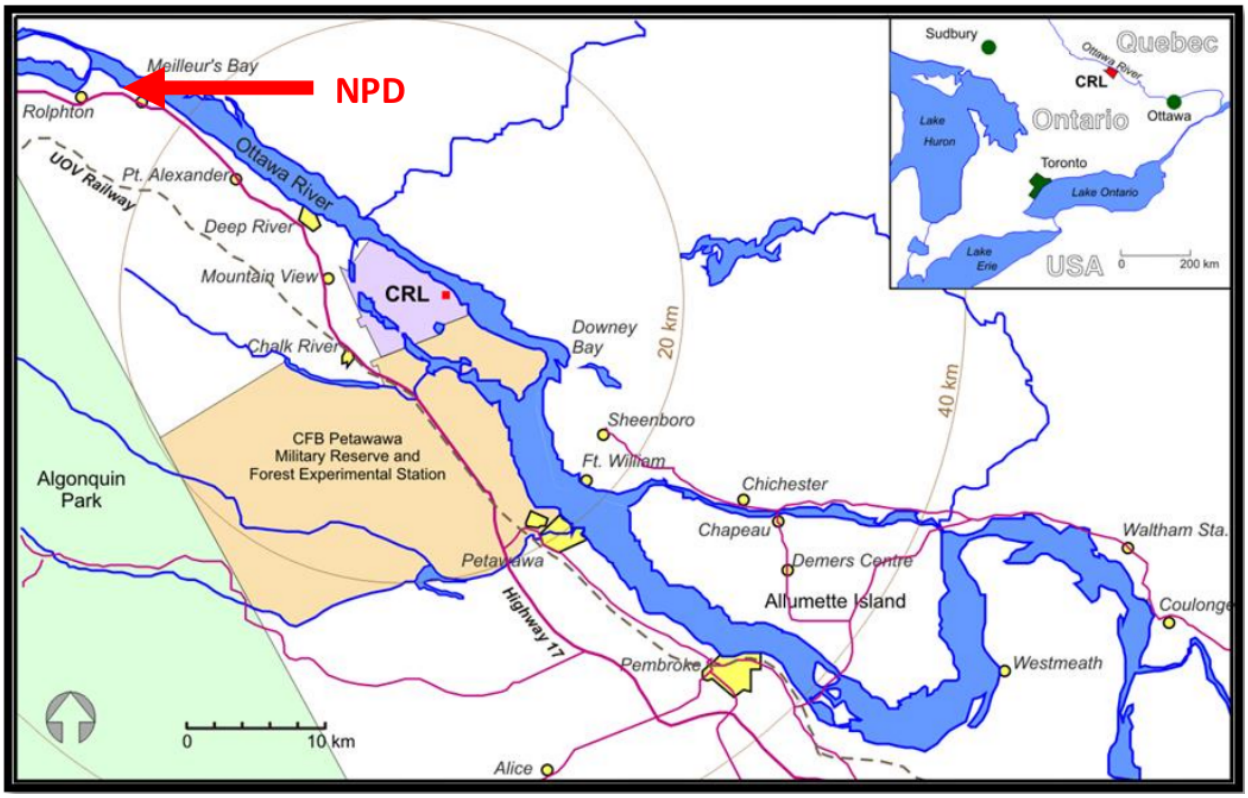


B 2 NUCLEAR POWER DEMONSTRATION REACTOR SITE

B 2.1 Location and Layout

The NPDDF site is on the southwest bank of the Ottawa River, in the Province of Ontario, ~160 km WNW from the city of Ottawa (Figure B-2). At this location, the Ottawa River runs along the boundary between the Province of Ontario and the Province of Quebec. The NPDDF site is 25 km northwest of the nuclear research facility Chalk River Laboratories (CRL), near the town of Rolphton and is 3 km downstream from the Des Joachims Dam and hydro-power generating station.

Figure B-2 Location of the NPD Site in Relation to the Ottawa River and Chalk River Laboratories



The NPDDF is situated within land owned by Atomic Energy Canada Limited (AECL). Highway 17 runs through the AECL land and the Facility is located around 750 m to the north of Highway 17, about 100 m from the Ottawa River (Figure B-3, Figure B-4).

There were previously a range of ancillary buildings which have now been removed and are not considered further (Figure B-5). There are also two landfill sites close to the NPDDF which are relevant because information on the shallow subsurface has been obtained from these locations.

All of the above grade structures will be removed during decommissioning, except for the ventilation stack which will remain for a period of time as supporting habitat for recovery of the Chimney Swift endangered species (which presently use the stack as a roost). The above-grade portion of the Main Building, specifically, will be demolished and its rubble will be disposed of in the subsurface rooms below the Main Building. It is possible to place all of its demolition waste into the condenser room (see Figure B-6) which sits below the Turbine Room (both are called the Turbine Room in the remainder of the PostSA for simplicity) (Stevenson *et al*., 2017). Thus, in this 4th iteration, it is assumed that the inventory of radioactive and hazardous materials associated with the above-grade structure is contained within the Turbine Room (in practice some other rooms may be used, for example bagged asbestos may be placed in the Control Wing).

Figure B-3 Topographic Map of AECL Land Surrounding the NPD Waste Facility

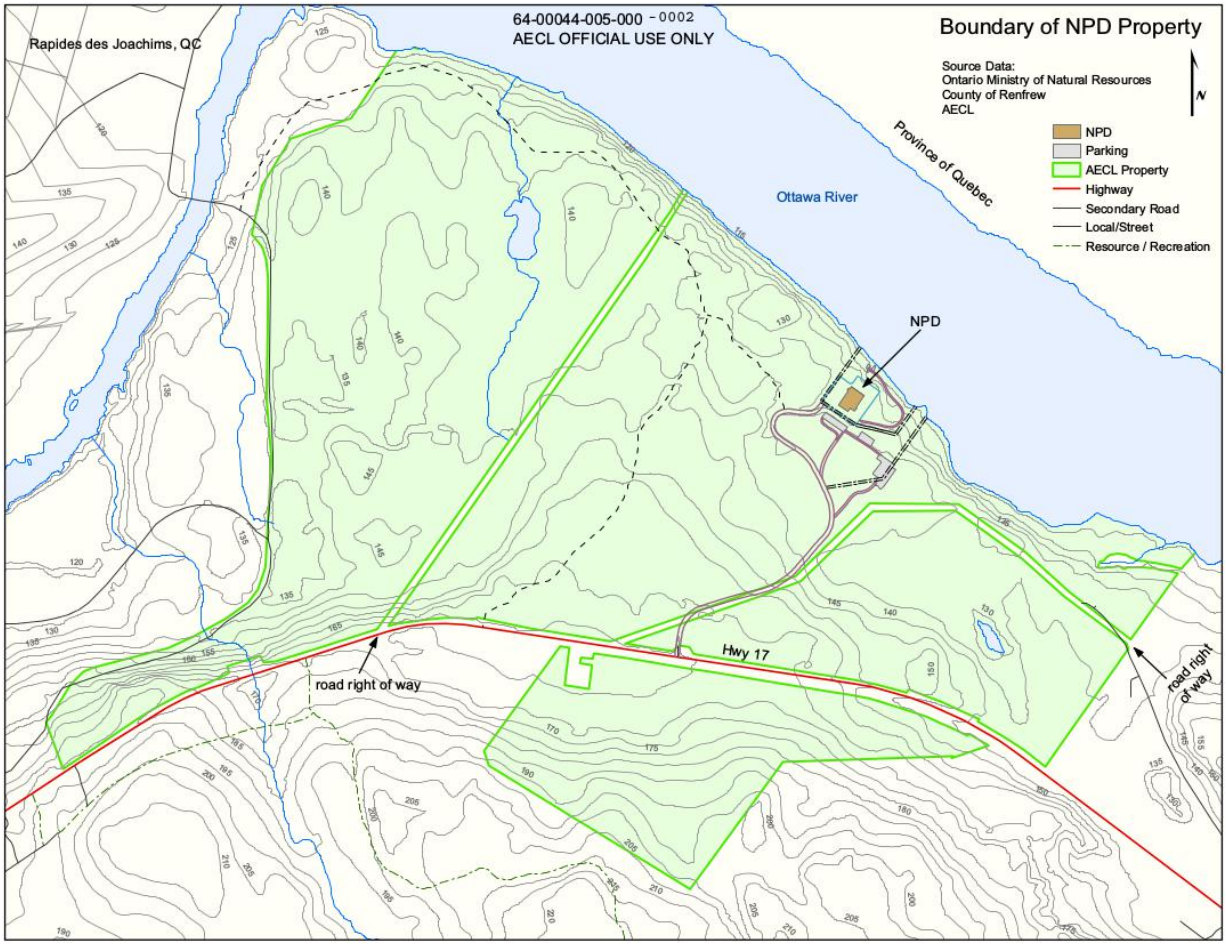


Figure B-4 Photograph of the NPD Taken During Storage with Surveillance



Figure B-5 Buildings and Structures Around the NPD from 2000

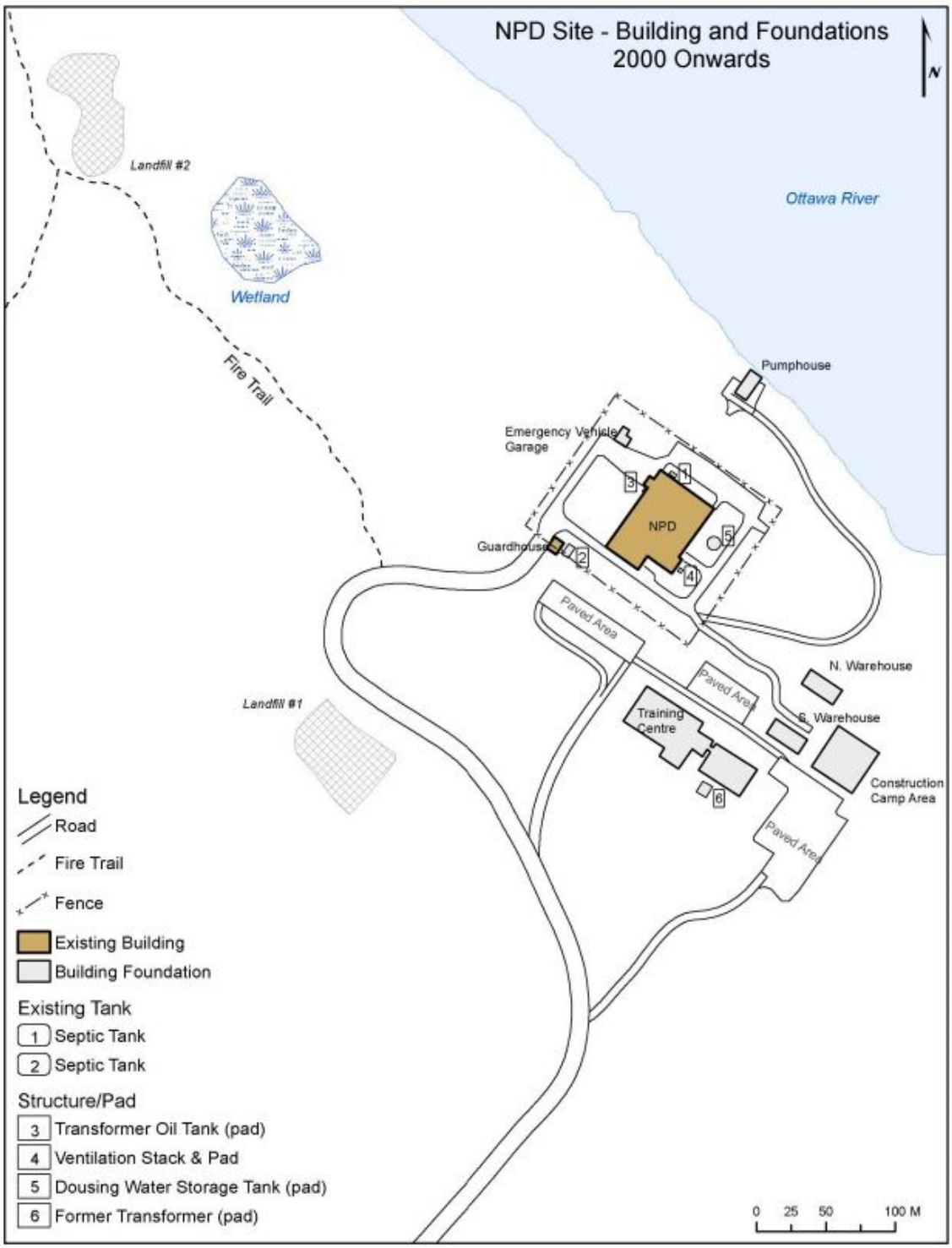
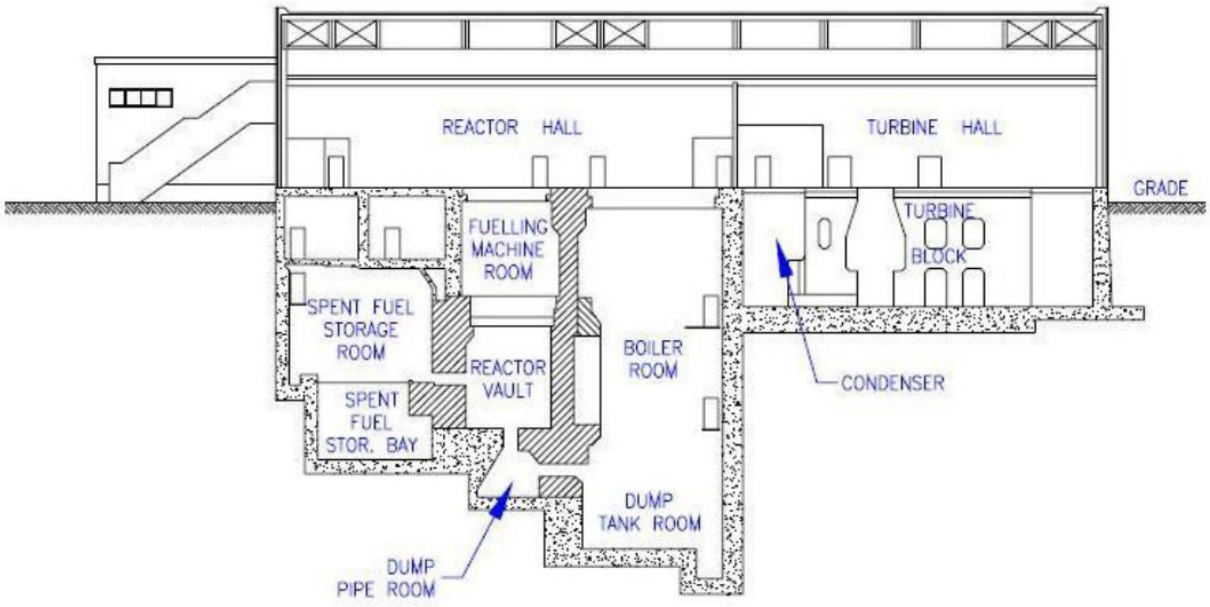


Figure B-6 Cross Section of the Main Building, Housing the Reactor, Boiler Room and Spent Fuel Storage Facility



The Main Building consists of the above grade structure and a number of rooms below grade, with the above grade structure providing a weather barrier to protect internal areas (Figure B-6). The Main Building is divided into the Nuclear Area and Non-Nuclear Area.

The main rooms in the Nuclear Area are:

- Spent Fuel Storage Room and Bay (herein referred to as Fuel Storage Room);
- Fuelling Machine Room;
- Reactor Vault;
- the Dump Pipe Room; and,
- Boiler Room.

The main rooms in the Non-Nuclear Area are the Turbine Hall (herein referred to as Turbine Room), the Reactor Hall and the Control Wing.

B 2.2 Site History

The Nuclear Power Demonstration Nuclear Generating Station (NPDNGS) was constructed between 1956 and 1961. During construction of the facility, the landscape was altered significantly to create man-made terraces on which the buildings could be sited. The reactor building was built in a pit dug through overburden and into bedrock. The concrete for the walls of the whole of the facility below bedrock was poured into a shuttered frame (Figure B-7), leaving a gap between the rock/overburden and the below-

grade exterior walls of the facility. The concrete walls have a membrane waterproofing or asphalt emulsion damp-proofing. The gap between the building and rock/overburden (Figure B-8, Figure B-9) was backfilled with concrete (based on Powerhouse Waterproofing and Backfilling Drawings NA25-f-2206 through NA25-f-2208).

Figure B-7 Construction of the Nuclear Power Demonstration Structure within the Void Excavated in Rock



Figure B-8 Backfilled Gap between Concrete Walls and the Rock and Overburden



Figure B-9 Construction of the Nuclear Power Demonstration Facility



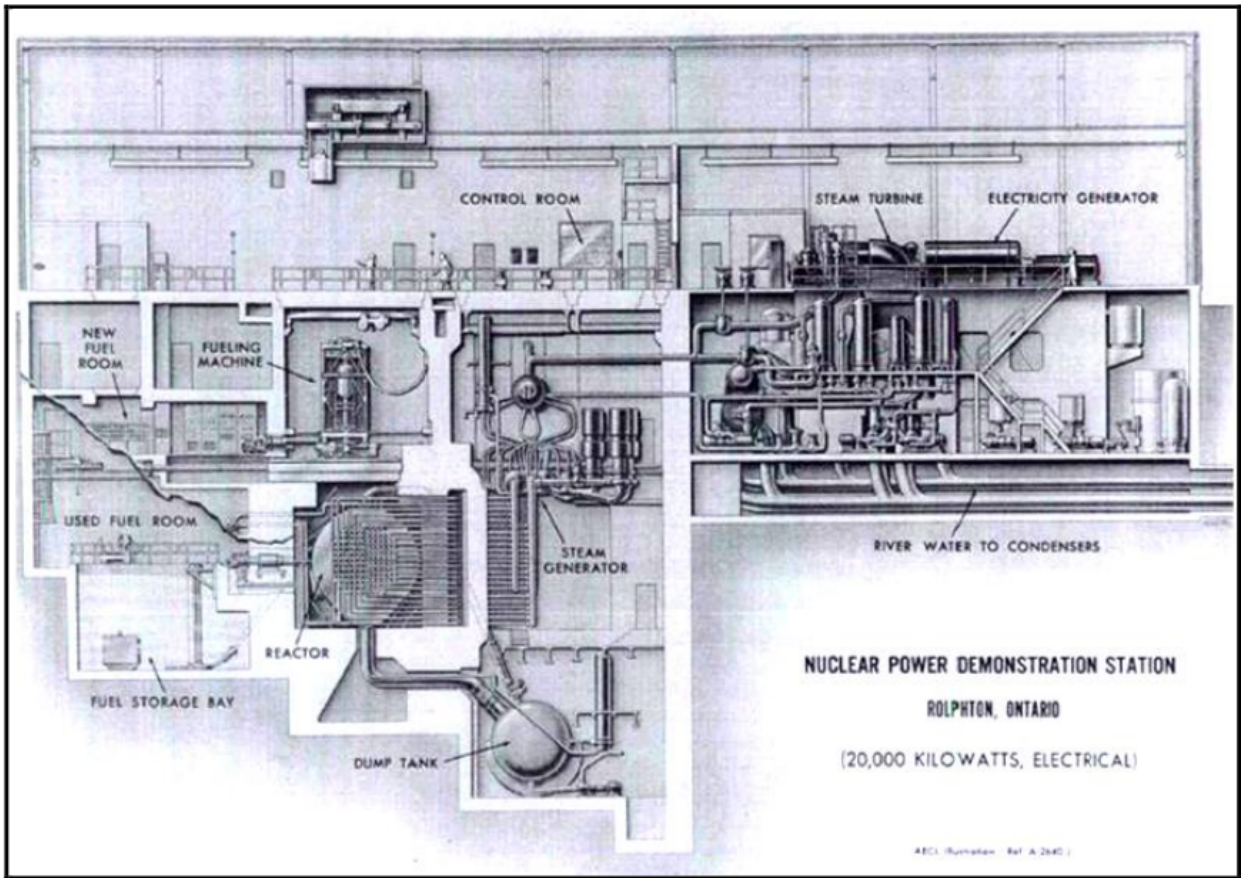
Figure B-10 Cooling Pipe Trench from the Reactor Site to the Ottawa River



Drains were constructed in the top surface of the bedrock to direct water away from the reactor building (see Section B 4.4). In addition, a trench was excavated through the overburden, down to rockhead, for cooling water and process discharge pipes (Figure B-10). These ran down to a pumphouse located at the edge of the river.

The reactor was a 20 MWe prototype for the CANada Deuterium Uranium (CANDU) reactor design, fueled with natural uranium and was operated between 1962 and 1987. During operations, the key components of the NPDNGS were the reactor, heat transport system, turbine, and electrical power generator equipment (Figure B-11). The reactor core, or Calandria, contains 132 horizontal pressure tubes in which fuel was inserted and was surrounded by the heavy water moderator. The heat transport system pumps circulated the hot pressurized heavy water through the reactor coolant tubes to a heat exchanger/boiler unit where the heat was transferred to the boiler steam and water system. Steam generated in the boilers drove the turbine/generator for electrical power generation. Two Fueling machine arms were used to move an average of 2 fuel bundles into and out of the reactor each day and the spent fuel bundles were transferred remotely into the fuel storage bay.

Figure B-11 Key Features of the NPDNGS During Operations



During reactor operations, a number of incidents were recorded (Seto, 2014). Some of these involved a failure in the cladding surrounding the uranium fuel. These are potentially important as they indicate that some fission products and actinides have been released to the primary circuit.

The NPDNGS was permanently shut down on 1987 May 24 and a three-phase decommissioning plan put in place. Phase I brought the facility to a safe, sustainable shutdown; Phase II is a period of storage with surveillance (SwS); Phase III is the proposed final and complete decommissioning and disposal of the site.

During Phase I, the heavy water was drained and flushed from the primary heat transport and moderator systems and shipped off site. The reactor was de-fuelled and the fuel bundles were transferred to the Chalk River Laboratories (CRL). The reactor vault was sealed except for ventilation ducting. Electrical generation equipment, non-nuclear process and control systems and ancillary components were removed. Decontamination activities were completed as required. The facility was functionally divided into a Nuclear-Area and Non-Nuclear-Area with any equipment or structures either radioactive or radioactively contaminated confined to the Nuclear-Area. Most cross connections between the two areas were blocked off, sealed or permanently locked.

The site is currently in Phase II, SwS, which involves routine monitoring, surveillance, inspection and repairs to maintain the integrity of the facility structures and components.

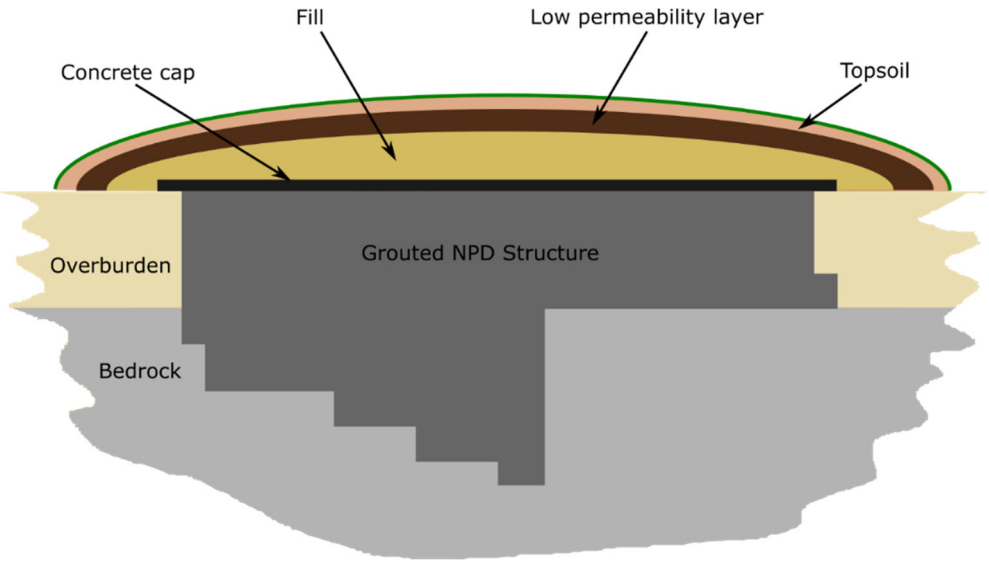
B 2.3 Decommissioning Strategy

The proposed in-situ disposal activities include removing the above-grade structure and placing redundant materials and demolition waste into the below-grade structure. The below grade structure will be filled by grouting using a BFS:PC (blast furnace slag) (Portland cement) grout formulation. Once the structure has been grouted a reinforced concrete cap will be installed over the nuclear area, and then an engineered barrier will be installed over the entire grouted structure. The engineered barrier consists of a multi-layer earthen cover incorporating a geotextile clay liner.

Grouting will proceed from the base of the facility in the lower Boiler Room (Dump Tank Room). The grout will be flowable such that it fills all voids as well as possible. Further information about the grout is provided in Appendix E (Models & Data). Prior to grouting, all rooms will have been examined to determine the need for modifications to ensure that grout is contained and to allow filling, air exhaust and heat removal during curing. Large volume equipment such as the helium storage tanks would be perforated to allow inflow of grout during filling to avoid any buoyancy issues.

Once the below-grade structure is grouted, a concrete cap will be installed over the nuclear area as well as an engineered barrier and earthen cover over the entire facility, which will be contoured to shed water. A simple conceptual design is shown in Figure B-12.

Figure B-12 Conceptual Illustration of the Main Conceptual Elements of the NPD Cap and Cover



B 2.4 Uncertainties

The geometry of the facility is well documented and available in various drawings, enabling the structures to be reproduced in the PostSA.

Although there is some information on the existing concrete and planned grout formulation, there are some uncertainties as to its long-term performance. The rate of physical degradation, and pH change, within the concrete will be an important consideration for the PostSA.

B 3 INVENTORY

B 3.1 Background

The contaminants associated with different locations within the NPDDF are discussed below. Data are available from:

- Measurements made in various rooms, including samples retrieved from the Reactor Vault, and
- Vault Neutron activation models of the Calandria and other material in the Reactor Vault.

Radionuclide inventories calculated with neutron activation codes are meant to be bounding and are based on conservative assumptions. Direct measurements provide waste verification, to demonstrate correspondence to the bounding PostSA inventory.

For some rooms within the NPDDF, measurement data are only available for a limited number of radionuclides. Where it is likely that other radionuclides would be present and have an impact on the PostSA, additional radionuclides have been added to the PostSA inventory. The approach used is scaling to measured ratios of radionuclides in the primary heating circuit. This is considered reasonable as the primary heating circuit is the main source of radiological contamination, and the distribution of radionuclides will be characteristic of any leakage from the reactor fuel. Porter (2022), and references therein, provides further details on the methods used to estimate the inventories. The full inventories used, accounting for any uncertainties, are presented in Appendix E.

B 3.2 Radionuclide Inventory

The radionuclide inventory has been progressively refined from the 1st Iteration PostSA to the 3rd Iteration PostSA as new information became available. The following discussions present the current understanding of the radionuclide inventory along with the progression through which it has been estimated. It should be noted Appendix B presents estimates of the inventory, as adopted from Porter (2022) and references therein. The inventory numbers in Appendix E, used in the main Normal Evolution Scenario (NES), are generally higher because they include an uncertainty factor on some rooms' inventory. Thus, the inventory presented here in Appendix B represents data as reported in NPDWF waste inventory reports, whereas the modelled inventory in Appendix E is more conservative and encompasses uncertainty.

B 3.2.1 Reactor Vault

The Reactor Vault inventory includes activated reactor components and structures such as the:

- concrete biological shield;
- carbon steel liner;
- aluminum Calandria vessel and Calandria tubes;
- Zircaloy pressure tubes; and,
- stainless-steel end fittings and components.

Modelling & Measurements

The 1st and 2nd Iterations of the PostSA used Smith (1988), which calculated the activity of the NPD reactor components after shutdown using the ORIGEN neutron activation code. This calculation was verified independently by Trottier and Edwards (2012), specifically focusing on the pressure tube and Calandria tube inventories.

The 3rd Iteration of the PostSA used Edwards & Adams (2019) which re-calculated the activity of the NPD reactor components (see Table B-1). This re-calculation, still using the ORIGEN code, replaced the 2-D neutron transportation code used by Smith (1988) with MCNP, a 3-D solver, and provided a detailed examination of potential impurities and uncertainties in the material compositions. This calculation superseded previous work which was originally performed soon after shutdown in 1988 and subsequently verified in 2012.

The NPD Closure Project also completed sampling of the various activated reactor materials to build confidence in the calculated inventory. This included sampling and laboratory analysis of the activated inner concrete of the Reactor Vault walls, carbon steel vault liner, aluminum Calandria vessel and a Calandria tube as well as the Zircaloy from a pressure tube. Sampling of the Calandria was undertaken by New Millennium Nuclear Technologies Incorporated (NMNTI). Collection of a sample of the stainless-steel components was not possible. These sample results, NMNTI (2017), used the empirical data, as well as re-estimates of the various reactor material masses from 3D modeling (based on original design drawings), to validate the activation product inventory modelled by Smith (1988), Edwards (2017) and subsequently, Edwards & Adams (2019).

A comparison of the results between Edwards & Adams (2019) and NMNTI (2017) indicates that:

- The total activation product inventory estimated using Edwards & Adams (2019) (1.04E+14 Bq) is conservative in comparison to the total activation product inventory estimated by sample results alone (1.01E+13 Bq) in NMNTI (2017).
- The modelled activation product inventory of the NPD reactor components (Edwards & Adams, 2019) appears to be largely conservative for the aluminum and Zircaloy reactor components.

- Tritium was overestimated in the aluminum components by Edwards & Adams (2019) and underestimated in the concrete. The total tritium inventory estimated by sampling results (NMNTI, 2017) was approximately 20 times lower than Edwards & Adams (2019).
- Edwards & Adams (2019) underestimates C-14 by 4 orders of magnitude in the bioshield concrete. This discrepancy is potentially due to errors in the starting N-14 composition or impurities in reactor materials. However, the total C-14 inventory estimated by Edwards & Adams (2019) is still approximately 20 times higher than the total inventory determined by sampling results (NMNTI, 2017).

Table B-1, taken from Porter (2022), provides a comparison of the sample results obtained (from NMNTI (2017)) and the most up-to-date modelling results, Edwards & Adams (2019). As sampling of the stainless steel was not possible (NMNTI, 2017), the comparator used is the verification work undertaken in 2017 which looked specifically at the NPD end fitting components (Edwards (2017)). Porter (2022) presents a composite total activity derived by using the higher activity between the NMNTI (2017) measurements and the Edwards & Adams (2019) estimates for each radionuclide in each material, expect for a small number of values where the measurement was used in preference, as it was thought more reliable (e.g., H-3 in aluminum).

Table B-1 Comparison of ORIGEN Neutron Flux calculations (Edwards, 2017, Edwards & Adams, 2019) and Sampling Data (NMNTI, 2017), as documented in Porter (2022)

Radionuclide	Aluminum		Concrete		Carbon Steel		Stainless Steel		Zircaloy		Composite Total Activity by Radionuclide (Bq)
	NMNTI (2017)	Edwards & Adams (2019)	NMNTI (2017)	Edwards & Adams (2019)	NMNTI (2017)	Edwards & Adams (2019)	Edwards (2017)	Edwards & Adams (2019)	NMNTI (2017)	Edwards & Adams (2019)	
	(Bq)										
H-3	9.13E+09	3.10E+13	1.41E+12	9.48E+03	2.35E+08	3.35E+07	-	2.04E+09	2.11E+11	7.36E+11	**2.16E+12**
C-14	2.97E+08	1.00E+11	2.40E+10	2.70E+06	8.13E+07	1.25E+09	5.55E+09	1.05E+11	5.30E+10	1.36E+12	**1.59E+12**
Cl-36	1.21E+07	4.58E+09	1.74E+08	7.17E+06	1.09E+07	-	-	2.64E+05	3.43E+07	2.50E+10	**2.98E+10**
Ca-41	-	9.21E+08	7.62E+09	3.56E+07	-	5.80E+06	-	3.28E+08	-	1.25E+09	**1.01E+10**
Co-60	4.16E+10	5.28E+11	3.18E+11	2.58E+08	1.17E+10	1.61E+11	3.04E+11	1.34E+13	2.79E+11	2.63E+12	**1.71E+13**
Ni-59	8.49E+08	2.17E+09	-	1.68E+06	-	8.37E+08	2.09E+09	1.54E+11	-	2.16E+11	**3.73E+11**
Ni-63	1.55E+11	5.22E+11	6.83E+10	1.55E+08	4.39E+09	3.96E+10	1.94E+11	1.44E+13	6.93E+12	3.36E+13	**4.86E+13**
Se-79	-	1.06E+04	-	2.06E+00	-	6.08E+05	-	1.77E+07	-	1.04E+05	**1.84E+07**
Sr-90	3.11E+09	2.97E+09	-	1.01E+06	2.91E+06	1.68E+08	-	3.55E+10	2.32E+10	2.55E+10	**6.43E+10**
Zr-93	-	2.76E+06	-	2.80E+03	-	3.67E+03	-	2.06E+06	2.90E+10	2.40E+11	**2.40E+11**
Nb-93m	-	4.97E+06	-	2.25E+03	-	2.55E+07	-	1.41E+09	-	1.94E+11	**1.95E+11**
Nb-94	-	0.00E+00	-	1.62E+05	-	5.84E+07	-	4.40E+09	1.85E+08	1.13E+10	**1.58E+10**
Tc-99	-	2.17E+06	-	3.94E+02	-	7.53E+06	-	4.12E+08	-	1.45E+08	**5.67E+08**
Ag-108m	-	3.42E+08	-	3.96E+03	-	8.63E+08	-	7.74E+10	-	2.16E+10	**1.00E+11**
Sn-121m	-	6.19E+07	-	1.60E+02	-	1.94E+06	-	7.56E+07	-	2.08E+11	**2.08E+11**
Sn-126	-	5.66E+04	-	3.32E+00	-	0.00E+00	-	3.71E+05	-	6.86E+05	**1.11E+06**
Sb-125	-	2.67E+07	-	1.55E+01	-	1.15E+06	-	2.52E+07	2.69E+10	9.05E+10	**9.06E+10**
I-129	-	3.76E+03	-	0.00E+00	-	0.00E+00	-	3.94E+04	-	5.25E+04	**9.56E+04**
Cs-135	-	6.68E+04	-	3.86E+01	-	1.79E+03	-	1.34E+06	-	7.45E+05	**2.15E+06**
Cs-137	6.91E+09	6.39E+09	-	1.07E+06	-	1.87E+08	-	4.82E+10	6.08E+10	7.79E+10	**1.33E+11**
Sm-151	-	4.71E+08	-	5.51E+05	-	3.07E+08	-	2.25E+09	-	7.60E+07	**3.11E+09**
Eu-152	2.76E+08	7.78E+09	1.23E+11	3.85E+07	5.92E+07	1.87E+07	-	1.26E+08	3.48E+09	7.51E+04	**1.34E+11**
U-234	-	7.04E+05	-	4.35E+05	-	2.76E+07	-	1.18E+07	-	1.35E+05	**4.07E+07**
U-235	-	2.08E+04	-	2.02E+04	-	1.26E+06	-	2.45E+05	1.55E+03	0.00E+00	**1.55E+06**
U-236	-	0.00E+00	-	1.02E+01	-	0.00E+00	-	1.51E+05	-	1.85E+04	**1.70E+05**
U-238	1.21E+05	4.68E+05	-	4.40E+05	-	2.79E+07	-	6.04E+06	7.74E+04	9.24E+04	**3.49E+07**
Np-237	-	0.00E+00	-	0.00E+00	-	0.00E+00	-	2.97E+04	-	3.09E+04	**6.06E+04**
Pu-238	8.96E+07	7.33E+07	8.30E+08	0.00E+00	-	7.26E+02	-	3.27E+08	6.27E+08	1.05E+09	**2.30E+09**
Pu-239	6.44E+07	1.47E+07	2.06E+07	1.98E+05	-	1.08E+08	-	1.49E+09	4.22E+08	1.54E+08	**2.10E+09**

Radionuclide	Aluminum		Concrete		Carbon Steel		Stainless Steel		Zircaloy		Composite Total Activity by Radionuclide (Bq)
	NMNTI (2017)	Edwards & Adams (2019)	NMNTI (2017)	Edwards & Adams (2019)	NMNTI (2017)	Edwards & Adams (2019)	Edwards (2017)	Edwards & Adams (2019)	NMNTI (2017)	Edwards & Adams (2019)	
	(Bq)										
Pu-240	-	4.24E+07	-	2.29E+01	-	1.39E+05	-	9.71E+08	-	4.80E+08	**1.49E+09**
Pu-241	-	1.12E+09	-	0.00E+00	-	1.50E+04	-	1.30E+10	8.05E+09	1.56E+10	**2.96E+10**
Pu-242	-	6.73E+05	-	0.00E+00	-	0.00E+00	-	3.57E+05	-	1.11E+07	**1.21E+07**
Am-241	-	1.36E+08	-	0.00E+00	-	0.00E+00	-	1.88E+09	1.28E+09	1.80E+09	**3.82E+09**
Am-243	-	9.67E+06	-	0.00E+00	-	0.00E+00	-	3.48E+05	-	1.64E+08	**1.74E+08**
Cm-243	-	5.45E+05	-	-	-	-	-	3.10E+05	-	9.27E+06	**1.01E+07**
Cm-244	-	9.95E+08	-	0.00E+00	-	0.00E+00	-	1.19E+06	-	1.58E+10	**1.67E+10**
Be-10	-	1.26E+05	-	0.00E+00	-	0.00E+00	-	5.14E+04	-	5.62E+04	**2.34E+05**
Al-26	-	4.18E+06	-	0.00E+00	-	0.00E+00	-	0.00E+00	-	0.00E+00	**4.18E+06**
P-32	-	3.20E+04	-	1.47E-01	-	4.80E+01	-	2.06E+03	-	4.80E+05	**5.14E+05**
Si-32	-	3.15E+04	-	0.00E+00	-	0.00E+00	-	1.76E+03		4.80E+05	**5.13E+05**
Ar-39	-	2.73E+07	-	3.28E+04	-	6.97E+04	-	5.85E+05	-	1.80E+08	**2.08E+08**
Fe-55	2.34E+10	8.77E+10	7.84E+10	9.91E+07	1.73E+10	1.46E+10	5.10E+10	3.15E+12	1.79E+11	1.25E+11	**3.51E+12**
Fe-60	-	7.25E+04	-	0.00E+00	-	0.00E+00	-	1.80E+05	-	1.74E+05	**4.27E+05**
Co-60m	-	7.25E+04	-	0.00E+00	-	0.00E+00	-	1.80E+05	-	1.74E+05	**4.27E+05**
Kr-85	-	1.08E+08	-	2.82E+04	-	5.41E+06	-	1.35E+09	-	7.82E+08	**2.24E+09**
Rb-87	-	0.00E+00	-	3.29E+04	-	0.00E+00	-	0.00E+00	-	0.00E+00	**3.29E+04**
Y-90	-	2.97E+09	-	1.01E+06	-	1.73E+08	-	7.09E+10	-	2.55E+10	**9.96E+10**
Nb-91	-	2.91E+04	-	0.00E+00	-	4.07E+05	-	1.39E+07	-	7.84E+06	**2.21E+07**
Mo-93	-	3.71E+06	-	0.00E+00	-	3.50E+07	-	1.93E+09	-	6.84E+08	**2.65E+09**
Ru-106	-	2.27E+01	-	4.62E-04	-	9.79E-02	-	1.22E+02	-	3.46E+02	**4.91E+02**
Pd-107	-	2.78E+04	-	0.00E+00	-	0.00E+00	-	1.07E+05	-	4.74E+05	**6.08E+05**
Ag-108	-	2.98E+07	-	3.44E+02	-	7.34E+07	-	6.73E+09	-	1.08E+09	**7.91E+09**
Ag-109m	-	3.00E+03	-	2.61E-07	-	1.01E+02	-	3.08E+04	-	3.06E+05	**3.40E+05**
Cd-109	-	3.00E+03	-	2.61E-07	-	1.01E+02	-	3.08E+04	-	3.06E+05	**3.40E+05**
Cd-113m	-	4.13E+07	-	2.15E+01	-	6.28E+08	-	2.21E+09	-	2.71E+07	**2.90E+09**
Sn-121	-	4.80E+07	-	1.24E+02	-	1.53E+06	-	5.87E+07	-	1.61E+11	**1.61E+11**
Te-125m	-	6.53E+06	-	3.79E+00	-	2.62E+05	-	6.14E+06	-	2.22E+10	**2.22E+10**
Sb-126m	-	5.66E+04	-	3.32E+00	-	0.00E+00	-	3.71E+05	-	6.86E+05	**1.11E+06**
Ba-133	-	1.02E+09	-	1.57E+06	-	0.00E+00	-	1.37E+03	-	1.19E+04	**1.03E+09**
Ba-137m	-	5.86E+09	-	1.01E+06	-	8.50E+07	-	4.55E+10	-	7.37E+10	**1.25E+11**

Radionuclide	Aluminum		Concrete		Carbon Steel		Stainless Steel		Zircaloy		Composite Total Activity by Radionuclide (Bq)
	NMNTI (2017)	Edwards & Adams (2019)	NMNTI (2017)	Edwards & Adams (2019)	NMNTI (2017)	Edwards & Adams (2019)	Edwards (2017)	Edwards & Adams (2019)	NMNTI (2017)	Edwards & Adams (2019)	
	(Bq)										
Cs-134	-	5.57E+05	-	2.89E-03	-	4.33E+00	-	3.60E+05	-	6.70E+06	**7.62E+06**
La-137	-	2.92E+05	-	1.18E+01	-	2.38E+05	-	1.41E+07	-	0.00E+00	**1.46E+07**
Pm-145	-	2.47E+08	-	4.60E+03	-	0.00E+00	-	0.00E+00	-	0.00E+00	**2.47E+08**
Pm-146	-	1.83E+05	-	0.00E+00	-	0.00E+00	-	2.16E+02	-	0.00E+00	**1.84E+05**
Pm-147	-	7.80E+06	-	9.03E+02	-	1.44E+06	-	1.60E+08	-	2.44E+07	**1.93E+08**
Eu-154	-	2.51E+10	-	1.38E+06	-	8.78E+05	-	6.75E+08	-	1.16E+09	**2.69E+10**
Eu-155	-	1.90E+09	-	1.25E+04	-	6.57E+04	-	3.18E+07	-	8.38E+07	**2.01E+09**
Tb-157	-	4.24E+07	-	1.46E+03	-	0.00E+00	-	0.00E+00	-	0.00E+00	**4.24E+07**
Tb-158	-	8.26E+06	-	0.00E+00	-	0.00E+00	-	0.00E+00	-	0.00E+00	**8.26E+06**
Ho-166m	-	3.73E+07	-	0.00E+00	-	0.00E+00	-	0.00E+00	-	0.00E+00	**3.73E+07**
Hf-182	-	0.00E+00	-	0.00E+00	-	0.00E+00	-	2.69E+03	-	4.44E+06	**4.44E+06**
Ta-182	-	3.17E+02	-	0.00E+00	-	1.36E-01	-	2.93E+03	-	4.44E+06	**4.44E+06**
Re-186	-	2.33E+03	-	0.00E+00	-	6.63E-01	-	8.64E+03	-	1.20E+06	**1.21E+06**
Re-186m	-	2.06E+03	-	0.00E+00	-	0.00E+00	-	7.91E+03	-	1.20E+06	**1.21E+06**
Pt-193	-	2.24E+06	-	0.00E+00	-	0.00E+00	-	0.00E+00	-	7.92E+08	**7.94E+08**
Tl-208	-	3.13E+05	-	1.13E+05	-	3.26E+06	-	4.98E+06	-	0.00E+00	**8.66E+06**
Pb-205	-	2.79E+04	-	0.00E+00	-	0.00E+00	-	1.26E+04	-	2.53E+05	**2.93E+05**
Pb-209	-	0.00E+00	-	2.25E+02	-	1.32E+04	-	1.24E+06	-	0.00E+00	**1.26E+06**
Pb-210	-	0.00E+00	-	3.67E+01	-	0.00E+00	-	0.00E+00	-	0.00E+00	**3.67E+01**
Pb-212	-	9.11E+05	-	3.14E+05	-	9.69E+06	-	1.38E+07	-	1.90E+03	**2.48E+07**
Bi-210	-	4.02E+01	-	3.67E+01	-	0.00E+00	-	0.00E+00	-	4.86E+02	**5.63E+02**
Bi-211	-	0.00E+00	-	2.96E+01	-	7.68E+03	-	1.97E+05	-	0.00E+00	**2.05E+05**
Bi-212	-	9.11E+05	-	3.14E+05	-	9.69E+06	-	1.38E+07	-	1.90E+03	**2.48E+07**
Bi-213	-	0.00E+00	-	2.25E+02	-	1.32E+04	-	1.24E+06	-	0.00E+00	**1.25E+06**
Po-210	-	4.02E+01	-	3.67E+01	-	0.00E+00	-	1.02E+00	-	4.86E+02	**5.64E+02**
Po-212	-	5.84E+05	-	2.01E+05	-	5.81E+06	-	8.87E+06	-	0.00E+00	**1.55E+07**
Po-213	-	0.00E+00	-	2.20E+02	-	1.29E+04	-	1.21E+06	-	0.00E+00	**1.23E+06**
Po-215	-	0.00E+00	-	2.96E+01	-	7.68E+03	-	1.97E+05	-	0.00E+00	**2.05E+05**
Po-216	-	9.11E+05	-	3.14E+05	-	9.41E+06	-	1.38E+07	-	1.90E+03	**2.45E+07**
At-217	-	0.00E+00	-	2.25E+02	-	1.32E+04	-	1.24E+06	-	0.00E+00	**1.26E+06**
Fr-221	-	0.00E+00	-	2.25E+02	-	1.32E+04	-	1.24E+06	-	0.00E+00	**1.26E+06**

Radionuclide	Aluminum		Concrete		Carbon Steel		Stainless Steel		Zircaloy		Composite Total Activity by Radionuclide (Bq)
	NMNTI (2017)	Edwards & Adams (2019)	NMNTI (2017)	Edwards & Adams (2019)	NMNTI (2017)	Edwards & Adams (2019)	Edwards (2017)	Edwards & Adams (2019)	NMNTI (2017)	Edwards & Adams (2019)	
	(Bq)										
Rn-220	-	9.11E+05	-	3.14E+05	-	9.33E+06	-	1.38E+07	-	1.90E+03	**2.44E+07**
Ra-224	-	9.11E+05	-	3.14E+05	-	9.32E+06	-	1.38E+07	-	1.90E+03	**2.44E+07**
Ra-225	-	0.00E+00	-	2.25E+02	-	1.32E+04	-	1.24E+06	-	0.00E+00	**1.26E+06**
Ra-228	-	3.28E+04	-	3.14E+05	-	9.17E+06	-	1.98E+06	-	0.00E+00	**1.15E+07**
Ac-225	-	0.00E+00	-	2.25E+02	-	1.32E+04	-	1.24E+06	-	0.00E+00	**1.26E+06**
Ac-228	-	3.28E+04	-	3.14E+05	-	9.15E+06	-	1.98E+06	-	0.00E+00	**1.15E+07**
Th-228	-	9.11E+05	-	3.14E+05	-	9.21E+06	-	1.38E+07	-	1.90E+03	**2.43E+07**
Th-229	-	0.00E+00	-	2.25E+02	-	1.32E+04	-	1.24E+06	-	0.00E+00	**1.26E+06**
Th-230	-	0.00E+00	-	3.15E+03	-	9.66E+04	-	2.59E+04	-	0.00E+00	**1.26E+05**
Th-231	-	2.08E+04	-	2.02E+04	-	1.26E+06	-	2.45E+05	-	0.00E+00	**1.55E+06**
Th-232	-	3.28E+04	-	3.14E+05	-	9.19E+06	-	1.98E+06	-	0.00E+00	**1.15E+07**
Th-234	-	4.68E+05	-	4.40E+05	-	2.79E+07	-	6.04E+06	-	9.24E+04	**3.49E+07**
Pa-234	-	0.00E+00	-	7.03E+02	-	4.33E+04	-	9.66E+03	-	0.00E+00	**5.37E+04**
Pa-234m	-	4.68E+05	-	4.40E+05	-	2.79E+07	-	6.04E+06	-	9.24E+04	**3.49E+07**
U-232	-	8.52E+05	-	0.00E+00	-	1.33E+03	-	1.15E+07	-	1.84E+03	**1.24E+07**
U-233	-	1.52E+06	-	5.72E+04	-	8.26E+06	-	3.13E+08	-	0.00E+00	**3.23E+08**
U-237	-	2.75E+04	-	1.84E-06	-	3.69E-01	-	3.18E+05	-	3.82E+05	**7.27E+05**
Am-242		3.35E+05		0.00E+00		0.00E+00		7.87E+06		3.37E+06	**1.74E+08**
Am-242m		3.37E+05		0.00E+00		0.00E+00		7.91E+06		3.39E+06	**1.16E+07**
Cm-242		2.77E+05		0.00E+00		0.00E+00		6.51E+06		2.79E+06	**1.16E+07**
Cm-245		1.14E+05		0.00E+00		0.00E+00		0.00E+00		1.83E+06	**9.58E+06**
Cm-246		3.64E+05		0.00E+00		0.00E+00		0.00E+00		5.25E+06	**1.94E+06**

Note: Values marked in red are those used to calculate the composite total activity.

In assessing sample results, NMNTI (2017) provided an implied inventory for fission product/actinide contamination of the pressure tubes and other components within the reactor vault (Table B-2), which was used in the 2nd iteration PostSA.

A more applicable inventory for assigned fuel failure contamination within the reactor vault is derived from intrusive samples obtained from remote entry to the Reactor Vault which are then applied over the surface area applicable to the room (McVeigh, 2019a; Porter, 2022). These results were provided to supersede the NMNTI (2017) results in the 3rd Iteration PostSA (Table B-2). The same approach regarding the Reactor Vault contamination is taken in this 4th iteration, but the given inventory is multiplied by 3 to account for uncertainty.

Transportation and deposition of contaminants due to fuel failure and activation/corrosion product distribution throughout the Primary Coolant System are deemed to be suitably bounded by the inventory captured in the primary heat transport and moderator systems, Table B-3.

An alternative inventory was considered in sensitivity calculations for the 3rd iteration PostSA, using only the measurement data collected by NMNTI (2017) and (McVeigh, 2019a). This was considered likely to represent a more realistic inventory, but was adopted as a sensitivity case because the remaining uncertainties in the inventory mean that it was most appropriate to use a conservatively derived inventory as a point of reference. The same approach has been used in this 4th Iteration PostSA, using the same data as reported in Porter (2022). In addition, another sensitivity case examines the modelled inventory, used in NES, but multiplied by a factor of two.

Table B-2 Comparison of Assigned Fuel Failure Contamination Inventory and Measured Results

Radionuclide	Assigned 1st PostSA Inventory	Assigned 2nd PostSA Inventory (NMNTI, 2017)	Assigned 3rd PostSA Inventory CNL Sampling and Application (McVeigh, 2019a)	Assigned 4th PostSA Measured Inventory – Reactor Vault Contamination (Porter, 2022)*
	(Bq)			
H-3	-	-	7.62E+08	7.62E+08
C-14	-	-	2.97E+09	2.97E+09
C-36	-	-	2.79E+07	2.79E+07
Fe-55	-	-	1.53E+08	1.53E+08
Co-60	-	-	2.52E+08	2.52E+08
Ni-63	-	-	1.05E+09	1.05E+09
Se-79	6.20E+04	-	-	-
Sr-90	5.14E+09	2.63E+10	2.68E+10	2.68E+10
Zr-93	3.06E+05	-	-	-
Nb-93m	3.44E+04	-	-	-
Nb-94	1.96E+01	-	-	-
Tc-99	2.31E+06	-	1.76E+07	1.76E+07
Ru-106	2.27E-01	-	-	-
Pd-107	1.23E+04	-	-	-
Cd-113	5.11E+05	-	-	-

Radionuclide	Assigned 1st PostSA Inventory	Assigned 2nd PostSA Inventory (NMNTI, 2017)	Assigned 3rd PostSA Inventory CNL Sampling and Application (McVeigh, 2019a)	Assigned 4th PostSA Measured Inventory – Reactor Vault Contamination (Porter, 2022)*
	(Bq)			
Sn-121	1.07E+04	-	-	-
Sn-121m				-
Sn-126	7.60E+04	-	-	-
Sb-125	6.70E+04	2.69E+10	-	-
I-129	4.54E+03	-	-	-
Cs-134	1.65E+04	-	-	-
Cs-135	1.12E+05	-	-	-
Cs-137	6.79E+09	6.77E+10	4.11E+10	4.11E+10
Pm-147	1.32E+06	-	-	-
Sm-151	3.45E+07	-	-	-
Eu-152	3.74E+05	-	-	-
Eu-154	2.57E+07	-	1.60E+08	1.60E+08
Eu-155	1.53E+06	-	-	-
Ho-166	1.14E+01	-	-	-
U-232	6.85E+01	-	-	-
U-234	6.29E+04	-	-	-
U-235	5.60E+03	1.55E+03	-	-
U-236	4.58E+04	-	-	-
U-238	6.13E+04	1.98E+05	-	-
Np-237	1.37E+04	-	-	-
Pu-238	5.28E+07	1.55E+09	1.47E+08	1.48E+08
Pu-239	6.20E+07	5.07E+08	9.98E+08 (1)	9.98E+08 (1)
Pu-240	9.84E+07	-	See Pu-239	See Pu-239
Pu-241	2.03E+09	8.05E+09	-	-
Pu-242	1.22E+05	-	-	-
Am-241	1.53E+08	1.28E+09	1.49E+09	1.49E+09
Am-242m	1.06E+06	-	-	-
Am-243	2.19E+05	-	-	-
Cm-243	1.34E+05	-	-	-
Cm-244	1.17E+06	-	-	-

(1) Combined activity for $^{239/240}$Pu

* In the Normal Evolution Scenario, the Reactor Vault Contamination is multiplied by 3, to account for the uncertainty.

B 3.2.2 Boiler Room

At the time of shutdown, the total activity estimated to have been deposited in the primary heat transport and moderator systems had been estimated to be 8.5×10^{11} Bq (Presley, 1988). This estimate was derived from a diminutive amount of data thus resulting in significant uncertainties.

More recently, characterization of the primary heat transport system (PHTS) and moderator systems (MOD) has involved an initial intrusive sampling campaign coupled with a qualitative survey intended to provide information on the general distribution of radionuclides as held-up contamination throughout the system. In 2021 the characterization report for the PHTS and MOD systems was updated to use the revised CNL methodology to simplify total activity estimates and to comment on quantifying uncertainty (Psotka, 2021). Using the maximum activity per surface area values, for both the PHTS and the MOD system for both gamma emitters and hard to detect nuclides, provided an approximation of the total concentration of radionuclides within these systems (Porter, 2022). The estimate of the total internal surface area was then used to estimate the total inventory. The estimated total radionuclide inventory for the primary heat transport and moderator system can be found in Table B-3, below, which is an excerpt from Section 6 of Porter (2022).

Table B-3 Total Radionuclide Inventory for Primary Heat Transport and Moderator Systems (Psotka, 2021; Porter, 2022)

Radionuclide	Radioactivity (Bq)	
	Moderator System	Primary Heat Transport System
Am-241	8.94E+05	6.08E+08
Cs-137	3.57E+06	2.38E+08
Pu-238	1.16E+05	5.56E+07
Pu-239/240	7.72E+05	5.74E+08
Pu-241	7.91E+06	4.62E+09
Sr-90	2.03E+06	4.07E+09
C-14	1.18E+07	1.27E+07
Co-60	1.92E+07	3.51E+09
Eu-154	-	5.39E+07
Eu-155	-	1.39E+07
Ni-63	1.10E+08	2.41E+09
H-3	4.55E+10	8.22E+09
Total	**4.57E+10**	**2.44E+10**

Additionally, minor or subsidiary systems have been characterized by Psotka (2021) (also reported in Porter, 2022) either through direct sampling or by conservative application of the primary heat and moderator systems radionuclide fingerprint. These data are presented in Table B-4 below and reflect the inventory of the following systems:

- Reactor Vault Ventilation Cooling System (RVCS);
- Moderator Helium System (MHS);
- Moderator Demineraliser (MD);
- Reflector Circuit (RC);
- Heat Transport System Collection (HTSCo);
- Heat Transport System Emergency Injection (HTSEI);
- Heat Transport System Demineraliser (HTSD);
- Heat Transport System Charging (HTSCh);
- Heat Transport System Standby Cooling (HTSSC);
- Sample Lines;
- Drain Lines.

For the HTSCo system, Pu-241 activity was inferred activity from Am-241 ingrowth based on the age of the waste being approximately 35 years old (NPD shut down in 1987). Although the reactor ran from 1962 to 1987, dating the waste to 1987 provided the most conservative scaling factor (Psotka, 2022).

Table B-4 Total Radionuclide inventory for Other Systems (Psotka, 2022; Porter, 2022)

Radionuclide	Other Systems											Radionuclide Totals
	RVCS	MHS	MD	RC	HTSCo	HTSD	HTSEI	HTSCh	HTSSC	Sample Lines	Drain Lines	
H-3	4.42E+07	9.77E+07	7.55E+08	5.76E+06	1.09E+07	1.74E+09	5.96E+08	2.10E+08	2.31E+08	2.56E+08	1.09E+09	5.04E+09
C-14	1.69E+05	1.17E+06	2.20E+05	2.87E+04	4.36E+04	3.02E+06	1.03E+06	3.64E+05	4.00E+05	4.44E+05	1.90E+06	8.79E+06
Cl-36	3.67E+05	0	0	0	0	0	0	0	0	0	0	3.67E+05
Co-60	0	0	2.71E+05	7.59E+04	1.19E+05	6.34E+08	2.17E+08	7.63E+07	8.40E+07	9.32E+07	3.98E+08	1.50E+09
Ni-63	2.48E+05	0	2.02E+06	1.02E+05	7.32E+05	5.67E+08	1.94E+08	6.82E+07	7.52E+07	8.34E+07	3.56E+08	1.35E+09
Sr-90	0	0	3.61E+04	0	8.61E+06	9.24E+08	3.16E+08	1.11E+08	1.22E+08	1.36E+08	5.80E+08	2.20E+09
Cs-137	0	0	0	0	0	0	0	0	0	0	0	0.00E+00
Eu-154	2.58E+05	1.30E+05	6.35E+04	0	5.84E+06	5.41E+07	1.85E+07	6.51E+06	7.17E+06	7.96E+06	3.40E+07	1.35E+08
Eu-155	0	0	N/A	0	0	1.09E+07	3.72E+06	1.31E+06	1.44E+06	1.60E+06	6.84E+06	2.58E+07
Pu-238	0	0	N/A	0	0	2.47E+06	8.44E+05	2.97E+05	3.27E+05	3.63E+05	1.55E+06	5.85E+06
Pu-239/240	0	0	2.13E+03	0	8.22E+03	1.31E+07	4.47E+06	1.57E+06	1.73E+06	1.92E+06	8.20E+06	3.10E+07
Pu-241	0	0	1.44E+04	0	8.95E+04	1.37E+08	4.69E+07	1.65E+07	1.82E+07	2.01E+07	8.60E+07	3.25E+08
Am-241	0	0	1.33E+05	0	4.00E+05	9.97E+08	3.41E+08	1.20E+08	1.32E+08	1.46E+08	6.26E+08	2.36E+09
System Totals	4.52E+07	9.90E+07	7.58E+08	5.97E+06	2.68E+07	5.23E+09	1.79E+09	6.29E+08	6.93E+08	7.68E+08	3.28E+09	**1.33E+10**

***Note**: For system acronyms, see previous paragraph.*

B 3.2.3 Fuelling Machine Room

As discussed in 0 above, the characterization of other minor or subsidiary systems was reported in Psotka (2022) (also reported in Porter, 2022), providing activities by system. Pu-241 activity was inferred activity from Am-241 ingrowth based on the age of the waste being approximately 35 years old (NPD shut down in 1987). Although the reactor ran from 1962 to 1987, dating the waste to 1987 provided the most conservative scaling factor (Psotka, 2022).

The fueling system was sampled and resulting activities applied appropriately to derive a system total activity, summarized in Table B-5.

Table B-5 Estimated Inventory of the Fuel Handling System (Psotka, 2022; Porter, 2022)

Radionuclide	Total Activity (Bq)
H-3	9.34E+07
C-14	3.07E+05
Co-60	2.82E+07
Ni-63	1.00E+08
Sr-90	1.17E+09
Tc-99	1.45E+06
Cs-137	2.06E+09
Eu-154	4.35E+06
Pu-238	2.69E+07
Pu-239/240	1.07E+08
Pu-241	1.27E+09
Am-241	1.49E+08
Total	**5.01E+09**

In 2017 legacy waste at NPDWF was assessed to reduce the stored wastes within the facility and on completion, 27 drums were identified that would remain in the facility post-closure (Vickerd, 2017; Porter, 2022). The drums were conservatively assessed to contain a total activity of 4.19E+09 Bq, and included as a waste item located in the Fuelling Machine Room (Porter, 2022). However, the final decision of the inclusion of the drums within the NPDDF facility has not been reached yet, and there is a possibility that the drums will be removed from the facility. Hence, the drums are not considered in this 4th Iteration PostSA.

B 3.2.4 Fuel Storage Room

The fuel storage room contains no significant radiological inventory aside from facility structural contamination. This area was a discrete survey unit during the building characterization campaign reported in McVeigh (2018a). Table B-6 provides the summary activity for this room.

It is noted that the activity concentration from the Fuel Storage Room is accounted for in the total radiological inventory within the below-grade facility structure (nuclear area), discussed in Section B 3.2.6, so it is not considered as a separate room in the model.

Table B-6 Summary of the Radiological Inventory of the Fuel Storage Room

Radionuclide	Activity Concentration (Bqg^{-1})	Activity (Bq)
H-3	1.44E-02	5.7E+09
C-14	6.74E-01	1.3E+07
Cl-36	2.50E-02	4.9E+05
Co-60	9.74E-04	1.9E+04
Sr-90	2.45E-02	4.8E+05
Tc-99	1.55E-02	3.1E+05
Cs-137	8.29E-01	1.6E+07
Pu-238	2.52E-02	5.0E+05
Pu-239/240	2.12E-02	4.2E+05
U-235	7.63E-03	1.5E+05
U-238	4.49E-02	8.9E+05
Total		**5.73E+09**

B 3.2.5 Turbine Room

Stevenson *et al*. (2017) provides volumes and weight estimates for demolition waste from the above grade NPD building. It also provides recommendations on how to place the demolition waste in the available space in the below grade structure. It confirms it is possible to place all above-grade demolition material into the condenser room (i.e., Turbine Room in the PostSA model).

Sampling and analysis have been conducted for concrete floor and lower walls in various rooms and is summarized in McVeigh (2018b). Tritium is the predominant radionuclide in the samples, however elevated concentrations of Cs-137 and Co-60 were also noted in a few samples from the Non-Nuclear Area. A total radiological inventory for the above-grade structure has been determined from these results and Table B-7 provides the total radiological inventory in the above-grade structure.

Table B-7 Total Radiological Inventory in the Non-Nuclear Area, Above-grade Structure Concrete Assumed to be in the Turbine Room

Radionuclide	Activity Concentration (Bqg^{-1})	Activity (Bq)
Am-241	5.31E-03	1.44E+06
C-14	1.90E+00	2.72E+08
Cs-137	4.02E-02	1.39E+06
Cl-36	1.43E-01	2.49E+07
Co-60	1.79E-03	3.64E+05
Ni-63	6.40E-02	1.18E+07
Pu-238	5.83E-03	2.79E+06
Pu-239/240	8.20E-03	9.96E+05
Sr-90	2.83E-02	4.80E+06
Tc-99	8.49E-03	1.52E+06
H-3	2.52E+02	4.65E+10
U-235	8.76E-03	1.78E+06
U-238	8.08E-02	2.55E+07
Total		**4.69E+10**

Also included in the Turbine Room inventory is asbestos from the boiler room. This asbestos waste is radiologically contaminated from operational incidents and accidents. The estimate of the radiological inventory of the 175 m^3 of waste presented in Table B-8 was determined by the previous laboratory analysis which indicated tritium as the only radionuclide present in detectable levels Kinectrics (2015). This is added to the Turbine Room inventory in the PostSA model.

Table B-8 Total Radiological Inventory from Generated Asbestos Waste

Radionuclide	Total Estimated Radioactivity (Bq)
H-3	1.83E+12

B 3.2.6 Facility Structure

Sampling and analysis have been conducted for concrete floor and lower walls in various rooms and summarized in McVeigh (2018b). Whereas the Non-Nuclear Area inventory has been assigned to the Turbine Room (see Section B 3.2.5), the balance of the facility structure is captured here and comprises the Nuclear Area (Table B-9). Tritium and C-14 are the predominant radionuclides in the samples; however, elevated concentrations of Cs-137, Am-241, Co-60 and Sr-90 were also noted in a few samples from the Nuclear Area. In order to provide a conservative estimate of radiological inventory as a result of contaminated facility structures, the following inputs or assumptions were used:

- The total surface areas within the below-grade Non-Nuclear and Nuclear Areas were summed.
- A maximum depth of 15 mm was assumed for the depth of contamination in the structure (for tritium this figure was doubled to account for its greater expected penetration depth).
- For each radionuclide, the mean concentration was calculated for the respective Non-Nuclear or Nuclear Area data.
- All radionuclide concentrations were applied over 100% of the available surface area and to the corresponding mass of material dependent on depth, resulting in a significantly conservative margin.

Table B-9 Total Radiological Inventory Within the Below-Grade Facility Structure

Radionuclide	Activity Concentration (Bqg^{-1})	Activity (Bq)
Am-241	2.21E-03	7.62E+05
C-14	1.84E+02	7.82E+10
Cs-137	9.64E-02	4.60E+07
Cl-36	9.42E-02	1.69E+07
Co-60	9.64E-03	3.23E+06
Ni-63	6.66E-02	7.12E+06
Pu-238	3.02E-02	9.70E+06
Pu-239/240	1.14E-02	2.15E+06
Sr-90	5.29E-02	1.21E+07
Tc-99	1.75E-02	3.39E+06
H-3	2.27E+03	1.75E+12
U-235	7.41E-03	1.93E+06
U-238	7.33E-02	3.12E+07
Total		**1.83E+12**

B 3.3 Non-Radioactive Contaminant Inventory

The inventory of non-radioactive contaminants is dominated by those frequently found at historic industrial facilities.

B 3.3.1 Lead

There is lead paint throughout the NPDDF, and in many places this paint has begun to chip off (Neville, 2015). Schruder & Vickerd (2017) have used sampling information to derive the mass of lead in paint.

There is also a significant quantity of lead associated with shielding. This lead is distributed throughout a number of rooms, with the majority located in the Fuelling Machine Room and its adjacent rooms. Much of the shielding lead is part of the NPDDF structure, e.g., as shot infill into voids (in select floors/ceilings), lead lining of doors and walls, and lead-containing bricks.

For the purposes of the PostSA, the lead inventory is assigned to rooms based on information from Schruder & Vickerd (2017) and Arcadis & Quintessa (2019) (also outlined in Porter, 2022), its original location, and taking into account decommissioning works:

- Turbine Room – 335 kg;
- Fuelling Machine Room and adjacent rooms – 173,690 kg, as follows:
  - Shielded cubicle rooms (2): 44,495 kg each, so 88,990 kg total;
  - Lead shot in the roof of the shielded cubicle Rooms (2): 7,924 kg each, so 15,848 kg total;
  - Floor Shield Gates (2): 22,852 kg each, so 45,704 kg total;
  - New Fuel Room – loose lead shielding brick wall: 23,148 kg total.
- Reactor Vault – 25,000 kg;
- Spent Fuel Storage Room – 7,300 kg, as follows:
  - Spent Fuel Storage Room: 4,500 kg (encased in steel);
  - Active Auxiliaries Room: 2,800 kg (lead shielding wall).
- Boiler Room – 18,797 kg;
- Below-Grade Lead Paint (distributed throughout below-grade structure): 397 kg.

B 3.3.2 Mercury

There is some limited mercury contamination in the boiler room. This is estimated to be less than 0.01 kg (Schruder & Vickerd, 2017; Porter, 2022).

B 3.3.3 Asbestos

Asbestos is present in the form of pipe insulation, floor tiles and building cladding (Athauda-Arachchige, 2015). Removal of accessible asbestos pipe insulation and equipment insulation from the non-nuclear areas was completed at the time of shutdown. During the SWS phase, all safely accessible asbestos has been removed from the nuclear area. The 2016 Waste Management Plan (Gillespie, 2016) includes information concerning asbestos wastes.

The current inventory estimate (Schruder & Vickerd, 2017; Porter, 2022) is dominated by 165 m^3 of waste stored outside the NPDDF in Sealand containers. There is also estimated to be around 20 m^3 in the walls of the above grade facility, and 10 m^3 in transite panels. In the below ground parts of the facility there is around 5 m^3 in the Reactor Vault and 30 m^3 in the Boiler Room (including asbestos containing materials in walls and penetrations throughout the nuclear area).

For the purposes of the PostSA it can be assumed that the above ground waste is relocated into the basement of the control wing (Turbine Room in PostSA model), so the inventory is:

- Turbine Room – 195 m^3
- Reactor Vault – 5 m^3
- Boiler Room – 30 m^3

B 3.3.4 PCBs

CNL will be removing all PCB ballasts in the facility before or during decommissioning. Therefore, there will be no PCBs remaining in the NPDDF at the time of closure.

B 3.3.5 Oils

All systems were drained during Phase I of decommissioning thus no significant volume of oil is anticipated within the facility. Evidence of a historical oil leak was found on the northwest corner of the main building and remediation was undertaken (ORAU, 2016) in the past.

B 3.3.6 Organic Materials

There will be some organics in the waste disposed within the NPD building, including organic additives in cement grout, polythene (polyethylene) bags, and asphalt from the roof that will be collapsed into the disposal facility (Arcadis, 2021). The available evidence suggests that the organic materials are unlikely to be significantly detrimental with respect to radiological risk. In addition, in safety assessments for radioactive waste disposal facilities in other countries, these (or similar) materials are not considered detrimental to safety. For more details, the reader is referred to Arcadis (2021).

The organic materials are therefore not explicitly considered in this safety assessment.

B 3.4 Uncertainties

Information on activation products within the reactor vault materials is considered to be of good quality.

The new verification work undertaken by Edwards & Adams (2019) indicates that the reference inventory used in this 4th Iteration PostSA (also used in the 3rd Iteration PostSA) is likely to be well within a factor of 2 and probably better for the analyzed radionuclides, based on the same assumptions concerning the operating history of the NPD. It may be possible that other activation products are present due to trace impurities in the materials which might be of significance, particularly where these involve long half-lives. Examples include Be-10 (from Be) and Pd-107 (from Pd).

The work by NMNTI (2017), used as a sensitivity case in this 4th Iteration PostSA, provides valuable additional information on the radionuclide content of structures within the Reactor Vault. Comparison of these results with the new activation product inventory estimated by Adams & Edwards (2019) suggests that the latter may be an overestimate by a factor of two, and significantly greater for some key radionuclides such as Ni-59. Though, measurement data are not available for Ag-108m, a particularly important radionuclide.

Some radionuclides also appear to have been underestimated when calculated by modelling, most notably tritium and C-14 in concrete and steels. This is likely to be due to the assumed composition of the materials.

Overall, whilst there remain uncertainties in the inventory, stemming from the modelling results, the measurements strongly suggest that the modelled inventory is significantly conservative. Whilst there remain these uncertainties, the modelling estimates together with the measured results therefore form a conservative, composite inventory which is used as a reference inventory in this 4th Iteration PostSA. See Appendix E (Models & Data) for the specific values used in this assessment.

The objective of the wider NPDDF sampling and characterization plan was written to limit the upper bound of the uncertainty of radionuclide inventories. The objective was 80% Upper Confidence Limit (UCL) of the mean concentration as results were utilized for waste disposition as opposed to a clearance decision. Although the distribution of radioactive contaminants varies dependent on their physical form, mobility, location, etc., the appropriate UCLs were generated using the results of sampling for the building and systems. At 80% confidence the average difference between the estimated mean and the UCL is less than a factor of 2 and at 95% this rises to a factor of 3.5 for the Nuclear Area structure (3 for the Non-Nuclear Area). A factor of 3 is therefore used to increase the inventory everywhere except the Reactor Vault to take into account the uncertainty in the inventory (more details are presented in Appendix E).

B 4 SUBSURFACE ENVIRONMENT

B 4.1 Tectonic Setting and Seismicity

The NPDDF site lies on the eastern edge of the Ottawa-Bonnechere Graben, an ancient rift valley in the Canadian Shield of Northeastern Ontario and Quebec (Figure B-13). This Graben was formed from the movement of two major fault zones known as the Mattawa and Petawawa faults. These faults are still active and are the source of earthquakes, such as the magnitude 6.2 Timiskaming earthquake in 1935 and the magnitude 5.2 Kipawa earthquake in 2000.

The NPDDF site lies within a zone categorized as a region with moderate seismic risk. Based on a probabilistic estimate of seismic disturbances for the next 100 years, the magnitude of peak horizontal velocity and peak horizontal acceleration have been shown to be quite low. A number of earthquakes have occurred in the vicinity of the NPDDF site. Of most relevance is the magnitude 5.0 Val-des-Bois, Quebec earthquake of 2010. This earthquake occurred in a region of moderate earthquake activity known as the West Quebec seismic zone. The largest historically damaging earthquakes in the region include a magnitude 6.0 near Montreal (Quebec) in 1732, a magnitude 6.2 near Timiskaming (Quebec) in 1935 and a magnitude 5.8 near Cornwall (Ontario) in 1944. Two moderate earthquakes have occurred near Timiskaming (Quebec) in 2000 of magnitude 5.2, and Plattsburgh (New York State) in 2002 of magnitude 5.1. Like the Val-des-Bois event, both of these moderate sized earthquakes were widely felt in Ontario, Quebec and the northern United States. Two moderate earthquakes occurred near the Ontario-Quebec border of magnitude 5.2 and magnitude 4.1 aftershock (near Shawville, Quebec) in 2013 and were felt in both provinces. A magnitude 4.0 earthquake, occurring about 30 km from Chalk River in 1963, would also have been strongly felt.

Figure B-13 Tectonic Setting of the NPDDF Site (Figure modified from Wikipedia)

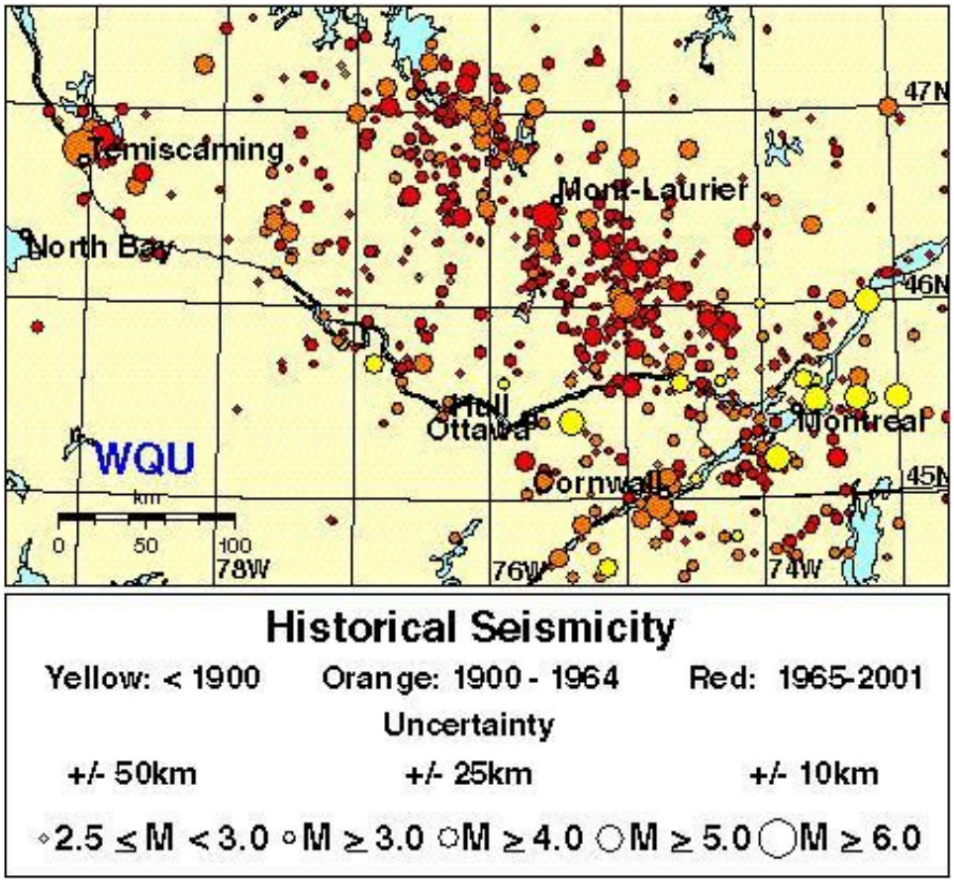


The strongest shaking of the site in the last 100 years was caused by the Timiskaming earthquake in 1935. Examination of seismic data since 1661 (Figure B-14) indicates some significant earthquakes have occurred in the region at greater distances from the NPDDF: in 1732 near Montreal (estimated magnitude of 6.0), 1816 near Montreal (estimated magnitude of 5.5 to 6), in 1929 at Attica, New York State (magnitude of 5.2), in 1983 in the Adirondacks of northern New York State (magnitude of 5.6), and in 1988 south of Chicoutimi, Quebec (magnitude of 6.0).

The outcome of the NPD Underground Structure Seismic Assessment (CNL, 2021) indicates that parts of the underground structure of NPDDF are not able to withstand a Chalk River Laboratories Design Basis Earthquake (CRL DBE), 1/10,000 years, and 1/50,000 years seismic event after grouting of the structure. As per the results obtained in this assessment, shear failures/cracks are the dominant failure modes for all cases. Below the bedrock elevation level, the NPDDF structure is socketed into surrounding bedrock on all sides and does not experience structural failure/cracking due to the continuous lateral support provided by the bedrock. The grouted structure, as well as the lateral support provided by the bedrock increases the stiffness of the NPDDF structure.

The preliminary slope stability assessment (Arcadis & Geofirma, 2021d) that considers earthquake-induced soil liquefaction, shows that the North Slope under current water level conditions is stable under static loading conditions and under loading conditions associated with a 1:2,250-year earthquake. Parts of the North Slope are stable, while some parts of the North Slope are unstable under a 1:10,000-year earthquake. The North Slope is likely to fail during a 1:50,000-year earthquake. It is unlikely that the predicted failures of the North Slope will result in the direct exposure of groundwater to a new ground surface that would be established following earthquake induced slope failures. Slope failures at the North Slope are expected to result in accumulations of failed granular materials on the lower half of the North Slope. Given the permeable nature of all soils that comprise the North Slope, the expected redistribution of soils following slope failure is unlikely to change groundwater flows from the NPDDF to the Ottawa River. For more details, the reader is referred to the preliminary slope stability assessment (Arcadis & Geofirma, 2021d).

Figure B-14 Regional Seismicity



B 4.2 Bedrock Geology and Resources

A detailed discussion and synthesis of geologic information for the site and the surrounding region is presented in the 2021 update of the Geosynthesis Report (Arcadis & Geofirma, 2022). Summary information is presented below.

As outlined in the Geosynthesis Report (Arcadis & Geofirma, 2022), bedrock at and in the local and regional area of the NPD site is Precambrian Canadian Shield. Historical regional mapping of the Precambrian bedrock places the NPD site within the lithostructural Opeongo Domain of the Algonquin (Lac Dumoine) Terrane of the Central Gneiss Belt, of the Grenville Province of the Canadian Shield. The Central Gneiss consists mainly of upper amphibolite and local granulite facies, quartzofeldspathic gneisses chiefly of igneous origin (orthogneiss) with subordinate paragneisses (sedimentary origin). Local bedrock geology in the vicinity of the NPDDF site is mapped by OGS as layered biotite gneisses and migmatites of uncertain protolith with minor amphibolite mafic gneiss. Similar bedrock lithology as light and dark hornblende biotite gneiss with relative mineralogical composition of biotite ~ hornblende < quartz and < plagioclase occurs at the adjacent Des Joachims hydroelectric power site.

For local on-site bedrock, mapping of bedrock outcrops (completed in 2019) identified NPD bedrock geology as interlayered granitic to monzonitic gneiss and biotite hornblende gneiss with minor gabbroic gneiss. Core logging of shallow bedrock boreholes (also completed in 2019) showed that subsurface bedrock is principally an interlayered sequence of metre-scale bands of granitic gneiss and hornblende gneiss, with minor bands of dioritic gneiss and hornblende K-feldspar gneiss. Metre-scale to sub-metre-scale pegmatite dykes and occasional diabase dykes intrude the gneissic rock sequence. Although these bedrock descriptions appear different, they are all consistent with the best overall description of the bedrock rock type at the NPD site as migmatitic biotite gneiss. Therefore, based on this information, the inferred mineralogy is plagioclase>quartz>K-feldspar>amphibolite~biotite. Based on Streckeisen ternary plot, the dominant lithologies at the NPD site vary from granite/granodiorite to quartz monzodiorite to quartz diorite to diorite/gabbro.

Results of a lineament mapping study completed over a 20 km by 20 km area centred on the NPDDF site, show that major brittle structures as faults oriented east-southeast – west-northwest (120-140º azimuth) are located north of the site, along the Ottawa River and south of the site in line with a series of small lakes including Colton Lake, Tee Lake, Lower/Upper Pergeon Lake (from northwest to southeast). A series of less well-defined east-southeast – west-northwest, north-south and east-west trending lineaments are located within close proximity to the site; however, there is no evidence to suggest that any of these lineaments extend to or within the NPD or NPDDF site boundaries.

The Geosynthesis Report (Arcadis & Geofirma, 2022) also examined the potential for economic geologic resources and found that economic geological resources in the vicinity of the NPD site include mining and aggregate pits and quarries. There is one active mining claim, for gneiss and granite building stone, located 12 km west of the NPDDF site at Mackey, Ontario and a past-producing silica sand and feldspar mine located north of Mackey on the Ottawa River. There are also two discretionary mineral occurrences for anorthosite and graphite located 13 km southwest and 28 km southeast, respectively of the NPDDF site. Several aggregate pits and/or quarries are located in the immediate vicinity with two former aggregate pits

located on the NPD site. Ultimately, significant future development of mineral extraction in close proximity to the NPDDF is not expected.

B 4.3 Surficial Geology

A detailed discussion and synthesis of information on the surficial geology of the site is presented in the 2021 update of the Geosynthesis Report (Arcadis & Geofirma, 2022). Summary information is presented below.

The NPDDF site is located on the northeast-facing slope of a former glacial and current fluvial spillway of the Ottawa River. The elevation of the ground surface drops from 164 meters above sea level (mASL) near Highway 17, to 128 mASL at the NPD buildings, to 111 mASL at the Ottawa River. In the area of the NPDDF buildings and structures, the post-glacial fluvial sand gravel deposits of the spillway are mixed with sand and gravel fill to form the surficial overburden and directly overlay bedrock. Elsewhere the fluvial sand and gravel deposits overlay silty sand to sand, gravel and cobble and boulder glacial till. Total overburden thickness ranges from about 2 m near the Ottawa River, 5 to 6 m adjacent to the NPDDF, to about 15 to 18 m southwest of the NPDDF, thinning to 5 to 7 m near Highway 17. The noteworthy bedrock high at borehole MW18-06 (Arcadis & Geofirma, 2022) creates an overburden thickness of about 3.0 m and limits the southeastward extent of the fluvial sand and gravel unit from the area of the NPDDF. Overburden thickness northwest of the NPDDF thins to zero where bedrock is exposed in the northwest part of the NPD site. Near and southwest of Highway 17 the glacial till is the surficial overburden.

Close to the reactor building, information on the overburden has been obtained. Pits show a thickness between 1.5 m and 7.5 m of generally clean, poorly sorted sand and gravel overlying a thin boulder till. The sand and gravel are highly permeable, providing good drainage and low water holding capacity.

During preparation of the site for construction, the overburden was removed and bedrock exposed at an elevation of about 123 m. Following construction of the subgrade portions of the NPDNGS, concrete was poured around the building to the height of the bedrock and then local fill (bouldery sand fill) was used to bring the surface to current grade at 128 m. The fill is approximately 5 m thick. In many cases, it was difficult to distinguish· between the fluvial deposited sand and gravel and the derived boulder sand fill.

B 4.4 Hydrogeology & Groundwater Modelling

Tile Drain System

A tile drain system with perforated steel pipe was installed in a shallow trench in the bedrock surface and surrounds the station on the east, south and west sides at an approximate elevation of 123 m (see Figure B-15). The drain intercepts water flowing towards the NPDDF and diverts it around the facility. Tile drain 1 collects substantial quantities of groundwater flowing along the base of the overburden and flows in this drain are seasonal.

There is little to no discharge from tile drain 2, suggesting the drain may be above the current water table level. Based on video inspection of tile drain 1, the tile drains show surface wear due to corrosion, the presence of significant flow, and the presence of debris sand and gravel. Video inspection is limited due to significant flows, although large pockets of debris sand and gravel were observed. Corrosion of the top of the pipe has occurred at approximately halfway between the building and the river, referred to as the "break" in the tile drain. The video inspection of tile drain 1, starting at manhole 1 and headed west, found a large increase in flow along this portion of the drain. This is discussed further under Groundwater Modelling (subsequent subsection).

The outlets of the tile drains are on the shoreline of the Ottawa River, 1 m to 2 m from the river depending on river elevation.

Figure B-15 Tile Drain Layout and Invert Elevations (Shkarupin & Miller, 2016)



Conceptual Hydrogeology (Arcadis & Geofirma, 2022)

A detailed discussion and synthesis of hydrogeologic information for the site is presented in the 2021 update of the Geosynthesis Report (Arcadis & Geofirma, 2022). Summary information is presented below.

Local groundwater flow systems and, to a lesser degree, intermediate groundwater flow systems at the NPD site are influenced by recharge rates, topography and geology. Local groundwater flow systems within the permeable sandy overburden will be the dominant groundwater system at the NPDDF site. These local groundwater flow systems will likely be recharged near Highway 17 and will discharge along the ground slope extending northeast to the Ottawa River and directly to the Ottawa River. Intermediate groundwater flow systems will likely exist at the NPDDF site between topographic highs located southwest of Highway 17 near Tee Lake with discharge to the Mattawa Fault and the Ottawa River. These intermediate flow systems will likely extend to depths of about 50 to 150 m based on available groundwater chemistry data and the elevation changes between bedrock near Tee Lake and the Ottawa River (~ 100 m).

The available geological and hydrogeological data for the NPD site supplemented by similar regional information from the CRL property and surrounding area indicate that the hydrogeology of the NPDDF site is conveniently described with reference to five hydrostratigraphic units. The five hydrostratigraphic units at the NPDDF site are:

- **The sand and gravel fill unit:** including reworked fluvial deposits and excavated bedrock is the youngest hydrostratigraphic unit. It is present near the NPD buildings and in the area northeast of the buildings that were subject to excavation for construction of the water intake line, discharge line, and tile drains between the buildings and the Ottawa River. Fill thickness at the NPD site is variable ranging from about 2 m near the Ottawa River to about 5-6 m near the NPD building.

- **The fluvial sand and gravel unit:** is the most widespread overburden unit at the NPD site and is the youngest hydrostratigraphic unit consisting of native material. It includes sand with various amounts of gravel, boulders and trace amounts of silt. The thickness of this hydrostratigraphic unit ranges from 5 m to 10 m at the NPD site.

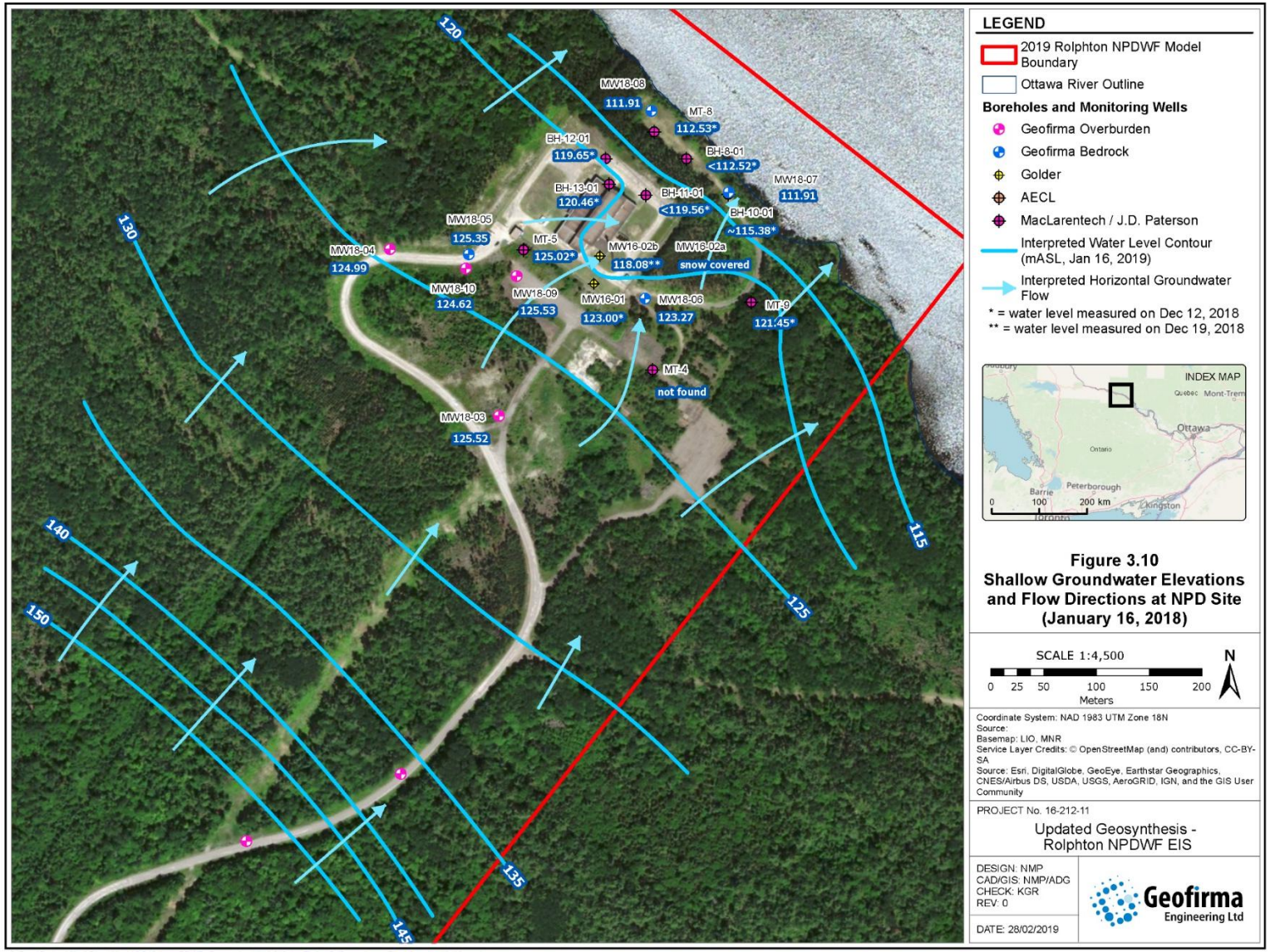
- **The silt to cobble glacial till hydrostratigraphic unit:** is the most widespread overburden hydrostratigraphic unit at the NPD site. It is found at ground surface near Highway 17 and at depth below the fluvial sand and gravel hydrostratigraphic unit northeast of Highway 17 on the NPD site. The upper metre or so of the silt to cobble glacial till unit has been locally subject to fluvial erosion by wave action resulting in a texture and likely hydraulic conductivity similar to the overlying fluvial sand and gravel unit. The thickness of the silt to cobble glacial till unit ranges from 0 to 2 m near the NPDDF up to 5 to 10 m northwest and southeast of NPDDF.

- **The boulder glacial till hydrostratigraphic unit:** is the oldest overburden unit at the NPD site and locally directly overlies competent bedrock in areas of bedrock depression. It consists of metre-size boulders with granular matrix material and underlies silt to cobble glacial till and fluvial sand and gravel where the silt to cobble till is absent. It is found northwest and southwest of the NPDDF, with thicknesses of 2 to 5 m.

- **The shallow bedrock hydrostratigraphic unit:** at bedrock depths of 0 to 50 m is the only bedrock unit considered for the NPDDF site based on the depth of excavations completed for construction of the NPDNGS (about 18 m into rock) and the assumption that essentially all of the local groundwater flow in bedrock will occur in the upper 50 m of bedrock.

Figure B-16 shows contoured water level measurements and interpreted directions of horizontal groundwater flow in overburden units and the uppermost intervals in shallow bedrock based on January 16, 2019 data.

Figure B-16 Shallow Groundwater Elevations and Flow Directions at NPD Site (Arcadis & Geofirma, 2022)



Major ion and trace element chemistry and radiological chemistry of the tile drain water as reported from sampling in 1990, 2014 and 2019 are very similar to shallow overburden groundwater at the NPDDF site. This similarity and plotting of major ion chemistry of tile drain water and other water types at the NPD site on Piper diagrams shows that groundwater from the area of Landfill 1 and the reactor area are the most likely sources of water to the tile drains. This is entirely reasonable as these two groundwater types are in close proximity to the tile drains or are clearly upgradient of the tile drains. Piper diagrams also show that upper and lower shallow bedrock groundwater and Ottawa River water are not sources of water to the tile drains.

Groundwater flows in the saturated sand and gravel fill, fluvial sand and gravel and glacial till hydrostratigraphic units are predominantly from southwest to northeast across the NPD site toward the tile drains and the Ottawa River. Groundwater flow via the sand and gravel backfill of the pumping intake and discharge line bedrock excavations is also a potentially important flow pathway for the NPD site under high water table conditions. For shallow bedrock, the predominant groundwater flow direction assuming a lack of major structural features such shear zones and faults is also from southwest to northeast toward the Ottawa River.

Recharge of the local groundwater system at the NPDDF site occurs primarily in the highland area northeast and southwest of Highway 17 where glacial till is exposed at surface. Some recharge also occurs on the upslope areas of the site between Highway 17 and Landfill 1 and near Landfill 2 where permeable alluvial (fluvial sand and gravel) deposits are exposed at surface. Groundwater discharge areas as springs and wetlands were historically noted on the overburden ground slopes northwest of NPDDF and between the area of the NPDDF and the Ottawa River prior to NPD construction. These springs are no longer observed at the site due groundwater collection by the tile drains.

A large portion of groundwater southwest and west of the NPD building, at least as far as Landfill 1 and likely upgradient of Landfill 1 and toward Landfill 2, discharges to the tile drain system that was trenched into the surface of the bedrock, surrounds the NPD reactor building and drains into the Ottawa River. Groundwater flow in the underlying shallow bedrock discharges upward to the overlying overburden in the area upgradient of the NPDDF, but mostly discharges to the Ottawa River either directly or via the Mattawa Fault that defines the course of the Ottawa River.

Groundwater Modelling (Arcadis & Geofirma, 2023a)

A detailed discussion and synthesis of hydrogeologic information for the site is presented in the 2021 update of the Geosynthesis Report (Arcadis & Geofirma, 2022), and detailed documentation of groundwater modelling is presented in the Groundwater Modelling Report (Arcadis & Geofirma, 2023a) and its companion report Near-field Groundwater Model (Arcadis & Geofirma, 2023b). Summary information is presented below.

Groundwater flow modelling for the NPD site was first completed in 2016 (Arcadis & Geofirma, 2016). The groundwater model was then updated in 2017 (Arcadis & Geofirma, 2017a) to encompass more detailed information from facility drawings, as well as water level and hydraulic conductivity measurements that had become available since the original 2016 modelling work. The groundwater model was updated in 2018 (Arcadis & Geofirma, 2018) in response to external comments, adding improved model discretization of the

facility, improved model domain boundary description, an alternative description of the tile drains (as seepage nodes rather than high-permeability features), and additional sensitivity and calibration cases. Groundwater modelling was updated in 2019 (Arcadis & Geofirma, 2019b) to incorporate the results of a detailed site characterization field program as well as the findings of the 2019 Geosynthesis Report (Arcadis & Geofirma, 2019a). The 2019 version of groundwater flow model was able to obtain satisfactory calibration by extending the model domain to the west and including permeable overburden features parallel to the river consistent with the geology at the site and some of the features observed in site characterization boreholes. A near-field groundwater flow and transport model was also developed in 2019, to provide detailed flow and transport information within and in the vicinity of the NPD facility. The near-field model considers only a small section of the groundwater flow model, obtaining boundary conditions from the groundwater flow model.

In 2023, an update to the groundwater model, near-field model and resaturation model (Arcadis & Geofirma, 2023a,b,c) considers the following:

- Inclusion of a deep section of tile drain 2, identified under the pressure-relief pit and connecting to the tile drain discharge pipe to the north-east of the building, downstream of manhole 3. This information was missing from previous groundwater flow models.
- Changes to CNL's planned concrete cap and engineering cover design.
- Updates to the measured tile drain flow data.
- Additional cases examining different material properties.
- Post model calibration, the models include grouted pipes in the pipe trench between the facility and the river.

For details of the calibration results, including best-estimates of material properties for each of the model layers (incorporating site characterization data), the reader is referred to the most recent versions of the Geosynthesis Report (Arcadis & Geofirma, 2022) and the Groundwater Modelling Report (Arcadis & Geofirma, 2023a).

Figure B-17 and Figure B-18 show the resulting calibrated velocities and groundwater table elevations (in plan view and cross section, respectively), corresponding to initial conditions early in the assessment timeframe when the tile drains are functioning and the facility concrete and grout and not yet degraded. The locations of the cross sections in Figure B-18 are shown by the vertical lines in Figure B-17.

Figure B-17 Plan View Showing Calibrated Model Water Table Elevations and Velocities (Arcadis & Geofirma, 2023a)

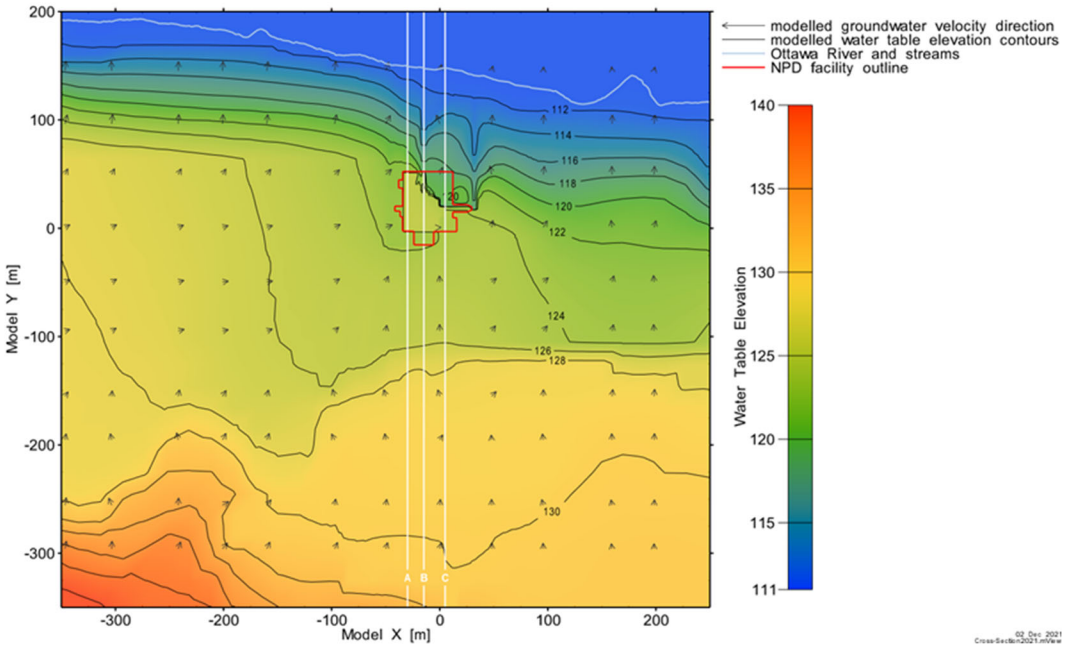
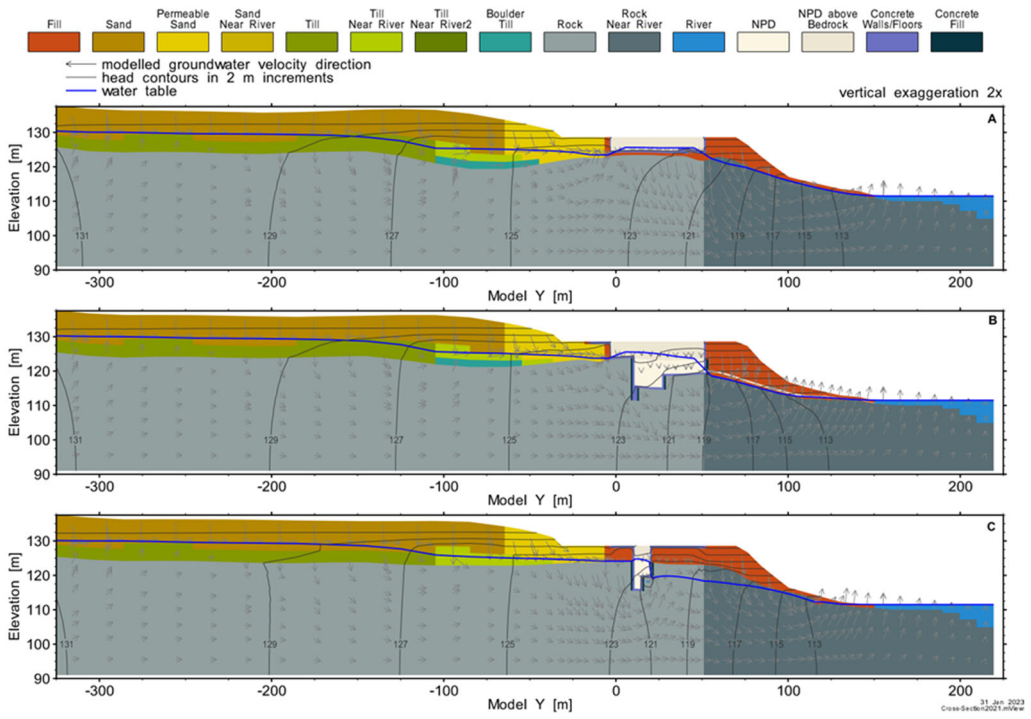


Figure B-18 Cross-Sections Showing Calibrated Model Head Contours, Velocities and Water Table (Arcadis & Geofirma, 2023a)



Groundwater modelling also included cases that align with PostSA scenarios., These correspond to particular time frames and conditions; for example, there are cases representing conditions for the first 100 y post-closure (year 0 to 100), for year 100 to year 1000 post-closure, and for year 1000 and onward post-closure. Table B-10 presents groundwater modelling results for flows through the facility, corresponding to initial conditions early in the assessment timeframe (i.e., 0 to 100 years post-closure), when the tile drains are functioning, and the facility concrete and grout are not yet degraded. (Note that the water mass balance errors in these post-simulation groundwater flow calculations can be attributed to the calculation method used by the groundwater flow model (see Arcadis & Geofirma, 2023a, Section 4.2)).

Table B-10 Groundwater Flows Through the NPD Facility (NES – 0 to 100 years) (Arcadis & Geofirma, 2023a)

m^3/s	Flow In	Flow Out	Difference
Lower Bedrock (102-111 m)	8.43E-10	7.62E-10	8.16E-11
Middle Bedrock (111-120 m)	2.38E-09	4.65E-09	-2.27E-09
Upper Bedrock (120-122 m)	2.77E-09	1.37E-09	1.41E-09
Saturated Overburden (above 122 m)	8.15E-11	5.68E-10	-4.86E-10
Recharge	1.34E-09	-	1.34E-09
Total	7.41E-09	7.34E-09	6.79E-11

Table B-11 presents groundwater modelling results for later conditions (i.e., 100 to 1000 years post-closure), when the tile drains are no longer intact and the cap is degraded.

Table B-11 Groundwater Flows Through the NPD Facility (NES – 100 to 1000 y) (Arcadis & Geofirma, 2023a)

m^3/s	Flow In	Flow Out	Difference
Lower Bedrock (102-111 m)	7.87E-10	8.77E-10	-8.99E-11
Middle Bedrock (111-120 m)	2.29E-09	6.82E-09	-4.54E-09
Upper Bedrock (120-122 m)	4.63E-09	5.29E-09	-6.59E-10
Saturated Overburden (above 122 m)	4.44E-09	5.74E-09	-1.30E-09
Recharge	6.10E-09	-	6.10E-09
Total	1.83E-08	1.87E-08	-4.85E-10

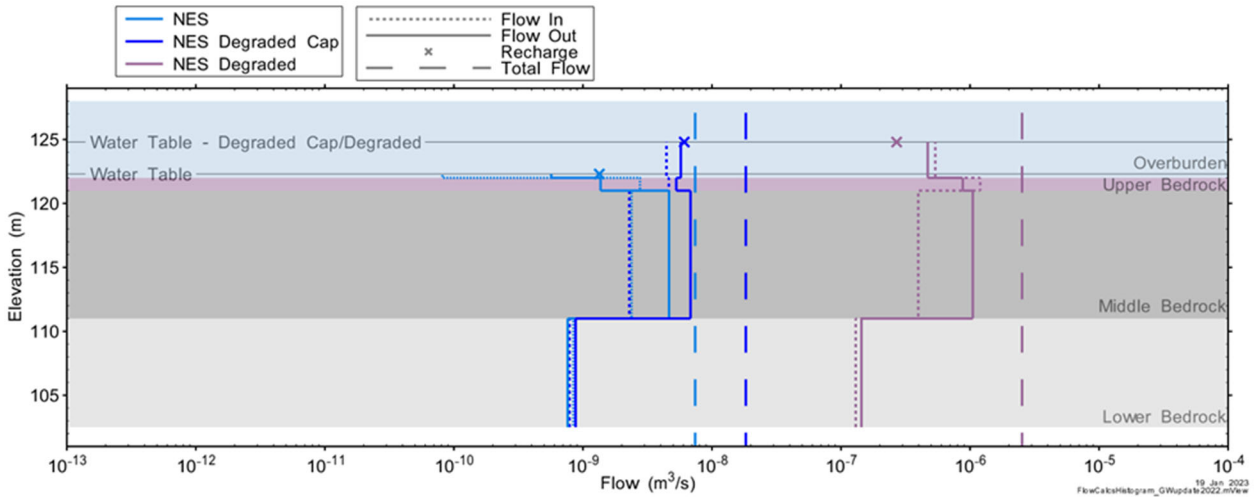
Table B-12 presents a summary of groundwater flows for much later conditions (i.e., 1000+ years post-closure), when the structure has also degraded.

Table B-12 Groundwater Flows Through the NPD Facility (NES – 1000+ years) (Arcadis & Geofirma, 2023a)

m^3/s	Flow In	Flow Out	Difference
Lower Bedrock (102-111 m)	1.30E-07	1.44E-07	-1.37E-08
Middle Bedrock (111-120 m)	3.97E-07	1.05E-06	-6.57E-07
Upper Bedrock (120-122 m)	1.20E-06	8.78E-07	3.18E-07
Saturated Overburden (above 122 m)	5.38E-07	4.70E-07	6.84E-08
Recharge	2.70E-07	0.00E+00	2.70E-07
Total	2.53E-06	2.54E-06	-1.43E-08

Figure B-19 shows flow through the building by comparing these three cases. From the results, it is evident that the sand, fill and tile drains dominate the flow response around the facility, with the facility hydraulic conductivity having a negligible impact on groundwater flows in the geosphere adjacent to the facility. Failure of the tile drains results in a slight decrease in geosphere flows adjacent to the facility with geosphere flows dominated by overburden flows. Failure of the tile drains also results in a small increase in the very small amount of flow entering the facility (approximately 35%). Springs also develop along the steep bluff downgradient of the facility. Degradation of the cap and cover also result in a small increase in recharge into the facility. When the building is degraded, and its hydraulic conductivity increased (i.e., in the 1000+ years post-closure case), flow through the building increases by two orders of magnitude, with only 11% increase attributable to increased recharge (Arcadis & Geofirma, 2023a).

Figure B-19 Flow Through the Building. Comparison of NES 0-100 years, NES 100-1000 years and NES 1000+ years Cases (Arcadis & Geofirma, 2023a)



For additional information and results the reader is referred to the 2022 groundwater modelling report (Arcadis & Geofirma, 2023a).

Resaturation (Arcadis & Geofirma, 2023c)

Detailed documentation of resaturation modelling is presented in the 2023 Resaturation Report (Arcadis & Geofirma, 2023c). Summary information is presented below.

Resaturation modelling for the NPD site was first completed in 2017 (Arcadis & Geofirma, 2017b). Resaturation modelling was updated in 2019 (Arcadis & Geofirma, 2020) to align with the up-to-date conceptual hydrogeology for the site (i.e., geosynthesis) and the 2019 groundwater model. Resaturation modelling was again updated in 2023 (Arcadis & Geofirma, 2023c) to incorporate information from the recently updated groundwater flow model (Arcadis & Geofirma, 2023a).

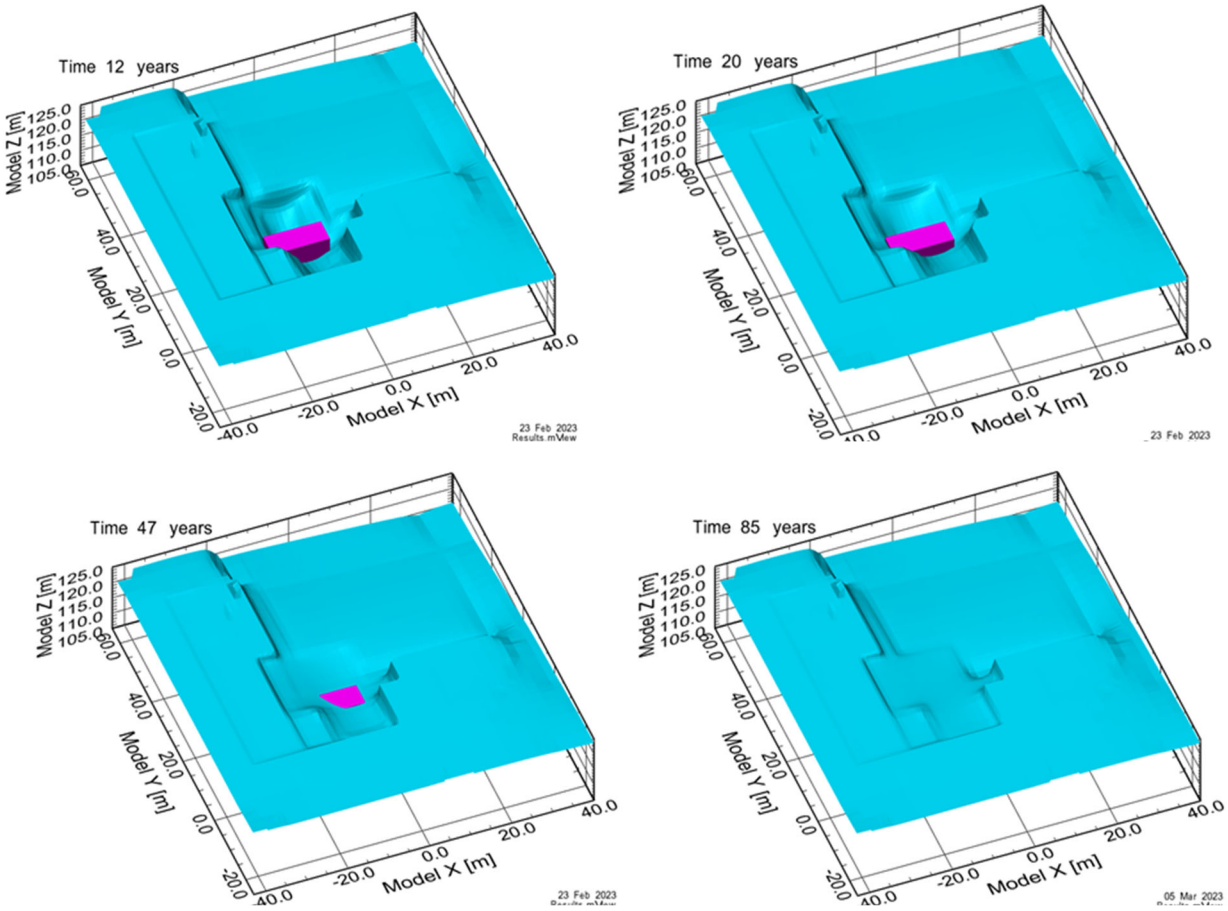
The resaturation model was built to investigate the timescales over which the NPDDF will resaturate once it is closed, and, to provide estimates of infiltration through the engineered cover and cap. The resaturation model differs from the groundwater model in that the resaturation model includes an improved description of the building dimensions and also describes the fill between the building and bedrock as concrete. Resaturation simulations were performed using TOUGH2 software, a general-purpose numerical simulation program for multi-phase fluid and heat flow in porous media developed and maintained by Lawrence Berkeley National Laboratory.

The resaturation model obtains its boundary conditions from the groundwater model, more specifically, it uses groundwater conditions corresponding to the first 100 years post-closure where the cap and facility have not yet degraded, and the tile drains are functioning.

Resaturation of the facility is assumed to have occurred (i.e., be complete) once water pressures within the facility have equilibrated with the surrounding geosphere, and groundwater flow is no longer oriented towards the interior of the facility. Due to residual gas saturations, some gas is still present within the facility once resaturation is considered complete. Based on a visual assessment, facility resaturation occurs at approximately 85 years. Water reaches the bottom of the reactor vault around 12 years, although water flowing through the reactor vault is still directed towards the interior of the facility. Figure B-20 presents the results as a three-dimensional view of the rising water table, at 12, 20, 47, and 85 years. The location of the Reactor Vault in Figure B-20 is indicated by the lilac box.

For additional information and results the reader is referred to the 2023 resaturation report (Arcadis & Geofirma, 2023c).

Figure B-20 Three-Dimensional View of Water Table at 12, 20, 47, and 85 years (Arcadis & Geofirma, 2023c)



Near-Field Groundwater Transport Through the Grouted Facility (Arcadis & Geofirma, 2023b)

Detailed documentation of near-field groundwater transport modelling is presented in the 2023 Near-Field Groundwater Model Report (Arcadis & Geofirma, 2023b). Summary information is presented below.

The near-field model was first developed in 2019 as a sub-set of the groundwater flow model (Arcadis and Geofirma, 2019c). The purpose of the near-field model was to quantify the groundwater flow moving between the different model compartments (facility rooms) considered in the post-closure model. It also included transport calculations to improve the understanding of transport between the rooms and the eventual discharge to the tile drains, springs along the hillside, and river. The Arcadis & Geofirma (2019c) study identified that, with the exception of the very degraded facility (far future), groundwater flow enters each room primarily through the top of the room (rather than the sides), and leaves primarily through the

bottom of the room. The amount of flow leaving through the bottom of the room decreases, and the amount leaving through the sides increases, in deeper rooms, while the majority of flow still leaves through the bottom. For a very degraded facility (far future), large amounts of groundwater enters the south side of each room, and leaves out the north side. The Arcadis & Geofirma (2019c) study also quantified room-to-room flows and transport paths; these were used to align the 3rd iteration PostSA model for consistency.

The near-field model was most recently updated in 2023 (Arcadis & Geofirma, 2023b). The same three scenario cases considered by the groundwater flow model were also modelled with the near-field flow and transport model.

Groundwater generally flows from the south-west to the north-east across the facility. Within each room, some water also flows in the top and out the bottom of the room. The total amounts of water flowing through each room is small, less than 30 L/year through the reactor vault for the NES 0 to 100 years case, 32 L/year for the NES 100 to 1000 years case, and 5,000 L/year for the NES 1000+ years case.

In the geosphere, flow is dominated by the deep tile drain 2 trench, except near the river where the tile drain 2 trench merges with the surrounding overburden. Geosphere flows are generally unaffected by changes to building material properties; e.g., the NES Degraded Cap and NES Degraded cases with no tile drains are similar, as the only difference in the cases are the hydraulic conductivities of the building materials.

The Arcadis & Geofirma (2023b) study also quantified room-to-room flows and transport paths; these were used to align this 4th iteration PostSA model for consistency.

For additional information and results the reader is referred to the 2023 near-field groundwater modelling report (Arcadis & Geofirma, 2023b).

B 4.5 Groundwater Chemistry

A detailed discussion and synthesis of hydrogeochemistry and groundwater quality information for the site is presented in the Geosynthesis Report (Arcadis & Geofirma, 2022). Summary information is presented below.

Overburden Groundwater

Previous studies (e.g., Killey (2014), Golder Associates Ltd. (2017), McVeigh (2018a), MacLarentech (1990), and Killey & Munch (1988, 1989)) provide a detailed summary of historical groundwater quality for the shallow (typically <12 mBGS) overburden at the NPD site, including groundwater quality in the vicinity of Landfill 1, Landfill 2 and the reactor buildings or NPD Station. More recent measurements have been obtained from a 2019 characterization field program, which focused on characterization of field parameters, major ions, trace metals, tritium, and gross beta and alpha. The 2019 field campaign included sampling and testing of deeper overburden groundwater (~12 to 20 mBFS).

Based on results from the 2019 field characterization program (synthesized in Arcadis & Geofirma, 2022), relatively deep overburden groundwater is dilute, Na-HCO_3 type with Ca-Cl/SO_4 as subordinate major ions.

Elevated Total Dissolved Solids (TDS) and $NaCl/SO_4$ signatures relative to historical overburden groundwater analyses likely reflects road salting of upgradient Highway 17 and NPD site roads (NaCl), deeper sampling intervals and influence of shallow bedrock groundwater (SO_4). Compared to historical overburden groundwater, the 2019 overburden groundwater is slightly less oxidizing. Tritium concentrations measured in 2019 are comparable to historical sampling of overburden at the NPD site with concentrations of <100 Bq/L, which is also less than the Health Canada tritium drinking water guideline of 7,000 Bq/L (HC, 2019). Gross alpha activity and gross beta activity were found to be between 0.25 Bq/L and 1.1 Bq/L. These activities are slightly higher than values reported for shallower overburden in Killey (2014). The reported gross alpha activity (1.1 Bq/L) at one particular well slightly exceeds Health Canada screening level of 0.5 Bq/L (HC, 2019). For more detailed results and their corresponding monitoring well locations, the reader is referred to the 2021 Geosynthesis Report (Arcadis & Geofirma, 2022).

Shallow Bedrock Groundwater

There were no historical studies of shallow bedrock groundwater chemistry at the NPD site specifically; historical information must instead be obtained from studies at the CRL property and used to infer conditions at the NPD site. This lack of historical data was a driver for the 2019 field characterization program to include sampling and analysis of shallow bedrock groundwater in order to close this information gap.

The 2019 groundwater sampling and testing program focussed on characterization of field parameters, major ions, trace metals, tritium, gross alpha activity and gross beta activity of shallow bedrock groundwater. Additionally, four CMT (continuous multi-channel tubing for multilevel groundwater monitoring) installations located downgradient of the NPDDF that showed elevated gamma readings in borehole geophysical logging were analyzed for radionuclides. No radionuclides were detected above reporting detection limits of 0.1 to 5 Bq/L. Data show that shallow bedrock groundwater at the NPD site in proximity to the NPDDF is dilute, predominantly Na-HCO_3 type with Ca-Cl/SO_4 as subordinate major ions. Compared to inferences from CRL data, the 2019 shallow bedrock groundwater at NPD is slightly more oxidizing as evident by lower iron concentrations. Relatively elevated tritium concentrations of 650 to 1350 Bq/L were reported at two wells upgradient of the NPDDF. Downgradient of the NPDDF tritium concentrations are lower at <100 to 190 Bq/L. Gross alpha and gross beta activity in shallow bedrock range from <0.10 Bq/L to 3.7 Bq/L. The cause of the elevated tritium concentrations in shallow bedrock upgradient of the NPDDF is not known. For more detailed results and their corresponding monitoring well locations, the reader is referred to the 2021 Geosynthesis Report (Arcadis & Geofirma, 2022).

*Other Geochemical Modelling – Grout Flushing and Lead Solubility (*Arcadis & Quintessa, 2020a,b)

Since the proposed grout formulation involves a BFS:PC blend rather than a PC blend, Arcadis & Quintessa (2020a) undertook geochemical modelling to understand the leaching and degradation behaviour of this blend. The flushing model developed in Arcadis & Quintessa (2020a) shows the progressive leaching of C-S-H or C-A-S-H by infiltrating water, leading to incongruent dissolution (decrease in Ca/Si in the solid) and calcite precipitation, and pH returning to “ambient” conditions after ~4000 pore water replacements. For further details and results, the reader is referred to the original Arcadis & Quintessa (2020a) document.

Based on the predicted grout degradation from Arcadis & Quintessa (2020a), a follow-up study (Arcadis & Quintessa, 2020b) was then undertaken to understand how this grout degradation behaviour could influence the mobility of lead (since there are considerable quantities of lead in the NPDDF). Arcadis & Quintessa (2020b) used thermodynamic modelling, as well as estimated pH changes from Arcadis & Quintessa (2020a), to: identify possible solubility-limiting solid phases for lead; identify lead solubility limits for the different pH ranges; and, to estimate lead sorption values (Kd values) for different flushing periods. For further details the reader is referred to the original Arcadis & Quintessa (2020b) document. The resulting solubility and sorption values selected for use in this PostSA are described further in the Models & Data Section (5) and its associated Appendix (E).

Other Geochemical Modelling – Alkalinity (Arcadis & Quintessa, 2020c)

Reactive transport simulations have also been developed to explore the potential for the development of an alkaline plume in subsurface water at the NPDDF due to the leaching of the grout (Arcadis & Quintessa, 2020c). A 2D model was constructed and three simulation cases were run using three different hydraulic conductivities. The results for pH show the evolution of pH in the facility and also downgradient of the facility, for 3 time periods. The results for porosity show the evolution of grout porosity within the facility over time. Results also identify the evolution of solids for each of the 3 cases, over time. Overall, Arcadis & Quintessa (2020c) concluded that modelling results suggest that it is unlikely that highly alkaline porewater arising from bulk grout leaching will lead to a significant elevation of pH downstream of the facility.

B 4.6 Uncertainties

The gaps between the bedrock and the exterior concrete walls of the facility were backfilled with concrete; however, the degree to which the concrete fills all the gaps is not clear and there is little information available on the type of concrete and its condition. This could have an impact on water flows around the NPD, as noted in relation to resaturation (Arcadis & Geofirma, 2023c).

The tile drain and the trench for the cooling pipes are likely to represent key elements in the hydrogeology of the site. The response of the hydrogeology to freeze and thaw cycles may also be of importance.

Uncertainty in the extent and hydrogeological properties of the fluvial sand and gravel layer located northwest of the NPDDF will have a negligible effect on the rate and location of overburden groundwater discharge from the NPDDF to the Ottawa River and hence the NPD closure and post-closure phases (Arcadis & Geofirma, 2022). Resolving the uncertainty on the location and hydrogeological properties of this fluvial sand and gravel layer would enhance the confidence in the 3-D groundwater flow model and the volumes of tile drain water, but that uncertainty primarily concerns the completeness of the site characterization work and not the fate of overburden groundwater discharge from the NPDDF to the Ottawa River (Arcadis & Geofirma, 2022).

Uncertainty in shallow bedrock hydrogeochemistry does not likely pose an adverse effect to closure and post-closure phases because, although there is some uncertainty in shallow bedrock groundwater chemistry, that uncertainty will have a negligible effect on the rate and location of groundwater discharges from the NPDWF to the adjacent Ottawa River (Arcadis & Geofirma, 2022). Minor changes in shallow groundwater chemistry will not change the fact that shallow bedrock groundwater from the NPDWF will discharge to the Ottawa River immediately northeast of the NPDWF with relatively short transit time (Arcadis & Geofirma, 2022). This uncertainty relates entirely to the completeness of site characterization work and not to the fate of overburden groundwater discharge from the NPDWF to the Ottawa River (Arcadis & Geofirma, 2022).

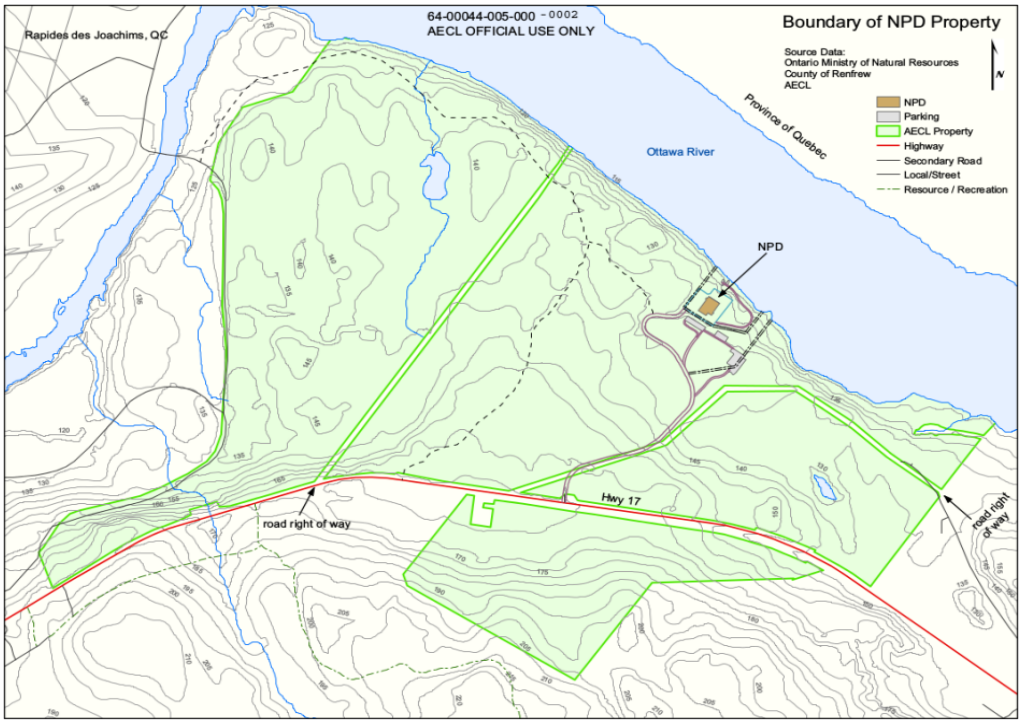
B 5 SURFACE ENVIRONMENT

B 5.1 Topography

The terrain in the vicinity of the NPDDF consists of gently rolling hills, interspaced with many small lakes. The topography is significantly different in the Laurentian hills on the other side of the river as the river follows a major fault line.

The NPDDF site is situated next to the Ottawa River, at an elevation of approximately 129 mASL (Geobase, 2011). The site is situated on a relatively flat area, dipping from a topographic high beginning on the north side of Tee Lake (approximately 225 mASL), to Ontario Highway 17, which has an elevation of approximately 164 mASL, continuing to the Ottawa River which has an average elevation of 111 mASL (Figure B-21).

Figure B-21 Topography of the NPD Site



During the construction of the NPDNGS, numerous man-made terraces and steep interconnecting benches were created for construction and security purposes. This activity has resulted in a highly modified landscape at the site.

B 5.2 Atmosphere

The meteorology and climate are similar to the conditions prevailing at Chalk River Laboratories located near the village of Chalk River, about 25 km to the southeast along the Ottawa River. The climate of the area is classified as humid continental, with warm summers, cold winters, and no distinct dry season.

Monthly precipitation has ranged from approximately 4 mm to 239 mm of water equivalent over the period 1961 to 2012. Over this period, the average annual precipitation (rain and snow) was 859 mm (Government of Canada, 2016), and the maximum and minimum for any given year was 1079 mm in 1972, and 667 mm in 2012 respectively.

Daily mean temperatures range from -12°C in January to 20°C in July (Leeson, 2016). The historic minimum is -36.3°C and the historic maximum is 36°C (Leeson, 2016).

The distribution of winds and directions shows little variability seasonally or annually. The winds are predominantly northwest and southeast parallel to the Ottawa River with wind speeds reaching over 20 km h^{-1}.

According to an article in the North Renfrew Times on 1984 July 15, a tornado touched down in the area between Deep River and Rolphton causing one death, many injuries and extensive damage along the Upper Ottawa Valley and Quebec.

This tornado lasted about 10 minutes, and the trees were flattened in the path of the tornado along the Ottawa River to just north of the Ontario Highway 17. The damage seemed to be limited to an area of about 2 km wide. The estimate of property damage was low, and the damage was confirmed mainly to outbuildings and a personal vehicle (Athauda-Arachchige, 2015).

Forest covers much of the NPDDF site and surrounding area. Forest fires may result from extremely dry conditions, lightning or human activities (e.g., campfires). Some pests, such as pine beetle, damage and kill trees, which increases the amount of dry, dead organic matter that can provide fuel for a fire. Firebreaks have been cut through forests on the site to minimize the risk of the spread of fire and to facilitate the fighting of a forest fire (Athauda-Arachchige, 2015). No records of the frequency of wildfires have been determined.

B 5.3 Surface Water Bodies

The Ottawa River is the dominant drainage feature in the area. All surface drainage on the NPDDF site ultimately drains to the Ottawa River. The Ottawa River is a large river with an average flow of 807 m^3 s^{-1} (ORRPB, 2020).

The probability of unplanned flooding by river water is not considered likely because control of the river water level is exercised by OPG's Des Joachims Generating Station, approximately 3 km upstream from NPD. The flow past the Des Joachims Dam is regulated according to the demands of the generating station and is zero for several hours of the month. The highest recorded level of the Ottawa River at NPD is 114 mASL. Seasonal fluctuations in the level of the river, between 110 m and 114 mASL, do not affect NPD.

In 2017, CNL completed a study which compared and summarized information from two OPG studies on potential Probable Maximum Flood (PMF) events along the Ottawa River (the first OPG study was completed in 1999 followed by an update in 2016). According to CNL (2017), the scenario that produced the PMF was a 1-in-10,000-year (i.e., 10^{-4} probability of occurrence) Probable Maximum Precipitation (PMP) event centered on the Lake Temiskaming basin, combined with 1-in-100-year snow accumulation. The 1999 flood elevation level estimated at Deep River was 131.1 mASL and at the NPD site was 132.2 mASL, whereas the 2016 estimate at Deep River was 117.8 mASL (a 2016 estimate was not provided specifically for the NPD site). CNL (2017) concluded that these conditions have a probability of occurrence of 10^{-6} y^{-1} and as such is considered to be a beyond design basis event.

There is no evidence for large scale extraction of groundwater for drinking water. The Laurentian Hills community of Chalk River derives its water from a lake and makes provision for testing water samples from wells belonging to individuals (http://www.laurentianhills.ca/). Downstream, the drinking water supply for most of the residents in Deep River is from the Ottawa River.

As discussed in Section B 4.4, at the NPDDF site, the Precambrian basement is likely to have a low permeability and overlying sands and gravels drain rapidly to the river.

B 5.4 Soil and Land Use

The river terraces in the area are overlain with a fluvial deposit of Uplands series soil. The topsoil is generally relatively thin but is sufficient to support forest. It is possible that in the future soil could develop if the processes that washed fine particles away from the ground surface no longer occur.

The NPDDF site is in a remote area, with relatively low population density. The Town of Laurentian Hills has a population of approximately 2,800 distributed over an area of 640 km^2 and contains the former village of Chalk River and the former hamlets of Point Alexander, and Rolphton.

The nearest population centers are Rapides des Joachims (population roughly 170, 3 km northwest) and Deep River (population roughly 4,200, 17 km southeast). To the west of NPD is the United Townships of Head, Clara, and Maria (population roughly 230, over an area of 730 km^2). Individual residents of Laurentian Hills live within 1 km of the facility boundary. The closest resident property is at Point Stewart on the Ottawa River, 1 km downstream of NPD.

With the exception of the Rapides des Joachims dam, there are no nearby industrial activities. Small businesses, such as mechanical garages and heavy equipment suppliers are located in the surrounding area.

The surrounding land is primarily used for recreational activities, such as the presence of sport and outfitter activities. Agricultural activities in the area are limited to garden plots managed by residents. Sport fishing is carried out in lakes outside of the NPDDF property, as well as in the Ottawa River, but there is no commercial fishing in the area.

The relatively short growing season and the typically poor soil quality mean that there are no significant commercial agricultural uses of the land, although in the past logging took place. The nearest area of significant agriculture and dairy farming is approximately 40 km downstream on the Quebec side of the river and 60 km downstream on the Ontario side. Approximately, 65 km downstream on the Ontario side of the Ottawa River is the city of Pembroke, which is the closest location of any significant industrial activity.

B 5.5 Biota

B 5.5.1 Plants

The NPDDF site is mainly wooded with the exception of open wetland areas. Wooded uplands generally range from 40-80 years old. Wetland areas on the NPDDF site are mainly found on the western half of the property, away from the well-drained margins of the river on which the NPDDF is constructed. The ecology is typical of the local natural and semi-natural environment. As noted, the land is not suitable to support any commercial agricultural development apart from forestry.

The ecology of the region is characteristic of the Eastern forest-boreal transition which includes broadleaf and mixed forest. This includes areas of lowland conifer forests (spruce, fir, pine and birch) as well as mixed hardwood and conifer forest on richer soils, where maple and beech are also present. In the wetland areas mats of moss can occur with a tree cover of spruce and tamarack.

No nationally or provincially endangered or threatened species of plants have been identified or recorded on the NPDDF site.

B 5.5.2 Wildlife

The less disturbed forest can be home to a complex and well-established wildlife ecosystem including many invertebrates and reptiles and birds such as various duck and other bird species.

The region supports larger mammals although rarely in high density. This includes wolves and coyotes, cougar, moose, black bear, lynx, snowshoe hare and white-tailed deer.

The nine species at risk that have been reported at the NPDDF site include: Bald Eagle, Chimney Swift, Common Nighthawk, Eastern Wood Pewee, Eastern Milksnake, Eastern Small-footed Myotis, Little Brown Myotis, Northern Myotis and the Monarch Butterfly.

At present the main species of concern are the Chimney Swifts as they roost in the ventilation stack during migration. The ventilation stack will be retained as part of the decommissioning plans in order to mitigate the risk associated with jeopardy of the Chimney Swift.

B 5.5.3 Aquatic Fauna and Flora

The NPDDF site is located in the reach of the Ottawa River extending approximately 90 km between La Passe and the Des Joachims Dam. This reach of the river consists of several lakes separated by short

rapids and supports diverse warm-water and cool-water fish communities consisting of at least 55 documented species. The provincially-rare fish species in the Ottawa River includes the American eel, lake sturgeon and river red horse. Typical catches from the river include walleye, northern pike, channel catfish, smallmouth bass, and lake sturgeon.

B 5.6 Uncertainties

The site and its surrounding environment are well characterized with considerable information available to characterize the land use and ecology. The poorly developed soil and semi-natural forested environment is, however, less frequently studied in post-closure safety assessment studies. Consequently, aspects such as plant and animal uptake factors may represent an important source of uncertainty.

In addition, safety assessment studies typically envisage (cautiously) the agricultural use of the site. In this case, such a land use, and associated exposure pathways, is unlikely for a considerable period of time due to the limiting factors of climate and soil quality.

B 6 APPROPRIATENESS FOR RADIOACTIVE WASTE DISPOSAL

Fundamentally, site characteristics are required that contribute to the objectives of the isolation and containment of radioactive wastes. In the context of the lower hazard offered by wastes suitable for near-surface disposal, there is less need to rely on the geological environment than is the case with higher active wastes. This is because engineered structures can provide a system of barriers that compensate for, and complement, aspects of the host environment.

When developing a disposal concept, site characteristics (both physical and chemical) are evaluated (in the manner described within this section) to ensure that the disposal system design is compatible with the site characteristics. This process is described by IAEA (2001). Following the multi-barrier principle, specific site characteristics can be balanced by appropriate technical solutions (e.g., use of cement-grout barriers) based on an understanding of the effects of relevant physical and chemical parameters within the disposal system. The objective is to compensate any limitations of the site with improved performance of the other parts of the system. The detailed design will therefore always be fully site-specific.

The key site characteristics that contribute to safety are shown in Table B-13. The site has clear benefits resulting from the established presence of the NPDDF for many decades. In addition to this, the geological setting provides a stable and predictable environment to contain and isolate the waste. Contaminants that are released from the facility are not substantially retained in the geosphere, but this does not limit the performance of the system, because the strong controls on groundwater transport result in its dispersal in the very large body of water that is the river, rather than a localized discharge to a smaller watercourse, or soils. Finally, while there is a degree of seismicity in the wider region, the NPDDF is embedded in the rock mass, mechanically a very strong environment. The risk of surface erosion due to the river is mitigated by the very large catchment of the river leading to predictable conditions, and evidence is provided by the limited post-glacial evolution of the location.

Table B-13 Site Characteristics Important to Radioactive Waste Disposal

Existing infrastructure and services	The NPDWF already exists at the site and has been present for over 50 years. In that time the site has been subject to monitoring to determine any effects on the facility, and vice-versa. Suitable infrastructure and services exist for the disposal of the waste at the site, or (e.g., in the case of grouting) can be readily brought to site.
Space availability	The NPDWF is already present at the location, with ample space available for any ancillary works required as part of the waste disposal.
Proximity to waste arisings	The wastes are present within the NPDWF; disposal within the Facility prevents the need for removal of the wastes, off-site transport, and disposal elsewhere. These (operational) factors are discussed elsewhere in the EIS.
Topography	The site is characterized by a dominant slope towards the Ottawa River, a legacy of the geological history of the region. The inclined bedrock slope provides a very strong control on the behavior of groundwater, meaning its movement and pathways are predictable and readily characterized. In relation to safety performance, the topographical control means that groundwater flowing from the NPDDF will be directed to the river as a point of release. This has a beneficial safety function as it means there is very limited potential for localized accumulation of contaminants in surface soils and sediments.
Climatology and hydrology	The climate and hydrology are well established by measurements and shown to be relatively predictable. The dominant surface water feature, the Ottawa River, is managed by dams; but, at the location of the site, the size and scale of the total river catchment means that it is very unlikely to be subject to major changes in flow.
Geological structure and its properties (geomechanics, geomorphology, fissures, faults, seismicity, etc.)	The geological structure of the site is established and predictable. There are no significant fracture zones apparently intersecting the location of the excavation for the NPDWF. The wider location does exhibit a degree of seismicity, but significant occurrences are located away from the site, mainly towards the north. As such, the bedrock geological environment can be concluded to be stable and robust. This is overlain by an overburden laid down since the last ice age. While having limited mechanical benefits to the NPDDF, this acts as barrier to protect the underlying features.
Hydrogeological and geochemical features (permeability, groundwater flow pattern, water chemistry, retardation processes, etc.)	Records from the original construction indicate that the bedrock is of low permeability. Subsequent hydrogeological testing (e.g., as synthesized in Arcadis & Geofirma, 2019a) substantiates this interpretation, and indicates that the bedrock will have a very limited role in the performance of the disposal system. The overburden, by contrast, is relatively unconsolidated and permits relatively high flow rates of groundwater, mainly at its base, with the water table sitting up to a few metres above the bedrock). This system permits relatively rapid transport of contaminants from the NPDDF to the river, leading to the overall conclusion that the geological barriers have a limited function in retaining contaminants, but strongly influence their migration pathway towards the river.
Geomorphological processes	The landscape has been shaped by glacial action, but is otherwise relatively stable. The slope from the Facility to the river could potentially be subject to erosion, but local evidence suggests it is stable, particularly with the anchoring vegetation.

IAEA (2001) note that the design can take into account, using safety assessment as a tool, the various events and processes (some normal, some abnormal and some accidental) that can significantly influence the safety of the disposal facility during the regulatory period of concern. Safety assessment can quantify the significance of these effects, and therefore provide a guide as to the overall suitability of the site. Furthermore, the outcomes of the safety assessment can aid the design to minimize the impact of such events and processes. In this respect, scenarios and calculation cases considered in the safety assessment provide further evidence of the suitability of the site.

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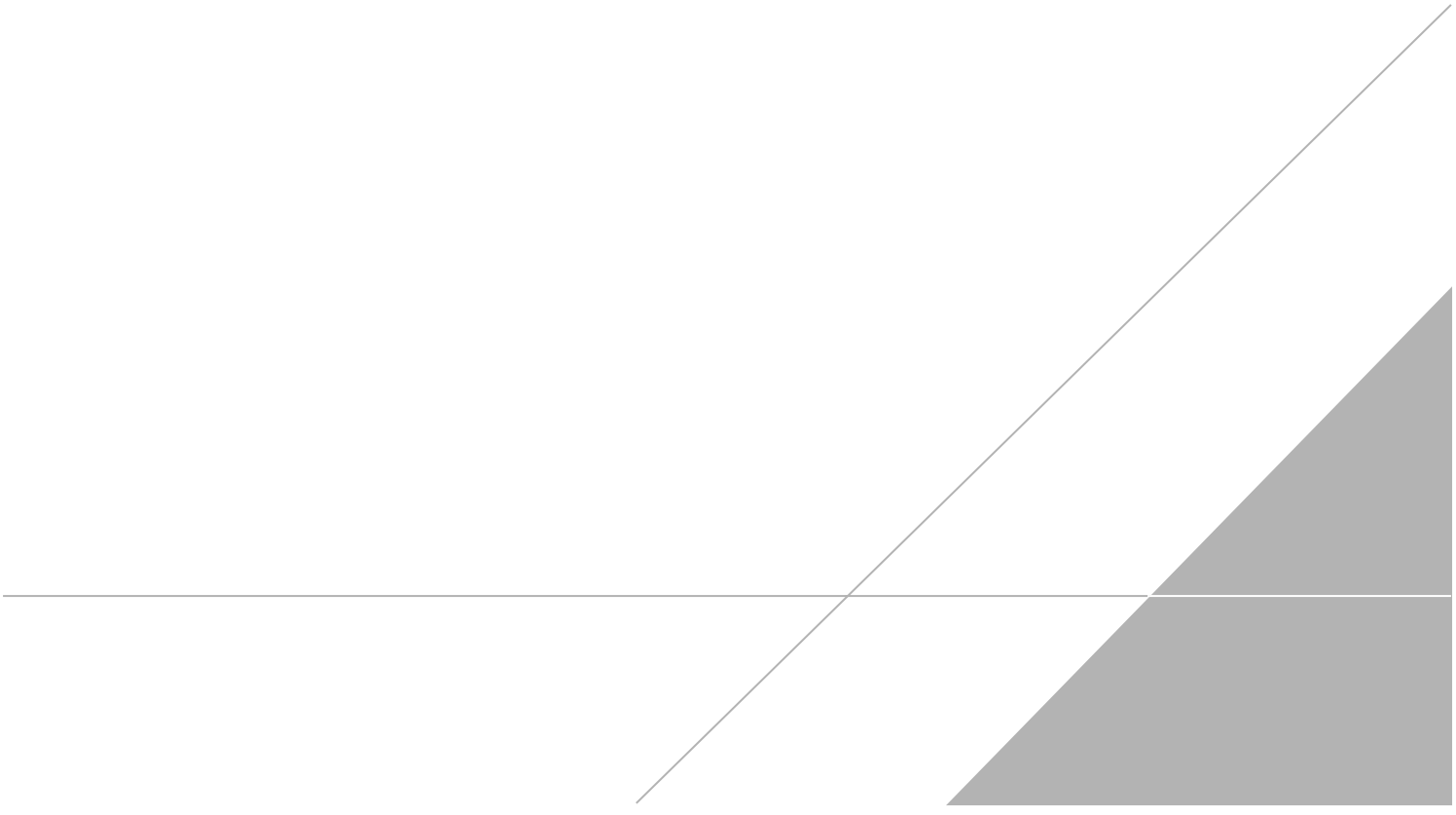
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APPENDIX C: FEATURES, EVENTS AND PROCESSES



APPENDIX C - FEPS

C 1 INTRODUCTION

Canadian Nuclear Laboratories (CNL, acting on behalf of Atomic Energy of Canada Limited, AECL) is proposing in-situ disposal of the Nuclear Power Demonstration Waste Facility (NPDWF), thereafter referred to as the Nuclear Power Demonstration Disposal Facility (NPDDF). This 4th Iteration Postclosure Safety Assessment (PostSA) will support the final EIS submission.

This 4th Iteration PostSA has been undertaken using international best practice, specifically the International Atomic Energy Agency's (IAEA's) Improving Safety Assessment Methodologies (ISAM) guidance (IAEA, 2004). This is a systematic, stepwise approach, the main stages of which are illustrated in Figure C-1. The PostSA has been documented in a way that corresponds to the ISAM approach, with a main report describing the key elements of the assessment and its outcomes.

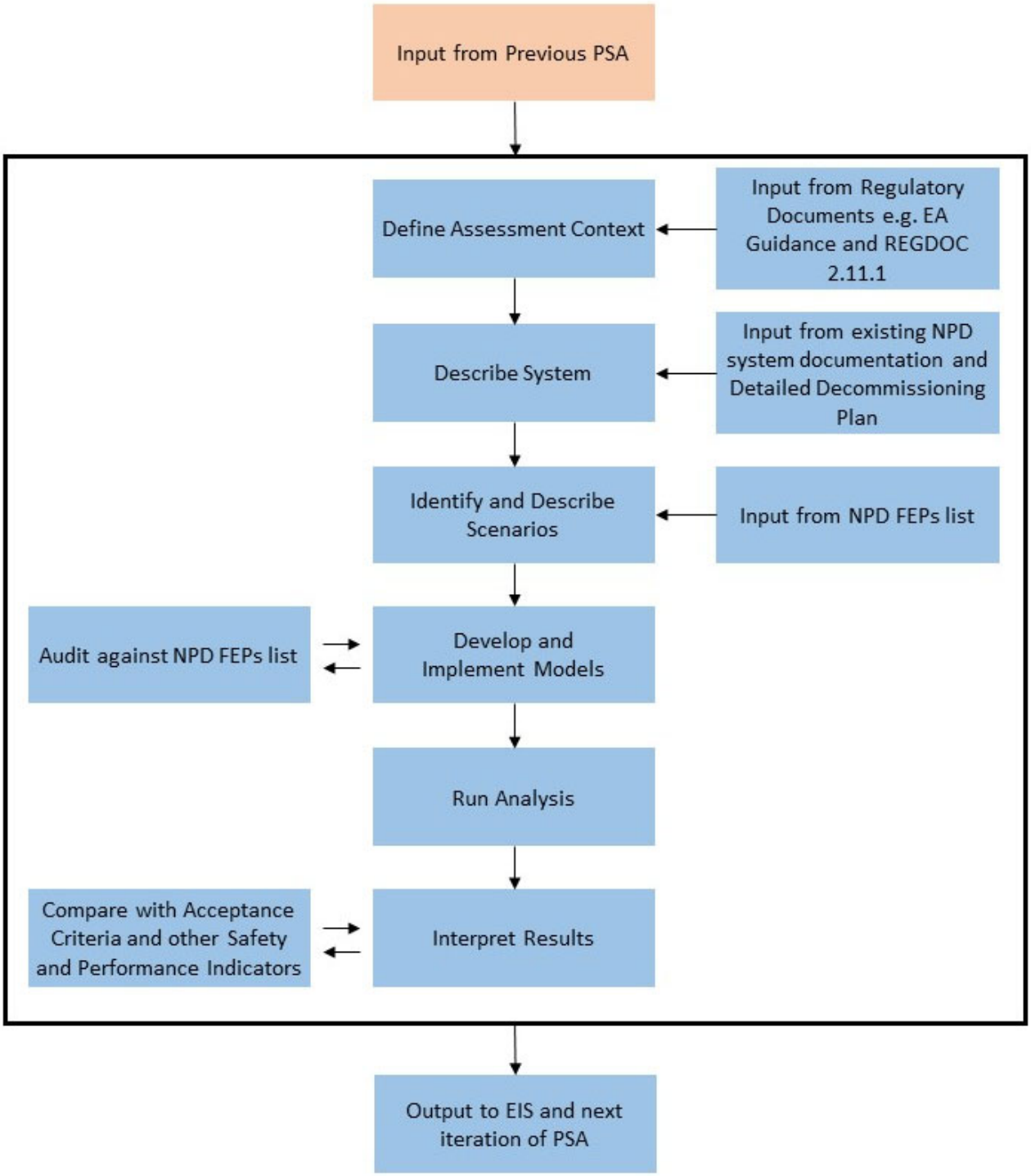
This appendix provides a key input into the third and fourth steps in which scenarios and models are developed. The scenarios and models are developed by examining the features, events and processes (FEPs) that could affect the long-term performance and safety of the Facility, including physical FEPs directly or indirectly influencing the release and transport of contaminants (radiological and non-radiological) from the Facility or subsequent radiation exposures to humans, as well as factors such as regulatory requirements or modelling issues that constrain or focus the analysis (IAEA, 2004).

The purpose of this appendix is to document a comprehensive description of the FEPs in terms of the NPDDF and its environment that captures all of the phenomena that are important to the long-term performance and safety of the Facility. The appendix also documents the relevance of each FEP to the Facility and the reasons to either include or exclude the FEP from the Facility safety analysis.

The appendix is organized as follows:

- Section C 1 describes the basis of the list of FEPs considered;
- Sections C 3 to C 7 examine each FEP in turn, provide a brief description and analysis, and conclude whether the FEP should be specifically included or excluded from the Postclosure Safety Assessment (PostSA).
- Section C 8 presents a list of the reports referenced in this appendix.

Figure C-1: Approach to Postclosure Safety Assessment, Adapted from ISAM (IAEA, 2004)



C 2 BASIS OF THE FEPS

The FEPs list was developed in a systematic manner following the Nuclear Energy Agency (NEA) International FEP list (NEA, 2015). Features, Events and Processes are identified based on the following categories:

- **Category 1 – External Factors:** the FEPs with causes or origins outside the assessed disposal system (repository, the surrounding geosphere and overlying biosphere).
- **Category 2 – Waste Package Factors:** the factors related to waste packages (i.e., waste forms and any associated packaging) and the associated release and migration of contaminants.
- **Category 3 – Facility Factors:** the factors related to the facility (i.e., including the excavation damaged and disturbed zones, and site investigation/monitoring boreholes but excluding the waste packages) and the associated migration of contaminants.
- **Category 4 – Geosphere Factors:** the factors related to the geosphere mechanically undisturbed by the construction of the repository and the associated migration of contaminants.
- **Category 5 – Biosphere Factors:** the factors related to the biosphere (the surface environment, humans and non-human biota) and the associated migration of contaminants.

In the case of Category 2 – Waste Package Factors it is important to note that while the NEA (2015, 2000) categories and sub-categories have been used, the focus is on waste forms and their characteristics as materials are being disposed *in-situ* without the use of waste packages.

FEPs included in the assessment are then categorized according to whether they are expected to occur in the future, or whether there is a small but significant possibility that they may occur.

- Normal Evolution – The FEP is expected to occur in the **Normal Evolution** of the system. These FEPs by default are also included in other scenarios.
- Disruptive Event – The FEP gives rise to a **Disruptive Event** (lower probability) scenario.

Finally, there are some FEPs representing factors that are out of scope, or of very low probability, but which provide useful information on system performance.

- “What If” – The FEP is highly unlikely, but a “**What If**” calculation may be of interest to examine its implications for the performance of the system.
- Defence-in-Depth – In addition, FEPs that represent factors that have a strong bearing on facility performance are selected for analysis as **Defence-in-Depth** cases.

Scenarios addressing uncertainties in the Normal Evolution (Sensitivity Cases) are included in the Postclosure Safety Assessment but are not driven by FEPs.

Table C-1 summarizes the FEPs assessed in this Appendix.

Regulatory feedback received by CNL notes that the PostSA's scenarios are developed using FEPs (NEA, 2014). However, the latest FEPs NEA version was published in 2019, thus warranting a check of the latest version of the NEA 2019 database (NEA, 2019).

The 2014 FEPs have therefore been compared to the 2019 FEPs. The table below shows the results of the comparison. The following approach was taken:

1. Where there is an additional FEP in 2019 compared to 2014, then this was addressed in one of two ways:
    a. If the 2019 FEP is addressed in another 2014 FEP, then a comment is inserted indicating in which 2014 FEP the 2019 FEP is addressed, and
    b. If the 2019 FEP is not addressed in the 2014 FEPs, the FEP was added to the 2014 FEPs list or a screening analysis was carried out to show that the 2019 FEP can be screened out, i.e., excluded.
2. Where there was an additional FEP in 2014 compared to 2019, it does not matter and so no action was taken.

A comparison of the 2019 FEPs with the 2014 FEPs indicates that many of the FEPs are equivalent in the two FEP lists. Where the 2019 FEPs are not identical or equivalent to the 2014 FEPs, it can be shown that either the 2019 FEP has been addressed by other 2014 FEPs or that the 2019 FEP can be excluded. For the few 2019 FEPs that are not addressed by other 2014 FEPs, a screening analysis indicates that these 2019 FEPs can be screened out.

It can be concluded that the 2014 FEP list covers most of the FEPs included in the 2019 FEP list. A screening analysis of the additional FEPs in the 2019 FEPs found that these additional FEPs can be screened out, i.e., excluded, and need not be included as FEPs assessment.

Table C-1: Comparison of NEA (2014) FEPs with NEA (2019) FEPs.

NEA (2014)		NEA (2019)		Comment
FEP #	FEP Name	FEP #	FEP Name	
1.1	Repository Issues	1.1	Repository Issues	Equivalent
1.1.1	Quality assurance and control	1.1.1	Quality assurance and control	Equivalent
1.1.2	Site investigations	1.1.2	Site investigations	Equivalent
1.1.3	Repository design	1.1.3	Design	Equivalent
1.1.4	Schedule and planning	1.1.4	Schedule and planning	Equivalent
1.1.5	Construction	1.1.5	Construction	Equivalent
1.1.6	Operation	1.1.6	Operation	Equivalent
1.1.7	Closure	1.1.7	Closure	Equivalent
1.1.8	Accidents and unplanned events	1.1.8	Accidents and unplanned events	Equivalent
1.1.9	Repository administrative control	1.1.9	Administrative control	Equivalent

NEA (2014)		NEA (2019)		Comment
FEP #	FEP Name	FEP #	FEP Name	
1.1.10	Monitoring	1.1.10	Monitoring	Equivalent
1.1.11	Repository markers	1.1.11	Records and markers	Equivalent
1.2	Geological Factors	1.2	Geological Factors	Equivalent
1.2.1	Tectonic movement	1.2.1	Tectonic movement	Equivalent
1.2.2	Orogeny	1.2.2	Orogeny	Equivalent
1.2.3	Deformation (elastic, plastic, or brittle)	1.2.3	Deformation (elastic, plastic, or brittle)	Equivalent
1.2.4	Seismicity	1.2.4	Seismicity	Equivalent
1.2.5	Volcanic and magmatic activity	1.2.5	Magmatic and volcanic activity	Equivalent
1.2.6	Metamorphism	1.2.6	Metamorphism	Equivalent
1.2.7	Hydrothermal activity	1.2.7	Hydrothermal activity	Equivalent
1.2.8	Regional erosion and sedimentation	1.2.8	Regional erosion and sedimentation	Equivalent
1.2.9	Diagenesis	1.2.9	Diagenesis	Equivalent
1.2.10	Pedogenesis	1.2.10	Pedogenesis	Equivalent
1.2.11	Salt diapirism and dissolution	1.2.11	Salt dissolution	NEA (2019) does not consider diapirism in FEP 1.2.11. It appears that diapirism is instead considered in NEA (2019) FEP 1.2.3.
1.2.12	Hydrological/Hydrogeological response to geological changes	1.2.12	Hydrological/Hydrogeological response to geological changes	Equivalent
1.2.13	Geomorphological response to geological changes	1.2.13	Geomorphological response to geological changes	Equivalent
-	-	1.2.14	Climatic responses to geological changes	NEA (2019) description: The climatic responses due to geological changes such as orogeny or volcanic activity caused by plate tectonics. Responses could be short-term (months to years), such as atmospheric cooling caused by volcanic eruptions, or long-term, such as the impact on atmospheric circulation caused by orogeny.

NEA (2014)		NEA (2019)		Comment
FEP #	FEP Name	FEP #	FEP Name	
				Screening: If there is cooling caused by volcanic eruptions elsewhere in the world, this would be expected to be short term and will not affect the results of the safety assessment over the assessment timeframe. Exclude
1.3	Climatic Factors	1.3	Climatic Factors	Equivalent
1.3.1	Global climate change	1.3.1	Global climate change	Equivalent
1.3.2	Regional and local climate change	1.3.2	Regional and local climate change	Equivalent
1.3.3	Sea level change	1.3.3	Sea level change	Equivalent
1.3.4	Periglacial effects	1.3.4	Periglacial effects	Equivalent
1.3.5	Local glacial and ice-sheet effects	1.3.5	Local glacial and ice-sheet effects	Equivalent
1.3.6	Warm climate effects (tropical and desert)	1.3.6	Warm climate effects (tropical and desert)	Equivalent
1.3.7	Hydrological response to climate change	1.3.7	Hydrological / Hydrogeological response to climate change	Equivalent
1.3.8	Ecological response to climate change	1.3.8	Ecological response to climate change	Equivalent
1.3.9	Human response to climate change	1.3.9	Human response to climate change	Equivalent
1.3.10	Geomorphological response to climate changes	1.3.10	Geomorphological response to climate changes	Equivalent
1.4	Future Human Actions	1.4	Future Human Actions	Equivalent
1.4.1	Human influences on climate	1.4.1	Human influences on climate	Equivalent
1.4.2	Social and institutional developments	1.4.2	Social and institutional developments	Equivalent
1.4.3	Technological developments	1.4.3	Technological developments	Equivalent

NEA (2014)		NEA (2019)		Comment
FEP #	FEP Name	FEP #	FEP Name	
1.4.4	Knowledge and motivational issues (repository)	1.4.4	Knowledge and motivational issues (repository)	Equivalent
1.4.5	Drilling activities	1.4.5	Drilling activities	Equivalent
1.4.6	Mining and other underground activities	1.4.6	Mining and other underground activities	Equivalent
1.4.7	Un-intrusive site investigation	1.4.7	Un-intrusive site investigation	Equivalent
1.4.8	Surface environment	1.4.8	Surface activities	Equivalent
1.4.9	Water management (groundwater and surface water)	1.4.9	Water management (groundwater and surface water)	Equivalent
1.4.10	Explosions and crashes	1.4.10	Explosions and crashes	Equivalent
1.4.11	Remedial actions	1.4.11	Remedial actions	Equivalent
1.4.12	Deliberate human intrusion	1.4.12	Deliberate human intrusion	Equivalent
1.5	Other External Factors	1.5	Other External Factors	Equivalent
1.5.1	Meteorites and human space debris	1.5.1	Meteorites and human space debris	Equivalent
1.5.2	Evolution of biota	1.5.2	Evolution of biota	Equivalent
2.1	Waste Form Characteristics and Properties	2.1	Waste Form	The descriptions are different, but it is a description of a subgroup not a Feature, Event or Process.
2.1.1	Waste state	-	-	Not a FEP in NEA (2019)
2.1.1.1	Solid	-	-	Not a FEP in NEA (2019)
2.1.1.2	Liquid	-	-	Not a FEP in NEA (2019)
2.1.1.3	Gas	-	-	Not a FEP in NEA (2019)
2.1.4	Contaminant inventory	2.1.1	Contaminant inventory	Equivalent
2.1.4.1	Radionuclide content	2.1.1.1	Radionuclide content	Equivalent
2.1.4.1	Chemical content	2.1.1.2	Chemical content	Equivalent
2.1.5	Waste form properties	2.1.2	Waste form characteristics and properties	NEA (2019) FEP 2.1.2 is covered by NEA (2014) FEPs 2.1.5 and 2.1.2.
2.1.2	Waste type			
2.1.2.1	Metallic wastes	2.1.2.1	Metals	Equivalent
2.1.2.2	Organic wastes	2.1.2.2	Organics	Equivalent
2.1.2.3	Non-metallic, inorganic wastes	2.1.2.3	Non-metals, inorganics	Equivalent
-	-	2.1.2.4	Immobilisation matrix	NEA (2019) description: The characteristics and properties of the waste immobilization

NEA (2014)		NEA (2019)		Comment
FEP #	FEP Name	FEP #	FEP Name	
				matrix/matrices at the time of emplacement in the repository. This NEA (2019) FEP is covered by the NEA (2014) FEP 2.1.3. (see below)
2.1.3	Waste conditioning matrix	-	-	Not a FEP in NEA (2019)
2.2	Waste Packaging Characteristics and Properties	2.2	Waste Packaging Characteristics and Properties	Equivalent
2.2.1	Containers	2.2.1	Container characteristics and properties	Equivalent
2.2.2	Overpacks	2.2.2	Overpack characteristics and properties	Equivalent
2.3	Waste Package Process	2.3	Waste Package Process	Equivalent
2.3.1	Thermal processes (waste package)	2.3.1	Thermal processes (waste package)	NEA (2014) considers all thermal effects from the engineered materials in the repository and the surrounding geology; NEA (2019) only considers internal thermal processes, and external thermal processes (i.e., from the repository and surrounding geosphere) are considered under separate FEPs 3.2.1 and 4.2.1.
2.3.1.1	Radiogenic heat production and transfer	2.3.1.1	Radiogenic heat production and transfer	Equivalent
2.3.1.2	Chemical heat production and transfer	2.3.1.2	Chemical heat production and transfer	Equivalent
2.3.1.3	Biological heat production and transfer	2.3.1.3	Biological heat production and transfer	Equivalent
2.3.1.4	Impact of thermal processes on other processes (waste package)	-	-	Not a FEP in NEA (2019).

NEA (2014)		NEA (2019)		Comment
FEP #	FEP Name	FEP #	FEP Name	
2.3.2	Hydraulic processes (waste package)	2.3.2	Hydraulic processes (waste package)	Equivalent
2.3.2.1	Saturation/Desaturation	2.3.2.1	Saturation/Desaturation	Equivalent
2.3.2.2	Thermal effects	2.3.2.2	Thermal effects	Equivalent
2.3.2.4	Impact of hydraulic processes on other processes (waste package)	2.3.2.3	Mechanical effects	NEA (2014) FEP 2.3.2.4 can cover NEA (2019) FEPS 2.3.2.3 and 2.3.2.4.
		2.3.2.4	Chemical effects	
2.3.2.3	Gas effects	2.3.2.5	Gas effects	Equivalent
2.3.3	Mechanical processes (waste package)	2.3.3	Mechanical processes (waste package)	Equivalent
2.3.3.1	Package deformation	2.3.3.1	Deformation	Equivalent
2.3.3.2	Material volume changes (waste package)	2.3.3.2	Material volume changes (waste package)	Equivalent
2.3.3.3	Movement	2.3.3.3	Movement	Equivalent
2.3.3.4	Stress corrosion cracking	2.3.3.4	Stress corrosion cracking	Equivalent
2.3.3.5	Gas explosion (waste package)	2.3.3.5	Gas explosion (waste package)	Equivalent
2.3.3.6	Impact of mechanical processes on other processes (waste package)	-	-	Not a FEP in NEA (2019).
2.3.4	Chemical processes (waste package)	2.3.4	Chemical processes (waste package)	Equivalent
2.3.4.1	pH conditions (waste package)	2.3.4.1	Evolution of pH conditions (waste package)	Equivalent
2.3.4.2	Redox conditions (waste package)	2.3.4.2	Evolution of redox conditions (waste package)	Equivalent
2.3.4.3	Perturbing species' conditions (waste package)	-	-	Not a FEP in NEA (2019)
-	-	2.3.4.3	Migration of chemical species (waste package)	NEA (2019) description: The migration of reactants into and reaction products from the waste package. Covered by NEA (2014) FEP 2.3.4.12 and FEPs 2.5.

NEA (2014)		NEA (2019)		Comment
FEP #	FEP Name	FEP #	FEP Name	
-	-	2.3.4.7	Complexation (waste package)	NEA (2019) description: The formation in the waste package of molecular entity by loose association involving two or more component molecular entities (ionic or uncharged), or the corresponding chemical species. Complexation is promoted through the presence on complexing agents (organics, inorganic ligands and microbes). Sources of these agents include organics in the waste package and inflowing water. This NEA (2019) FEP is covered by NEA (2014) FEP 2.3.4.9 and NEA (2014) FEP 2.5.2.7.
2.3.4.4	Corrosion (waste package)	2.3.4.4	Corrosion (waste package)	Equivalent
2.3.4.5	Polymer degradation	2.3.4.5	Alteration (waste form/waste package)	NEA (2019) FEP 2.3.4.5 is covered by three FEPs in NEA (2014): FEPs 2.3.4.5, 2.3.4.6 and 2.3.4.7.
2.3.4.6	Dissolution (waste package)			
2.3.4.7	Mineralisation (waste package)			
2.3.4.8	Precipitation reactions (waste package)	2.3.4.6	Precipitation (waste package)	Equivalent
2.3.4.9	Chelating agent effect (waste package)	-	-	Not a FEP in NEA (2019).
2.3.4.10	Colloid formation (waste package)	2.3.4.8	Colloid formation (waste package)	Equivalent
2.3.4.11	Chemical concentration gradients (waste package)	-	-	Not a FEP in NEA (2019).
2.3.4.12	Impact of chemical processes on other	-	-	Not a FEP in NEA (2019).

NEA (2014)		NEA (2019)		Comment
FEP #	FEP Name	FEP #	FEP Name	
	processes (waste package)			
2.3.5	Biological processes (waste package)	2.3.5	Biological processes (waste package)	Equivalent
2.3.5.1	Microbial growth and poisoning (waste package)	2.3.5.1	Microbial growth and decline (waste package)	Equivalent
2.3.5.2	Microbially/biologically mediated processes (waste package)	2.3.5.2	Microbially/biologically mediated processes (waste package)	Equivalent
2.3.5.3	Impact of biological processes on other processes (waste package)	-	-	Not a FEP in NEA (2019)
2.3.6	Radiological processes (waste package)	2.3.6	Radiological processes (waste package)	Equivalent
2.3.6.1	Radioactive decay and ingrowth (waste package)	2.3.6.1	Radioactive decay and ingrowth (waste package)	Equivalent
2.3.6.2	Radiolysis (waste package)	2.3.6.2	Radiolysis (waste package)	Equivalent
2.3.6.3	Helium production	2.3.6.3	Helium production	Equivalent
2.3.6.4	Radiation attenuation	-	-	Not a FEP in NEA (2019)
2.3.6.5	Radiation damage (waste package)	2.3.6.5	Radiation damage (waste package)	Equivalent
-	-	2.3.6.6	Criticality (waste form/waste package)	Description: The possibility and effects of spontaneous nuclear fission chain reactions within the waste package. Critically requires a sufficient concentration and localised mass (critical mass) of fissile isotopes (e.g. U-235, Pu-239) and is more likely to occur in the presence of neutron moderating materials, such as water, in a suitable geometry; a chain reaction is less likely to occur in the

NEA (2014)		NEA (2019)		Comment
FEP #	FEP Name	FEP #	FEP Name	
				presence of neutron absorbing isotopes (e.g. Pu-240). This 2019 FEP is covered by NEA (2014) FEP 3.2.6.5.
2.3.6.6	Impact of radiological processes on other processes (waste package)	-	-	Not a FEP in NEA (2019)
2.3.7	Gas generation (waste package)	-	-	Not a FEP in NEA (2019)
2.3.7.1	Metal corrosion (waste package)	-	-	Not a FEP in NEA (2019)
2.3.7.2	Organic degradation (waste package)	-	-	Not a FEP in NEA (2019)
2.3.7.3	Radon production (waste package)	2.3.6.4	Radon production (waste package)	Equivalent
2.3.7.4	Radiolysis (waste package)	-	-	Not a FEP in NEA (2019)
2.3.7.5	Volatilisation (waste package)	-	-	Not a FEP in NEA (2019)
2.3.7.6	Gas dissolution (waste package)	-	-	Not a FEP in NEA (2019)
2.3.7.7	Gas-induced failure	-	-	Not a FEP in NEA (2019)
2.3.7.8	Impact of gas generation on other processes (waste package)	-	-	Not a FEP in NEA (2019)
2.4	Contaminant Release (from waste form)	2.4	Contaminant Release (from waste form)	Equivalent
2.4.1	Liquid-mediated release	2.4.1	Liquid-mediated release	NEA (2019) description: The processes resulting in the release of contaminants in a liquid phase from the waste form. Included is the release of contaminants in the aqueous phase from liquid waste forms and release of contaminants in non-aqueous phase liquids.

NEA (2014)		NEA (2019)		Comment
FEP #	FEP Name	FEP #	FEP Name	
				NEA (2014) description: FEPs related to the release of radiotoxic and chemotoxic species into water in the aqueous phase from the waste form. NEA (2019) also includes ***non-aqueous*** phase liquids. There are no non-aqueous phase liquids in NPD.
2.4.1.1	Liquid wastes	-	-	Not a FEP in NEA (2019)
2.4.1.2	Dissolution (waste form)	2.4.1.1	Dissolution (waste form)	Equivalent
2.4.1.3	Diffusion (waste form)	2.4.1.2	Diffusion (waste form)	NEA (2019) description: The diffusion of contaminants from the waste form in a fluid phase. This phase may be liquid water but ***may alternatively be non-aqueous liquid or a gas***. Diffusion results in the net flux of contaminants from a region of higher concentration to one of lower concentration. The rate of diffusion is a function of temperature, viscosity of the fluid and the size (mass) of the associated molecules. NEA (2014) description: Aqueous diffusion of radiotoxic and chemotoxic species from the waste form. For example, on contact with

NEA (2014)		NEA (2019)		Comment
FEP #	FEP Name	FEP #	FEP Name	
				water, radiotoxic and chemotoxic species in a waste form may dissolve and diffuse into the water. This process is controlled by the chemical environment and by the waste form composition and structure. There are no non-aqueous phase liquids in NPD. Gaseous diffusion is included in other 2014 FEPs.
2.4.1.4	Speciation and solubility (waste form)	2.4.1.3	Speciation and solubility (waste form)	Equivalent
2.4.1.5	Sorption and desorption (waste form)	2.4.1.4	Sorption and desorption (waste form)	Equivalent
2.4.1.6	Complexation (waste form)	-	-	Not a FEP in NEA (2019)
2.4.1.7	Colloids	-	-	Not a FEP in NEA (2019)
2.4.2	Gas-mediated release	2.4.2	Gas-mediated release	Equivalent
2.4.2.1	Gaseous wastes	-	-	Not a FEP in NEA (2019)
2.4.2.2	Radon production (waste form)	-	-	Not a FEP in NEA (2019) but NEA (2019) FEP 2.4.2 includes results from various gas production processes such as radon production (FEP 2.3.6.4), biochemical processes resulting in volatilization (e.g. FEPs 2.3.4.5 and 2.3.5.2) and radiolysis resulting in hydrogen production (FEP 2.3.6.2).
2.4.2.3	Volatilisation (waste form)	-	-	
2.4.2.4	Radiolysis (waste form)	-	-	
2.4.3	Solid-mediated release	2.4.3	Solid-mediated release	Equivalent
2.4.4	Human-action-mediated release	2.4.4	Human-action-mediated release	Equivalent

NEA (2014)		NEA (2019)		Comment
FEP #	FEP Name	FEP #	FEP Name	
2.5	Contaminant Transport (waste package)	2.5	Contaminant Migration (waste package)	Equivalent
2.5.1	Transport pathway (waste package)	-	-	Not a FEP in NEA (2019)
2.5.2	Water-mediated transport (waste package)	2.5.1	Water-mediated migration (waste package)	Equivalent
2.5.2.1	Advection (waste package)	2.5.1.1	Advection (waste package)	Equivalent
2.5.2.2	Dispersion (waste package)	2.5.1.2	Dispersion (waste package)	NEA (2014) description: Dispersion is the spread in the spatial distribution of contaminants with time because of differential rates of advective or convective transport through the waste package. NEA (2019) description: The spread in the spatial distribution of contaminants with time in the waste package because of differential rates of ***and pathways*** for advective transport through the waste package. Change in description does not change analysis.
2.5.2.3	Molecular diffusion (waste package)	2.5.1.3	Diffusion (waste package)	Equivalent
2.5.2.4	Dissolution, precipitation, and mineralization (waste package)	2.5.1.4	Dissolution, precipitation, and crystallization (waste package)	Equivalent
2.5.2.5	Speciation and solubility (waste package)	2.5.1.5	Speciation and solubility (waste package)	Equivalent
2.5.2.6	Sorption and desorption (waste package)	2.5.1.6	Sorption and desorption (waste package)	Equivalent

NEA (2014)		NEA (2019)		Comment
FEP #	FEP Name	FEP #	FEP Name	
2.5.2.7	Complexation (waste package)	-	-	Not a FEP in NEA (2019)
2.5.2.8	Colloid transport (waste package)	2.5.1.7	Colloid transport (waste package)	Equivalent
2.5.3	Gas-mediated transport (waste package)	2.5.2	Gas-mediated migration (waste package)	Equivalent
3.1	Repository Characteristics and Properties	3.1	Repository Characteristics and Properties	The descriptions are different, but they describe a subgroup, not a FEP.
3.1.1	Design	-	-	Not a FEP in NEA (2019)
3.1.2	Buffer/backfill	3.1.1	Buffer/backfill	Equivalent
3.1.3	Room/tunnel seals	3.1.2	Room/tunnel seals	Equivalent
3.1.4	Shaft/ramp seals	3.1.3	Shaft/ramp seals	Equivalent
-	-	3.1.4	Borehole seals	NEA (2019) description: The physical, chemical and biological characteristics and properties of any site investigation/ monitoring boreholes at the time of sealing. FEP added to list of FEPs analyzed, see Section C 5.1.4
3.1.5	Other engineered features	3.1.5	Other engineered features	Equivalent
3.1.6	Excavation damaged and disturbed zones	3.1.6	Excavation damaged and disturbed zones	Equivalent
3.2	Repository Processes	3.2	Repository Processes	Equivalent
3.2.1	Thermal processes (repository)	3.2.1	Thermal processes (repository)	Equivalent
3.2.1.1	Thermal conduction and convection			
3.2.1.2	Impact of thermal processes on other processes (repository)			
3.2.2	Hydraulic processes (repository)	3.2.2	Hydraulic processes (repository)	Equivalent
3.2.2.1	Resaturation/ desaturation (repository)	3.2.2.1	Resaturation/ desaturation (repository)	Equivalent

NEA (2014)		NEA (2019)		Comment
FEP #	FEP Name	FEP #	FEP Name	
3.2.2.2	Piping/hydraulic erosion	3.2.2.2	Piping/hydraulic erosion	Equivalent
3.2.2.3	Impact of hydraulic processes on other processes (repository)	-	-	Not a FEP in NEA (2019)
3.2.3	Mechanical processes (repository)	3.2.3	Mechanical processes (repository)	Equivalent
3.2.3.1	Material volume changes (repository)	3.2.3.1	Material volume changes (repository)	Equivalent
3.2.3.2	Creep	3.2.3.2	Creep	Equivalent
3.2.3.3	Collapse of openings	3.2.3.3	Collapse of openings	NEA (2014) description: The collapse of tunnels and boreholes, including cave-ins, roof settling, and rock bursts. Potential effects include damage to the waste packages, buffer, backfill and other seals, and changes to water flow conditions in the repository and surrounding geosphere. NEA (2019) description: The collapse of tunnels, ***shafts*** and boreholes, including cave-ins, roof settling, and ***spalling*** and rock bursts. Collapses could occur where voids remain post-closure (e.g. because galleries or not backfilled, or because backfill emplacement is not 100% efficient, resulting in there being residual headspace). The additions of “shaft” and “spalling” to the 2019 FEP description is not relevant for NPD.

NEA (2014)		NEA (2019)		Comment
FEP #	FEP Name	FEP #	FEP Name	
-	-	3.2.3.4	Gas-induced dilation (repository)	NEA (2019) description: the dilation of repository materials due to gas pressure. FEP included in list of FEPs analyzed, see Section C 5.2.3.4
3.2.3.4	Gas explosion (repository)	3.2.3.5	Gas explosion (repository)	Equivalent
3.2.3.5	Impact of mechanical processes on other processes (repository)	-	-	Not a FEP in NEA (2019)
3.2.4	Chemical processes (repository)	3.2.4	Chemical processes (repository)	Equivalent
3.2.4.1	pH conditions (repository)	3.2.4.1	Evolution of pH conditions (repository)	Equivalent
3.2.4.2	Redox conditions (repository)	3.2.4.2	Evolution of redox conditions (repository)	Equivalent
3.2.4.3	Perturbing species' concentrations (repository)	-	-	Not a FEP in NEA (2019)
3.2.4.4	Corrosion (repository)	3.2.4.4	Corrosion (repository)	Equivalent
3.2.4.5	Dissolution (repository)	3.2.4.5	Alteration (repository)	Equivalent
3.2.4.6	Mineralisation (repository)			
3.2.4.7	Precipitation reactions (repository)	3.2.4.6	Precipitation of solid phases (repository)	Equivalent
3.2.4.8	Chelating agent effects (repository)	-	-	Not a FEP in NEA (2019)
-	-	3.2.4.7	Complexation (repository)	NEA (2019) description: The formation in the repository materials of a molecular entity by loose association involving two or more component molecular entities (ionic or uncharged), or the corresponding chemical species. Complexation is promoted through the presence of complexing agents (organics, inorganic ligands and microbes).

NEA (2014)		NEA (2019)		Comment
FEP #	FEP Name	FEP #	FEP Name	
				Sources of these agents include organics in the waste package and inflowing water. Covered by NEA (2014) FEP 3.2.4.8 and 3.3.2.7.
3.2.4.9	Colloid formation (repository)	3.2.4.8	Colloid formation (repository)	Equivalent
3.2.4.10	Chemical concentration gradients (repository)	-	-	Not a FEP in NEA (2019)
-	-	3.2.4.3	Migration of chemical species (repository)	NEA (2019) description: The migration of reactants into and reaction products from the repository. Chemical species can migrate into and out of the repository and its various components by advection (head/pressure gradient driven) and diffusion (chemical potential gradient driven). Where solutions with different concentrations are separated by a semi-permeable membrane there may be osmotic transport of water. Chemical concentration gradients in the repository and its various components could be caused by various factors. Migration of chemical species by advection may cause concentration gradients that drive diffusive transport. Temperature gradients may produce concentration gradients by influencing the chemical reactions that occur between fluids (e.g. liquid water, non-aqueous liquids and

NEA (2014)		NEA (2019)		Comment
FEP #	FEP Name	FEP #	FEP Name	
				gases) and between solids and fluids, and the rates of these reactions. Temperature gradients may also lead to advective (convective) migration. Heterogeneities in the spatial distribution of waste packages and repository materials. This is covered by NEA (2014) FEP 3.2.4.10 and FEP 3.3.
3.2.4.11	Impact of chemical processes on other processes (repository)	-	-	Not a FEP in NEA (2019)
3.2.5	Biological processes (repository)	3.2.5	Biological processes (repository)	Equivalent
3.2.5.1	Microbial growth and poisoning (repository)	3.2.5.1	Microbial growth and decline (repository)	Equivalent
3.2.5.2	Microbially/biologically mediated processes (repository)	3.2.5.2	Microbially/biologically mediated processes (repository)	Equivalent
3.2.5.3	Impact of biological processes on other processes (repository)	-	-	Not a FEP in NEA (2019)
3.2.6	Radiological processes (repository)	3.2.6	Radiological processes (repository)	Equivalent
3.2.6.1	Radioactive decay and ingrowth (repository)	3.2.6.1	Radioactive decay and ingrowth (repository)	Equivalent
3.2.6.2	Radiolysis (repository)	3.2.6.2	Radiolysis (repository)	NEA (2019) description: The dissociation of molecules by ionising radiation in the repository surrounding the waste package. The actual composition and amount of the radiolysis products that will be formed is controlled by the radiation dose rate and by the compositions and amounts of ***the solid and fluid phases*** contained in the

NEA (2014)		NEA (2019)		Comment
FEP #	FEP Name	FEP #	FEP Name	
				repository surrounding the waste package. NEA (2014) description: Radiolysis of any ***water*** in the repository environment immediate adjacent to the waste packages (especially for high-level waste and spent fuel) can produce species such as free hydrogen and oxygen which can impact the chemical conditions in the repository (e.g. the redox potential) (see FEP 3.2.7.4). These are equivalent FEPs.
3.2.6.3	Radiation attenuation (repository)	-	-	Not a FEP in NEA (2019)
3.2.6.4	Radiation damage (repository)	3.2.6.4	Radiation damage (repository)	Equivalent
3.2.6.5	Criticality	3.2.6.5	Criticality	Equivalent
3.2.6.6	Impact of radiological processes on other processes (repository)	-	-	Not a FEP in NEA (2019)
3.2.7	Gas generation (repository)	-	-	Not a FEP in NEA (2019)
3.2.7.1	Metal corrosion (repository)	-	-	Not a FEP in NEA (2019)
3.2.7.2	Organic degradation (repository)	-	-	Not a FEP in NEA (2019)
3.2.7.3	Radon production (repository)	3.2.6.3	Radon production (repository)	Equivalent
3.2.7.4	Radiolysis (repository)	-	-	Not a FEP in NEA (2019)
3.2.7.5	Volatilisation (repository)	-	-	Not a FEP in NEA (2019)
3.2.7.6	Gas dissolution (repository)	-	-	Not a FEP in NEA (2019)
3.2.7.7	Gas-induced failure (repository)	-	-	Not a FEP in NEA (2019)
3.2.7.8	Impact of gas generation on other processes (repository)	-	-	Not a FEP in NEA (2019)

NEA (2014)		NEA (2019)		Comment
FEP #	FEP Name	FEP #	FEP Name	
3.3	Contaminant Transport (repository)	3.3	Contaminant Migration (repository)	Equivalent
3.3.1	Transport Pathway (repository)	-	-	Not a FEP in NEA (2019)
3.3.2	Water-mediated migration (repository)	3.3.1	Water-mediated migration (repository)	Equivalent
3.3.2.1	Advection (repository)	3.3.1.1	Advection (repository)	Equivalent
3.3.2.2	Dispersion (repository)	3.3.1.2	Dispersion (repository)	Equivalent
3.3.2.3	Molecular diffusion (repository)	3.3.1.3	Diffusion (repository)	Equivalent
3.3.2.4	Dissolution, precipitation, and mineralisation (repository)	3.3.1.4	Dissolution, precipitation, and crystallization (repository)	Equivalent
3.3.2.5	Speciation and solubility (repository)	3.3.1.5	Speciation and solubility (repository)	Equivalent
3.3.2.6	Sorption and desorption (repository)	3.3.1.6	Sorption and desorption (repository)	Equivalent
3.3.2.7	Complexation (repository)	-	-	Not a FEP in NEA (2019)
3.3.2.8	Colloid transport (repository)	3.3.1.7	Colloid transport (repository)	Equivalent
3.3.3	Gas-mediated transport (repository)	3.3.2	Gas-mediated migration (repository)	Equivalent
3.3.4	Solid-mediated transport (repository)	3.3.3	Solid-mediated migration (repository)	Equivalent
3.3.5	Human-action-mediated transport (repository)	3.3.4	Human-action-mediated transport (repository)	Equivalent
4.1	Geosphere Characteristics and Properties	4.1	Geosphere Characteristics and Properties	Equivalent
4.1.1	Stratigraphy	4.1.1	Configuration	Equivalent
4.1.2	Host rock lithology			Equivalent
4.1.3	Large-scale discontinuities	4.1.2	Large-scale discontinuities	Equivalent
4.1.4	Geological resources	4.1.3	Geological resources	Equivalent
4.1.5	Undetected features	4.1.4	Undetected features	Equivalent
4.1.6	Current geothermal state	4.1.5	Geothermal characteristics and properties	Equivalent
4.1.7	Current hydraulic state	4.1.6	Hydraulic characteristics and properties	Equivalent

NEA (2014)		NEA (2019)		Comment
FEP #	FEP Name	FEP #	FEP Name	
4.1.8	Current stress state	4.1.7	Mechanical characteristics and properties	Equivalent
4.1.9	Current geochemical state	4.1.8	Geochemical characteristics and properties	Equivalent
4.1.10	Current biological state	4.1.9	Biological characteristics and properties	Equivalent
4.1.11	Current gas state	-	-	Not a FEP in NEA (2019)
4.2	Geosphere Processes	4.2	Geosphere Processes	Equivalent
4.2.1	Thermal processes (geosphere)	4.2.1	Thermal processes (geosphere)	Equivalent
4.2.1.1	Thermal effects of repository (geosphere)			
4.2.1.2	Thermal effects of climate change (geosphere)			
4.2.1.3	Other processes affecting future thermal conditions in geosphere			
4.2.2	Hydraulic processes (geosphere)	4.2.2	Hydraulic processes (geosphere)	Equivalent
4.2.2.1	Hydraulic effects of repository (geosphere)			
4.2.2.2	Hydraulic effects of climate change (geosphere)			
4.2.2.3	Other processes affecting future hydraulic conditions in geosphere			
4.2.3	Mechanical processes (geosphere)	4.2.3	Mechanical processes (geosphere)	Equivalent
4.2.3.1	Mechanical effects of repository (geosphere)			
4.2.3.2	Mechanical effects of climate change (geosphere)			
4.2.3.3	Other processes affecting future mechanical conditions in geosphere			
4.2.4	Chemical processes (geosphere)	4.2.4	Chemical processes (geosphere)	Equivalent

NEA (2014)		NEA (2019)		Comment
FEP #	FEP Name	FEP #	FEP Name	
4.2.4.1	Chemical effects of repository (geosphere)			
4.2.4.2	Chemical effects of climate change (geosphere)			
4.2.4.3	Other processes affecting future chemical conditions in geosphere			
4.2.5	Biological processes (geosphere)	4.2.5	Biological processes (geosphere)	Equivalent
4.2.5.1	Biological effects of repository (geosphere)			
4.2.5.2	Biological effects of climate change (geosphere)			
4.2.5.3	Other processes affecting future biological conditions in geosphere			
4.2.6	Radiological processes (geosphere)	4.2.6	Radiological processes (geosphere)	Equivalent
4.2.7	Gas processes (geosphere)	-	-	Not a FEP in NEA (2019)
4.2.7.1	Gas sources (geosphere)	-	-	Not a FEP in NEA (2019)
4.2.7.2	Radon production (geosphere)	-	-	Not a FEP in NEA (2019)
4.2.7.3	Volatilisation (geosphere)	-	-	Not a FEP in NEA (2019)
4.2.7.4	Gas dissolution (geosphere)	-	-	Not a FEP in NEA (2019)
4.2.7.5	Gas-induced dilation (geosphere)	-	-	Not a FEP in NEA (2019)
4.3	Contaminant Transport (geosphere)	4.3	Contaminant Migration (geosphere)	Equivalent
4.3.1	Transport pathway (geosphere)	-	-	Not a FEP in NEA (2019)
4.3.2	Water-mediated transport (geosphere)	4.3.1	Water-mediated migration (geosphere)	Equivalent
4.3.2.1	Advection (geosphere)	4.3.1.1	Advection (geosphere)	Equivalent
4.3.2.2	Dispersion (geosphere)	4.3.1.2	Dispersion (geosphere)	Equivalent
4.3.2.3	Molecular diffusion (geosphere)	4.3.1.3	Diffusion (geosphere)	Equivalent
4.3.2.4	Matrix diffusion	4.3.1.4	Matrix diffusion	Equivalent

NEA (2014)		NEA (2019)		Comment
FEP #	FEP Name	FEP #	FEP Name	
4.3.2.5	Dissolution, precipitation, and mineralisation (geosphere)	4.3.1.5	Dissolution, precipitation, and crystallization (geosphere)	Equivalent
4.3.2.6	Speciation and solubility (geosphere)	4.3.1.6	Speciation and solubility (geosphere)	Equivalent
4.3.2.7	Sorption and desorption (geosphere)	4.3.1.7	Sorption and desorption (geosphere)	Equivalent
4.3.2.8	Complexation (geosphere)	-	-	Not a FEP in NEA (2019)
4.3.2.9	Colloid transport (geosphere)	4.3.1.8	Colloid transport (geosphere)	Equivalent
4.3.3	Gas-mediated transport (geosphere)	4.3.2	Gas-mediated migration (geosphere)	Equivalent
4.3.4	Solid-mediated transport (geosphere)	4.3.3	Solid-mediated migration (geosphere)	Equivalent
4.3.5	Human-action-mediated transport (geosphere)	4.3.4	Human-action-mediated transport (geosphere)	Equivalent
5.1	Surface Environment	5.1	Surface Environment	Equivalent
5.1.1	Topography and morphology	5.1.1	Topography and morphology	Equivalent
5.1.2	Biomes	5.1.2	Biomes	Equivalent
5.1.3	Soil and sediment	5.1.3	Soil and sediment	Equivalent
5.1.3.1	Surface soils	5.1.3.1	Surface soils	Equivalent
5.1.3.2	Overburden	5.1.3.2	Overburden	Equivalent
5.1.3.3	Aquatic sediments	5.1.3.3	Aquatic sediments	Equivalent
5.1.4	Near-surface aquifers and water-bearing features	5.1.4	Near-surface aquifers and water-bearing features	Equivalent
5.1.5	Terrestrial surface water bodies	5.1.5	Terrestrial surface water bodies	Equivalent
5.1.5.1	Wetlands	5.1.5.1	Wetlands	Equivalent
5.1.5.2	Lakes and rivers	5.1.5.2	Lakes and rivers	Equivalent
5.1.5.3	Spring and discharge zones	5.1.5.3	Spring and discharge zones	Equivalent
5.1.6	Coastal features	5.1.6	Coastal features	Equivalent
5.1.7	Marine features	5.1.7	Marine features	Equivalent
5.1.8	Atmosphere	5.1.8	Atmosphere	Equivalent
5.1.9	Vegetation	5.1.9	Vegetation	Equivalent
5.1.10	Animals	5.1.10	Animals	Equivalent
5.1.11	Climate and weather	5.1.11	Climate and weather	Equivalent

NEA (2014)		NEA (2019)		Comment
FEP #	FEP Name	FEP #	FEP Name	
5.1.12	Hydrological regime and water balance (near-surface)	5.1.12	Hydrological regime and water balance (near-surface)	Equivalent
5.1.13	Erosion and deposition	5.1.13	Erosion and deposition	Equivalent
5.1.14	Ecological / biological / microbial systems	5.1.14	Ecological / biological / microbial systems	Equivalent
5.2	Human Behaviour	5.2	Human Characteristics and Behaviour	Equivalent
5.2.1	Human characteristics (physiology, metabolism)	5.2.1	Physical characteristics	Equivalent
5.2.2	Age, gender and ethnicity			
5.2.3	Diet and fluid intake	5.2.3	Diet and fluid intake	Equivalent
5.2.3.1	Farming diet	5.2.3.1	Farming diet	Equivalent
5.2.3.2	Hunter/gatherer diet	5.2.3.2	Hunter/gatherer diet	Equivalent
5.2.3.3	Other diets	5.2.3.3	Other diets	Equivalent
5.2.4	Habits (excluding diet)	5.2.4	Habits (excluding diet)	Equivalent
5.2.5	Community characteristics	5.2.2	Community characteristics	Equivalent
5.2.5.1	Community type	5.2.2.1	Community type	Equivalent
5.2.8	Natural/semi-natural land and water use			
5.2.9	Rural/agricultural land and water use			
5.2.10	Urban/industrial land and water use			
5.2.11	Leisure and other uses of the environment			
5.2.5.2	Community location	5.2.2.2	Community location	Equivalent
5.2.5.3	Water source	5.2.2.3	Water source	Equivalent
5.2.6	Food preparation and water processing	5.2.5	Food preparation and water processing	Equivalent
5.2.7	Dwellings	5.2.2.4	Dwellings	Equivalent
5.3	Contaminant Transport (Biosphere)	5.3	Contaminant Migration (Biosphere)	Equivalent
5.3.1	Water-mediated transport (biosphere)	5.3.1	Water-mediated migration (biosphere)	Equivalent
5.3.1.1	Groundwater discharge to biosphere	5.3.1.1	Groundwater discharge to biosphere	Equivalent
5.3.1.2	Transport associated with surface soil and overburden	5.3.1.2	Migration associated with surface soil and overburden	Equivalent

NEA (2014)		NEA (2019)		Comment
FEP #	FEP Name	FEP #	FEP Name	
5.3.1.3	Transport associated with surface water bodies	5.3.1.3	Migration associated with surface water bodies	Equivalent
5.3.1.4	Dissolution and precipitation (biosphere)	5.3.1.4	Dissolution and precipitation (biosphere)	Equivalent
5.3.1.5	Speciation and solubility (biosphere)	5.3.1.5	Speciation and solubility (biosphere)	Equivalent
5.3.1.6	Sorption and desorption (biosphere)	5.3.1.6	Sorption and desorption (biosphere)	Equivalent
5.3.1.7	Complexation (biosphere)	-	-	Not a FEP in NEA (2019)
5.3.1.8	Colloid transport (biosphere)	5.3.1.7	Colloid transport (biosphere)	Equivalent
5.3.2	Gas-mediated transport (biosphere)	5.3.2	Gas-mediated migration (biosphere)	Equivalent
5.3.2.1	Gas discharge to biosphere			
5.3.2.2	Radon production (biosphere)			
5.3.2.3	Volatilisaition from soil/water			
5.3.5	Atmospheric transport and deposition			
5.3.3	Solid-mediated transport (biosphere)	5.3.3	Solid-mediated migration (biosphere)	Equivalent
5.3.4	Human-action-mediated transport (biosphere)	5.3.4	Human-action-mediated migration (biosphere)	Equivalent
5.3.6	Biologically-mediated transport	-	-	Not a FEP in NEA (2019)
5.3.7	Foodchains and uptake of contaminants	5.3.5	Uptake of contaminants by animals and plants	Equivalent
-	-	5.3.6	Radioactive decay and ingrowth (biosphere)	NEA (2019) description: The spontaneous disintegration or de-excitation of an atomic nucleus, resulting in the emission of sub-atomic particles and energy and the formation of a new progeny (or “daughter”) nucleus in the biosphere. FEP added to list of FEPs analyzed, see Section C 7.3.6

NEA (2014)		NEA (2019)		Comment
FEP #	FEP Name	FEP #	FEP Name	
5.4	Exposure Factors	5.4	Exposure Factors	Equivalent
5.4.1	Contaminated drinking water and food	5.4.1	Contaminated drinking water and food	Equivalent
5.4.2	Contaminated non-food products	5.4.2	Contaminated non-food products	Equivalent
5.4.3	Other contaminated environmental media	5.4.3	Other contaminated environmental media	Equivalent
5.4.4	Exposure modes	5.4.4	Exposure modes	Equivalent
5.4.4.1	Exposure of humans	5.4.4.1	Exposure of humans	Equivalent
5.4.4.2	Exposure of biota other than humans	5.4.4.2	Exposure of biota other than humans	Equivalent
5.4.5	Dosimetry and biokinetics	5.4.5	Dosimetry and biokinetics	Equivalent
5.4.5.1	Dosimetry and biokinetics for humans	5.4.5.1	Dosimetry and biokinetics for humans	Equivalent
5.4.5.2	Dosimetry and biokinetics for biota other than humans	5.4.5.2	Dosimetry and biokinetics for biota other than humans	Equivalent
5.4.6	Radiological toxicity/effects	5.4.6	Radiological toxicity/effects	Equivalent
5.4.6.1	Radiological toxicity/effects for humans	5.4.6.1	Radiological toxicity/effects for humans	Equivalent
5.4.6.2	Radiological toxicity/effects for biota other than humans	5.4.6.2	Radiological toxicity/effects for biota other than humans	Equivalent
5.4.7	Chemical toxicity/effects	5.4.7	Chemical toxicity/effects	Equivalent
5.4.7.1	Chemical toxicity/effects for humans	5.4.7.1	Chemical toxicity/effects for humans	Equivalent
5.4.7.2	Chemical toxicity/effects for biota other than humans	5.4.7.2	Chemical toxicity/effects for biota other than humans	Equivalent
5.4.8	Radon and radon daughter exposure	-	-	Not a FEP in NEA (2019)

C 3 EXTERNAL FACTORS

The FEPs with causes or origins outside the assessed disposal system (Facility, the surrounding geosphere and overlying biosphere).

External factors are generally not influenced (or are only weakly influenced) by processes within the disposal system and are natural or human-induced factors of a regional and/or global nature. Decisions related to Facility design, operation and closure are included in this group because these are outside the temporal boundary of the disposal system for the purpose of the PostSA. External Factors are often represented as boundary conditions or initiating events and processes in developing scenarios and associated models of the disposal system.

The five subcategories under External Factors are:

1.1 Facility
1.2 Geological Factors
1.3 Climatic Factors
1.4 Future Human Actions
1.5 Other External Factors

C 3.1 Facility

The factors related to decisions taken, and events occurring during the life cycle of the Facility (e.g., site investigation, design, construction, operation and closure).

These factors could have an influence on the postclosure performance of the Facility and, therefore, have to be considered in associated safety assessments. For initial assessments (i.e., prior to Facility construction), assumptions have to be adopted and documented concerning the status of these factors. However, as the Facility program progresses (from site investigation to design to construction to operation to closure) more information from the actual program can be directly used in associated assessments. Certain factors relate to features (such as Facility design (FEP 1.1.3)), while others relate to events (such as Facility closure (FEP 1.1.7)) or processes (such as monitoring (FEP 1.1.10)).

There are 11 subcategories under Facility:

1.1.1 Quality assurance and control
1.1.2 Site investigations
1.1.3 Design
1.1.4 Schedule and planning
1.1.5 Construction
1.1.6 Operation
1.1.7 Closure
1.1.8 Accidents and unplanned events
1.1.9 Administrative control
1.1.10 Monitoring
1.1.11 Records and markers

C 3.1.1 FEP # 1.1.1 Quality Assurance and Control

Description

The quality assurance and control procedures and tests undertaken during site investigation, design, construction, operation and closure of the Facility, including the construction of engineered features.

It can be expected that a range of quality control measures will be applied during the Facility life cycle. These may be invoked in a PostSA to make the assumption that the disposal system functions as planned. Similarly, deficiencies in QA and quality control may lead to poorer than planned performance.

Screening Analysis

The reference assumption is that the Facility is constructed under an appropriate quality assurance regime and with appropriate measures being taken to limit the extent and permeability of the grouted Facility engineered barriers.

Poor construction techniques could impact on the performance of the Facility. Therefore, a Disruptive Event scenario is required to include consideration of enhanced permeability and potentially other deficiencies in the Facility which could result from poor construction.

Screening Decision

All post-closure scenarios, Disruptive Event (Extreme Degradation), Defence-in-Depth (Role of Grout; Role of Existing Facility Structure).

C 3.1.2 FEP # 1.1.2 Site Investigations

Description

The investigations carried out to characterize the Facility site, both prior to and during Facility construction and operation, establish baseline conditions and provide site-specific data for the PostSA. The extent of site investigation affects the degree of uncertainty associated with the assessment. Investigation boreholes could be conduits for groundwater flow if not appropriately sealed and so need to be sealed appropriately.

Screening Analysis

Available data from the existing site characterization is being used in the assessment.

All scenarios assume that any site investigation activity undertaken to characterize the Site has no detrimental impact on safety.

FEP Screening

All post-closure scenarios.

C 3.1.3 FEP # 1.1.3 Design

Description

The design and layout of the Facility, including both the safety concept, i.e. the general features of Facility and their safety functions, and the more detailed engineering specification for decommissioning and closure.

Screening Analysis

The current NPD Waste Facility (NPDWF) includes above grade and below grade structures. All of the above grade structures will be removed during decommissioning and most will be disposed of in the subsurface vaults beneath the Main building. The above grade structures are therefore only of interest for post closure safety if they introduce additional contaminants into the system or hinder grouting of the vaults. The inventories are discussed in FEP 2.1.1.

The main rooms in the Nuclear Area are:

- Fuelling Machine Room (herein referred to as Fuelling Room);
- Boiler Room;
- Reactor Vault;
- Fuel Storage Room; and
- Dump Pipe Room.

Sub-surface rooms are planned to be backfilled with grout.

The Facility design is an essential component of the Safety Assessment and so needs to be included.

Screening Decision

All post-closure scenarios, Defence-in-Depth (Role of Grout; Role of Existing Facility Structure).

C 3.1.4 FEP # 1.1.4 Schedule and Planning

Description

The sequence of events and activities occurring during Facility construction, operation and closure.

Relevant events may include assembly and operation of grout batch mixing plant, grouting of below grade structures, removal of above ground structures, installation of concrete cap and engineered barrier, final Site restoration and long-term care and maintenance.

Screening Analysis

The sequence of events and time between events may have implications for long-term performance, e.g., decay of activity, material degradation, chemical and hydraulic changes during the operational phase. From the perspective of postclosure performance, the main consideration is the date of closure, and the duration of any postclosure period of institutional control. The latter could prevent human intrusion. Thus, the most

important effect of a longer institutional control period is to prevent human intrusion for longer. The 2nd iteration of the Postclosure Safety Assessment (Arcadis *et al*., 2017) included a scenario examining this, and the results showed that extending the period of institutional control from 100 y to 300 y does not substantially reduce the dose rate to an inadvertent human intruder.

Screening Decision

Normal Evolution; Disruptive Events – Site Investigation (Inadvertent Human Intrusion), and Excavation of Above-Bedrock Facility; What If (Facility Mass Excavation).

C 3.1.5 FEP # 1.1.5 Construction

Description

Factors related to construction activities at the Facility including e.g., grouting of below grade structures, and installation of concrete cap and engineered barrier.

Screening Analysis

The Facility will be assumed to be constructed in line with its design (Normal Evolution). It is also necessary to examine, in the PostSA, the consequences of the potential failure of quality controls to detect the use of poor construction techniques (Disruptive Event, see FEP 1.1.1).

Incomplete grouting and/or pathways through the backfilled rooms is potentially of significance, and can be assessed with sensitivity calculations.

Screening Decision

Normal Evolution, Disruptive Events (Extreme Degradation; Fault Zone Activation).

C 3.1.6 FEP # 1.1.6 Operation

Description

The operation of the Facility including for example, the placing of wastes from above ground positions in their final position below grade within the Facility, placing of any backfill materials and the management of any water and gas in the Facility prior to closure.

Screening Analysis

The Facility will be assumed to be operated in line with its design (Normal Evolution). However, potential operational issues that might impact postclosure performance and safety include poor backfilling of the Facility (Disruptive Event, linked to FEP 1.1.1). This could leave permeable volumes in the system and cause potential subsidence.

Screening Decision

Normal Evolution, Disruptive Event (Extreme Degradation; Fault Zone Activation).

C 3.1.7 FEP # 1.1.7 Closure

Description

Factors related to the cessation of waste emplacement operations at the Facility and the backfilling and closure of the Facility. These closure activities are undertaken mainly to prevent human access into and limit the migration of contaminants from the Facility.

Screening Analysis

The Facility will be assumed to be closed in line with its design (Normal Evolution). Potential operational issues that might impact postclosure performance and safety include poor sealing of the Facility (Disruptive Event, linked to FEP 1.1.1). For example, the NPDDF cooling water piping will be grouted and the structure and outfall pipes will be capped. Any poor sealing or the long-term degradation of these structures could impact the performance of the disposal system. The Postclosure Safety Assessment should therefore also examine the significance of the grout as a barrier to radionuclide release and the overall performance of the NPDDF.

Screening Decision

Normal Evolution, Disruptive Event (Extreme Degradation; Fault Zone Activation), Defence-in-Depth (Role of Grout).

C 3.1.8 FEP # 1.1.8 Accidents and Unplanned Events

Description

The accidents and unplanned events during construction, operation and closure which might have an impact on long-term performance and safety of the Facility.

Accidents are events that are outside the range of normal operations. Unplanned events include deliberate deviations from operational plans, e.g., in response to an accident, unexpected geological event or unexpected waste arising during operations.

Screening Analysis

An accident or unplanned event could occur during closure construction, operation and closure activities (e.g., engineered cover installation). Such an event will not negatively impact the Facility performance because activities will be carried out with knowledge of the Facility and associated hazards and with a mitigation plan. This FEP is therefore not relevant to long-term performance and safety.

Screening Decision

Screen Out – Out of scope.

C 3.1.9 FEP # 1.1.9 Administrative Control

Description

The administrative measures, and time period, used to control events at or around the site during site investigation, construction, operation and closure, and after closure.

The responsibility for administrative control of the site before closure of the Facility during the construction and operational phases, and subsequently following closure of the Facility may not be the same. Furthermore, the type of administrative control may vary depending on the stage in the Facility lifetime.

Screening Analysis

The responsibility for the Facility administrative control may vary during its lifetime. Consistent with international practice (IAEA, 1999), it is assumed that records will be available at least until the end of the 100-y institutional control. After the institutional control period, it is assumed that Facility administrative controls are no longer effective. This FEP is relevant to the Facility long-term performance and safety insofar as it precludes human intrusion (e.g., FEP 1.4.5) for a period of time and is thus part of the Normal Evolution scenario. The most important effect of a longer institutional control period is to prevent human intrusion for longer. The 2nd iteration of the Postclosure Safety Assessment (Arcadis *et al*., 2017) included a scenario examining this, and the results show that extending the period of institutional control from 100 y to 300 y does not substantially reduce the dose rate to an inadvertent human intruder.

Screening Decision

Normal Evolution; Disruptive Events – Site Investigation (Inadvertent Human Intrusion), and Excavation of Above-Bedrock Facility; What If (Facility Mass Excavation).

C 3.1.10 FEP # 1.1.10 Monitoring

Description

Features, Events and Processes related to any monitoring that is carried out during operations or following closure of sections of, or the total, Facility. This includes monitoring for operational safety and also monitoring of parameters related to the long-term safety and performance.

Screening Analysis

NPD's environmental monitoring procedure during Storage and Surveillance is documented in CNL Report No. 64-509247-PRO-001. It includes sampling the Ottawa River water, soil and vegetation, ambient radiation and Ottawa River fish. Additional monitoring plans (i.e., an Effluent Monitoring Plan, Environmental Monitoring Plan, and Groundwater Monitoring Plan) are being developed as part of Environmental Impact Statement (EIS) follow-up, in accordance with CSA N288.5 (2011), CSA N288.4 (2010), and CSA N288.7(2015).

The design and operation of the Facility monitoring program provides a safety indicator and performance indicator. Facility monitoring will not impact long-term performance and safety, thus, this FEP is not relevant to the Facility long-term performance and safety.

Screening Decision

Screen Out – Out of scope.

C 3.1.11 FEP # 1.1.11 Records and Markers

Description

The retention of records of the content and nature of a Facility after closure and also the placing of permanent markers at or near the site.

These records and markers will allow future generations to recall or identify the existence and nature of the Facility following closure, and influence events such as future intrusion into the Facility. The loss of such records and markers will increase the likelihood of inadvertent intrusion sometime in the future.

Screening Analysis

It is expected that records of the Facility will be kept allowing future generations to identify or recall the existence and nature of the Facility following closure. Internationally, the use of site markers has been proposed where the intention is that the location and nature of the Facility might be recalled even in the event of a lapse of present-day administrative controls.

Consistent with international practice (IAEA, 1999), it is assumed that records and markers will be available at least until the end of the 100-y institutional control. This FEP is relevant to the long-term performance and safety of the Facility insofar as it precludes human intrusion (e.g. FEP 1.4.5) for a period of time and is thus part of the Normal Evolution scenario.

Screening Decision

Normal Evolution; Disruptive Events – Site Investigation (Inadvertent Human Intrusion), Excavation of Above-Bedrock Facility; What If (Facility Mass Excavation).

C 3.2 Geological Factors

The factors related to the long-term processes arising from the wider geological setting and their effects on the performance and safety of the disposal system.

Geological processes and effects with causes or origin outside the temporal and/or spatial boundaries of the disposal system but impact the system local to the Facility.

There are 13 subcategories under Geological Factors:

1.2.1 Tectonic movement
1.2.2 Orogeny
1.2.3 Deformation (elastic, plastic, or brittle)
1.2.4 Seismicity
1.2.5 Magmatic and volcanic activity
1.2.6 Metamorphism
1.2.7 Hydrothermal activity
1.2.8 Regional erosion and sedimentation
1.2.9 Diagenesis
1.2.10 Pedogenesis
1.2.11 Salt diapirism and dissolution
1.2.12 Hydrological/Hydrogeological response to geological changes
1.2.13 Geomorphological response to geological changes

C 3.2.1 FEP # 1.2.1 Tectonic Movement

Description

Tectonic movements are movements of rock masses as a result of movements of the Earth's crustal plates; regionally the surface rocks respond to the underlying movements of plates.

Screening Analysis

Tectonic activity is most likely to occur at or near plate boundaries. The site is located in the Ottawa-Gatineau region in Ontario, within the stable interior of the large North American tectonic plate (see Figure C-2), i.e., far from active tectonic plate boundaries (see location information in Arcadis & Geofirma, 2022; see also Figure C-2). The most recent major tectonic event affecting the area was the development of the Ottawa Bonnechere Graben, a rift valley initially formed about 600 million years ago and reactivated between 208 and 66 million years ago (AECL, 1996). This FEP is not relevant for the timescale of concern.

Screening Decision

Screen Out – Out of scope.

C 3.2.2 FEP # 1.2.2 Orogeny

Description

The forces and events leading to a large structural deformation of the Earth's lithosphere due to the movement of tectonic plates resulting in the formation of mountains.

Orogenesis generally occurs at tectonic plate margins where different plates are in contact and is associated with crustal deformation, faulting, folding and subduction and resulting seismicity and magmatic/volcanic activity.

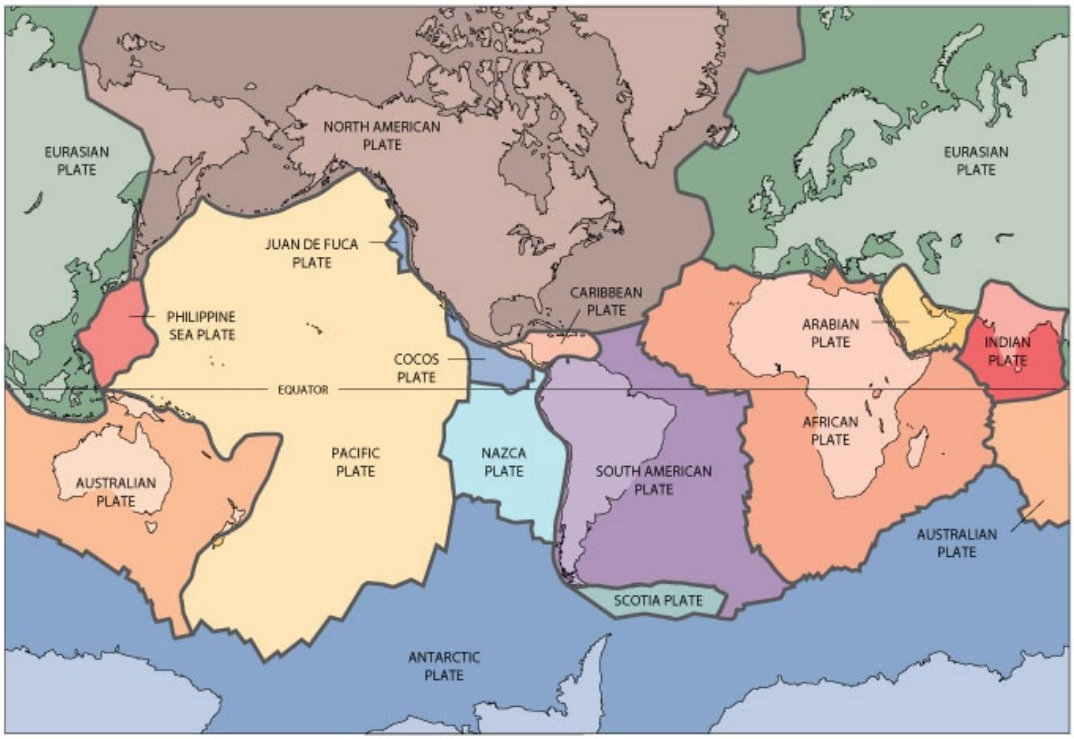
Screening Analysis

The Ottawa-Gatineau region is located far from active tectonic plate boundaries (see location information in Arcadis & Geofirma, 2022; see also Figure C-2). The most recent major tectonic event affecting the area was the development of the Ottawa Bonnechere Graben, a rift valley initially formed about 600 million years ago and reactivated between 208 and 66 million years ago (AECL, 1996). This FEP is not relevant for the timescale of concern.

Screening Decision

Screen Out – Out of scope.

Figure C-2: North American Plate and Its Boundaries with Other Major Tectonic Plates



Note: U.S. Geological Survey map available at http://pubs.usgs.gov/gip/dynamic/slabs/html

C 3.2.3 FEP # 1.2.3 Deformation (elastic, plastic, or brittle)

Description

The physical deformation of geological structures in response to geological forces such as tectonic movement, orogeny, magmatism, diapirism, and loading and unloading of the crust by glaciation /deglaciation or by sedimentation/erosion.

This includes faulting, fracturing, extrusion, compression of rocks and can result in basin formation. Compressional or tensional forces in the Earth's crust may result in the activation of existing faults and, less likely, the generation of new faults.

It also includes the forcing of high plasticity and low density material, such as salt, mud or magma, into more brittle and dense overlying rocks, often along fractures or zones of structural weakness.

Screening Analysis

Deformation due to tectonic movements and orogeny is unlikely over the timescale of interest. As outlined in Ganopolski *et al.,* (2016), anthropogenic climate change is likely to delay the next glaciation to beyond 100,000 y from now. Thus, glaciation is not credible within the assessment timeframe.

Screening Decision

Screen Out – Out of scope.

C 3.2.4 FEP # 1.2.4 Seismicity

Description

The release of accumulated geologic stress via rapid relative movements within the Earth's crust usually along existing faults or geological interfaces.

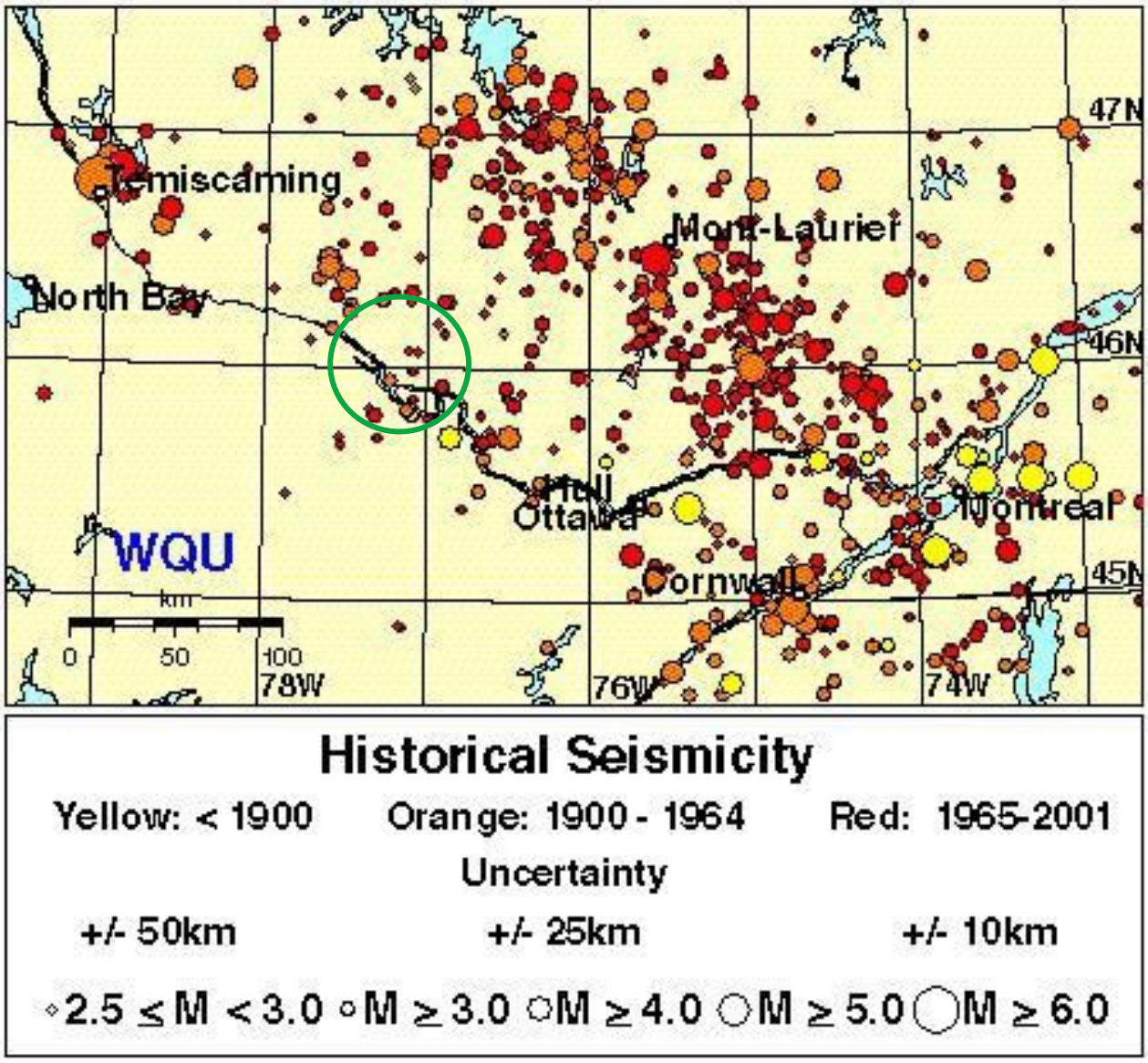
Seismic events are most common in tectonically active or volcanically active regions at or near crustal plate margins. The accompanying release of energy may result in ground movement and/or rupture, e.g. earthquakes, and result in waves on oceans and other water bodies (tsunamis). They can also occur in regions where ice sheets have advanced and /or retreated and, therefore, differential subsidence and /or uplifting of the crust occurs due to isostasy. Human-induced seismic events (e.g., caused by fluid injection) may occur both in naturally seismically active areas and in areas characterized by low background seismicity.

Observations have shown that the effects and magnitude of a seismic event are greater at the surface than underground. The potential effects of seismic events on the Facility include for example, shaking and mechanical damage to the concrete foundation, grout backfill and waste materials.

Screening Analysis

The NPDDF is located along the northern Ottawa-Bonnechere graben within the Grenville Structural Province of the Canadian Shield. Faults occur on both large and small scales (tens of kilometres to a few meters in length) throughout the Grenville Structural Province (CNL, 2013). The Ottawa River follows a major fault line adjacent to the NPDDF. Seismicity in Ontario is characterized by diffuse patterns of activity, ranging in degree from nearly a-seismic to moderately active (CNL, 2013). NPDDF lies within a broad belt of seismicity in the eastern part of the province. Most seismic events in this region have been small to moderate in magnitude, but there have been a few significant larger earthquakes (CNL, 2013). Figure C-3 shows the historical seismic activity. The green circle shows the immediate vicinity of the NPDDF.

Figure C-3: Historical Seismicity



Within this region, the Earth's crust is being compressed. Once the accumulated stress exceeds the strength of the crust, it is released by slippage along reactivated faults of the Ottawa-Bonnechere graben. Natural Resources Canada's mapping of the region places NPDDF at the boundary between areas that have a 10% probability of experiencing an earthquake with Intensity VI (widely felt but no structural damage) and Intensity VII (mild to moderate damage to buildings).

CNL's updated (2021a) *NPD Underground Structure Seismic Assessment* report selected and examined the effects of a 1-in-2,250 y event, a 1-in-10,000 y event, and a 1-in-50,000 y event, on the NPDDF. For a 1-in-2250-y event, results of CNL (2021a) indicate that the facility will experience cracking in the above-bedrock portion of the facility (particularly at the interface between the above-bedrock and below-bedrock portions of the facility), but no cracking in the below-bedrock portion of the facility. For a 1-in-10,000-y event, results of CNL (2021a) again indicate that the above-bedrock portion of the facility will experience more extensive cracking while the below-bedrock portion of the facility will not. Results of CNL (2021a) are again similar for the 1-in-50,000-y event, where the portion of the facility above-bedrock will experience significant cracking while the below-bedrock portion of the facility will not. The reader is referred to CNL (2021a) for further information on the selection, definition, and assessment of seismic events and their impacts on the facility.

It is assumed that the facility will experience one or more 1-in-2,250-y events. Furthermore, given that the facility will remain in place long into the future, it is assumed to experience seismic events of even greater magnitudes, such as a 1-in-10,000-y event.

Seismic events of even greater magnitudes (such as a 1-in-50,000 y event) may have further impacts on the Facility's long-term performance and safety due to early degradation of engineered barriers, and this requires evaluation. Seismicity is reflected in the PostSA through degradation of engineered barriers and fault zone activation (due to occurrence of an extreme seismic event damaging the facility but also creating a fracture zone).

Screening Decision

Normal Evolution, Disruptive Events – Extreme Degradation, Fault Zone Activation.

C 3.2.5 FEP # 1.2.5 Magmatic and Volcanic Activity

Description

The processes associated with sub-surface molten rock (magma) and surface volcanoes.

Magma is molten, mobile rock material, generated within or below the Earth's crust, which gives rise to igneous rocks when solidified. Magmatic activity occurs when there is intrusion of magma into solid rocks or extrusion of the magma at the earth's surface.

A volcano is a vent or fissure in the Earth's surface through which one or more of the following may flow/be expelled: magma; mud; solid and plastic fragments; liquid droplets; and hot gases. Around 95% of active

volcanoes occur at lithospheric plate boundaries. The other 5% are associated with lithospheric hot spots and rifts which correspond to weak areas in the Earth's crust and are caused by plumes of rising magma that have their origin within the asthenosphere. The high temperatures and pressures associated with magmatic and volcanic activity may result in permanent changes in the surrounding rocks (FEP 1.2.6).

Effects of magmatic/volcanic activity on the geosphere could include creation, activation and sealing of faults, changes in topography, changes in rock stress, deformation of rock and changes to groundwater composition and temperatures. It may also drive hydrothermal circulation. The Facility may be disrupted indirectly owing to changes in temperature, groundwater flow or groundwater chemistry that are caused by magmatism. Direct effects on the Facility include disruption by intersection of the Facility by a magmatic dike or fracture caused by volcano-tectonic activity. Flowing magma and/or associated fluids that intersect the Facility and that also reach the surface may give rise to dispersion of wastes in a plume of volcanic ejecta and in lava flows.

Screening Analysis

There are no known current regions of volcanic activity in Ontario. Volcanic activity is not expected to influence Ontario for millions of years (Quintessa *et al*., 2011). This FEP is not relevant for the NPDDF site geographical setting.

Screening Decision

Screen Out – Out of scope.

C 3.2.6 FEP # 1.2.6 Metamorphism

Description

The processes by which rocks are changed by the action of heat (T>200 °C) and/or pressure at depth (usually several kilometres) beneath the Earth's surface or in the vicinity of magmatic activity or active faulting.

The past metamorphic history of a host rock may be important to understanding its present-day characteristics and future evolution. Ongoing metamorphism can activate, create or seal faults; change topography and rock stress; deform rock structures; and alter groundwater composition, temperatures and pressures.

Screening Analysis

This FEP is not relevant for the NPDDF site and the timescale of concern. The Facility is located near the surface, and its performance and safety will not be impacted by metamorphism.

Screening Decision

Screen Out – Out of scope.

C 3.2.7 FEP # 1.2.7 Hydrothermal Activity

Description

The processes associated with high temperature groundwater, including processes such as heat-driven groundwater flow and hydrothermal alteration of minerals in the rocks through which the high temperature groundwater flows.

These processes are often complex and strongly coupled; for example, mineral precipitation and/or alteration could cause fracture infilling, thereby impeding groundwater flow, and potentially modifying groundwater salinity, resulting in the occurrence of a new set of mineral alteration reactions, and so forth. Groundwater temperature is influenced by large-scale geological and hydrogeological properties of the rock, such as the location of geothermal heat sources, thermal conductivity, location of recharge and discharge areas and hydraulic conductivity.

Screening Analysis

This is not a relevant FEP for the Facility because, given its shallow depth, the Facility will not be impacted by hydrothermal activity.

Screening Decision

Screen Out – Out of scope.

C 3.2.8 FEP # 1.2.8 Regional Erosion and Sedimentation

Description

The large-scale (geological) removal and accumulation of rocks and sediments, with associated changes in topography and geological/hydrogeological conditions at the Facility site.

Screening Analysis

Large scale geological erosion and sedimentation could occur due to glacial, fluvial and aeolian processes.

The surficial geology at the site consists primarily of sands, underlain by sandy glacial tills. The glacial sediments were deposited during the last North American continental glaciation (the Wisconsin), which occurred between 110 000 and 12 000 years ago. This was the most recent of a series of periods of continental glaciation with durations of about 100 000 years separated by inter-glacial periods with durations of a few tens of thousands of years, extending back through the Pleistocene epoch, spanning 1.5 million y. No sediments from previous glacial and interglacial periods in the NPDDF region have been preserved. The sands currently found at CRL were deposited after the most recent glaciation by the Ottawa River during periods of much higher flow when the river drained the precursors of the upper Great Lakes, and pro-glacial Lake Agassiz between 11 000 and 5 000 years before present. There has been limited reworking of some of the fluvial deposits by wind. There is a potential for wind erosion of surficial sands at CRL, although the velocities sufficiently high to transport dry, un-stabilized local sands occur infrequently (AECL, 1996).

Large scale geological erosion and sedimentation is highly unlikely to be relevant for the Facility on the timescales of concern because the next glaciation is not expected until after the assessment timeframe (i.e. as outlined in Ganopolski *et al.,* (2016), glaciation is likely to be delayed beyond 100,000 y due to anthropogenic climate change).

Note that in addition, surface erosion at the site is addressed in FEP 5.1.13, which is concerned with more local processes over shorter periods of time.

Screening Decision

Screen Out – Out of scope.

C 3.2.9 FEP # 1.2.9 Diagenesis

Description

The processes by which deposited sediments at or near the Earth's surface are formed into rocks by compaction, cementation and crystallization, i.e. under conditions of temperature and pressure normal to the upper few kilometers of the Earth's crust.

Diagenesis refers to processes occurring within the host rock subsequent to initial sedimentation. It includes all the chemical, physical, and biological changes, modifications, or transformations undergone by sediments after sedimentation, and during and after its lithification. It occurs under conditions of pressure and temperature that are normal to the surficial or outer part of the Earth's crust. It excludes metamorphism (FEP 1.2.6), which generally occurs at greater depths and at higher temperatures.

Screening Analysis

The Facility is located near the surface in the unconsolidated overburden above the bedrock. No significant physical and chemical changes to the bedrock properties are expected over the assessment period. This FEP is not relevant for the NPDDF site.

Screening Decision

Screen Out – Out of scope.

C 3.2.10 FEP # 1.2.10 Pedogenesis

Description

The origin and development of soils, with reference to the factors responsible for the formation of soil from unconsolidated parent material.

Screening Analysis

Pedogenesis depends upon climatic conditions and their impact on weathering processes, as well as on rock mineral composition, topography and biological processes. Pedogenesis may affect biosphere uptake

and near-surface system evolution as it involves hydrological, atmospheric and biological processes at or near surface on timescales of a few hundred to thousands of years. The effect may result in an improvement of land quality on a time relevant to the PostSA and merits inclusion in the Normal Evolution scenario.

Screening Decision

All post-closure scenarios.

C 3.2.11 FEP # 1.2.11 Salt Diapirism and Dissolution

Description

Salt diapirism and dissolution involves the large-scale evolution of salt formations. Diapirism is the lateral or vertical intrusion or upwelling of either buoyant or non-buoyant rock, into overlying strata (the overburden) from a source layer. Dissolution of the salt may occur where the evolving salt formation is in contact with ground waters with salt content below saturation.

Screening Analysis

The geosynthesis report (Arcadis & Geofirma, 2022) provides a detailed description of the geologic materials and hydrostratigraphic units relevant to the site. This FEP is not relevant because there are no salt formations at the site.

Screening Decision

Screen Out – Out of scope.

C 3.2.12 FEP # 1.2.12 Hydrological/Hydrogeological Response to Geological Changes

Description

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.

Screening Analysis

Continental glaciation may re-occur in the region around the Facility, and could affect groundwater flow but the timescale for such reoccurrence is estimated to be more than 100,000 y (Ganopolski *et al.*, 2016). Initial development of the Ottawa-Bonnechere graben occurred between 700 and 600 million y ago, with a second episode of tensional faulting occurring between 150 and 90 million y ago (Turner, 2008).

Large-scale geological changes are not relevant for the site and the timescale of concern. However, if river levels were to drop due to extreme environmental change leading to much reduced precipitation over a wide area (e.g., the onset of glaciation), discharge from the NPDDF could exit along the shore rather than beneath the river. This is considered as a What If case.

Hydrological/hydrogeological response to climate change, specifically, is addressed via FEP 1.3.7.

Screening Decision

What If (River Level Fall).

C 3.2.13 FEP # 1.2.13 Geomorphological Response to Geological Changes

Description

The surface landform changes on a regional and local scale, i.e., the general configuration of the Earth's surface, caused by large-scale geological changes.

The evolution of a landscape is impacted by geological and climatic conditions. In turn, these can impact hydrological and biological conditions which also affect landscape evolution. Examples of landforms directly resulting from geological changes are rift valleys and volcanoes.

Screening Analysis

The Ottawa-Gatineau region is located far from active tectonic plate boundaries (see location information in Arcadis & Geofirma, 2022; see also Figure C-2). The most recent major tectonic event affecting the area was the development of the Ottawa Bonnechere Graben, a rift valley initially formed between 700 and 600 million y ago, with a second episode of tensional faulting occurring between 150 and 90 million y ago (Turner, 2008). This FEP is not relevant for the timescale of concern.

There are no known current regions of volcanic activity in Ontario. Volcanic activity is not expected to influence Ontario for millions of years (Quintessa *et al.,* 2011). This FEP is not relevant for the NPDDF site geographical setting.

Some degree of geomorphological change may be expected as a result of glaciation (FEP 1.3.2). However, as indicated in Ganopolski *et al*. (2016), glaciation is not anticipated to occur within the 10,000-y assessment timeframe.

Note that in addition, surface erosion at the site is addressed in FEP 5.1.13, which is concerned with more local processes over shorter periods of time.

Screening Decision

Screen Out – Out of scope.

C 3.3 Climatic Factors

The factors related to the long-term processes arising from global climate changes and consequent regional effects on Facility performance and safety.

Climatic processes and effects with causes or origin outside the temporal and/or spatial boundaries of the disposal system but that impact the system local to the Facility.

There are 10 subcategories under Climatic Factors:

1.3.1 Global climate change
1.3.2 Regional and local climate change
1.3.3 Sea level change
1.3.4 Periglacial effects
1.3.5 Glacial and ice-sheet effects
1.3.6 Warm climate effects (tropical and desert)
1.3.7 Hydrological response to climate change
1.3.8 Ecological response to climate change
1.3.9 Human response to climate change
1.3.10 Geomorphological response to climate changes

C 3.3.1 FEP # 1.3.1 Global Climate Change

Description

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, c.f. FEP 1.3.2.

Screening Analysis

Global warming needs to be considered in the postclosure safety assessment. The predicted increase in global temperature and corresponding increase in precipitation at the site (CNL, 2019b) need to be included as part of a Normal Evolution Scenario.

Global warming is also expected to delay the onset of glaciation beyond the assessment timeframe. Thus, large scale geological changes associated with glaciation will not occur for 100,000 y, as a result of anthropogenic climate change (Ganopolski *et al*., 2016). This is beyond the expected 10,000-y timescale of concern. Therefore, glaciation is not included in the assessment.

Other effects are already captured in existing scenarios, e.g., in the Sensitivity (River Dilution Factor) Case and ‘What-If’ River Level Fall scenario.

Screening Decision

Normal Evolution, Sensitivity (River Dilution Factor), What If – River Level Fall Scenario.

C 3.3.2 FEP # 1.3.2 Regional and local climate change

Description

Features, Events and Processes related to the possible future changes, and evidence for past changes, of climate at a Facility 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.

Screening Analysis

Temperature and precipitation changes as a result of regional and local climate changes could potentially affect the long-term safety of the facility.

The impacts of climate change are accounted for in sensitivity cases for the Normal Evolution scenario.

Large scale geological changes associated with glaciation will not occur for 100,000 y, as a result of anthropogenic climate change (Ganopolski *et al.,* 2016). This is beyond the 10,000-y assessment timeframe. Therefore, glaciation is not included in the assessment.

Screening Decision

All post-closure scenarios.

C 3.3.3 FEP # 1.3.3 Sea level change

Description

The changes in sea level which may occur as a result of global climatic change and regional geological change, e.g. isostatic movements.

The component of sea-level change involving the interchange of water between land ice and the sea is referred to as eustatic change. As ice sheets melt so the ocean volume increases and sea levels rise. Sea level at a given location will also be affected by vertical movement of the land mass, e.g. depression and rebound due to glacial loading and unloading, referred to as isostatic change.

Screening Analysis

The NPDDF site is situated on the Ottawa River, at an elevation of approximately 125 mASL (above sea level). The site is situated on a regionally relatively flat area, dipping from a topographic high beginning on the north side of Tee Lake (approximately 225 mASL), to highway 17, which has an approximate elevation of 160 mASL, continuing to the Ottawa River which has an average elevation of 111 mASL (MacLarentech, 1990). Sea level change is not relevant.

Screening Decision

Screen Out – Out of scope.

C 3.3.4 FEP # 1.3.4 Periglacial Effects

Description

The physical processes and associated landforms in cold but ice-sheet-free environments within the region/locality of the Facility.

A key feature of such environments is the formation of large volumes of permanently frozen subsurface soils and rock, called permafrost. Permafrost layers will isolate the surface from the groundwater, forcing regional groundwater flows to discharge at local unfrozen zones (called taliks) under lakes or large rivers. A volume of high salinity water may form at the lower boundary of the permafrost freezing zone. Permafrost will also prevent meltwater, produced during seasonal thaws, from percolating downwards, resulting in a saturated surface layer and possibly mass movement of soil on slopes.

The advance or retreat of ice sheets will lead to a change to or from periglacial conditions. These will be accompanied by changes in drainage and watershed systems, which will affect near-surface groundwater flow, and changes in the plant, animal and human communities, which will affect potential exposure pathways.

Screening Analysis

The freezing index in the region is 1164 degree-days (each degree below 0ºC in mean outdoor temperature, averaged over a 24 hour period, is a degree-day) (AECL, 2008). Frost penetration depth for the area is 1.65 m (AECL, 1996). Frost penetration in the soils could result in the formation of ice lenses and the heaving that accompanies the development of ice. Most of the near surface soils at the site contain less than 1% of particles finer than 0.02 mm (coarse silt) and are not susceptible to ice lens formation (AECL, 1996). Frost penetration would also not be expected to affect the Facility itself, but could affect the uppermost portions in the engineered cover, leading to degradation (e.g., in the cap).

These processes could lead to changes in the overall landscape, drainage patterns and watershed dynamics, all of which may affect groundwater flow. Associated changes in plant, animal and human communities will also affect exposure pathways and exposure.

Screening Decision

All post-closure scenarios.

C 3.3.5 FEP # 1.3.5 Glacial and Ice-sheet Effects

Description

The effects of glaciers and ice sheets within the region/locality of the Facility, e.g., changes in the geomorphology, erosion, meltwater, mechanical and hydraulic effects.

Erosional processes (abrasion, over-deepening) associated with glacial action, especially advancing glaciers and ice sheets, and with glacial meltwaters beneath the ice mass and at the margins, can lead to

morphological changes in the environment e.g. U-shaped valleys, hanging valleys, fjords and drumlins. Depositional features associated with glaciers and ice sheets include moraines and eskers.

The pressure of the ice mass on the landscape may result in significant hydrogeological effects and even depression of the regional crustal plate and associated seismic events and activation of existing faults. During and after the glaciation, the groundwater flow paths might change due to various effects, ranging from the changed gradients around the ice sheet, to changes in the permeability of near-surface systems due to permafrost. The ice sheets may introduce oxygenated water, possibly during the period of ice sheet advance or retreat, when head gradients are largest.

Screening Analysis

The last de-glaciation was 11,000 y ago. Glacial Lake Agassiz drainage through the Ottawa Valley occurred between 10,800 and 8,900 y ago with flows up to 100,000 m^3/s. As outlined in Ganopolski *et al.* (2016), anthropogenic climate change is likely to delay the next glaciation to beyond 100,000 y from now. Thus, glaciation is not credible within the 10,000-y assessment timeframe. This FEP is therefore not relevant for the timescales of concern.

Screening Decision

Screen Out – Out of scope.

C 3.3.6 FEP # 1.3.6 Warm Climate Effects (Tropical and Desert)

Description

The effects of warm tropical and desert climates, including seasonal, meteorological and geomorphological effects specific to these climates within the region/locality of the Facility.

If the regional climate becomes tropical, then the region may experience extreme weather patterns (monsoons, hurricanes) that could result in flooding, storm surges and high winds with implications for erosion. The high temperatures and humidity associated with tropical climates result in rapid biological degradation.

In more arid regions, total rainfall, erosion and recharge may be dominated by infrequent storm events. Desertification as a result of extended drought could lead to deforestation and loss of grassland; dust storms might become a common feature causing soil erosion; alkali flats might form causing the accumulation of salts and contaminants at the soil surface. A lowered water table would affect natural biota, and might also lead to the use of deep water-supply wells to support local agriculture (or to use of distant water supplies).

These changes may also be associated with rapid alteration of topography associated with enhanced effects of erosion.

Screening Analysis

The climate of the site area is classified as humid continental with warm summers, cold winters and no distinct dry season (Turner, 2008). The climate change predictions in CNL (2019b) indicate increases in temperature of between 0.6° to 7.8° (with 2.2° and 3.9° being more central estimates), and increases in precipitation of between 1% to 3% per degree of increased temperature. Thus, the development of warm tropical or desert climate around the site is not considered to be plausible over the timescales of concern. This FEP is not relevant for the site geographical setting.

Screening Decision

Screen Out – Out of scope.

C 3.3.7 FEP # 1.3.7 Hydrological Response to Climate Change

Description

The changes in hydrology and hydrogeology, e.g., recharge, sediment load and seasonality, in response to climate change within the region/locality of the Facility.

The hydrology of a region is closely coupled to climate. Climate controls the amount of precipitation and evaporation, seasonal ice and snow cover, and thus the soil water balance, degree of soil saturation, surface run-off, changes in sediment load characteristics and groundwater recharge. Vegetation and human actions may modify these responses. Potential effects include climate-induced evolution of surface-water bodies, such as the formation of lakes and rivers, or their loss by sedimentation and infilling, river-course meander and long-lasting flooding or drying of low-lying areas.

Screening Analysis

Drainage at the site generally follows northwest-southeast trending depressions coinciding with faults and then drains via intersecting cross faults to the Ottawa River (topographic low area). Precipitation falling on topographically high areas results in the recharge of the shallow-scale groundwater system, which includes the overburden and the upper surface of fractured bedrock.

The hydrology will respond to climate change. Climate controls the amount of precipitation and evaporation, seasonal ice cover and thus the soil water balance, extent of soil saturation, surface runoff, and groundwater recharge (IAEA, 2004). Thus, climate change could impact the amount of precipitation, evaporation, seasonal snow, soil saturation, surface run-off and groundwater recharge. Hydrological/hydrogeological response to climate changes is related to the regional scale and since climate change (FEP 1.3.1 and FEP 1.3.2) is relevant to the Facility long-term performance and safety, this FEP is also relevant.

However, based on climate change predictions in CNL (2019b), the estimated increases in annual precipitation are unlikely to change river levels to the extent that would cause flooding of the facility. This is due to the fact that there is a significant slope and height difference (16 m) between the facility and the river. The potential effect of severe erosion (more extreme than erosion in the Normal Evolution, e.g. due to extreme climate change) can be examined in a Disruptive Event scenario for perspective.

It is also possible that the river level could fall. In the onset of a glacial episode, ice sheet development to the north of the site could result in less precipitation entering the Ottawa River, as it accumulates as snow and ice. Similarly, a change leading to dryer conditions over much of Canada could have similar consequences. In either case, the result could be a reduction in the level of the river and adjustment of the hydrogeology local to the NPDDF. This could lead to a larger proportion of the contaminated groundwater discharging through surface springs rather than to the riverbed.

Screening Decision

Normal Evolution, Sensitivity (River Dilution Factor), Disruptive Event (Surface Erosion), What If (River Level Fall).

C 3.3.8 FEP # 1.3.8 Ecological Response to Climate Change

Description

The changes in ecology, e.g., vegetation, animal and plant populations, in response to climate change within the region/locality of the Facility.

The ecology of an environment is responsive to climate changes. The current ecosystem at a site can be expected to evolve as a result of global warming in the next millennium. In the longer term, glacial cycling could result in significant changes to the ecosystem found at a site.

Screening Analysis

According to Wills (2013), the NPDDF site supports a diverse mix upland area with some wetland areas scattered throughout. Coniferous and mixed shade-intolerant (e.g., pine, oak, poplar) forests, which are consistent with surrounding forests, predominate because of the warm microclimate found in the area. Human disturbance, including logging of white pine in the 1800s and 1900s, and forest fires, has also influenced the current vegetation cover.

The ecology of the region is linked to climate and will change as a result of climate change. Ecology response to climate changes is related to the regional scale and since climate change (FEP 1.3.1 and FEP 1.3.2) is relevant to the Facility long-term performance and safety, this FEP is also relevant. A specific situation of interest, albeit highly uncertain, would be a modification in the climate sufficient to permit a much greater degree of agriculture at the location.

Screening Decision

All post-closure scenarios.

C 3.3.9 FEP # 1.3.9 Human Response to Climate Change

Description

The changes in human behavior, e.g., habits, diet, size of communities, dwelling types and location, in response to climate change within the region/locality of the Facility.

Climate affects the abundance and availability of natural resources such as water and the types of crops that can be grown. It also affects the activities and needs of humans; for instance, a colder climate would likely increase the time spent indoors and heating fuel needs. The more extreme a climate, the greater the extent of human control over the resources required to maintain agricultural productivity, e.g., through the use of controlled agricultural environments (greenhouses). Some climate changes may be sufficiently extreme that the region becomes uninhabitable on a permanent basis. Conversely, some climate changes may make a region more attractive for human habitation. These latter effects would influence the location and habits of humans.

Screening Analysis

Human response is closely linked to climate and human behavior and will change as a result of climate change. Climate affects the abundance and availability of natural resources such as water, as well as the types of crops that can be grown. The more extreme a climate, the greater the extent of human control over these resources is necessary to maintain agricultural productivity, e.g., through the use of dams, irrigation systems and controlled agricultural environments (greenhouses). Climate changes could result in the region becoming more attractive for human habitation or result in the region becoming uninhabitable. In broad terms, substantial change in the local climate is not expected within the assessment timeframe (noting that glaciation is expected to occur beyond this). However, it is possible that modest changes might alter the resource potential of the land, particularly if a change in temperature or growing period permitted a greater degree of agricultural exploitation.

The habits and characteristics of the human critical group will change as a result of climate change, thus this FEP is relevant to the Facility long-term performance and safety.

Screening Decision

All post-closure scenarios.

C 3.3.10 FEP # 1.3.10 Geomorphological Response to Climate Changes

Description

The geomorphological responses to climate changes that cause changes to surface landforms within the region/locality of the Facility.

The evolution of a landscape is impacted by geological and climatic conditions. In turn, these can impact hydrological and biological conditions which also affect landscape evolution. Examples of landforms directly resulting from climatic changes are periglacial landforms such as solifluction lobes and pingos.

Screening Analysis

The geomorphology of the region is linked to climate and will change as a result of climate change. Geomorphological response to climate changes is related to the regional scale and some degree of geomorphological change may be expected as a result of glaciation (FEP 1.3.2). Glaciation is not credible within the 10,000-y assessment timeframe, based on anthropogenic climate change (Ganopolski *et al.*, 2016).

Screening Decision

Screen Out – Out of scope.

C 3.4 Future Human Actions

The factors related to human actions and regional practices, in the postclosure period (future), that can potentially affect the performance of the natural (geological) and/or engineered barriers, and consequently the performance and safety of the disposal system.

Human actions with causes or origin outside the temporal and/or spatial boundaries of the disposal system but impact the system local to the Facility. Included in this category of FEPs are thus intrusive actions, but not the passive behavior and habits of the local population (FEP 5.2).

There are 12 subcategories under Future Human Actions

1.4.1 Human influences on climate
1.4.2 Social and institutional developments
1.4.3 Technological developments
1.4.4 Knowledge and motivational issues [Facility]
1.4.5 Drilling activities
1.4.6 Mining and other underground activities
1.4.7 Un-intrusive site investigation
1.4.8 Surface activities
1.4.9 Water management (groundwater and surface water)
1.4.10 Explosions and crashes
1.4.11 Remedial actions
1.4.12 Deliberate human intrusion

C 3.4.1 FEP # 1.4.1 Human Influences on Climate

Description

The human activities that could affect the change of climate either globally or in a region.

For example, man-made emissions of “greenhouse” gases such as CO_2 and CH_4 have been implicated as factors in global warming which could act to delay or even prevent the next glaciation cycle. It is also possible that there will be an active effort to maintain conditions close to the present ones; as is indicated by current efforts to reduce causes of global warming. Regionally, climate can be modified by de-forestation.

Screening Analysis

In the near term, human induced global warming may cause changes whose impacts can be locally important (e.g., changes in precipitation). Changes in regional land-use typically have a less significant impact on climate.

In the long term, man-made emissions of greenhouse gases have been implicated as factors in global warming. Peltier (2011) notes that the initiation of a glacial episode would be inhibited by current levels of greenhouse gases, which in turn, are affected by human actions.

Changes to the current climate may affect the Facility long-term performance and safety. A reference climate evolution pattern will be required to underpin model development. The key effects are increased temperature and precipitation (CNL, 2019b).

Screening Decision

Normal Evolution.

C 3.4.2 FEP # 1.4.2 Social and Institutional Developments

Description

The changes in social patterns and degree of local government, planning and regulation.

Potentially significant social and institutional developments include: changes in planning controls and environmental legislation; demographic change and urban development; changes in land use; and loss of records or societal memory of the Facility location and hazards.

Screening Analysis

The overall final end-state for the site is to have non-impacted areas returned to AECL for unrestricted use, following the reference 100-y period of institutional control (Titterington, 2016). Use of the Facility for industrial purposes is assumed to occur after the reference institutional control period. Potential social and institutional developments may include: changes in land use, change in regulatory requirements, loss of archives/records of the Facility, loss of societal memory, changes in planning controls and environmental legislation, and demographic change and urban development. The decisions made in the future concerning

social and institutional development may impact the Facility long-term performance and safety. The reference institutional assumption is that control is maintained of the site for at least 100 y. The most important effect of a longer institutional control period is to prevent human intrusion for longer. The 2nd iteration of the Postclosure Safety Assessment (Arcadis *et al.,* 2017) included a scenario examining this, and the results show that extending the period of institutional control from 100 y to 300 y does not substantially reduce the dose rate to an inadvertent human intruder.

Screening Decision

Normal Evolution, Disruptive Events – Site Investigation (Inadvertent Human Intrusion), Excavation of Above-Bedrock Facility; What If (Facility Mass Excavation).

C 3.4.3 FEP # 1.4.3 Technological Developments

Description

Future developments in human technology and changes in the capacity and motivation to implement technologies.

This may include retrograde developments, e.g., loss of capacity to implement a technology. Of interest are those technologies that might change the capacity of humans to intrude deliberately or otherwise into a Facility, to cause changes that would affect the movement of contaminants, and to affect exposure to those contaminants or its health implications. A lower level of technology might make it less likely that intrusion could be technically achieved. An improved level of technology might make intrusion more likely but as well might imply increased knowledge of the risks and how to control them. Other possibilities include advances that lead to the prevention or cure of radiation-induced cancers, and advances in food production (recent changes include hydroponics) that could lead to new exposure routes or altered levels of exposure.

Screening Analysis

The technological developments of interest are those that might change the capacity of humans to intrude deliberately or otherwise into the Facility, to cause changes that would affect the movement of contaminants and affect the exposure pathways or health implications.

Technical developments in the future are likely but are unpredictable over the timescale of concern. This FEP is outside the scope of long-term performance and safety assessment.

Screening Decision

Screen Out – Out of scope.

C 3.4.4 FEP # 1.4.4 Knowledge and Motivational Issues [Facility]

Description

The degree of knowledge of the existence, location and/or nature of the Facility, including reasons (motivation) for deliberate interference with, or intrusion into, a Facility after closure with complete or incomplete knowledge.

Some future human actions could directly or indirectly impact upon Facility performance. These actions may be associated with complete, incomplete or no knowledge of the Facility.

Screening Analysis

Aside from the operations and activities undertaken by CNL, other land uses of the site are currently prohibited due to restricted public access. No hunting or fishing is permitted on the site property and the site is not used for traditional purposes by aboriginal people. No commercial lumbering currently takes place at the site.

Future deliberate intrusion (i.e., waste recovery) would be taken with full knowledge of the Facility's existence, location and associated hazards (see FEP 1.4.12). It is an accepted basis of PostSA that deliberate intrusion is beyond the scope of the safety analysis as the intruders would be responsible for their own safety.

Screening Decision

Screen Out – Out of scope.

C 3.4.5 FEP # 1.4.5 Drilling Activities

Description

Any type of drilling activity in the vicinity of or within the Facility.

These may be taken with or without knowledge of the Facility (FEP 1.4.4). Drilling activities might be carried out for a number of reasons, including: the pumping of water from aquifers; the exploration for mineral and energy resources; the production of geothermal energy; and scientific studies.

Screening Analysis

Inadvertent human intrusion (i.e., exploratory drilling) would have no knowledge or awareness of the Facility and this could occur after the reference institutional control period. Inadvertent human intrusion could potentially impact the Facility performance and result in a human exposure pathway.

Drilling activities may be carried out for many reasons including: exploratory and/or exploitation for natural resources, water well, research or site characterization studies, hydrothermal resources and geothermal energy production. This FEP is relevant to the Facility long-term performance and safety.

Screening Decision

Disruptive Events – Site Investigation (Inadvertent Human Intrusion), Excavation of Above-Bedrock Facility, Overburden Well, Bedrock Well; What If (Facility Mass Excavation).

C 3.4.6 FEP # 1.4.6 Mining and Other Underground Activities

Description

Any type of mining or excavation activity carried out in the vicinity of or within the Facility.

These may be taken with or without knowledge of the Facility (FEP 1.4.4). These activities include conventional blasting and excavation practices, strip mining and solution mining. Reasons for mining and related activities include: recovery of nearby natural resources such as minerals; excavation of another Facility for the storage or disposal of nuclear waste; excavation for storage or disposal of other wastes (e.g., natural gas storage, CO_2 sequestration); excavation for storage of valuable material such as petroleum products; and construction of underground shelters for military purposes.

Screening Analysis

There is only a small amount of mining and quarrying in the whole of Renfrew County. There are no known mineral occurrences of economic significance on the property and there is no significant mineral potential on the site (AECL, 1996). A more recent review of mining and mineral records was performed in Arcadis & Geofirma (2022), which identified the following:

- Two (2) former aggregate pit records were found within the NPD site (likely related to the construction of the facility), though these pits are no longer operational today.
- One (1) record for an active mining claim (for gneiss and granite building stone) was identified, located 12 km west of the NPDDF site near Mackey.
- One (1) record of a past mine without reserves was identified near the Mackey area (silica sand and feldspar).
- Two (2) records of discretionary mineral occurrences (anorthosite and graphite) were identified in the region, located 13 km southwest and 28 km southeast, respectively of the NPDDF site.

Therefore, mining and other underground activities in the vicinity of the Facility are highly unlikely.

Screening Decision

Disruptive Events – Site Investigation (Inadvertent Human Intrusion), Excavation of Above-Bedrock Facility; What If (Facility Mass Excavation).

C 3.4.7 FEP # 1.4.7 Un-intrusive Site Investigation

Description

Any airborne, surface or other remote investigations of a Facility site after Facility closure.

Such investigations, such as prospecting for geological resources, might occur after information on the location of a Facility has been lost. The evidence of the Facility, e.g., discovery of an old shaft and/or a magnetic anomaly (due to the large amount of metal in the Facility), might itself prompt investigation, including research of historical archives. This FEP excludes all drilling activities, including those that do not penetrate into the Facility; they are covered by FEP 1.4.5.

Screening Analysis

Future deliberate un-intrusive site investigations of the Facility will be undertaken after consideration of the safety aspects and associated hazards. Un-intrusive site investigations will result in negligible human exposure because the waste is buried below the surface, soil provides shielding and the short duration of the investigation. Un-intrusive site investigations will not have an effect on the Facility long-term performance and safety and are therefore screened out on the basis of negligible consequences.

Screening Decision

Screen Out.

C 3.4.8 FEP # 1.4.8 Surface Activities

Description

The human activities that may be carried out in the surface environment which can potentially affect the performance of the engineered and/or geological barriers, or the exposure pathways.

Examples include: changes in land use; quarrying and trenching; excavation for industrial purposes such as construction of a building; excavation for archaeological purposes; residential and road construction; and major earthmoving projects, such as construction of dikes and dams (which could alter the landscape and expose subsoil, unconsolidated sediments, or bedrock and change groundwater recharge and discharge locations or affect groundwater flow regimes). Excludes those FEPs related to water management (FEP 1.4.9).

Screening Analysis

Surface activities during the operation, closure and institutional control periods would be taken with full knowledge of the Facility's existence, location and associated hazards. Surface activities occurring after the reference institutional control period could occur with partial knowledge or without knowledge of the Facility. Examples of surface activities include construction of a building, construction of a road and site investigations. The associated surface activities could include excavation, quarrying, trenching, ploughing, digging, blasting, loading, and hauling. Surface activities (inadvertent human intrusion) could potentially impact the performance and safety of the Facility. This FEP is relevant to the Facility long-term performance and safety.

Screening Decision

All post-closure scenarios.

C 3.4.9 FEP # 1.4.9 Water Management (Groundwater and Surface Water)

Description

Groundwater and surface water management including water extraction, reservoirs, dams and river management.

Water is a valuable resource and water extraction and management schemes provide increased control over its distribution and availability through construction of dams, barrages, canals, pumping stations and pipelines. Groundwater and surface water may be extracted for human domestic use (e.g. drinking water, washing), agricultural uses (e.g. irrigation, animal consumption) and industrial uses. Extraction and management of water may affect the movement of contaminants to and in the surface environment. The drilling of water wells is considered under Drilling activities (FEP 1.4.5).

Screening Analysis

The area surrounding the site lies entirely within the Ottawa River watershed. Deep River, Petawawa and Pembroke all use the Ottawa River for their municipal drinking water supply while residents of closer surrounding communities such as Rolphton and Alexander Point may draw water directly from the river. The Village of Chalk River draws its drinking water supply from the Chalk River.

In the vicinity of the site, the Ottawa River is regulated for the purpose of hydroelectric power generation. The three closest generating sites are the Otto Holden Generating Station (Mattawa, approximately 100 km upstream of the site), the Des Joachims Generating Station (Rolphton, approximately 3 km upstream) and the Chenaux Generating Station (Chenaux, approximately 70 km downstream). New major water management projects would be subject to environmental impact statements.

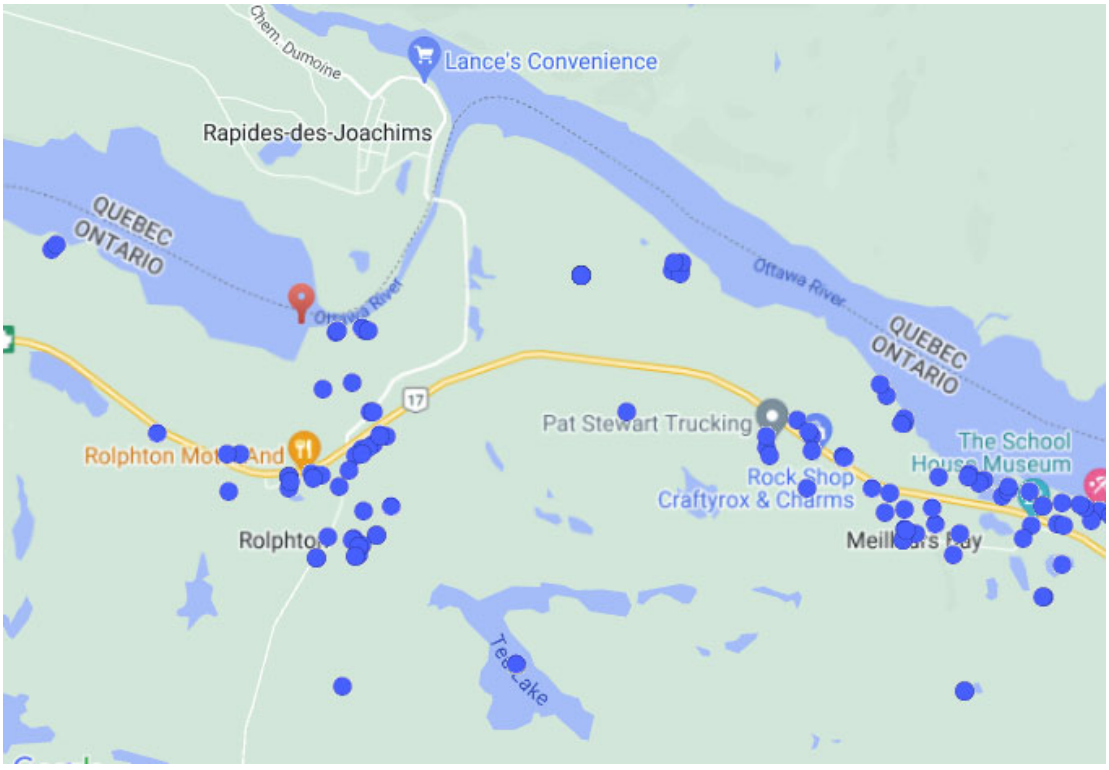
In the future, it is possible that the Ottawa River is no longer dammed, which could affect the river dynamics. It is also possible that in the future there might be a catastrophic failure of dams leading to a surge in the river. This was assessed by OPG in 1999, updated by OPG in 2016, and compared and summarized most recently by CNL in 2017 (CNL, 2017). According to CNL (2017), the 1999 OPG work identified the return period for such a flood based on a Probable Maximum Flood (PMF) involving a 1-in-10,000-y (i.e., 10^{-4} annual probability of occurrence) rainfall occurring (Probable Maximum Precipitation (PMP)) along with a 1-in-100-y snow accumulation. In total, this PMF is an event with a 10^{-6} annual return period (1-in-a-million y). When the PMF is used to determine dam failure scenarios, OPG's 1999 study concluded the frequency to be less than 1-in-10-million y. CNL (2017) mentions that the purpose of OPG's 1999 work was "to establish flood limits for emergency planning", and further that "the conservatism inherent in this modelling was desirable and allowed Emergency Evacuation plans in heavily populated areas to be more conservative". CNL (2017) compared the 1999 and 2016 results and noted that the basis for the PMF and its associated return period was the same, i.e., a 1-in-10,000-y PMP rainfall plus a 1-in-100-y snow accumulation, however, the 2016 predicted flood elevation levels are lower than those from 1999 (due to improvements in how topography is taken into account). For example, the 1999 flood elevation level estimated at Deep River was 131.1 mASL and at the NPD site was 132.2 mASL, whereas the 2016 estimate at Deep River was 117.8 mASL (a 2016 estimate was not provided specifically for the NPD site). The

highest NPDWF estimate, 132.2 mASL, corresponds to a water level increase of 23.5 m), compared to the NPDWF's elevation at 129 mASL. While this might not overtop the cap, it could denude surrounding ground by removing some of the overburden and thus change the pathways to the surface. This might be of significance and so the FEP is relevant to consider as a Disruptive Event scenario, noting the extreme nature of the assumptions required to generate the event.

At present, there are drains around the Facility that manage groundwater. In the future, these may cease to function and result in changes to groundwater flow patterns. This can be expected to occur naturally over time and is therefore represented in Normal Evolution scenario.

After the reference institutional control period, there is a potential that the groundwater or surface water in the vicinity of the Facility could be used as a source of water for human use and/or industrial purposes. Water wells are relatively common in the vicinity (Figure C-4), drilled to a depth between 15 m and 100, into the bedrock. Figure C-4 shows that the there are few wells in the immediate vicinity of the NPDDF, with the only ones on the site being emplaced for monitoring reasons. In the longer term, however, restrictions may lapse and the pattern of wells seen in the locality extend into the vicinity of the Facility to extract water. This water use could introduce pathways for contaminant movement and may impact the Facility long-term performance and safety. This requires representation in Disruptive Event scenarios involving a well.

Figure C-4: Water Wells in the Vicinity of the NPDDF Site



Note: Water wells are indicated with blue circles. Data from https://www.ontario.ca/page/map-well-records, retrieved on 21 July 2023.

Screening Decision

Normal Evolution, Disruptive Events – Surface Erosion, Overburden Well, Bedrock Well.

C 3.4.10 FEP # 1.4.10 Explosion and Crashes

Description

The deliberate or accidental explosions and crashes that might have some impact on a closed Facility.

Examples include underground nuclear testing, aircraft crash on the site, acts of war or sabotage, accidental equipment or chemical explosions or fires inside or near the Facility, and explosion of nuclear or chemical bombs at the Facility site. These events could affect the performance of the Facility in a variety of ways, such as changes to the integrity of the host rock and failure of seals.

Screening Analysis

The Facility is remote and therefore the only plausible crash that could occur is an aircraft crash. An aircraft crashing in the Chalk River Laboratories (CRL) Controlled Areas is a disruptive event with a very low frequency of 1.9×10^{-5} per annum (CNL, 2013). The frequency of aircraft crashing at the smaller NPDDF site is correspondingly smaller. This is event is very unlikely to occur, and is therefore screened out on the basis of low probability.

Screening Decision

Screen Out.

C 3.4.11 FEP # 1.4.11 Remedial Actions

Description

The actions that might be taken following Facility closure to remedy problems with a Facility arising from its sub-standard performance, disruption by some natural event or process, or inadvertent or deliberate damage by human actions.

The main issue of concern is that the remedial actions may worsen the situation, possibly because it was incorrectly determined that the Facility performance was impaired, or because remedial actions are improperly undertaken or unknowingly defeat important barriers. Another possibility is that contaminated materials from remedial activities may not be adequately stored or disposed.

Screening Analysis

Remedial actions of the Facility may occur during closure or the institutional control period and will be carried out with the knowledge of the Facility and associated hazards. Remedial actions will not therefore negatively impact the Facility performance and safety, and are assumed to improve the Facility performance and safety. No remedial actions are assumed for the Postclosure phase. The FEP is therefore screened out as being out of scope.

Screening Decision

Screen Out – Out of scope.

C 3.4.12 FEP # 1.4.12 Deliberate Human Intrusion

Description

The reasons for and nature and consequences of deliberate intrusion into a Facility after closure with complete or incomplete knowledge.

Deliberate intrusion could occur for reasons that include: undertaking of remedial activities to correct real or perceived faults in the Facility performance (FEP 1.4.11); authorised retrieval of materials from the Facility; unauthorised retrieval of radioactive material for malicious reasons including sabotage and war; and archaeological exploration that is driven by the observed or inferred presence of Facility structures or contents. The potential effects of deliberate intrusion include removal of contaminants from the Facility to the surface environment.

Screening Analysis

Future deliberate intrusive actions within the Facility would only be carried out after consideration of the safety aspects. The assumption for any deliberate human intrusion is that any society wishing to recover the Facility emplaced materials would have the technology to understand and mitigate the short-term and long-term hazards. Deliberate human intrusion is not relevant to the long-term performance of the Facility as it is deemed to be out of scope of the assessment.

Screening Decision

Screen Out – Out of Scope.

C 3.5 Other External Factors

Any other external scenario-generating factors not accommodated in FEP categories 1.1 to 1.4.

There are 2 subcategories under Other External Factors

1.5.1 Meteorites and human space debris
1.5.2 Evolution of biota

C 3.5.1 FEP # 1.5.1 Meteorites and Human Space Debris

Description

The possibility of a large meteorite or human space debris impact occurring at or close to the Facility site and related consequences.

The impact could cause phenomena such as the creation of a crater, activation, creation and sealing of faults, and physical and chemical changes in rock. The probability of impact of a meteorite sufficiently large

and close to a Facility to cause damage to the Facility can be estimated based on the estimated frequency of large meteorite impacts in the past, and taking account of the Facility depth.

Screening Analysis

Wuschke *et al.* (1995) provide a generic assessment of the probability and consequences of meteor impact on a repository. This indicates that meteorites of sufficient size to substantially disturb the ground are assessed having a probability of less than 10^{-6} y^{-1} of impacting the Facility. The FEP can therefore be screened out on the basis of low probability.

Screening Decision

Screen Out.

C 3.5.2 FEP # 1.5.2 Evolution of Biota

Description

The biological evolution of humans, other animal or plant species, by both natural selection and selective breeding/culturing.

Over the timescales considered in some safety assessments, natural evolution of animal and plant species is possible. The rate varies between organisms, and can be very rapid in bacteria and microbes. Forced evolution of animal and plant species by selective breeding and genetic manipulation, especially species used for human foods, has occurred over very recent time scales. Humans are also subject to biological evolution, although perhaps to a lesser degree because they tend to modify the environment to suit their needs. Evolution may affect anatomical features and physiological processes.

Screening Analysis

Biological evolution, whether driven by natural random genetic variation and selection or by deliberate future human actions, is not predictable in any quantitative manner. Change could increase or decrease sensitivity of species to radionuclides and other contaminants.

It is likely that some microbial adaptation would occur, but unlikely that it would lead to dramatically new species because the main materials present in the repository are also present in natural settings. The repository environment would already have microbial species. Since the native species already span a variety of niches, the presence of a repository will likely affect which species prosper (and at which time) rather than fostering the creation of substantively different species by mutagenesis or natural evolution.

In the NPDDF closure assessment, consistent with the recommendations of ICRP Publication 81 (ICRP, 2000), human doses are calculated for a reference person whose characteristics are based on current human physiology. Similarly, the general characteristics of biota are assumed to remain similar to current biota. Thus, species evolution is not considered in the NPDDF postclosure assessment as it is out of scope.

Screening Decision

Screen Out – Out of scope.

C 4 WASTE PACKAGE FACTORS

The factors related to waste packages (i.e., waste forms and any associated packaging) and the associated release and migration of contaminants.

The five subcategories under Waste Package Factors are:

2.1 Waste Form
2.2 Waste Packaging Characteristics and Properties
2.3 Waste Package Processes
2.4 Containment Release [waste package]
2.5 Containment Migration [waste package]

C 4.1 Waste Forms

The waste at the time of emplacement in the Facility, following any pre-disposal treatment and/or conditioning.

Waste can often be treated (e.g., volume reduction) and/or conditioned (e.g., immobilization) prior to packaging to produce a range of waste forms for disposal. Postclosure safety assessment needs to account for the proposed/actual waste forms to be disposed in the Facility since they will affect the release and migration of contaminants from the waste form.

There are 2 subcategories under Waste Form:

2.1.1 Contaminant inventory
2.1.2 Waste form characteristics and properties

C 4.1.1 FEP # 2.1.1 Contaminant Inventory

Description

The content of radioactive and non-radioactive contaminants in the various waste forms disposed in the Facility.

Estimates of inventories (radiological and non-radiological) are required for all radionuclides and hazardous designated substances disposed in the Facility. The potential impact of radionuclides and hazardous designated substances in the waste on human and non-human biota are considered in FEP 5.4.6 and FEP 5.4.7.

The following more specific factors are discussed under separate entries:

2.1.1.1 Radionuclide content
2.1.1.2 Chemical content

C 4.1.1.1 FEP # 2.1.1.1 Radionuclide Content

Description

The inventory of radioactive isotopes (radionuclides) of all elements in the various waste forms disposed in the Facility.

Postclosure safety assessments require consideration of the release, migration and fate of radioactive contaminants.

Screening Analysis

The majority of the radiological inventory within the Facility is associated with reactor core components (calandria and pressure tubes), the biological shield, the heat transport system, and the moderator system. Other rooms of the NPDDF also have some radioactive material associated with them, but account for less than about 12% of the total activity. The potential release, migration and fate of these radionuclides is relevant to the Facility long-term performance and safety and are relevant to the Normal Evolution of the system and all alternative scenarios stemming from it.

Uncertainty in the radionuclide inventory can be addressed by incorporating measured data and using a sensitivity case. The normal evolution scenario uses an updated waste inventory obtained from the latest waste inventory report (Porter, 2022). For the reactor vault, this is based on the reference radionuclide inventory that is derived using the higher values obtained from modelling or sample analyses. For the balance of the radioactive inventory, a factor of 3 is applied to ensure the source term is appropriately bounded.

Two sensitivity cases are also performed that look at the: i) impact of using only measured data of radionuclide concentrations, without any uncertainty factors; and ii) impact of increasing the NES inventory by a factor of 2.

Screening Decision

All post-closure scenarios

C 4.1.1.2 FEP # 2.1.1.2 Chemical Content

Description

The inventory of non-radioactive species in the various waste forms disposed in the Facility.

Postclosure safety assessments often require consideration of the non-radioactive contaminants.

Screening Analysis

Hazardous designated substances in the Facility include industrial chemicals, asbestos materials (such as pipe insulation, floor tiles and transite building cladding), lead-based paint, lead bricks and sheets. Polychlorinated biphenyls (PCBs) in fluorescent light fixture ballasts would have been removed before or during decommissioning such that none remain at the time of closure, whereas small quantities of mercury in thermostats and switches remain in the Facility. The potential release, migration and fate of non-radioactive contaminants from these hazardous designated substances is relevant to the Facility long-term performance and safety.

Screening Decision

All post-closure scenarios.

C 4.1.2 FEP # 2.1.2 Waste Form Characteristics and Properties

Description

The physical, chemical and biological characteristics and properties of the waste forms at the time of disposal in the Facility.

Information is required on the mass and volume of each waste form type, as well as information on the associated thermal, hydraulic, mechanical, chemical, biological, and radiological characteristics. Consideration should also be given to whether each type is in the solid, liquid or gas phase since the phase will affect the release and migration of contaminants from the waste form. Most will be in the solid phase including wastes that have been solidified through treatment and/or conditioning. Limits on the acceptance of wastes in the liquid or gas phase are usually specified in the waste acceptance criteria.

The following more specific factors are discussed under separate entries:

2.1.2.1 Metals (e.g., aluminum metal, carbon steel, stainless steel, and Zircaloy components)
2.1.2.2 Organics (e.g., polychlorinated biphenyls)
2.1.2.3 Non-metals, inorganics (e.g., asbestos)
2.1.2.4 Immobilization matrix (e.g., high-density concrete with lead and radionuclides in the reactor walls)
2.1.2.5 Deposits on surfaces

C 4.1.2.1 FEP # 2.1.2.1 Metals

Description

The characteristics and properties of metallic waste forms that may be disposed in the Facility.

Screening Analysis

The dominant metal waste forms disposed in the Facility include:

- Aluminum metal components – calandria tubes, calandria shell, end reflector stepped-tube;
- Carbon steel components – feeder tubes, tube end supports, steel vault liner;
- Stainless steel components – end fittings, closure plug assemblies, fuel latch assemblies, fuel spacer sleeves;
- Zircaloy coolant pressure tubes.

The characteristics and properties of the metal waste forms affect the release of radionuclides embedded within them. This FEP therefore affects the long-term performance and safety of the Facility. A review of the expected corrosion behaviour of various metallic waste forms included in the PostSA is given in the Waste Form Synthesis Report (CNL, 2021b), which concludes that none of the various factors that could lead to an enhanced rate of radionuclide release under disposal conditions have a significant impact on the release rate. Only once the concrete grout has been degraded and the pore-water pH decreases (estimated to be well after 10,000 y in general) is there a possibility of an increased rate of corrosion of carbon steel when compared with that of either stainless steel or zirconium alloys.

Hazards associated with metal contaminants themselves are covered in FEP 2.1.1.2.

Screening Decision

All post-closure scenarios

C 4.1.2.2 FEP # 2.1.2.2 Organics

Description

The characteristics and properties of organic waste forms that may be disposed in the Facility.

Screening Analysis

The characteristics and properties of organics may affect the release of radionuclides embedded within them.

Organic materials were examined in Arcadis & Quintessa (2021). By quantity, the primary organic materials that would be present in the facility are: 1) organic additives within the grout; 2) polyethene (polyethylene) plastic bags (containing waste); and, 3) asphalt from the roof of the above grade structure, which will have been deposited into the turbine room.

Arcadis & Quintessa (2021) examined these three organic materials using readily available information. Arcadis & Quintessa (2021) found that it is not possible to be certain of the significance for the post-closure safety of the NPDWF of these materials and their breakdown products. It is possible to carry out bounding calculations that could determine plausible upper limits on the effects. But to quantify the significance fully

requires more information. Arcadis & Quintessa (2021) notes that even in the absence of such calculations, the available evidence suggests that the organic materials are unlikely to be significantly detrimental with respect to radiological risk. In safety assessments for radioactive waste disposal facilities in other countries (e.g., for an intermediate level waste (ILW) repository in the UK) these (or similar) materials are not considered detrimental to safety. Indeed, polyethylene and bitumen are used in barrier systems for a number of radioactive waste facilities. In other safety assessments, concerns related to organics are cellulose degradation products, non-aqueous phase liquids (NAPLs) involving halogenated plastics (e.g., polyvinyl chloride), and gas generation from degradation of organics. None of these apply to the NPDWF's organics (i.e., grout additives, plastic bags, asphalt) because (Arcadis & Quintessa, 2021):

a) these are not cellulosic;
b) if the polythene bags used to wrap asbestos wastes are typical of UN-approved bags that are widely marketed for asbestos disposal; such bags contain very little plasticizer, if any. And even if these bags do contain plasticizer, the effects on radionuclide mobility are expected to be much less than the effect of a similar quantity of cellulose degradation product (available evidence suggests <10% and most likely <1%); and,
c) gas generation from cement additives will not be an issue, since these additives are mostly bound to solid cement phases and the alkaline conditions will greatly diminish or prevent microbial activity that is necessary to generate gas from the organics. In the reducing conditions that will likely become established within the NPDWF, gas generation from polyethylene and bitumen will be very slow, both materials being chemically poorly reactive under these conditions.

Thus, the organics that would be present in the NPDWF are not anticipated to have significant consequences for radionuclide mobility. Hazards associated with the organic contaminants themselves are covered in FEP 2.1.1.2.

Screening Decision

Screen Out.

C 4.1.2.3 FEP # 2.1.2.3 Non-metals, Inorganics

Description

The characteristics and properties of non-metallic, inorganic waste forms that may be disposed in the Facility.

Screening Analysis

Asbestos materials such as pipe insulation, floor tiles and transite building cladding will be present. The potential effects of these materials on the release, migration and fate of associated radionuclides is not considered to be significantly different from other wastes present in the Facility.

Hazards associated with the contaminants themselves are covered in FEP 2.1.1.2.

Screening Decision

Screen Out.

C 4.1.2.4 FEP # 2.1.2.4 Immobilization Matrix

Description

The characteristics and properties of the waste immobilization matrix/matrices at the time of emplacement in the Facility.

The presence of a waste immobilization matrix in the waste form will affect the release and migration of contaminants from the waste form. A range of immobilization matrices might be used including glass, cement and bitumen. Information is required on the mass and volume of each matrix, as well as information on the associated thermal, hydraulic, chemical and mechanical characteristics.

Screening Analysis

The contaminants themselves are not considered to be immobilized in the sense that conventionally this involves the addition of an immobilizing medium to wastes in a container to form a discrete waste package However, grout will be added to all rooms, under the reference decommissioning plan. This can be considered to be a form of immobilization and the effects of grout on radionuclide mobility can be represented in the model through its effect on processes such as advection and sorption. .

The potential effects of not grouting parts of the facility are considered in Defence-in-Depth calculations.

Screening Decision

All post-closure scenarios.

C 4.1.2.5 FEP # 2.1.2.5 Deposits on Surfaces

Description

The characteristics and properties of surficial deposits of various waste forms that may be disposed in the Facility.

Screening Analysis

These surficial deposits will be free to dissolve instantaneously, as they are not held within any other material, but are instead deposited onto a surface. An example of this is the deposits of fission products that have been left on many of the reactor core materials. The potential release, migration and fate of radionuclides associated with surface deposits is relevant to the Facility long-term performance and safety.

Screening Decision

All post-closure scenarios.

C 4.2 Waste Packaging Characteristics and Properties

The physical, chemical and biological characteristics and properties of the waste packaging (i.e., the waste package excluding the waste form) at the time of emplacement in the Facility.

Waste forms will typically be placed in packaging prior to disposal. The postclosure safety assessment needs to account for the proposed/actual waste packaging to be used in the Facility since it might act as a barrier to contaminant migration, especially if the packaging also contains backfill material. In addition, the waste packaging and any backfill will contribute to the inventory of Facility materials (such as metals and concrete) that affects the evolution of Facility conditions and potential migration of contaminants.

Certain waste packages might contain a mixture of different wastes (e.g. both metallic and organic), although constraints on the mixing of certain wastes are likely to be imposed by the waste acceptance criteria for the Facility and its wastes.

There are 2 subcategories under Waste Packaging Characteristics and Properties:

2.2.1 Container characteristics and properties
2.2.2 Overpack characteristics and properties

C 4.2.1 FEP # 2.2.1 Containers

Description

The physical, chemical, and biological characteristics and properties of the containers at the time of emplacement in the Facility.

A range of containers might be used in the Facility with differing materials and sizes. Information is required on materials (e.g., concrete, carbon steel, stainless steel, copper), masses and volumes, as well as information on the associated thermal, hydraulic, chemical and mechanical characteristics.

Screening Analysis

Generally, waste forms have not been placed in containers. Some historical waste is presently stored in steel drums but conservatively no credit is taken for these containers. However, the contaminants stored in these containers are included in the assessment and, conservatively, are available for leaching immediately upon failure of the containers.

Screening Decision

Screen Out – Out of Scope.

C 4.2.2 FEP # 2.2.2 Overpacks

Description

The physical, chemical, and biological characteristics and properties of any overpack at the time of emplacement in the Facility.

An overpack is a container that is used to secure or shield one or more inner containers and in some disposal concepts is used for disposal (as well as transport and storage). Information is required on materials (e.g. concrete, carbon steel, stainless steel), masses and volumes, as well as information on the associated thermal, hydraulic, chemical and mechanical characteristics.

Screening Analysis

Overpacks will not be used in this Facility.

Screening Decision

Screen Out – Out of Scope.

C 4.3 Waste Package Processes

The processes occurring within the waste packages resulting in their evolution in the Facility.

The focus is on processes affecting the evolution of waste packages after they have been emplaced in the Facility. If there is an extended (several decades or more) storage period for waste packages prior to their emplacement in the Facility, there might be a need to also consider processes operating during the storage period.

The coupled nature of certain processes will need to be taken into account, as will the impact of key Facility and geosphere features (FEPs 3.1 and 4.1) and their associated processes (FEPs 3.2 and 4.2). Processes relating to the release and migration of contaminants affecting the waste packages are considered under FEPs 2.4 and 2.5.

For some waste packages, similar processes can affect the waste form and the waste packaging and so it can be appropriate to consider them together. However, for certain other waste packages, for which the characteristics of the waste form and waste packaging are significantly different (e.g., those containing vitrified high-level waste or spent fuel), the processes will be different. In such cases, it will be necessary to consider processes affecting the waste form and waste packaging separately. This can be done by sub-dividing each FEP into: A) Waste Form; and B) Waste Packaging.

As this Facility does not include waste packages the following discussion focuses on waste forms. These are considered to be the principal sources of radioactivity (e.g., the reactor vessel and internals) and do not include the mass backfill added to the NPDDF as part of decommissioning.

There are 6 subcategories under Waste Package Processes:

2.3.1 Thermal processes [waste form]
2.3.2 Hydraulic processes [waste form]
2.3.3 Mechanical processes [waste form]
2.3.4 Chemical processes [waste form]
2.3.5 Biological processes [waste form]
2.3.6 Radiological processes [waste form]

C 4.3.1 FEP # 2.3.1 Thermal Processes [waste form]

Description

The internal thermal processes that affect the waste form.

External thermal processes (i.e., from the Facility and surrounding geosphere) are considered separately under FEPs 3.2.1 and 4.2.1.

The heat generated by radioactive decay of the radionuclides in the fuel will increase the temperature of the waste form. Higher temperatures generally increase the rate of reactions undergone by the waste form. Theoretically, higher temperatures could also affect the rate of migration of contaminants out of the waste form. In the case of the NPDDF, however, fuel has been removed from the disposed waste.

The following more specific factors are discussed under separate entries:

2.3.1.1 Radiogenic heat production and transfer
2.3.1.2 Chemical heat production and transfer
2.3.1.3 Biological heat production and transfer

C 4.3.1.1 FEP # 2.3.1.1 Radiogenic Heat Production and Transfer

Description

The production and transfer of heat originating from radioactive decay in the waste form.

Screening Analysis

Heat generation from radiation attenuation is a function of the decay rate and the nature of the waste. For example, heat generation from high level waste and spent fuel will initially be high and impact the Facility and surrounding geosphere. The radioactive waste in the NPDDF generates a negligible amount of heat.

Screening Decision

Screen Out.

C 4.3.1.2 FEP # 2.3.1.2 Chemical Heat Production and Transfer

Description

The production and transfer of heat originating from chemical processes affecting the waste form.

Screening Analysis

Heat production resulting from chemical processes occurring within the waste form (e.g., reaction of aluminum with alkaline waters) is expected to be small. Heat generated from curing of the grout (concrete) is discussed in FEP 3.2.1.

Screening Decision

Screen Out.

C 4.3.1.3 FEP # 2.3.1.3 Biological Heat Production and Transfer

Description

The production and transfer of heat originating from biological processes affecting the waste form.

Screening Analysis

No significant quantities of organic material are located in the Facility.

Screening Decision

Screen Out.

C 4.3.2 FEP # 2.3.2 Hydraulic Processes [waste form]

Description

Hydraulic and hydrogeological processes that affect the waste form and the overall hydraulic/hydrogeological evolution of the near field environment 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 Facility.

The following more specific factors are discussed under separate entries:

2.3.2.1 Saturation/desaturation
2.3.2.2 Thermal effects
2.3.2.3 Mechanical effects
2.3.2.4 Chemical effects
2.3.2.5 Gas effects

C 4.3.2.1 FEP # 2.3.2.1 Saturation/desaturation

Description

The saturation or desaturation of the waste form.

Screening Analysis

The saturation or desaturation of the waste form will be affected by the hydraulic conditions in the Facility and the surrounding geosphere. The degree of saturation of the waste form will impact the mobility of associated contaminants. Wastes will be unsaturated initially, and the Facility will gradually re-saturate until equilibrated with surrounding hydraulic heads. Thereafter it is assumed that it will remain at the same head as surrounding rock. Resaturation has been studied in Arcadis & Geofirma (2023c).

Screening Decision

All post-closure scenarios, except Disruptive Event – Site Investigation (Inadvertent Human Intrusion), and What If (Facility Mass Excavation).

C 4.3.2.2 FEP # 2.3.2.2 Thermal Effects

Description

The impact of thermal effects on hydraulic processes influencing the waste form.

Screening Analysis

No significant thermal processes are expected at the Facility (see FEP 2.3.1) with the exception of that associated with grout curing (covered in FEP 3.2.1). This is anticipated to dissipate well before the end of institutional control and will not affect hydraulic processes in any significant way.

Screening Decision

Screen Out.

C 4.3.2.3 FEP # 2.3.2.3 Mechanical Effects

Description

The impact of mechanical effects on hydraulic processes influencing the waste form.

The evolution of the waste form's mechanical condition over time (FEP 2.3.3) can influence the associated hydraulic conditions (for example material volume changes resulting in changes in hydraulic properties) and contaminant transport rates.

Screening Analysis

No (significant) swelling is expected in the waste forms over time. Over time the corrosion of metals in the reactor structure will lead to a loss of strength and, ultimately, it may collapse, but this will not have any significant implications for hydraulic properties that influence radionuclide release and transport. It is noted that hydraulic properties of the Facility (FEP 3.2.2) are potentially significant, however.

Screening Decision

Screen Out.

C 4.3.2.4 FEP # 2.3.2.4 Chemical Effects

Description

The impact of chemical effects on hydraulic processes influencing the waste form.

The evolution of the waste form's chemistry over time (FEP 2.3.4) can influence the associated hydraulic conditions (for example alteration/precipitation of waste components will result in changes in hydraulic properties).

Screening Analysis

The metal components in the reactor vault will, over time, corrode in groundwater. This will not affect hydraulic processes, although it is important for radionuclide release into water (see FEPs 2.4.1, 2.4.2 and 2.4.3).

Screening Decision

Screen Out.

C 4.3.2.5 FEP # 2.3.2.5 Gas Effects

Description

The impact of gas effects on hydraulic processes influencing the waste form.

Screening Analysis

The generation and migration of gases in the waste form due to chemical processes (FEP 2.3.4) can potentially affect the associated hydraulic conditions (for example the generation of gas can slow the saturation of waste forms).

Gas could be produced by, e.g., corrosion of the carbon steel waste form, however the volume generated, and rate of generation, will be such that it is not expected to limit the re-saturation of the Facility.

Screening Decision

Screen Out.

C 4.3.3 FEP # 2.3.3 Mechanical Processes [waste form]

Description

The internal and external mechanical processes that affect the waste form.

This includes the effects of thermal, hydraulic and mechanical loads imposed on the waste form by other Facility components and the surrounding geosphere.

This group of FEPs is concerned with the wastes themselves. Mechanical processes associated with the grout is covered in FEP 3.2.3. However, it is noted that, once grouted, internal mechanical processes will be negligible.

The following more specific factors are discussed under separate entries:

2.3.3.1 Deformation
2.3.3.2 Material volume changes [waste form]
2.3.3.3 Movement
2.3.3.4 Stress corrosion cracking
2.3.3.5 Gas explosion [waste form]

C 4.3.3.1 FEP # 2.3.3.1 Deformation

Description

The deformation of the waste form resulting from large loads and pressures imposed on it by both internal and external sources.

Screening Analysis

The NPDDF is located near the surface and therefore mechanical processes in deep rock are largely irrelevant to its long-term performance and safety. Mechanical processes within the Facility that might occur during decommissioning and are taken into account in the pre-closure phase. For the postclosure phase, it is assumed that the grouted structure is stabilized and deformation of the waste form will not have any effect. Note that mechanical effects of the Facility itself are covered in FEP 3.2.3.

Screening Decision

Screen Out.

C 4.3.3.2 FEP # 2.3.3.2 Material Volume Changes [waste form]

Description

The effects of volume changes in waste form materials.

Screening Analysis

Corrosion of the metals within the reactor vault will result in an increase in their volume. The reactor vault will be grouted and it is possible to select a grout formulation that accommodates some expansion of the metals without significant effect on the surrounding vault walls. Although the BFS grout selected for the NPDDF is not designed to accommodate expansion of metals due to corrosion, there will be sufficient void space in the reactor and associated piping to provide space for the corrosion products. Corrosion of the Al by the grout will also provide some void spaces in the grout from formation of bubbles due to hydrogen generation.

Screening Decision

Screen Out.

C 4.3.3.3 FEP # 2.3.3.3 Movement

Description

The movement of the waste form in the Facility.

Movement could result from mechanical stresses on the waste form caused by, for example, mass redistribution in the Facility. It could also result from seismic events (see FEP 1.2.4).

Screening Analysis

In the far future, the corrosion of the metal wastes in the Reactor Vault will reduce their structural integrity and, ultimately, they will collapse. Earthquakes could also cause the material to collapse. This will not, however, have any significant consequence for the long-term performance of the Facility.

Screening Decision

Screen Out.

C 4.3.3.4 FEP # 2.3.3.4 Stress Corrosion Cracking

Description

The conjoint action of stress and a corrosive environment which leads to the formation of a crack in the waste packaging which would not have developed by the action of the stress or environment alone.

May mechanically weaken the waste packaging and promote subsequent failure or other corrosion mechanisms. May be accelerated if a chemical agent (such as hydrogen and chloride) is attracted to and accumulates at a defect or crack site.

Screening Analysis

While the process might occur within the Reactor Vessel it does not have any containment function therefore there is no significant consequence. No other containers are used in the Facility.

Screening Decision

Screen Out.

C 4.3.3.5 FEP # 2.3.3.5 Gas Explosion [waste form]

Description

An explosion resulting from the ignition of a flammable gas mixture in the waste form.

Some gases produced from the corrosion and degradation of waste forms (FEPs 2.3.4.4 and 2.3.5.2) might be flammable or might form an explosive mixture; for instance, hydrogen and methane could mix with oxygen and explode to damage the waste package.

Screening Analysis

Hydrogen will be evolved from the corrosion of metals in the Reactor Vault. The rate of evolution will be low, however, and the gas is likely to largely dissolve in water. Furthermore, a gas explosion can only occur if a flammable gas mixture forms and there is a source of ignition or the gas mixture has the capability to auto-ignite. These conditions are highly unlikely to occur in the postclosure period.

Screening Decision

Screen Out.

C 4.3.4 FEP # 2.3.4 Chemical Processes [waste form]

Description

The chemical/geochemical processes that affect the waste forms.

This includes the effects of chemical/geochemical influences on the waste form by other Facility components and the surrounding geosphere. These processes can in turn be affected by thermal processes (e.g., chemical processes can be accelerated/initiated as temperature increases) and hydraulic processes (e.g., the water flow rate through the waste package).

The following more specific factors are discussed under separate entries:

2.3.4.1 Evolution of pH conditions [waste form]
2.3.4.2 Evolution of Eh conditions [waste form]
2.3.4.3 Migration of chemical species [waste form]
2.3.4.4 Corrosion [waste form]
2.3.4.5 Alteration [waste form]
2.3.4.6 Precipitation [waste form]
2.3.4.7 Complexation [waste form]
2.3.4.8 Colloid formation [waste form]

C 4.3.4.1 FEP # 2.3.4.1 Evolution of pH Conditions [waste form]

Description

The temporal evolution of the waste form's pH from its initial state.

This depends on a number of factors, including the pH of the surrounding water, the water flow rate through the waste form and the characteristics of the waste form.

Screening Analysis

The pH of the waste forms in the Facility will be influenced by the alkaline conditions in and around the grout. The pH of the wastes themselves will not change, but the pH of the surrounding water will influence corrosion rates. This aspect is covered in FEP 3.2.4.

Screening Decision

Screen Out.

C 4.3.4.2 FEP # 2.3.4.2 Evolution of Eh Conditions [waste form]

Description

The temporal evolution of the waste package's Eh from its initial state.

This depends on a number of factors, including the Eh conditions of the surrounding water and the consumption rate of any available oxygen. Oxygen-deficient (anaerobic) conditions promote the formation of lower, and often less soluble, oxidation states of elements, promote relatively slow corrosion and microbial processes, and minimize the rate of gas generation.

Screening Analysis

Broadly, the Eh of the waste forms in the Facility will be oxidizing because it is in the near surface environment. It is possible that the corrosion of the waste will consume dissolved oxygen and lead to anaerobic conditions within the vault itself. Corrosion rates in both aerobic and anaerobic conditions are likely needed to be considered.

Screening Decision

All post-closure scenarios, except Disruptive Event – Site Investigation (Inadvertent Human Intrusion), and What If (Facility Mass Excavation).

C 4.3.4.3 FEP # 2.3.4.3 Migration of Chemical Species [waste form]

Description

The migration of reactants into and reaction products from the waste form.

Screening Analysis

Chemical species can migrate into and out of the waste form by advection (pressure gradient driven) and diffusion (chemical gradient driven) affecting the waste form's physical and chemical evolution (including pH and Eh conditions). Chemical concentration gradients in the waste form could be caused by various factors such as temperature changes, radiolysis and different electrochemical potentials between various materials. These can affect the corrosion rate and other factors such as sorption to corrosion products.

Screening Decision

All post-closure scenarios, except Disruptive Event – Site Investigation (Inadvertent Human Intrusion), and What If (Facility Mass Excavation).

C 4.3.4.4 FEP # 2.3.4.4 Corrosion [waste form]

Description

The destruction of the metallic component(s) of the waste form by chemical reaction with water in liquid or vapour form.

Corrosion of the waste form can occur by a number of processes such as generalized (or uniform), localized and galvanic corrosion. Metals are subject to uniform corrosion at rates that are dependent on the chemical and physical (and possibly biological) environment, while localized formation of cavities in a metal surface is caused by non-uniform corrosion. Galvanic corrosion occurs when two different metals are in electric contact. Metal corrosion will result in the generation of hydrogen gas under anaerobic conditions.

Screening Analysis

Metallic waste forms in the Facility (see FEP 2.1.2.1) will corrode with time. This is a key process as activation products in the metals will be released only as they corrode. The corrosion rates will depend on the metals present (Zircaloy, stainless steel and aluminum) and the chemical environment in the vault (see FEP 3.4.2).

A review of the expected corrosion behaviour of various metallic waste forms included in the PostSA is given in the Waste Form Synthesis Report (CNL, 2021b), which concludes that none of the various factors that could lead to an enhanced rate of radionuclide release under disposal conditions have a significant impact on the release rate. Only once the concrete grout has been degraded and the pore-water pH decreases (expected to be well after 10,000 y) is there a possibility of an increased rate of corrosion of carbon steel when compared with either stainless steel or zirconium alloys.

Screening Decision

All post-closure scenarios, except Disruptive Event – Site Investigation (Inadvertent Human Intrusion); and What If (Facility Mass Excavation).

C 4.3.4.5 FEP # 2.3.4.5 Alteration [waste form]

Description

The alteration of the waste form by chemical processes such as dissolution.

Screening Analysis

Dissolution is the dissolving of solid waste form materials in a solvent, typically water. The wastes, principally metallic structures, will corrode and dissolve. The chemical environment of the waste package (e.g., pH, Eh) is likely to evolve over time, and these changes could lead to the evolution of species dissolution. See FEPs 2.3.4.1 and 2.3.4.2.

Screening Decision

All post-closure scenarios, except Disruptive Event – Site Investigation (Inadvertent Human Intrusion), and What If (Facility Mass Excavation).

C 4.3.4.6 FEP # 2.3.4.6 Precipitation [waste form]

Description

The precipitation of an element from the aqueous phase to the solid phase in the waste form.

Screening Analysis

Precipitation can be affected by chemical conditions in the waste form (particularly pH, Eh and the concentration of complexing ions). The mass of precipitates could increase until dissolution of the waste form ceases, after which the mass would decrease as the precipitate itself dissolves. The solubility-limited

concentration is determined by the equilibrium constant for the dissolution of the solubility limiting solid phase and the equilibrium constants for the formation of other soluble species, usually complexes. In some cases, metastable solution-solid reactions may give rise to higher aqueous concentrations than would arise by true solubility limitation by the most thermodynamically stable phase (e.g., the metastable phase chalcedony causes aqueous silica concentrations to be higher than would be explained by equilibrium between aqueous silica and thermodynamically stable quartz). Supersaturation is often required in order for the chemical potential to become high enough to initiate precipitation. Similarly, the presence of complexing ions can increase solubility, and cause elements to remain in solution under conditions when they would otherwise be expected to precipitate.

In practice, while precipitants will undoubtedly form, their formation and subsequent dissolution can be aggregated into the bulk release rate of contaminants, meaning the FEP can be treated implicitly.

Screening Decision

All post-closure scenarios, except Disruptive Event – Site Investigation (Inadvertent Human Intrusion), and What If (Facility Mass Excavation).

C 4.3.4.7 FEP # 2.3.4.7 Complexation [waste form]

Description

The combination of individual atom groups, ions or molecules to create one large ion or molecule in the waste form.

Screening Analysis

Complexes are usually highly stable, a factor that can, together with other factors, increase significantly the solubility and mobility of certain elements. Complexation is promoted through the presence of complexing agents (organics, inorganic ligands and microbes). Sources of these agents include organics in the waste form and inflowing water. The inflowing water is expected to be conditioned by the upstream engineering and thus not contain any significant amounts of complexants. There will not be a source of complexants in the reactor vault, so the process is screened out.

Complexation related to the facility is discussed in FEP #3.2.4.7.

Screening Decision

Screen Out.

C 4.3.4.8 FEP # 2.3.4.8 Colloid Formation [waste form]

Description

The formation of very fine particles (with diameters typically less than 10 µm) that can affect the migration of contaminants from the waste form.

Particles of clay minerals, silica, iron oxy-hydroxides, other minerals, organic and bio-organic macromolecules, and contaminants themselves (e.g., Pu(IV)) may form the colloid phase. Sources can include materials in the waste form itself (e.g. organic wastes), other Facility components (e.g. bentonite and cementitious materials) and inflowing groundwater. Colloid formation may be promoted by steep chemical gradients, such as at an interface where the Eh or pH changes abruptly because of chemical or biological activity. The thermodynamic stability of colloids depends upon various factors, such as the chemistry and surface charge of the colloid and the chemistry of the dispersion medium. Colloid stability generally decreases as ionic strength (salinity) increases.

Screening Analysis

The formation of colloids within the waste at the NPDDF is unlikely because colloids typically form from clay minerals, organic and bio-organic molecules and these are not present at NPDDF in significant amounts (see also FEP #2.1.2.2).

Contaminant interactions and transport with colloids are unlikely to be of significant relevance to the Facility long-term performance and safety. The Facility structure and grout will act to filter out any colloidal material from incoming groundwater, meaning that the process is unlikely to be relevant to the performance of the Facility. Therefore, naturally-occurring colloids in groundwater could not enter the facility with incoming groundwater (e.g. due to the grout), be introduced with grout material, or be produced in the repository from degradation of the wastes or erosion of the grout. The low hydraulic conductivity of the Facility will prevent any significant colloidal transport. This is supported by, for example:

- Evidence from the Maqarin natural analogue site indicates that the amount of colloidal material generated by cements will probably be low (Smellie, 1998).
- Although colloids could potentially penetrate some low porosity spaces, their transport is retarded: Experiments have shown that even colloids that were deliberately introduced into rock fractures have shown no breakthrough at observation points although other tracers have reached the observation points in the expected time scales, indicating that colloid transport through fractured media acted more as a filter than a conduit for colloids (Vandergraaf *et al.*, 2011).
- Similarly, Cramer & Smellie (1994) and Pusch (2001) argue that due to the low porosity in engineered barriers, colloid transport through these materials would be inhibited.

It should also be noted that if the grouted reactor materials remain alkaline, colloid formation is expected to be suppressed because of high dissolved calcium concentrations in the pore water from the grout (Swanton *et al.*, 2010).

Screening Decision

Screen Out.

C 4.3.5 FEP # 2.3.5 Biological Processes [waste form]

Description

The biological/biochemical processes that affect the waste forms.

The following more specific factors are discussed under separate entries:

2.3.5.1 Microbial growth and poisoning [waste form]
2.3.5.2 Microbially/biologically mediated processes [waste form]

C 4.3.5.1 FEP # 2.3.5.1 Microbial Growth and Poisoning [waste form]

Description

The processes affecting the growth and decline of microbes in the waste form.

Screening Analysis

The waste forms are assumed not to be affected by biological processes to any significant degree. Microbial activity is expected to be low or non-existent in the waste form because of the limited organic and nutrient sources present.

Screening Decision

Screen Out.

C 4.3.5.2 FEP # 2.3.5.2 Microbially/biological Mediated Processes [waste form]

Description

The biological processes affecting the waste form such as degradation of organics, nitrate and sulphate ions, biofilm growth and volatilization.

Screening Analysis

The waste forms are assumed not to be affected by biological processes to any significant degree. Microbial activity is expected to be low or non-existent in the waste form because of the limited organic and nutrient sources present.

Screening Decision

Screen Out.

C 4.3.6 FEP # 2.3.6 Radiological Processes [waste form]

Description

The effects of radiation emitted from the waste form, and the overall radiogenic evolution of the waste forms.

The following more specific factors are discussed under separate entries:

2.3.6.1 Radioactive decay and ingrowth [waste form]
2.3.6.2 Radiolysis [waste form]
2.3.6.3 Helium production
2.3.6.4 Radon production [waste form]
2.3.6.5 Radiation damage [waste form]
2.3.6.6 Criticality [waste form]

C 4.3.6.1 FEP # 2.3.6.1 Radioactive Decay and Ingrowth [waste form]

Description

The spontaneous disintegration or de-excitation of an atomic nucleus, resulting in the emission of sub-atomic particles and energy and the formation of a new progeny (or "daughter") nucleus in the waste package.

Screening Analysis

Radioactive decay results in the reduction in the activity of the radionuclides in the waste form. Where a precursor radionuclide decays to a progeny radionuclide, this causes the ingrowth of progeny in the waste form. In postclosure assessments, radioactive decay chains are often simplified, e.g., by neglecting the shorter-lived radionuclides in release and migration calculations and representing them as being in secular equilibrium with longer-lived parents for the purposes of exposure assessment. This FEP is relevant to the long-term performance and safety of the Facility.

Screening Decision

All post-closure scenarios.

C 4.3.6.2 FEP # 2.3.6.2 Radiolysis [waste form]

Description

The dissociation of molecules by ionizing radiation in the waste form.

Screening Analysis

Waste forms may contain a mixture of air, water vapour, and liquid water. The radiolysis of water within a waste form can produce molecular species such as hydrogen, oxygen, and hydrogen peroxide which can impact the chemical conditions in the waste form and the wider Facility. The actual composition and amount

of the radiolysis products that will be formed is controlled by the radiation dose rate and by the composition and amount of the air and water mixture contained in the waste form. The radionuclide concentrations within the reactor structures are not sufficiently high to cause any significant degree of radiolysis within the waste form.

Screening Decision

Screen Out.

C 4.3.6.3 FEP # 2.3.6.3 Helium Production

Description

The production of helium gas from alpha decay of radionuclides in the waste form.

Screening Analysis

In the absence of a waste package or container, gases such as helium generated within the waste form from radioactive decay could be released into the Facility. Due to the low inventories of alpha-emitting radionuclides in the Facility, this production can be neglected.

Screening Decision

Screen Out.

C 4.3.6.4 FEP # 2.3.6.4 Radon Production [waste form]

Description

The production of radon gas from the decay of uranium, thorium and radium in the waste form. The main radon isotope considered in assessments is Rn-222 (the longest-lived isotope at 3.82 days).

Screening Analysis

Radon gas generation is expected from the decay of uranium, thorium and radium contained in the waste forms. The quantities of radon precursor radionuclides within the inventory are, however, small, and thus over the assessment timescales radon production rates will always be very low. Radon exposure, as an explicit pathway, will be trivial compared with other pathways and can therefore be screened out.

Screening Decision

Screen Out.

C 4.3.6.5 FEP # 2.3.6.5 Radiation Damage [waste form]

Description

The damage caused to the waste package by radiation.

Radiation damage from fission and alpha decay may affect waste packages, influencing their chemical stability and resulting in their failure.

Screening Analysis

The concentration of radionuclides in the Facility is not sufficiently high that radiation damage will occur. Some degree of radiation damage may have occurred within the structure historically, due to reactor operation, but this can be taken into account in the properties of the materials at closure.

Screening Decision

Screen Out.

C 4.3.6.6 FEP # 2.3.6.6 Criticality [waste form]

Description

The possibility and effects of spontaneous nuclear fission chain reactions within the waste.

Criticality requires a sufficient concentration and localized mass (critical mass) of fissile isotopes (e.g., U-235, Pu-239) and also presence of neutron moderating materials in a suitable geometry; a chain reaction is liable to be damped by the presence of neutron absorbing isotopes (e.g., Pu-240).

Screening Analysis

The Facility does not contain any significant quantity of nuclear fuel that could result in nuclear criticality. Following shutdown of the NPD reactor, the primary heat transport and moderator systems heavy water was drained and shipped off-site. The reactor was de-fueled and the fuel bundles were transported to CRL for storage. Residual fuel contamination will be present but at levels that are far below that required for a criticality to be possible.

Screening Decision

Screen Out – Out of scope.

C 4.4 Contaminant Release [waste form]

The processes that directly affect the release of contaminants from the waste form.

These processes are controlled by the Facility environment (physical, chemical and biological) and the waste form composition and structure.

There are 4 subcategories under Contaminant Release [waste form]:

2.4.1 Liquid-mediated release
2.4.2 Gas-mediated release
2.4.3 Solid-mediated release
2.4.4 Human-action-mediated release

C 4.4.1 FEP # 2.4.1 Liquid-mediated Release

Description

The processes resulting in the release of contaminants in the aqueous phase from the waste form.

The following more specific factors are discussed under separate entries:

2.4.1.1 Dissolution [waste form]
2.4.1.2 Diffusion [waste form]
2.4.1.3 Speciation and solubility [waste form]
2.4.1.4 Sorption and desorption [waste form]

C 4.4.1.1 FEP # 2.4.1.1 Dissolution [waste form]

Description

The dissolving of contaminants from the waste form into solution on contact with water.

For some waste forms (e.g., glass), this process can be very slow and result in the slow congruent release of contaminants contained within the waste form. For others, such as those with surface contamination or those that are readily soluble on contact with water, this process can be very rapid and result in the instantaneous release of contaminants contained within the waste form.

Screening Analysis

Dissolution is a relevant contaminant release pathway, since contaminants may dissolve into water that has infiltrated the Facility. The dissolution process is dependent on the solubility of the contaminant. Precipitation and crystallization may occur due to chemical reactions. Dissolution may impact the contaminant mobility and the contaminant transport pathway and is relevant to the Facility long-term performance and safety. For

activation products, the controlling factor for contaminant release will be the rate of corrosion of the metal matrix. For fission products and actinides present as contamination, it can conservatively be assumed that they dissolve instantaneously. In the presence of grout, lead will corrode, and can thus be released in solution. Arcadis & Quintessa (2020a) have examined the dependency of lead solubility and sorption on pH, which provides the basis to represent the dissolution and release of lead under the anticipated future chemical conditions in the Facility.

Screening Decision

All post-closure scenarios, except Disruptive Event – Site Investigation (Inadvertent Human Intrusion), and What If (Facility Mass Excavation).

C 4.4.1.2 FEP # 2.4.1.2 Diffusion [waste form]

Description

The diffusion of contaminants from the waste form into water.

Screening Analysis

Diffusion results in the net flux of contaminants from a region of higher concentration to one of lower concentration. The rate of diffusion is a function of temperature, viscosity of the fluid and the size (mass) of the associated molecules.

Contaminants released from the waste form can diffuse into the surrounding grout. These conditions might be expected to occur initially, when the low hydraulic conductivity of the Facility prevents any significant advective flows through the wastes. This FEP is therefore relevant to the long-term performance and safety of the Facility.

Screening Decision

All post-closure scenarios, except Disruptive Event – Site Investigation (Inadvertent Human Intrusion), and What If (Facility Mass Excavation).

C 4.4.1.3 FEP # 2.4.1.3 Speciation and Solubility [waste form]

Description

The chemical speciation and solubility processes affecting the release of contaminants from the waste form under Facility conditions.

Screening Analysis

The concentration of an element in aqueous solution (at equilibrium) reflects the solubility of the solid compounds which contain the element. Factors such as temperature, gas partial pressure, ionic strength, the presence of complexing agents and pH and Eh conditions affect solubility. These factors affect the chemical form and speciation of the element. Thus, different solids of the same element may have different

solubilities in a particular solution. Contaminant speciation and solubility are very important factors affecting the behaviour and transport of radionuclides and non-radiological chemicals.

Although it is unlikely that the elements with which radionuclides are associated will be present in sufficient quantities to result in solubility limitation, the process might be relevant for non-radioactive contaminants and is thus retained for lead, specifically (Arcadis & Quintessa, 2020a). This element is present in some NPDDF rooms in tonne quantities.

Screening Decision

All post-closure scenarios, except Disruptive Event – Site Investigation (Inadvertent Human Intrusion), and What If (Facility Mass Excavation).

C 4.4.1.4 FEP # 2.4.1.4 Sorption and Desorption [waste form]

Description

The sorption/desorption processes affecting the release of contaminants from the waste form under Facility conditions.

Sorption describes the physical-chemical interaction where dissolved species adhere to a solid phase. Desorption is the opposite. Two sorption-desorption processes are commonly considered: ion-exchange processes involving an electrostatic or ionic attraction between charged dissolved species and oppositely charged surfaces; and chemisorption involving the formation of a chemical bond. Neutral species and (usually) anions are generally not strongly sorbed.

Screening Analysis

Sorption will occur onto waste materials, although the significance of the process will be limited in the context of sorption onto other components of the system, such as the grout materials (FEP 3.3.1.6).

Screening Decision

All post-closure scenarios, except Disruptive Event – Site Investigation (Inadvertent Human Intrusion), and What If (Facility Mass Excavation).

C 4.4.2 FEP # 2.4.2 Gas-mediated Release

Description

The release of contaminants in gas or vapour phase or as fine particulate or aerosol in gas or vapour from the waste form.

Gas-mediated release can arise from various gas production processes such as radon production (FEP 2.3.6.4), biochemical processes resulting in volatilization (e.g., FEPs 2.3.4.5 and 2.3.5.2) and radiolysis resulting in hydrogen production (FEP 2.3.6.2). C-14 can be incorporated into carbon dioxide or methane, I-129 can be incorporated into iodine gas or methyl iodide, and tritium (H-3) can be incorporated

into hydrogen gas or water vapour. Gas mediated-release can also include the direct release of gases from gaseous waste forms (e.g., Kr isotopes).

Screening Analysis

There are two aspects of gas mediated release to be considered:

(a) related to organic degradation processes; and,
(b) corrosion processes, most notably (for the NPDDF) iron(steel), lead and aluminum.

These are discussed below.

(a) Potential for Gas Generation by Organic Degradation:

In both deep and shallower repository systems, the capacity for generation of gases, such as carbon dioxide (CO_2) and methane (CH_4), has been considered in a number of assessments/reviews (e.g. for the DGR in Canada, at the Low-Level Waste Repository in the UK, and by Radioactive Waste Management Ltd for a deep geological facility concept for low and intermediate wastes) (e.g., Quintessa & Geofirma, 2011; LLWR, 2011; Limer *et al*., 2011; Williams *et al*., 2016). In general, carbon dioxide and methane generated by waste degradation processes will be expected in systems where there is a significant amount of organic material (such as cellulose) present in low and intermediate-level waste streams. The rates of CO_2 and CH_4 generation will depend on microbial activity, which in turn, depends on factors such as water availability, nutrient availability, oxygen availability, pH, *inter alia* (Williams *et al*., 2016). For the NPD facility, it is considered that the process of gases being generated by organic materials degradation can be ruled out as there is not anticipated to be any significant organic content present in the structure when it is closed: There are two types of organic material at the NPDDF both with limited quantities:

(i) Generated PPE waste during decommissioning. This is generated at a rate of only 10 m^3/y during decommissioning (See section 4.4.1.3 of the EIS).
(ii) Structural material. The volume of all construction materials was determined based on a review of engineering drawings and presented in *NPD Decommissioning - Waste Quantities, 64-508600-761-000-0001 Rev. 0, 2008 March*. The total organics due to NPD construction material is on the order of <500 m^3.

(b) Corrosion of Metals:

Any oxygen trapped in the facility at closure is likely to be consumed by aerobic corrosion processes, but anaerobic corrosion is likely to dominate after closure.

Iron (Steel)

Steel corrosion under aerobic condition can be represented by the reaction:

$4Fe + 3O_2 + 2H_2O = 4FeOOH$,

whereas, anaerobic corrosion that leads to $H_{2(g)}$ production can be represented by:

$Fe + 2H_2O = Fe(OH)_2 + H_{2(g)}$,

$3Fe(OH)_2 = Fe_3O_4 + H_{2(g)} + 2H_2O$

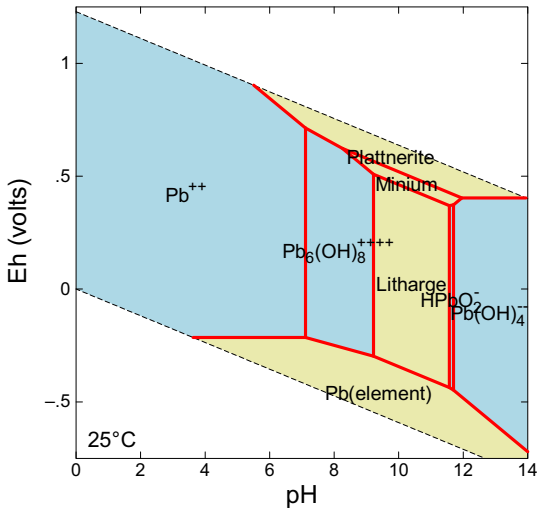
(conversion of ferrous hydroxide to magnetite via the Schikkor reaction).

The general corrosion rate of carbon steels (often considered for container lifetime calculations) under the strongly alkaline conditions associated with leaching of cementitious materials (grouts, concretes) will be very slow, reference values assumed are 0.1 µm/y, with values potentially being lower (~0.01 to ~0.1 µm/y), with passivation being promoted by alkaline conditions (CNL, 2021b). The rate of corrosion of Zircaloy cladding is similarly low.

Lead

Lead (Pb) may also corrode, under relatively higher Eh (more oxidising) conditions. Pb(II) compounds may be stable (such as PbO), with native lead potentially being stable under lower Eh (reducing) conditions (Figure C-5).

Figure C-5 Eh-pH Diagram for Lead Generated using Generated using Geochemist's Workbench and the Thermoddem database (BRGM, 2017) (a Pb2+ = 10-3).



Under alkaline conditions associated with cement/grout leaching, lead corrosion can, depending on Eh-pH conditions and dissolved silica concentrations, be represented by reactions such as:

$PbO + OH^- = HPbO_2^-$

$Pb + OH^- + H_2O = HPbO_2^- + H_{2(g)},$

$Pb + 2\ OH^- + 2\ H_2O = Pb(OH)_4^{--} + H_{2(g)},$

or in the presence of dissolved silica associated with cement porefluids:

$Pb + H_4SiO_{4(aq)} = H_2O + PbSiO_3 + H_{2(g)}$

Lead corrosion rates are not as well described as they are for steel. In a recent review of lead behaviour in a geological repository for radioactive wastes, it is stated that: *"no laboratory experimental data could be found for reducing near field (cementitious) conditions where sulphide*

was present and/or the Eh was sufficiently low to stabilise metallic lead. However, the data of Goodwin & Guenther (1988) and Goodwin et al., (2011) do show that as the dissolved oxygen concentration tends towards zero and the partial pressure of hydrogen increases, the rate of corrosion tends towards zero" (Bryan, 2016). For assessment of corrosion rate at the UK low Level Waste Repository (LLWR), an expert elicitation produced rates of ~1 to ~31 µm /y for "reducing" and "oxidising" conditions in vaults (at pH ~11, Smith & Jackson, 2013). Therefore, rates of lead corrosion are likely to be relatively low (and potentially tend towards zero if $H_{2(g)}$ cannot readily escape), but potentially not as low as they are likely to be for steel or Zircaloy.

In the presence of grout, lead will corrode, and secondary solids are likely to form (Arcadis & Quintessa, 2020a). The solubility of secondary lead solids (such as lead silicate) are lower under the pH conditions associated with low alkalinity grout blends (pH ~10-11) compared with fresh Portland cement (pH 12-13) (Arcadis & Quintessa, 2020a) (Fig. 2).

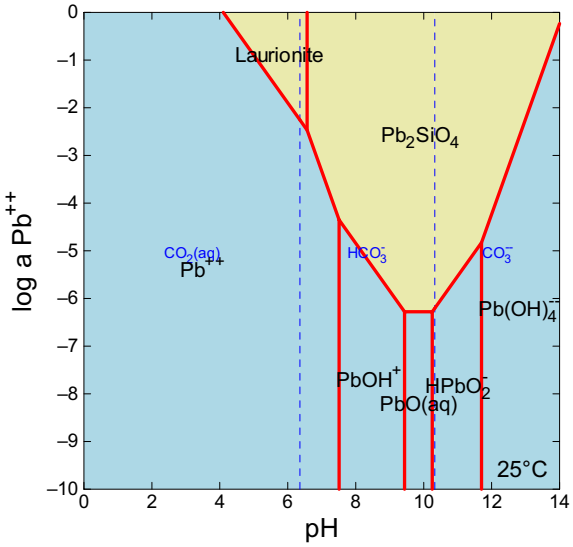


Fig. 2. Solubility diagram for lead (from Arcadis & Quintessa, 2020a).

Aluminum

Under near-neutral pH conditions, oxide forms on aluminum (Al) leading to corrosion resistance. However, Al is likely to undergo extensive corrosion under alkaline conditions associated with grout, leading to the production of $H_{2(g)}$ for example:

$$Al + OH^- + H_2O = 1.5\ H_{2(g)} + AlO_2^-$$

The corrosion rates of Al are rapid compared to those of other metals in the presence of grout with very high initial rates (equivalent to several millimetres per year) falling (over laboratory timescales) to hundreds or tens of micrometres per year, depending on the alloy and grout composition (see review by Hoch *et al*., 2010). The potential for corrosion of Al during grouting at the facility and the need for hydrogen safety measures has been assessed (Hongqiang, 2017). Given the high potential for Al corrosion and the high rates expected in the presence of grout, it is very likely that corrosion of Al will occur predominantly during decommissioning where grout directly comes into contact with Al, and during initial resaturation of the facility with water that has been conditioned by

cementitious materials. Therefore, it is very likely that significant generation of $H_{2(g)}$ due to Al corrosion will not occur after the period of institutional control.

Gas Generation Potential Resulting from Corrosion Processes

The ability of corrosion reactions to proceed will depend on the availability of water to react with metal surfaces and the ability of H_2 (partitioned between gaseous and dissolved forms) to be transported away from the metal surface. If water cannot be replenished quickly enough corrosion will not proceed. If the porosity of material in contact with the metals is relatively low or "tortuous", solute and gas transport and therefore corrosion, will be restricted and rates could be lower than those observed in some laboratory experiments. It should also be noted that as $H_{2(g)}$ is generated and transported through the facility, it could react with any "pockets" of residual oxygen left after facility closure, leading to production of liquid water.

As described in the previous narrative, $H_{2(g)}$ generation rates for steel and Zircaloy are very low and pH conditions will promote passivation, so the consequent gas generation from these sources will be insufficient to lead to any significant bulk gas accumulation. It is likely that corrosion of Pb will be slow and could be limited by water availability.

Releases of any $H_{2(g)}$ generated due to metals corrosion from the facility are likely to be limited by diffusion out of the capping materials. Therefore, the potential for $H_{2(g)}$ to act as a carrier gas is very limited, as is the potential for $H_{2(g)}$ to be an explosion hazard in the post-closure phase of the facility.

Thus, there is limited potential for gas generation and gas-mediated transport of contaminants which may affect the exposure pathways, and the impacts on human and non-human biota.

Screening Decision

Screen Out.

C 4.4.3 FEP # 2.4.3 Solid-mediated Release

Description

The release of contaminants in solid phase from the waste form.

This might result from processes such as the fluvial erosion of the Facility (FEPs 1.2.8), the glacial erosion of the Facility (FEP 1.3.5) or magmatic/volcanic activity affecting the Facility (FEP 1.2.5).

Screening Analysis

Relevant contaminant solid-mediated transport processes including transport by erosion may affect the exposure pathways, and the impacts on human and non-human biota. The mechanisms by which there may be a solid-mediated release are: by human intrusion (site investigation), glacial disruption (not credible based on the 10,000 y assessment timeframe), surface erosion, excavation of above-bedrock facility, or mass excavation (which is considered to be a What If FEP (FEP 1.3.5)).

Screening Decision

Disruptive Events – Site Investigation (Inadvertent Human Intrusion), Excavation of Above-Bedrock Facility, and Surface Erosion; What If (Facility Mass Excavation).

C 4.4.4 FEP # 2.4.4 Human-action-mediated Release

Description

The release of contaminants from the waste form as a direct result of human actions.

This might result from processes such as drilling into or excavation of the waste form (FEPs 1.4.5 and 1.4.6) and might result in the release of contaminants into the Facility and/or directly into the biosphere.

Screening Analysis

Human-action-mediated transport of contaminants includes inadvertent and deliberate processes (without prior knowledge of the waste) that disturb the Facility such as drilling into or excavation of the waste form (FEP 1.4.5). The human intrusion actions into the Facility will impact the contaminant transport and exposure pathways. Human intrusion by drilling is assigned as a Disruptive Event scenario, so this FEP is likewise treated. Human-action mediated transport of contaminants is relevant to the Facility long-term performance and safety.

Screening Decision

Disruptive Events – Site Investigation (Inadvertent Human Intrusion) and Excavation of Above-Bedrock Facility; What If (Mass Excavation).

C 4.5 Contaminant Migration [waste package]

The processes that directly affect the migration of contaminants through the waste package once they have been released from the waste form.

There are 2 subcategories under Contaminant Migration [waste package] with water-mediated migration being further subdivide as follows:

2.5.1 Water-mediated migration
- 2.5.1.1 Advection [waste package]
- 2.5.1.2 Dispersion [waste package]
- 2.5.1.3 Diffusion [waste package]
- 2.5.1.4 Dissolution, precipitation and crystallization [waste package]
- 2.5.1.5 Speciation and solubility [waste package]
- 2.5.1.6 Sorption and desorption [waste package]
- 2.5.1.7 Colloid transport [waste package]

2.5.2 Gas-mediated [waste package]

Screening Analysis

As this Facility does not include waste packages none of these FEPs are relevant to the Facility long-term performance and safety and are excluded from the analysis.

Screening Decision

Screened Out – Out of scope.

C 5 FACILITY FACTORS

The factors related to the Facility (including the excavation damaged and disturbed zones, and site investigation/monitoring boreholes but excluding the waste packages) and the associated migration of contaminants.

The three subcategories under Facility Factors are:
3.1 Facility Characteristics and Properties
3.2 Facility Processes
3.3 Contaminant migration [through Facility]

C 5.1 Facility Characteristics and Properties

The initial physical, chemical and biological characteristics and properties of the Facility components (excluding the waste packages).

This will include information concerning the thermal (e.g., thermal conductivity, heat capacity), hydraulic (e.g., porosity, permeability, capillary pressure), chemical (e.g., chemical composition) and mechanical (e.g., density, Poisson's ratio, Young's modulus) properties of the various Facility components.

There are 6 subcategories under Facility Characteristics and Properties:

3.1.1 Buffer/backfill
3.1.2 Room/tunnel seals
3.1.3 Shaft/ramp seals
3.1.4 Borehole seals
3.1.5 Other engineering features
3.1.6 Excavation damaged and disturbed zones

C 5.1.1 FEP # 3.1.1 Buffer/backfill

Description:

The physical, chemical and biological characteristics and properties of the buffer/backfill at the time of waste emplacement in the Facility.

Buffer and backfill are sometimes used synonymously. In some HLW/spent fuel concepts, the term buffer is used to mean material immediately surrounding a waste form and having some chemical and/or mechanical buffering role, whereas backfill is used to mean material used to fill other underground openings. However, in ILW/LLW (intermediate level waste/low level waste) concepts the term backfill is used to describe the material placed between waste forms, which may have a chemical and/or mechanical role. Buffer/backfill materials may include clays, cement and mixtures of cement with aggregates, e.g., of crushed rock.

In this appendix, the Buffer/Backfill material is the grout.

Screening Analysis

The reference strategy is for all below grade areas of the Facility to be backfilled with grout to the extent practicable to fill voids in the waste form. The nuclear area will then be covered with a concrete cap and the entire footprint of the facility with an engineered barrier. The grout will play a chemical role in retarding contaminant transport and a mechanical role in preventing collapse of underground openings. It will also provide a barrier to groundwater flow through the Facility. Contaminants can be transported through the backfill by diffusion or through moving groundwater. Important backfill characteristics are its hydraulic conductivity, porosity, and contaminant diffusivity and capacity factors. This FEP is relevant to the Facility long-term performance and safety.

Defence-in-Depth cases can explore the benefit of grouting in terms of postclosure performance.

More rapid than expected degradation of the backfill is considered in a Disruptive Event scenario (see FEP 1.1.1).

Screening Decision

Normal Evolution, Defence-in-Depth (Role of Grout), Disruptive Event (Extreme Degradation; Fault Zone Activation).

C 5.1.2 FEP # 3.1.2 Room/Tunnel Seals

Description

The physical, chemical and biological characteristics and properties of the seals in the waste emplacement rooms/tunnels at the time of sealing.

The design-basis characteristics of any walls/plugs that are used to close the emplacement rooms and access tunnels. Sealing materials may include clay bricks, cement bricks and cement plugs.

Screening Analysis

The Facility has pipes that were used as drainage, and to draw water from the Ottawa River during operation. These pipes will need to be sealed to prevent undesirable flow paths for water and contaminants. In addition, any exterior wall penetrations will also need to be sealed up. The properties of the seals could change over time, for example resulting from long-term thermal and mechanical tectonic processes, affecting their performance over different time frames. This FEP is relevant to the Facility long-term performance and safety.

More rapid than expected degradation of these seals is considered in a Disruptive Event scenario (see FEP 1.1.1).

Screening Decision

Normal Evolution, Disruptive Event (Extreme Degradation; Fault Zone Activation).

C 5.1.3 FEP # 3.1.3 Shaft/Ramp Seals

Description

The physical, chemical and biological characteristics and properties of the shaft/ramp seals at the time of sealing.

The design-basis characteristics of any seals that are used to close the shafts/ramps. Sealing materials may include clays, cement and mixtures of cement with aggregates, e.g. of crushed rock.

Screening Analysis

This Facility does not have any shafts or ramps that will require sealing and thus this FEP is not relevant to the assessment.

Screening Decision

Screen Out – Out of scope.

C 5.1.4 FEP # 3.1.4 Borehole Seals

Description

The physical, chemical and biological characteristics and properties of any site investigation/ monitoring boreholes at the time of sealing.

The design-basis characteristics of any seals that are used to close any site investigation/monitoring boreholes. Sealing materials may include clays, cement and mixtures of cement with aggregates, e.g. of crushed rock.

Screening Analysis

There are a number of monitoring boreholes around the Facility that are used for measuring groundwater. While these boreholes are situated around the Facility, they do not penetrate the Facility. Given the in-situ closure method being used and the fact that the Facility sits below grade, these boreholes will not provide a release path to the environment.

Screening Decision

Screen Out – Out of scope.

C 5.1.5 FEP # 3.1.5 Other Engineered Features

Description

The physical, chemical and biological characteristics and properties of the engineered features (other than waste packages, buffer/backfill, and seals) when first constructed.

Such features can include rock bolts, shotcrete, tunnel and shaft liners, silo walls, any services and equipment not removed before closure.

Screening Analysis

The proposed in-situ decommissioning activities include removing the above ground structure and placing redundant materials and demolition waste into the below grade structure within the existing concrete structure. The below grade structure will be sealed by grouting. Once the below-grade structure is grouted, a concrete cap will be emplaced to cover the footprint of the below grade nuclear area. The entire footprint of the facility will be covered with an engineered barrier containing drainage layers, finished with topsoil, and contoured to shed water. The engineered barrier will cover the fully grouted Facility.

The other engineered features necessary to represent are therefore:

- the existing Facility structure;
- the concrete cap;
- the contoured multilayer engineered barrier.

The engineered structure was constructed when the NPD was built, more than 50 y ago. It nevertheless appears to maintain a low permeability to water, based on past evidence from the volumes of water pumped out from the sump. Over longer periods of time the concrete will gradually degrade and its hydraulic conductivity will increase. In addition, any exterior wall penetrations will need to be sealed up.

The concrete cap will be placed over the nuclear area of the Facility. This provides a barrier against intrusion and will also, together with the multilayer cap, act to shed water and thus reduce infiltration into the

unsaturated parts of the structure. It will also gradually degrade, with freeze-thaw cycling potentially being a factor.

The multilayer engineered barrier will also provide a barrier to infiltration as well as providing a substrate for a natural cover of plants over the Facility. It may also be affected by freeze-thaw cycling.

All aspects will need to be represented in the postclosure safety assessment as all provide a safety function.

The properties of all these components will change with time through degradation. A Disruptive Event scenario also considers more rapid degradation due to unforeseen circumstances (see FEP 1.1.1). The Postclosure Safety Assessment should also examine the significance of the existing Facility structure as a barrier to radionuclide release and the overall performance of the NPDDF.

Screening Decision

Normal Evolution, Disruptive Event (Extreme Degradation; Fault Zone Activation), Defence-in-Depth (Role of Existing Facility Concrete Structure).

C 5.1.6 FEP # 3.1.6 Excavation Damaged and Disturbed Zones

Description

The zone of rock around caverns, tunnels, shafts or other underground openings that may be mechanically disturbed during excavation.

The extent and properties depend on factors such as the nature of the host rock, the excavation method, and the location and effectiveness of seals and grouts around the rooms and tunnels. The extent of damage will decrease with increasing distance from the excavation wall and there will be transition from the excavation damaged zone to the excavation disturbed zone to the undisturbed host rock. The zones are likely to have different properties to the undisturbed host rock, e.g. opening of fractures or change of hydraulic properties due to stress relief. FEPs affecting the undisturbed host rock are considered under Geosphere Factors (FEP 4).

Screening Analysis

Because the Facility is being decommissioned in-situ, significant digging or excavation activities are not anticipated as part of the project. However, the disturbed zone resulting from historical activities (e.g., excavation of the Facility) and the emplacement of surface demolition debris occurred at the Facility that will need to be considered in the assessment. Specifically, there is a gap between the Facility concrete walls and the excavated void in the bedrock that has been backfilled with concrete.

Screening Decision

All post-closure scenarios, except Disruptive Event – Site Investigation (Inadvertent Human Intrusion), and What If (Facility Mass Excavation).

C 5.2 Facility Processes

The processes occurring within the Facility resulting in its evolution (excluding the waste package).

The primary focus is on processes occurring in the Facility and the excavation damaged and disturbed zones after Facility closure. However, some consideration is required of processes occurring pre-closure, especially if there is an extended timescale (tens of years) between Facility construction and closure. The operational phase of a Facility (when it is open and ventilated) may influence long-term safety relevant properties of some Facility components (mechanical, hydraulic and geochemical properties of the host rock in the vicinity of the Facility). For example, for argillaceous media, a process that should be considered is the oxidation of the host rock and its potential impact on the engineering components in the postclosure period.

The coupled nature of certain processes will need to be taken into account, as will the impact of key waste form, waste packaging and geosphere features (FEPs 2.1, 2.2 and 4.1) and their associated processes (FEPs 2.3 and 4.2). Processes relating to the migration of contaminants through the Facility are considered under FEP 3.3.

There are 6 subcategories under Facility Processes:

3.2.1 Thermal processes [Facility]
3.2.2 Hydraulic processes [Facility]
3.2.3 Mechanical processes [Facility]
3.2.4 Chemical processes [Facility]
3.2.5 Biological processes [Facility]
3.2.6 Radiological processes [Facility]

C 5.2.1 FEP # 3.2.1 Thermal Processes [Facility]

Description

The internal and external thermal processes that affect the buffer/backfill, seals and other engineered features, and the overall thermal evolution of the Facility.

Internal thermal processes are those that arise from the waste packages (FEP 2.3.1) and other metallic, organic or cementitious materials within the Facility. These in turn can result from chemical processes, such as the corrosion of metallic material, degradation of organic material and hydration of cementitious material in the Facility. External thermal processes are those that arise from the surrounding geosphere (FEP 4.2.1).

The thermal evolution of the Facility will be affected by heat transfer due to gradients in temperature caused by heat conduction or convective flow which in turn will be affected by the thermal characteristics (thermal conductivity, heat capacity) of the engineered features and the surrounding geosphere. The temperature and associated gradients could have a number of effects, such as inducing thermal expansion and stresses in the Facility components (that could cause cracks to form) and changes in fluid densities and viscosities, which in turn could affect the movement of fluids in the Facility.

Screening Analysis

Heat generated from the curing of the backfill will cause temperatures within the Facility to rise following in-situ decommissioning operations. However, this heat is expected to have dissipated by the end of the institutional control period. It will not be of consequence to postclosure performance.

Screening Decision

Screen Out.

C 5.2.2 FEP # 3.2.2 Hydraulic Processes [Facility]

Description

The hydraulic/hydrogeological processes that affect the seals and other engineered Facility features, and the overall hydraulic/hydrogeological evolution of the Facility.

This includes the effects of hydraulic/hydrogeological influences on the Facility components by the waste packages and surrounding geosphere. These processes can in turn be affected by thermal processes (e.g. through changes in water density and viscosity), chemical processes (e.g. alteration/precipitation of Facility components resulting in changes in hydraulic properties) and mechanical processes (e.g. material volume changes resulting in changes in hydraulic properties).

The following more specific factors are discussed under separate entries:

3.2.2.1 Desaturation/re-saturation
3.2.2.2 Piping/hydraulic erosion

C 5.2.2.1 FEP # 3.2.2.1 Desaturation/Resaturation

Description

The establishment of unsaturated conditions near the Facility during the construction and operation phases, and the subsequent return to saturated conditions.

The timing of desaturation/resaturation of the Facility (including the excavation damaged and disturbed zones) will be affected by a variety of factors, including the characteristics of the Facility components and surrounding geosphere (e.g. capillary effects), the performance of the Facility seals, and the evolution of temperature and gas pressure in the Facility.

Screening Analysis

Following closure, water will flow towards the Facility and the near-field will resaturate. Flow directions will stabilize following saturation and will be consistent with the original flow field. The process of resaturation will be controlled by the hydraulic properties of the concrete cap and the existing concrete walls of the NPDDF. The rate of resaturation will likely vary at different locations within the Facility. The time of unsaturated conditions and the time to resaturate different areas will affect the local temperature, chemistry, stress states and groundwater flow rates.

Note that the resaturation timescale will be dependent on the properties of the engineered structures. Arcadis & Geofirma (2023c) have most recently examined the process of resaturation with models and constrained the resaturation timescale.

Screening Decision

All post-closure scenarios, except Disruptive Event – Site Investigation (Inadvertent Human Intrusion), and What If (Facility Mass Excavation).

C 5.2.2.2 FEP # 3.2.2.2 Piping/Hydraulic Erosion

Description

The hydraulic erosion of the buffer/backfill.

Water may flow into the Facility, e.g., through intersecting hydraulically active fractures. If the rate of inflow exceeds the rate of uptake by the buffer/backfill, then active flow channels or 'pipes' may develop in the buffer/backfill. Continuing flow through these pipes could result in progressive erosion of the buffer which, over time, may result in a reduction in the density of the buffer/backfill that could compromise its barrier functions.

Screening Analysis

There are no features that could lead to any significant piping effects and therefore the FEP is not considered to be of any consequence to the postclosure performance of the Facility.

Screening Decision

Screen Out.

C 5.2.3 FEP # 3.2.3 Mechanical Processes [Facility]

Description

The mechanical processes that affect the seals and other engineered Facility features, and the overall mechanical evolution of the Facility.

This includes the effects of thermal, hydraulic and mechanical loads imposed on Facility components by adjacent Facility components, the waste packages and the surrounding geosphere.

The following more specific factors are discussed under separate entries:

3.2.2.3 Material volume changes [Facility]
3.2.2.4 Creep
3.2.2.5 Collapse of openings
3.2.2.6 Gas-induced dilation [Facility]
3.2.2.7 Gas explosion [Facility]

C 5.2.3.1 FEP # 3.2.3.1 Material Volume Changes [Facility]

Description

The effects of volume changes in materials used in the Facility.

Examples include the shrinkage/expansion of concrete, the corrosion of metals and the swelling of bentonite.

Screening Analysis

The Facility will be backfilled with grout. The grout, which is essentially concrete, is expected to exhibit negligible swelling over the postclosure time period. Steel corrosion can lead to volume change which has the potential to degrade concrete (e.g., corrosion of rebar) but such effects are assumed to be relatively localized.

Insofar as it is plausible that some material expansion may occur, consequent effects on material properties (principally the hydraulic conductivity) can be considered to be subsumed into the Disruptive Event scenario that considers the degradation of engineering (see FEP 1.1.1). The facility reaching its degraded state immediately at the end of the 100-y institutional control period is considered in a sensitivity case.

Screening Decision

Sensitivity (Rapid Degradation), Disruptive Events (Extreme Degradation; Fault Zone Activation).

C 5.2.3.2 FEP # 3.2.3.2 Creep

Description

The plastic movement of buffer/backfill material under an imposed load.

The buffer and backfill materials can creep or move as a result of imposed loads such as the weight of the waste packages or lithostatic pressure from and creep of the surrounding geosphere.

Screening Analysis

The effects of backfill (grout) creep are expected to be minor with the exception of creep resulting from seismic activity. It is assumed to have stabilized by the time of closure and is thus screened out as being of no consequence to postclosure safety.

Screening Decision

Screen Out.

C 5.2.3.3 FEP # 3.2.3.3 Collapse of Openings

Description

The collapse of tunnels, shafts and boreholes, including cave-ins, roof settling, and rock bursts.

Potential effects include damage to the waste packages, buffer/backfill and other seals, and changes to water flow conditions in the Facility and surrounding geosphere.

Screening Analysis

The design of this Facility calls for the waste to be placed within the walls of the below ground structure. This will then be filled with grout, which will occupy any voids in the waste. There will therefore be no significant openings within the Facility. If any collapse was to occur, it would affect the hydraulic properties of the engineered system and so is captured in the Disruptive Event for degradation of engineered barriers.

Screening Decision

Disruptive Event (Extreme Degradation; Fault Zone Activation).

C 5.2.3.4 FEP # 3.2.3.4 Gas-induced Dilation [Facility]

Description

The dilation of Facility materials due to gas pressure.

Under certain conditions, the Facility gas pressure might become sufficiently high to cause physical damage to the Facility seals and allow the movement of gas as a discrete phase within stress- or pressure-induced microscopic porosity in the seals.

Screening Analysis

Gas generation is not a significant process in the long term in the Facility (see FEP 2.3.2.5) so the FEP is screened out.

Screening Decision

Screen Out.

C 5.2.3.5 FEP # 3.2.3.5 Gas Explosion [Facility]

Description

An explosion resulting from the ignition of a flammable gas mixture in the Facility.

Some gases produced from the corrosion and degradation of waste packages and/or engineered Facility features and/or the surrounding geosphere might be flammable or might form an explosive mixture. For instance, hydrogen and methane could mix with oxygen and explode to damage the Facility and its seals.

However, a gas explosion can only occur if a flammable gas mixture forms and there is a source of ignition or the gas mixture has the capability to auto-ignite.

Screening Analysis

Methane production is expected to be minor due to the non-putrescible type of materials emplaced in the Facility. Hydrogen evolution will be at a slow rate and cannot be assumed to accumulate in volumes that may be explosive. There is also no ignition source, so the probability of an explosion is very unlikely.

Screening Decision

Screen Out.

C 5.2.4 FEP # 3.2.4 Chemical Processes [Facility]

Description

The chemical/geochemical processes that affect the seals and other engineered Facility features, and the overall chemical/geochemical evolution of the Facility.

This includes the effects of chemical/geochemical influences on Facility components by the waste packages, adjacent Facility components and the surrounding geosphere. These processes can in turn be affected by thermal processes (e.g., chemical processes can be accelerated/initiated as temperature increases), hydraulic processes (e.g., the water flow rate through the Facility) and radiological processes (e.g., radiolysis of Facility water which can impact pH and Eh conditions).

The following more specific factors are discussed under separate entries:

3.2.4.1 Evolution of pH conditions [Facility]
3.2.4.2 Evolution of Eh conditions [Facility]
3.2.4.3 Migration of chemical species [Facility]
3.2.4.4 Corrosion [Facility]
3.2.4.5 Alteration [Facility]
3.2.4.6 Precipitation [Facility]
3.2.4.7 Complexation [Facility]
3.2.4.8 Colloid formation [Facility]

C 5.2.4.1 FEP # 3.2.4.1 Evolution of pH Conditions [Facility]

Description

The temporal evolution of pH within the Facility.

This depends on a number of factors, including the pH of the water in the surrounding geosphere, the water flow rate through the Facility and the characteristics of the Facility seals and other engineered features. The evolution of pH within the Facility can be important in determining the mobility of certain elements through its impact on solubility and sorption, and in determining the evolution of the Facility seals.

Screening Analysis

The leaching of concrete and grout will produce high concentrations of calcium ions and increase the pH within the NPDDF (Arcadis & Quintessa, 2018). Groundwater in the Facility will react with cement causing the pH to rise by dissolution of the small amounts of NaOH and KOH hydroxides present in the cement. As high-pH waters are displaced by incoming groundwater, the pH will be controlled by the dissolution of $Ca(OH)_2$, which will buffer the pH. The rate of this process is controlled by the water turnover, which is likely to be slow due to the low hydraulic conductivity of the concrete. Over time, leaching of the C-S-H gels will progress and ultimately the pH will begin to reduce and the porosity increase, resulting in an increased hydraulic conductivity and decreased strength.

This is a key aspect of the Facility that requires representation in the postclosure safety assessment. The rate of degradation is an aspect that will be explored with a Disruptive Event scenario (see FEP 1.1.1).

Screening Decision

All post-closure scenarios, except Disruptive Event – Site Investigation (Inadvertent Human Intrusion), and What If (Facility Mass Excavation).

C 5.2.4.2 FEP # 3.2.4.2 Evolution of Eh Conditions [Facility]

Description

The temporal evolution of the Facility's Eh.

This depends on a number of factors, including the Eh conditions of the water in the surrounding geosphere, the water flow rate through the Facility and the consumption rate of any available oxygen. Oxygen-deficient (anaerobic) conditions promote the formation of lower, and often less soluble, oxidation states of elements, promote relatively slow corrosion and microbial processes, and minimize the rate of gas generation. The evolution of Eh within the Facility can be important in determining the mobility of certain elements through its impact on solubility and sorption.

Screening Analysis

The porewater composition in the Facility, including the electrochemical potential and pH discussed in FEP 3.2.4.1, is important in determining the properties of contaminants (e.g., sorption and solubility) and is included in the safety analysis. Local Eh conditions may be important, particularly in the reactor vault if the metal corrosion is sufficient to significantly deplete oxygen.

Screening Decision

All post-closure scenarios, except Disruptive Event – Site Investigation (Inadvertent Human Intrusion), and What If (Facility Mass Excavation).

C 5.2.4.3 FEP # 3.2.4.3 Migration of Chemical Species [Facility]

Description

The migration of reactants into and migration of reaction products from the Facility.

Chemical species can migrate into and out of the Facility and its various components by advection (pressure gradient driven) and diffusion (chemical gradient driven) affecting the associated physical and chemical evolution (including pH and Eh conditions). Chemical concentration gradients in the Facility and its various components could be caused by various factors such as temperature gradients and heterogeneities in the spatial distribution of waste packages and Facility materials. The formation of chemical concentration gradients may lead to the dissolution and precipitation of chemical compounds with subsequent opening or plugging of flow paths.

The presence of certain species, such as chloride, sulphide, sulphate and potassium, can affect the evolution of the Facility and its seals, for example through promoting the corrosion of metals (high chloride/sulphide concentrations), the degradation of cement (high sulphate concentrations) and the illitisation of bentonite (high potassium concentrations). Sources of such species can include the waste packages and water from the geosphere surrounding the Facility.

Screening Analysis

Contaminant transport in the backfill (i.e., the grout) could occur by both advection (in cracks and through the bulk material when it has degraded to a sufficient degree) and diffusion. The dominant mechanism depending on the groundwater velocity in the backfill. Contaminant transport is expected to be diffusion dominated in the backfill initially, before gradually transitioning to an advective regime as the engineering degrades. As has been noted, the rate of degradation is an important aspect that is explored with Disruptive Event scenarios (see FEP 1.1.1 etc.).

Screening Decision

Normal Evolution, Disruptive Events (Extreme Degradation; Fault Zone Activation).

C 5.2.4.4 FEP # 3.2.4.4 Corrosion [Facility]

Description

The destruction of the metallic components of the Facility by chemical reaction with water in liquid or vapour form.

Corrosion of Facility metals (e.g., rock bolts, ventilation ducts and rails) that are not removed at closure can occur by a number of processes such as generalized (or uniform), localized and galvanic. Metals are subject to uniform corrosion at rates that are dependent on the chemical and physical (and possibly biological) environment, while localized formation of cavities in a metal surface is caused by non-uniform corrosion. Galvanic corrosion occurs when two different metals are in electric contact. Metal corrosion will result in the generation of hydrogen gas under anaerobic conditions.

Screening Analysis

The main metallic materials within the Facility, excluding the wastes themselves, will be rebar set into concrete. Over long time periods this will gradually corrode, but the cement will offer chemical conditioning that reduces the corrosion rate significantly. Ultimately, some cracking may occur and this is one of several contributing mechanisms that together can be represented by increasing hydraulic conductivity as the concrete degrades.

Screening Decision

Normal Evolution, Disruptive Event (Extreme Degradation; Fault Zone Activation).

C 5.2.4.5 FEP # 3.2.4.5 Alteration [Facility]

Description

Alteration, including its evolution in time, of Facility materials by chemical processes such as dissolution, leaching, chloride and sulphide/sulphate attack, carbonation, illitisation.

Dissolution is the dissolving of solid Facility materials in a solvent, typically water. The chemical environment of the Facility and its components (e.g., pH and Eh) is likely to evolve over time, and these changes could lead to changes in the aqueous species that are dissolved.

Leaching can result in the reduction of pH in concrete in the long-term. Chloride attack can increase concrete porosity by increasing the leaching of portlandite and reduce concrete strength. Sulphide attack results from the conversion of hydrogen sulphide to sulphuric acid which causes a reduction in concrete pH. Sulphate attack depletes the reservoir of alkalinity (calcium hydroxide) in the concrete and can also result in a reduction in concrete strength. Whilst carbonation reduces the ability of concrete to impose high pH conditions on water by reacting with calcium hydroxide, it has the potential to heal cracks, sealing them to ingress by water through the production of calcium carbonate which has low solubility. Thus, carbonation can counter the effects of leaching and chloride/sulphate attack.

Illitisation may affect bentonite converting the smectite into illite resulting in the loss of bentonite's swelling capacity. The reaction is strongly dependent upon time, temperature and availability of potassium ions.

Screening Analysis

Facility materials, in particular cementitious materials, will be altered over time by chemical processes as indicated in FEPs 3.2.4.1 to 3.2.4.4. Alteration should be considered in the safety assessment.

Screening Decision

All post-closure scenarios, except Disruptive Event – Site Investigation (Inadvertent Human Intrusion), and What If (Facility Mass Excavation).

C 5.2.4.6 FEP # 3.2.4.6 Precipitation [Facility]

Description

The precipitation processes, including their evolution in time, affecting Facility materials.

Precipitation can be affected by chemical conditions in the Facility (particularly pH, Eh and the concentration of complexing ions) and can occur if there is an abrupt change in the chemical environment, especially at the interface between different Facility components. For example: iron/smectites interactions at interfaces between metallic components and host rock, buffer/backfills or seals; iron/cement interactions at interfaces between metallic components and concrete seals; and cement/clay interactions at interfaces between concrete seals and buffer/backfills or host rock.

The presence of complexing ions can increase solubility, and cause elements to remain in solution under conditions when they would otherwise be expected to precipitate.

Screening Analysis

Contaminant concentrations will be highest in the vicinity of the waste forms, which are the contaminant sources, but will generally decrease away from the waste form so precipitation away from the waste form is less likely to occur. However, precipitation could occur if the chemical environment (including groundwater composition, Eh, pH, temperature, etc.) changes abruptly. As precipitation decreases contaminant concentrations in fluids and thus contaminant fluxes out of the Facility, neglecting to account for contaminant precipitation in the Facility is conservative.

Screening Decision

Screen Out.

C 5.2.4.7 FEP # 3.2.4.7 Complexation [Facility]

Description

The combination of individual atom groups, ions or molecules to create one large ion or molecule in the Facility materials.

The resulting complexes are usually highly stable, a factor that can, together with other factors, increase significantly the solubilities and mobility of certain elements. Complexation is promoted through the presence of complexing agents (organics, inorganic ligands and microbes). Sources of these agents include organics in the waste package and engineered components of the Facility (such as organic cement additives), and water from the geosphere surrounding the Facility.

Screening Analysis

Complexing agents in the Facility groundwater (organics such as humic and fulvic acids; byproducts of microbial activity; inorganic ions such fluoride and nitrate anions; etc.) could chemically bind with a contaminant to form another stable species. The formation of such new species can increase (or decrease)

the solubility of the complexed element and can modify transport properties, for instance, by forming a neutral or anionic complex that is less likely to sorb. This process is implicitly included in sorption coefficients.

Screening Decision

All post-closure scenarios, except Disruptive Event – Site Investigation (Inadvertent Human Intrusion), and What If (Facility Mass Excavation).

C 5.2.4.8 FEP # 3.2.4.8 Colloid Formation [Facility]

Description

The formation of very fine particles (with diameters typically less than 10 μm) that can affect the migration of contaminants in the Facility.

Particles of clay minerals, silica, iron oxy-hydroxides, other minerals, organic and bio-organic macromolecules may form the colloid phase. Sources can include materials in the waste package (e.g. cementitious materials, organic wastes), Facility materials (e.g. bentonite and cementitious materials) and inflowing groundwater. Colloid formation may be promoted by steep chemical gradients, such as at an interface where the Eh or pH changes abruptly because of chemical or biological activity. The thermodynamic stability of colloids depends upon varied factors, such as the chemistry and surface charge of the colloid and the chemistry of the dispersion medium. Colloid stability generally decreases as ionic strength (salinity) increases.

Screening Analysis

The formation of colloids within the facility at the NPDDF is unlikely because colloids typically form from clay minerals, organic and bio-organic molecules and these are not present at NPDDF in significant amounts (see also FEP 2.1.2.2).

Naturally-occurring colloids in groundwater could reach the Facility with groundwater, but would likely be filtered-out by the low hydraulic conductivity of the facility structure and grout backfill (see discussion and supporting references under FEP 2.3.4.8). The low hydraulic conductivity of the Facility will prevent any significant colloidal transport for the foreseeable future, and therefore the FEP has been screened out.

Screening Decision

Screen Out.

C 5.2.5 FEP # 3.2.5 Biological Processes [Facility]

Description

The biological/biochemical processes that affect the seals and other engineered Facility features, and the overall biological/biochemical evolution of the Facility.

This includes the effects of biological/biochemical influences on Facility components by the waste forms and surrounding geosphere. In addition to the microbes that might be present prior to Facility construction, a range of microbes can be expected to be introduced into the Facility during its construction and operational phases. Some could be present in the waste forms, whereas others could be introduced as the emplacement rooms are excavated and infrastructure erected. Only some of the microbes present at Facility closure will find the subsequent conditions suitable for their growth. Besides requiring certain types of nutrients, individual microbial populations will only operate under particular conditions of temperature, pH, Eh and salinity.

Biological and biochemical processes affect the release and migration of contaminants in gas (through the generation of carbon dioxide, methane and hydrogen sulphide) and the groundwater pathway (through microbially-induced corrosion and the formation of biofilms and organic complexation agents).

The following more specific factors are discussed under separate entries:

3.2.5.1 Microbial growth and poisoning [Facility]
3.2.5.2 Microbially/biologically mediated processes [Facility]

C 5.2.5.1 FEP # 3.2.5.1 Microbial Growth and Poisoning [Facility]

Description

The processes affecting the growth and decline of microbes in the Facility.

Growth requires the presence of suitable nutrients in the Facility, such as simple organic molecules containing oxygen, nitrogen and/or sulphur, and organics derived from wastes. Poisoning of microbial processes can occur due to changes in temperature and chemical conditions in the Facility but extremophiles can survive and thrive outside the range at which most microbes flourish.

Screening Analysis

Microbial growth will not be a significant process due to lack of nutrients in the Facility.

Screening Decision

Screen Out.

C 5.2.5.2 FEP # 3.2.5.2 Microbially/Biologically Mediated Processes [Facility]

Description

The biological processes affecting the Facility such as degradation of organics, nitrate ions and sulphate ions, biofilm growth and volatilization.

Microbiological/biological processes can lead to the formation of acidic and oxidizing species that can participate in corrosion of the metals and promotion of reducing conditions in the Facility. Bacteria may also result in the conversion of gases (e.g., carbon dioxide and hydrogen into methane – methanogenesis), and restrict the movement of water through the generation of biofilms on Facility surfaces. The rate of volatilization is controlled by changes in pressure, temperature and concentration of volatiles in the Facility.

Screening Analysis

Microbial growth will not be significant due to lack of nutrients in the Facility.

Screening Decision

Screen Out.

C 5.2.6 FEP # 3.2.6 Radiological Processes [Facility]

Description

The effects of radiation emitted from the waste in the waste packages on the seals and other Facility engineered features, and the overall radiogenic evolution of the Facility.

The following more specific factors are discussed under separate entries:

3.2.6.1 Radioactive decay and ingrowth [Facility]
3.2.6.2 Radiolysis [Facility]
3.2.6.3 Radon production [Facility]
3.2.6.4 Radiation damage [Facility]
3.2.6.5 Criticality [Facility]

C 5.2.6.1 FEP # 3.2.6.1 Radioactive Decay and Ingrowth [Facility]

Description

The spontaneous disintegration or de-excitation of an atomic nucleus, resulting in the emission of sub-atomic particles and energy and the formation of a new progeny (or "daughter") nucleus in the Facility.

Radioactive decay and ingrowth will affect any radionuclides released from the waste forms into the Facility. In postclosure assessment, radioactive decay chains are often simplified, e.g., by neglecting the shorter-lived radionuclides in release and migration calculations.

Screening Analysis

There are a number of radioactive isotopes within the waste, as described in FEP 2.1.1.1 which will decay, and potentially ingrow into other isotopes.

Screening Decision

All post-closure scenarios.

C 5.2.6.2 FEP # 3.2.6.2 Radiolysis [Facility]

Description

The dissociation of molecules by ionizing radiation in the Facility surrounding the waste form.

Radiolysis of any water in the Facility environment immediate adjacent to the waste forms can produce species such as free hydrogen and oxygen which can impact the chemical conditions in the Facility (e.g., the Eh conditions). The actual composition and amount of the radiolysis products that will be formed is controlled by the radiation dose rate and by the composition and amount of the air and water mixture contained in the Facility surrounding the waste form.

Screening Analysis

Radionuclide concentrations within the Facility will be insufficient for any significant radiolysis effects, therefore the FEP is screened out.

Screening Decision

Screen Out.

C 5.2.6.3 FEP # 3.2.6.3 Radon production [Facility]

Description

The production of radon gas from the decay of uranium, thorium and radium in the Facility.

The main radon isotope considered in assessments is Rn-222 (the longest-lived isotope at 3.82 days). The uranium, thorium and radium may be waste-derived and/or naturally occurring.

Screening Analysis

Radon gas generation is expected from the decay of uranium, thorium and radium contained in the waste forms. The quantities of radon precursor radionuclides within the inventory are, however, small and radon production rates will be very low. Radon exposure, as an explicit pathway, will be trivial compare with other pathways and can therefore be screened out.

Screening Decision

Screen Out.

C 5.2.6.4 FEP # 3.2.6.4 Radiation Damage [Facility]

Description

The damage caused to the Facility materials surrounding the waste form by radiation.

Radiation damage from radioactive decay in the Facility materials surrounding the waste form. This could detrimentally affect the properties of the sealing materials such bentonite.

Screening Analysis

The concentration of radionuclides in the Facility is not sufficiently high that radiation damage will occur. Some degree of radiation damage may have occurred within the structure historically, due to reactor operation, but this can be taken into account in the properties of the materials at closure.

Screening Decision

Screen Out.

C 5.2.6.5 FEP # 3.2.6.5 Criticality [Facility]

Description

The possibility and effects of spontaneous nuclear fission chain reactions within the Facility.

Criticality requires a sufficient concentration and localized mass (critical mass) of fissile isotopes (e.g., U-235, Pu-239) and also presence of neutron moderating materials in a suitable geometry; a chain reaction is liable to be damped by the presence of neutron absorbing isotopes (e.g., Pu-240).

Screening Analysis

The Facility does not contain any significant concentrations of nuclear fuel that could result in a nuclear criticality. Following shutdown of the NPD reactor, the primary heat transport and moderator systems heavy water was drained and shipped off-site. The reactor was de-fueled and the fuel bundles were transported to CRL for storage.

Screening Decision

Screen Out – Out of scope.

C 5.3 Contaminant Migration [through Facility]

Description

The processes that directly affect the migration of contaminants in the Facility once they have been released from the waste packages.

Contaminant migration through the waste package is considered under FEP 2.5.

There are 4 subcategories under Contaminant Migration [Facility]:

3.3.1 Water-mediated migration [Facility]
3.3.2 Gas-mediated migration [Facility]
3.3.3 Solid-mediated migration [Facility]
3.3.4 Human-action-mediated migration [Facility]

C 5.3.1 FEP # 3.3.1 Water-mediated Migration [through Facility]

Description

The processes related to migration of contaminants in Facility water in the aqueous phase (including dissolved gases).

The following more specific factors are discussed under separate entries:

3.3.1.1 Advection [Facility]
3.3.1.2 Dispersion [Facility]
3.3.1.3 Diffusion [Facility]
3.3.1.4 Dissolution, precipitation, and crystallization [Facility]
3.3.1.5 Speciation and solubility [Facility]
3.3.1.6 Sorption and desorption [Facility]
3.3.1.7 Colloid transport [Facility]

C 5.3.1.1 FEP # 3.3.1.1 Advection [Facility]

Description

The migration of dissolved contaminants by the flow of the water through the Facility by advection.

The rate of advection will vary depending on hydraulic, thermal and density conditions in the Facility and surrounding geosphere and the integrity of the Facility seals.

Screening Analysis

Contaminant transport by advection in the grout and the Facility structure affects the long-term performance of the Facility by providing a pathway for release. Advective conditions will not necessarily occur initially, but as the cement degrades advection will become established.

Screening Decision

All post-closure scenarios, except Disruptive Event – Site Investigation (Inadvertent Human Intrusion), and What If (Facility Mass Excavation).

C 5.3.1.2 FEP # 3.3.1.2 Dispersion [Facility]

Description

The spread in the spatial distribution of contaminants with time in the Facility because of differential rates of advective transport through the Facility.

Dispersion can occur in the direction of flow (longitudinal dispersion) and perpendicular to the direction of flow (transverse dispersion).

Screening Analysis

Dispersion is expected to occur in the Facility, particularly if significant cracking evolves. It can be represented coupled to advection.

Screening Decision

All post-closure scenarios, except Disruptive Event – Site Investigation (Inadvertent Human Intrusion), and What If (Facility Mass Excavation).

C 5.3.1.3 FEP # 3.3.1.3 Diffusion [Facility]

Description

The diffusion of contaminants through the Facility.

Diffusive migration is driven by chemical potential gradients, can be affected by thermal gradients, and can thus be in any direction. It can occur in moving or stagnant Facility water. Diffusion can be the most important migration mechanisms in situations where Facility water flow is very slow.

Screening Analysis

Transport of contaminants by diffusion is important in the near-field Facility (backfill) when the backfill is not significantly degraded. At this phase of the evolution of the Facility it is likely to be the main transport mechanism through the Facility and needs to be considered in the safety analysis.

Screening Decision

All post-closure scenarios, except Disruptive Event – Site Investigation (Inadvertent Human Intrusion), and What If (Facility Mass Excavation).

C 5.3.1.4 FEP # 3.3.1.4 Dissolution, Precipitation, and Crystallization [Facility]

Description

The dissolution, precipitation and crystallization of contaminants in the Facility under prevailing Facility conditions.

Dissolution is the process by which constituents of a solid or gas dissolve into solution and can migrate out of the Facility. Dissolution is controlled by changes in pressure, temperature and gas concentrations in the Facility.

Precipitation and crystallization are processes by which solids are formed out of liquids and are controlled by changes in pressure, temperature and concentrations of chemical species. Precipitation occurs when chemical species in solution react to produce a solid that does not remain in solution. Crystallization is the process of producing pure crystals of an element, molecule or mineral from a fluid or solution undergoing a cooling process.

Screening Analysis

Dissolution is a fundamental mechanism that will lead to the release of contaminants in groundwater, and is therefore represented in the model. Cautiously, it is assumed that dissolution can occur instantaneously for contamination, as the contaminants of interest are present in very small quantities on object surfaces. For radionuclides and lead present within bulk materials (activated metals and lead metal), dissolution is most appropriately represented as a corrosion-controlled mechanism, with the rate of corrosion determining the rate of dissolution, subject to any solubility constraints.

Contaminant concentrations will be highest in the vicinity of the waste forms, which are the contaminant sources, but will generally decrease away from the waste form so precipitation away from the waste form is less likely to occur. However, precipitation could occur if the chemical environment (including groundwater composition, Eh, pH, temperature, etc.) changes abruptly or if in-growth from radioactive decay produces a local increase in concentration. Such conditions are not expected within the Facility therefore the FEP is not considered to be a major factor in controlling contaminant migration. Solubility in the vicinity of the waste forms can be considered as a limiting factor on contaminant concentrations.

Screening Decision

All post-closure scenarios, except Disruptive Event – Site Investigation (Inadvertent Human Intrusion), and What If (Facility Mass Excavation).

C 5.3.1.5 FEP # 3.3.1.5 Speciation and Solubility [Facility]

Description

The chemical speciation and solubility processes affecting contaminant migration through the Facility under prevailing Facility conditions.

The concentration of an element in aqueous solution (at equilibrium) reflects the solubility of the solid compounds which contain the element. Factors such as temperature, gas partial pressure, ionic strength, the presence of complexing agents and pH and Eh conditions affect solubility. These factors affect the chemical form and speciation of the element. Thus, different solids of the same element may have different solubilities in a particular solution.

Screening Analysis

Solubility limitation is not expected outside the waste forms (i.e., within the grout) because the concentration of contaminants in the grout will be below the solubility limit (assuming similar chemical conditions across the Facility). This is because any release from the waste itself will be solubility controlled.

However, Arcadis & Quintessa (2020a) indicates that, in the case of lead, the solubility limits in near neutral conditions might be higher than those in alkaline (grouted) locations, so for this element it may be necessary to represent solubility more broadly.

Screening Decision

All post-closure scenarios, except Disruptive Event – Site Investigation (Inadvertent Human Intrusion), and What If (Facility Mass Excavation).

C 5.3.1.6 FEP # 3.3.1.6 Sorption and Desorption [Facility]

Description

The sorption/desorption processes affecting the migration of contaminants through the Facility under prevailing Facility conditions.

Sorption describes the physical-chemical interaction where dissolved species adhere to a solid phase. Desorption is the opposite. Two sorption-desorption processes are commonly considered: ion-exchange processes involving an electrostatic or ionic attraction between charged dissolved species and oppositely charged surfaces; and chemisorption involving the formation of a chemical bond. Neutral species and (usually) anions are generally not strongly sorbed.

Screening Analysis

Sorption is element-specific and depends on the speciation of contaminants, as well as the solid phase composition and surface characteristics.

Sorption processes in the backfill materials of the engineered barrier system is important at retarding the migration of key contaminants. Uncertainties in solubility limitation can be examined in sensitivity case.

Reduced sorption of grout and concrete are examined in a sensitivity case.

Screening Decision

All post-closure scenarios, except Disruptive Event – Site Investigation (Inadvertent Human Intrusion), and What If (Facility Mass Excavation), Sensitivity (Reduced Near-Field Sorption), Sensitivity (Reduced Sorption in Near-field and Far-field).

C 5.3.1.7 FEP # 3.3.1.7 Colloid Transport [Facility]

Description

The transport of colloids and interaction of contaminants with colloids migrating through the Facility under prevailing Facility conditions.

Colloids (particles with diameters typically less than 10 μm) may influence contaminant migration in a variety of ways: retarding migration by sorption of aqueous radionuclide species and subsequent filtration; or, enhancing migration by sorption and migration with flowing groundwater. Sources can include materials in the waste package (e.g., organic wastes), the Facility (e.g., bentonite and cementitious materials) and inflowing groundwater (see FEP 3.2.4.8). The contaminants themselves could also form intrinsic colloids.

Screening Analysis

Colloids, which occur naturally in groundwater, could enter the Facility with groundwater, be introduced with backfill material, or be produced in the repository. Colloids may be produced in the Facility during degradation of the wastes or erosion of the buffer and backfill materials.

Colloids will, however, be effectively filtered out by the cement. Therefore, colloidal transport within the Facility is not considered to be significant.

Screening Decision

Screen Out.

C 5.3.2 FEP # 3.3.2 Gas-mediated Migration [through Facility]

Description

The migration of contaminants in gas or vapour phase or as fine particulate or aerosol in gas or vapour through the Facility.

Gases may be generated from the wastes, e.g., hydrogen gas, C-14-labelled carbon dioxide or methane (FEP 2.4.2) and Facility materials, e.g., corrosion of metal wastes (FEP 3.2.4.4). Aerosols or particulates may be transported along with non-radioactive gases, or gases may expel contaminated water ahead of them.

Screening Analysis

If a gas phase exists in the Facility, e.g., before saturation of the Facility or as a result of gas generation, the gaseous contaminants may move through the gas phase (by diffusion), or be transported with the gas phase (by convection or advection) out of the Facility. Alternatively, gas pressures could be sufficiently high to form an unsaturated phase where two-phase flow is important, or to expel contaminants dissolved in groundwater from parts of the Facility and geosphere. The only situation that this could occur in is considered to be site investigation drilling that penetrates the facility.

Screening Decision

Disruptive Event – Inadvertent Human Intrusion (Site Investigation) and What If (Mass Excavation).

C 5.3.3 FEP # 3.3.3 Solid-mediated Migration [from Facility]

Description

The migration of contaminants in solid phase from the Facility.

This might result from processes such as the fluvial erosion of the Facility (FEP 1.2.8), the glacial erosion of the Facility (FEP 1.3.5) or magmatic/volcanic activity affecting the Facility (FEP 1.2.5).

Screening Analysis

Relevant contaminant solid-mediated transport processes including transport by erosion may affect the exposure pathways, and the impacts on human and non-human biota. Surface erosion, e.g. as a result of a river flood following a catastrophic failure of dams has been assessed not to sufficient to affect the Facility (although it may remove some overburden materials). The only mechanisms by which there may be a solid-mediated release from the Facility is by glacial disruption or human intrusion. Glaciation is not credible based on the 10,000 y assessment timeframe (see details under FEP# 1.3.5). Human-intrusion related release is addressed under FEP# 3.3.4 below.

Screening Decision

Screen Out – No relevant processes or events that could initiate solid release from the Facility. ###

C 5.3.4 FEP # 3.3.4 Human-action-mediated Migration [from Facility]

Description

The migration of contaminants from the Facility as a direct result of human actions.

This might result from processes such as drilling into or excavation of the Facility (FEPs 1.4.5 and 1.4.6) and might result in the migration of contaminants directly into the geosphere and/or biosphere.

Screening Analysis

Human-action-mediated transport of contaminants includes inadvertent and deliberate processes (without prior knowledge of the waste) that disturb the Facility such as drilling into or excavation of the waste form (FEP 1.4.5). The human intrusion actions into the Facility will impact the contaminant transport and exposure pathways. Human intrusion by drilling is assigned as a Disruptive Event scenario, so this FEP is likewise treated. Human-action mediated transport of contaminants is relevant to the Facility long-term performance and safety.

Screening Decision

Disruptive Event – Site Investigation (Inadvertent Human Intrusion), and What If (Facility Mass Excavation).

C 6 GEOSPHERE FACTORS

The factors related to the geosphere mechanically undisturbed by the construction of the Facility and the associated migration of contaminants.

The geosphere excludes the excavation damaged and disturbed zones surrounding the Facility, and site investigation/monitoring boreholes. These are considered under Facility Factors (FEP 3), for example excavation damaged and disturbed zones (FEP 3.1.6) and collapse of openings (FEP 3.2.3.3).

The three subcategories under Geosphere Factors are:
4.1 Geosphere Characteristics and Properties
4.2 Geosphere Processes
4.3 Containment Migration [geosphere]

C 6.1 Geosphere Characteristics and Properties

The spatial, physical, chemical and biological characteristics and properties of the geosphere prior to Facility construction.

The inhomogeneity and uncertainty of these characteristics and properties also needs to be considered.

There are 9 subcategories under Geosphere Characteristics and Processes:

4.1.1 Stratigraphy
4.1.2 Large-scale discontinuities
4.1.3 Geological resources
4.1.4 Undetected features
4.1.5 Geothermal characteristics and properties
4.1.6 Hydraulic characteristics and properties
4.1.7 Mechanical characteristics and properties
4.1.8 Geochemical characteristics and properties
4.1.9 Biological characteristics and properties

C 6.1.1 FEP # 4.1.1 Stratigraphy

Description

The succession and spatial extent of the rocks that form the geosphere.

Typically, rocks are divided into specified rock formations with similar properties and characteristics. These various geological formations help to isolate the Facility from the surface environment. Consideration needs to be given to the vertical thickness and horizontal extent of each rock formation.

Screening Analysis

The most recent detailed description of the geology and stratigraphy of the site is provided in the Arcadis *& Geofirma* (2022) *Geosynthesis Report*. A brief summary of notable points is included below.

The NPDDF site is located on the northeast-facing slope of a former glacial and current fluvial spillway of the Ottawa River. Overburden thickness at the NPD site ranges from about 2 m near the Ottawa River up to about 15-18 m southwest of the NPDDF and thinning to 5 to 7 m near Highway 17. Overburden thickness adjacent to the NPDDF building averages 5 to 6 m. Based on available information, five hydrostratigraphic units have been identified at the NPDDF site (Arcadis & Geofirma, 2022):

- Sand and gravel fill unit;
- Fluvial sand and gravel unit;
- Silt to cobble glacial till unit;
- Boulder glacial till unit; and,
- Shallow bedrock unit.

Overall, bedrock at and in the local and regional area of the NPD site is Precambrian Canadian Shield. Local bedrock geology in the vicinity of the NPDDF site is mapped by OGS as layered biotite gneisses and migmatites of uncertain protolith with minor amphibolite mafic gneiss. Mapping of bedrock outcrops from on-site field measurements identify NPD bedrock geology as interlayered granitic to monzonitic gneiss and biotite hornblende (Arcadis & Geofirma, 2022).

The NPDDF sits in both the overburden and bedrock. The relevant material properties of the undisturbed host rock must be adequately characterized in the safety assessment as these properties may play an important role in determining where surface water infiltrates into the geological system, and where deep groundwaters eventually discharge. Factors such as sorption coefficients are also associated with the geological characteristics.

Screening Decision

All post-closure scenarios.

C 6.1.2 FEP # 4.1.2 Large-scale Discontinuities

Description

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.

Some of these features might form preferential groundwater flow and contaminant migration pathways, reducing the effectiveness of some portion of the geosphere (as a barrier) or focusing contaminant releases into the biosphere at particular discharge locations. However, some large-scale discontinuities can also result in reduced conductivity and contaminant migration.

Screening Analysis

Earlier drilling work performed by Hydro-Electric Power Commission of Ontario (1956) and summarized by Canadian General Electric Company Ltd., (1962) interpreted the potential for a large 90m-wide shear zone to exist. So, this was a topic of particular attention in the Arcadis & Geofirma (2022) *Geosynthesis Report* and its supporting on-site field studies. The Arcadis & Geofirma (2022) Geosynthesis Report determined that:

- Historic photographs taken during the original excavation and construction of the facility do not show the presence of such a shear zone.
- On-site field investigations into the shallow bedrock (performed in 2019) show no evidence of such a shear zone or similar major structural feature in the vicinity of the study.
- Lineament analysis found no evidence of such a shear zone.

Based on information from the recent 2019 field investigations and Arcadis & Geofirma (2022) *Geosynthesis Report*, the presence of a large-scale discontinuity feature (such as a shear zone or similar feature) is not credible. However, the impact of the increased hydraulic conductivity (and thus flow) in bedrock is considered in a sensitivity case, and the undetected fracture zone is considered in a “What If” case.

Screening Decision

Sensitivity (Geosphere Bedrock Hydraulic Conductivity), What If (Undetected Fracture Zone).

C 6.1.3 FEP # 4.1.3 Geological Resources

Description

The resources within the geosphere, particularly those that might encourage investigation or excavation at or near the Facility site.

Typically, geological resources will include natural resources such as oil, gas, solid minerals, water and geothermal resources. Can also include the presence of suitable rocks for the storage of gases by humans for subsequent use (e.g., natural gas) or sequestration (e.g., carbon dioxide). The presence of geological resources in the vicinity of the Facility will increase the probability of disruptive human actions (FEP 1.4.5 and 1.4.6) that might compromise the isolation of the Facility. Some resources (e.g., gas, water and geothermal resources) might affect the migration of contaminants through the geosphere (see FEP 4.3).

Screening Analysis

There is only a small amount of mining and quarrying in the whole of Renfrew County. There are no known mineral occurrences of economic significance on the property and there is no significant mineral potential on the site (AECL, 1996). A more recent review of mining and mineral records was performed in Arcadis & Geofirma (2022), which identified the following:

- Two (2) former aggregate pit records were found within the NPD site (related to the construction of the facility), though these pits are no longer operational today.

- One (1) record for an active mining claim (for gneiss and granite building stone) was identified, located 12 km west of the NPDDF site near Mackey.
- One (1) record of a past mine without reserves was identified near the Mackey area (silica sand and feldspar); and,
- Two (2) records of discretionary mineral occurrences (anorthosite and graphite) were identified in the region, located 13 km southwest and 28 km southeast, respectively of the NPDDF site.

Aside from mines, Arcadis & Geofirma (2022) did identify records for a group of aggregate pits/quarries, the closest of which is located approximately 10 km south of the facility. At the NPDDF site however, overburden materials may be inappropriate for extraction (at least at depth) as the pebbles and cobbles are reportedly larger in diameter than would typically be preferred for commercial uses (see FEP 1.4.6).

Nevertheless, because overburden aggregate pits do exist in the region, the potential for overburden removal can be considered - the consequences of which are similar to those that would occur if it were removed by a natural event like a severe flood (see FEP 1.4.9) and so the unlikely event of aggregate removal can be considered to be a What If case.

Screening Decision

Disruptive Events – Site Investigation (Inadvertent Human Intrusion), Excavation of Above-Bedrock Facility, and What If (Facility Mass Excavation).

C 6.1.4 FEP # 4.1.4 Undetected Features

Description

The natural or man-made features within the geosphere that may not be detected during the site investigation (e.g., fracture zones, faults, brine pockets, old mine workings and boreholes).

These features could play a role in the transport of groundwater to and from the Facility and the associated migration of contaminants. Some physical features of the geological environment may remain undetected during site surveys and even during pilot tunnel excavations. The nature of the geological environment will indicate the likelihood that certain types of undetected features may be present and the site investigation may be able to place bounds on the maximum size or minimum proximity to such features.

Screening Analysis

The construction of the site involved extensive reworking of the ground (Titterington, 2016). As such, the properties and condition of the ground in which the NPDDF sits can be considered to be relatively well known. The excavation into the bedrock would have revealed any features relevant to flow in the vicinity of the NPDDF, while the removal then replacement of the overburden will result in a relatively homogeneous medium. On this basis, the probability of significant undetected features is extremely low.

Furthermore, earlier drilling work performed by Hydro-Electric Power Commission of Ontario (1956) and summarized by Canadian General Electric Company Ltd., (1962) interpreted the potential for a large 90m-

wide shear zone to exist. So, identification of any such potential features was a topic of particular attention in the Arcadis & Geofirma (2022) *Geosynthesis Report* and its supporting on-site field studies. The Arcadis & Geofirma (2022) *Geosynthesis Report* determined that:

- Historic photographs taken during the original excavation and construction of the facility do not show the presence of such a shear zone or similar large feature.
- On-site field investigations into the shallow bedrock (performed in 2019) show no evidence of such a shear zone or similar major structural feature in the vicinity of the study.
- Lineament analysis found no evidence of such a shear zone.

Based on information from the excavation and construction of the facility, from the recent 2019 field investigations, and from the interpretations in the Arcadis & Geofirma (2022) *Geosynthesis Report*, the presence of an undetected large-scale feature (such as a shear zone or similar feature) is not credible. However, the impact of increased hydraulic conductivity (and thus flow) in bedrock is considered in a sensitivity case by using a bedrock conductivity one order of magnitude greater (from Arcadis & Geofirma (2022) Geosynthesis Report and Arcadis & Geofirma (2023a) Groundwater Modelling Report) than that identified in the calibrated model. Similarly, the impact of the undetected fracture zone is considered in a "What If" case, by applying the higher conductivity to the entire bedrock downgradient of the facility, which represents a very highly weathered and/or fractured bedrock zone.

Screening Decision

Sensitivity (Geosphere Bedrock Hydraulic Conductivity), What If (Undetected Fracture Zone).

C 6.1.5 FEP # 4.1.5 Geothermal Characteristics and Properties

Description

The geothermal characteristics and properties of the geosphere prior to Facility construction.

Consideration needs to be given to geothermal characteristics and properties such as the thermal conductivity and heat capacity of the various rock formations.

Screening Analysis

There is no geothermal activity in the vicinity of the site. The ground surface (down to a depth of perhaps several metres at most) will respond to annual temperature variation, for example it may remain frozen for a period through winter. This will influence recharge and could potentially involve some freeze-thaw effects. However, on the timescales of relevance to postclosure safety assessment such variations need not be explicitly represented.

Screening Decision

Screen Out.

C 6.1.6 FEP # 4.1.6 Hydraulic Characteristics and Properties

Description

The hydraulic and hydrogeological characteristics and properties of the geosphere prior to Facility construction.

Consideration needs to be given to hydraulic characteristics and properties such as the hydraulic conductivity, fracture frequency and connectivity, porosity, tortuosity and pore water pressure of the various rock formations.

Screening Analysis

The hydraulic processes in the geosphere provide a key mechanism for the transport of radionuclides from the NPDDF to the accessible environment. A synthesis of geologic and hydrogeologic information - integrating regional data along with recent on-site measurements - is provided in the Arcadis & Geofirma (2022) *Geosynthesis Report*. Groundwater flow modelling is described in the Arcadis & Geofirma (2023a and 2023b). Groundwater flow modelling (Arcadis & Geofirma, 2023a,b) is based on the information in the Geosynthesis Report (Arcadis & Geofirma, 2022).

Screening Decision

All post-closure scenarios, Sensitivity (Geosphere Overburden Hydraulic Conductivity), Sensitivity (Geosphere Bedrock Hydraulic Conductivity).

C 6.1.7 FEP # 4.1.7 Mechanical Characteristics and Properties

Description

The mechanical characteristics and properties of the geosphere prior to Facility construction.

Consideration needs to be given to mechanical characteristics and properties such as the stress regime and compressive and shear strength of the various rock formations.

Screening Analysis

The mechanical properties of the geosphere are not important in terms of the stability of the Facility, as the excavation is demonstrably stable and the Facility sits within it. Mechanical properties might be relevant in response to a significant seismic event, in which they would determine the extent to which ground acceleration is transmitted to the NPDDF structure and thus whether it could degrade the engineering. In this respect, the FEP is related to FEP 1.2.4 and the Disruptive Event scenarios Degradation of Engineered Barriers. See also discussion for FEP 1.2.4 regarding response to seismic events.

CNL's updated (2021a) *NPD Underground Structure Seismic Assessment* report selected and examined the effects of a 1-in-2250 y event, a 1-in-10,000 years event, and a 1-in-50,000 y event, on the NPDDF. For a 1-in-2250-y event, results of CNL (2021a) indicate that the facility will experience cracking in the above-

bedrock portion of the facility (particularly at the interface between the above-bedrock and below-bedrock portions of the facility), but no cracking in the below-bedrock portion of the facility. For a 1-in-10,000-y event, results of CNL (2021a) again indicate that the above-bedrock portion of the facility will experience more extensive cracking while the below-bedrock portion of the facility will not. Results of CNL (2021a) are again similar for the 1-in-50,000-y event, where the portion of the facility above-bedrock will experience significant cracking while the below-bedrock portion of the facility will not. The reader is referred to the original CNL (2021a) assessment for further information on the selection, definition, and assessment of seismic events and their impacts on the facility.

The preliminary slope stability assessment (Arcadis & Geofirma, 2021) that considers earthquake-induced soil liquefaction, shows that the North Slope under current water level conditions is stable under static loading conditions and under loading conditions associated with a 1:2,250-y earthquake. Parts of the North Slope are stable, while some parts of the North Slope are unstable under a 1:10,000-y earthquake. The North Slope is likely to fail during a 1:50,000-y earthquake. It is unlikely that the predicted failures of the North Slope will result in the direct exposure of groundwater to a new ground surface that would be established following earthquake induced slope failures. Slope failures at the North Slope are expected to result in accumulations of failed granular materials on the lower half of the North Slope. Given the permeable nature of all soils that comprise the North Slope, the expected redistribution of soils following slope failure is unlikely to change groundwater flows from the NPDDF to the Ottawa River. For more details, the reader is referred to the preliminary slope stability assessment (Arcadis & Geofirma, 2021).

Screening Decision

All post-closure scenarios, except Disruptive Event – Site Investigation (Inadvertent Human Intrusion), and What If (Facility Mass Excavation).

C 6.1.8 FEP # 4.1.8 Geochemical Characteristics and Properties

Description

The geochemical characteristics and properties of the geosphere prior to Facility construction.

Consideration needs to be given to geochemical characteristics and properties such as pH and Eh conditions, rock mineral composition, groundwater composition, salinity and chemical gradients.

Screening Analysis

The hydrogeochemical regime at the present day will influence the chemical composition of groundwater contacting the wastes and hence the rate of waste degradation together with the rate at which radionuclides are leached from the waste and transported through the near field and geosphere. Most notably, the geochemistry will influence the sorption of contaminants and thus their transport velocity in the geosphere. This is a key factor to represent in the postclosure safety assessment. A hydrogeochemical analysis of the potential evolution of an alkaline plume in the vicinity of the Facility has shown that it is unlikely that highly alkaline porewater arising from bulk grout leaching will lead to a significant elevation in pH downstream from the facility (Arcadis & Quintessa, 2020b).

Screening Decision

All post-closure scenarios.

C 6.1.9 FEP # 4.1.9 Biological Characteristics and Properties

Description

The biological characteristics and properties of the geosphere prior to Facility construction.

Consideration needs to be given to biological characteristics and properties such as the extent and composition of microbe populations.

Screening Analysis

Microbial populations may be present in the geosphere (for example at the bedrock-overburden interface) there will not be a substantial organic component at depth and thus the chemical conditions will be controlled primarily by inorganic processes.

Screening Decision

Screen Out.

C 6.2 Geosphere Processes

The processes occurring within the geosphere resulting in its evolution.

The primary focus is on processes occurring after Facility closure but consideration is also required of processes occurring pre-closure, i.e. during Facility construction and operation. The pre-closure phase of a Facility is likely to influence properties of the geosphere relevant to its long-term safety such as the geothermal, hydraulic, stress and geochemical conditions in the rocks in the vicinity of the Facility.

The coupled nature of certain processes will need to be taken into account, as will the impact of key waste form, waste packaging and Facility features (FEPs 2.1, 2.2 and 3.1) and their associated processes (FEPs 2.3 and 3.2). Processes relating to the migration of contaminants through the geosphere are considered under FEP 4.3.

There are 6 subcategories under Geosphere Processes:

4.2.1 Thermal processes [geosphere]
4.2.2 Hydraulic processes [geosphere]
4.2.3 Mechanical processes [geosphere]
4.2.4 Chemical processes [geosphere]
4.2.5 Biological processes [geosphere]
4.2.6 Radiological processes [geosphere]

C 6.2.1 FEP # 4.2.1 Thermal Processes [Geosphere]

Description

The thermal processes that affect the host rock and other rock units, and the overall thermal evolution of the geosphere.

Consideration needs to be given to the distribution of heat in the geosphere by conduction and transport (convection) in fluids, and the resulting thermal field or gradient. The thermal evolution of the geosphere will be affected by its thermal characteristics. Changes in thermal conditions in the geosphere due to the impact of the Facility and its wastes (FEPs 3.2.1 and 2.3.1) and glacial/inter-glacial cycling (FEP 1.3.5) need to be considered, together with the impact of any geosphere heat sources (e.g., Magmatic and volcanic activity (FEP 1.2.5) and Hydrothermal activity (FEP 1.2.7)).

The temperature and associated gradients could have a number of effects, such as causing changes in fluid densities and viscosities, which in turn could affect the movement of fluids through the geosphere.

Screening Analysis

As the wastes are not significantly heat generating and the Facility is located at a shallow depth below the surface, changes in temperature are likely to be limited to the response to annual variations in surface temperature at the site while the current climatic conditions persist. As noted previously, freeze-thaw cycling could degrade engineered materials at the surface (e.g., cap) but this can be subsumed into an overall degradation rate and represented as part of the Normal Evolution of the Facility.

Changes in temperature at depth could occur during periglacial and glacial conditions (FEP 1.3.5), with the main effect being due to the development of frozen ground and potentially taliks. However, glacial conditions are not credible within the 10,000 y assessment timeframe (see discussion under FEP 1.3.5).

Screening Decision

Normal Evolution.

C 6.2.2 FEP # 4.2.2 Hydraulic Processes [Geosphere]

Description

The hydraulic/hydrogeological processes that affect the host rock and other rock units, and the overall hydraulic/hydrogeological evolution of the geosphere.

This includes the effects of hydraulic changes arising from the Facility (e.g., the potential dewatering of the rock immediately surrounding the Facility and the modification of groundwater flow directions) (FEP 3.2.2), the geosphere (e.g., seismicity (FEP 1.2.4) and regional erosion and sedimentation (FEP 1.2.8) that can cause changes in flow pathways, permeabilities and head distributions) and the biosphere (e.g. glacial/inter-glacial cycling that might result in ice sheet advance/retreat over the site impacting groundwater recharge and hydraulic gradients (FEP 1.3.5)).

In addition, consideration needs to be given to movement of water through the geological units and the factors that control the movement including recharge and discharge zones, groundwater flow systems, density effects due to salinity gradients or temperature gradients.

Screening Analysis

Hydraulic processes in the geosphere surrounding the NPDDF provide the main mechanism for the transport of contaminants from the Facility. Upon closure, the Facility will gradually resaturate via inflows of groundwater through the Facility walls. Once this process is complete (it may take decades or more) the hydrogeology will reach a steady state until the engineered materials degrade sufficiently to permit flow through them. Hydraulic processes in the geosphere, principally advection and dispersion, are therefore an essential component of the representation of the Facility.

Screening Decision

All post-closure scenarios.

C 6.2.3 FEP # 4.2.3 Mechanical Processes [Geosphere]

Description

The mechanical processes that affect the host rock and other rock units, and the overall mechanical evolution of the geosphere.

This includes the effects of changes in rock stress and rock mass strength due to the excavation, construction and long-term presence of the Facility (FEP 3.2.3). For example, if the Facility gas pressure approaches lithostatic pressure, the pressure can cause physical damage to geosphere and allow the movement of gas as a discrete phase within stress- or pressure-induced microscopic porosity. The geosphere can also be affected by the collapse/creep of rocks into Facility openings or Facility gas explosions.

Other factors originating in the geosphere or biosphere such as tectonic movement (FEP 1.2.1), deformation (elastic, plastic, or brittle) (FEP 1.2.3), ice sheet advance/retreat over the site (FEP 1.3.5), and mining and other underground activities (FEP 1.4.6) can also impact the mechanical evolution of the geosphere.

Screening Analysis

The rock is demonstrably stable upon excavation and can be considered to be in an equilibrium state with the engineered Facility and overburden. There are not expected to be any ongoing mechanical processes that require representation in the geosphere modelling for the postclosure safety assessment.

Under external conditions (e.g., seismic, glaciation) the mechanical properties of the geosphere will become important. In relation to an earthquake, mechanical processes in the rock (specifically the bedrock) will transport the energy into the Facility, degrading the structure. Further discussion of the effects of a seismic event are available under FEP# 1.2.4.

Similarly, the compressional, then expansive, forces applied by the advance/retreat of a glacier would be important to consider. However, glaciation is not credible within the 10,000 y assessment timeframe (see discussion under FEP# 1.3.5).

Screening Decision

Normal Evolution, Disruptive Events – Extreme Degradation, Fault Zone Activation.

C 6.2.4 FEP # 4.2.4 Chemical Processes [Geosphere]

Description

The geochemical processes that affect the host rock and other rock units, and the overall geochemical evolution of the geosphere.

This includes the effects of changes in geochemical conditions (e.g., Eh and pH) due to the excavation, construction and long-term presence of the Facility. For example, the use of cement in the Facility (e.g., in waste packages, backfill and construction) can result in the development of an alkaline plume in the vicinity of the Facility. Other factors such as ice sheet advance/retreat over the site (FEP 1.3.5) can also impact geochemical conditions in the geosphere by introducing meltwater with different compositional and thermal properties into the geosphere.

Other potentially important geochemical processes affecting the geosphere include the migration of chemical species, the alteration of chemical species by processes such as dissolution, leaching and carbonation, and the precipitation of chemical species.

Screening Analysis

A variety of chemical processes will occur in the geological environment. The key ones from the perspective of the postclosure safety analysis are those that affect radionuclide mobility. In this respect, a variety of processes are usually aggregated as the empirical measure of sorption (partitioning between solid and liquid). Sorption is dependent on the substrate and geochemistry. Aspects that will control sorption processes at the NPDDF site are therefore the geology and geochemistry. In respect of the latter, the large volume of cementitious materials in the NPDDF may result in increasing the pH downstream of the Facility.

Screening Decision

All post-closure scenarios, except Disruptive Event – Site Investigation (Inadvertent Human Intrusion), and What If (Facility Mass Excavation).

C 6.2.5 FEP # 4.2.5 Biological Processes [Geosphere]

Description

The biological/biochemical processes that affect the host rock and other rock units, and the overall biological/biochemical evolution of the geosphere.

This includes the effects of changes in conditions, e.g. on microbe populations, due to the excavation, construction and long-term presence of the Facility.

Screening Analysis

The biological characteristics of the geosphere (FEP 4.1.9) are such that biological and biogeochemical processes will not have a significant effect on the postclosure evolution of the Facility and its environment. On this basis, they are screened out due to insignificant consequences.

Screening Decision

Screen Out.

C 6.2.6 FEP # 4.2.6 Radiological Processes [Geosphere]

Description

The effects of radiation emitted from the Facility on the host rock immediately surrounding Facility, and the overall radiogenic evolution of the geosphere.

Any radiolysis impacts are expected to be limited to the rock immediately surrounding the Facility and there is unlikely to be a sufficient concentration and localized mass (critical mass) of fissile isotopes to cause criticality. Nevertheless, there will be radioactive decay and ingrowth of radionuclides in the geosphere. In postclosure assessment, radioactive decay chains are often simplified, e.g. by neglecting the shorter-lived radionuclides in geosphere migration calculations. Furthermore, the decay of waste-derived and/or naturally-occurring uranium, thorium and radium results in the production of radon gas.

Screening Analysis

Processes associated with the ionizing emissions of radionuclides (e.g., radiolysis, radiation damage) will not be of any significance in the geosphere as radionuclide concentrations will be well below those in the Facility itself and thus insufficient for any tangible effects to occur. Physical processes associated with radionuclides, such as radioactive decay and ingrowth, will however occur, and require representation in the safety analysis.

Screening Decision

All post-closure scenarios.

C 6.3 Contaminant Migration [Geosphere]

The processes that directly affect the migration of contaminants in the geosphere.

There are 4 subcategories under Contaminant Migration [geosphere]:

4.3.1 Water-mediated migration [geosphere]
4.3.2 Gas-mediated migration [geosphere]
4.3.3 Solid-mediated migration [geosphere]
4.3.4 Human-action-mediated migration [geosphere]

C 6.3.1 FEP # 4.3.1 Water-mediated Migration [Geosphere]

Description

The processes related to migration of contaminants within the geosphere in the aqueous phase (including dissolved gases).

The following more specific factors are discussed under separate entries:

4.3.1.1 Advection [geosphere]
4.3.1.2 Dispersion [geosphere]
4.3.1.3 Diffusion [geosphere]
4.3.1.4 Matrix diffusion
4.3.1.5 Dissolution, precipitation, and crystallization [geosphere]
4.3.1.6 Speciation and solubility [geosphere]
4.3.1.7 Sorption and desorption [geosphere]
4.3.1.8 Colloid transport [geosphere]

C 6.3.1.1 FEP # 4.3.1.1 Advection [Geosphere]

Description

The migration of dissolved contaminants by the flow of the water through the geosphere.

The rate of advection will vary depending on hydraulic, thermal and density conditions in the geosphere and Facility. Fluid flow driven by temperature, chemical or electrical gradients, rather than due to hydraulic pressure gradients is called thermal, chemical or electrical osmosis depending on the driving gradient.

Screening Analysis

Advection occurs where a sufficiently permeable medium connects a region of higher hydraulic head to lower head. The advective velocity is determined by the hydraulic conductivity and the head gradient. Within the NPDDF system the main advective region is the overburden where a relatively permeable medium overlies the basement rock and conducts groundwater from higher ground to the Ottawa River. The NPDDF lies partially in this region. There are historic engineered features of higher permeability that act to channel the flow around the NPDDF.

In the underlying bedrock, the hydraulic conditions are such that rates of advection will be much lower and will be orientated upwards from regions of higher head at depth.

The hydraulic conductivity, and thus flow, in the bedrock is many orders of magnitude lower than in the overburden, so its contribution to flows of potentially contaminated water from the NPDDF will be insignificant. Furthermore, the flow direction in the bedrock will only serve to direct any contaminated groundwater directly to the overburden. For this reason, it is not considered necessary to represent the bedrock explicitly, but rather to focus on the flows in the overburden.

Screening Decision

All post-closure scenarios.

C 6.3.1.2 FEP # 4.3.1.2 Dispersion [Geosphere]

Description

The spread in the spatial distribution of contaminants with time in the geosphere because of differential rates of advective transport through the geosphere.

Variations in water velocity and pathways cause dispersion, i.e., the spatial spreading of contaminants from advective transport. Dispersion can occur in the direction of flow (longitudinal dispersion) and perpendicular to the direction of flow (transverse dispersion).

Screening Analysis

Dispersion arises from the spatial variability of media and resulting differences in transit time between two points due to the range of available pathways. Dispersion is therefore a feature of all media in which advective transport occurs. The significance of dispersion is that it acts to broaden out in time the release of contaminants at a downstream receptor, therefore resulting in both a distribution in time and also a decrease in the peak concentrations. Dispersion is therefore a feature relevant to the normal evolution of the Facility.

Screening Decision

All post-closure scenarios.

C 6.3.1.3 FEP # 4.3.1.3 Diffusion [Geosphere]

Description

The diffusion of contaminants through the geosphere.

Diffusive migration is driven by chemical potential gradients, can be affected by thermal gradients, and can thus be in any direction. Diffusion can be the most important migration mechanisms in situations where groundwater flow in the geosphere is very slow.

Screening Analysis

The phenomenon of diffusion occurs in all fluids where there is a concentration gradient. In groundwater, it is often dominated by advection, however. While it is likely to be relevant (at least for a period) within the Facility, the hydraulic conductivity of the geological materials is expected to be such that advection always dominates diffusion.

Screening Decision

Screen Out.

C 6.3.1.4 FEP # 4.3.1.4 Matrix Diffusion [Geosphere]

Description

The diffusion of contaminants laterally between a flowing fracture and the network of microfractures and micropores within the rock matrix.

Occurs in geospheres with fracture flow systems and can operate into/from the rock matrix depending upon the direction of the chemical gradient.

Screening Analysis

Matrix diffusion is a process that is relevant where flow is primarily via fractures. Although the bedrock is fractured, for the purposes of the postclosure safety assessment it can readily be represented as an equivalent porous medium. As such, matrix diffusion, as a process, is not necessary to represent as it will not have significant consequence in the overall description of contaminant transport.

Screening Decision

Screen Out.

C 6.3.1.5 FEP # 4.3.1.5 Dissolution, Precipitation, and crystallization [Geosphere]

Description

The dissolution, precipitation and crystallization of contaminants in the geosphere under prevailing geosphere conditions.

Dissolution is the process by which constituents of a solid or gas dissolve into solution and can migrate through the geosphere. Dissolution is controlled by changes in pressure, temperature and gas concentrations in the geosphere.

Precipitation and crystallization are processes by which solids are formed out of liquids and are controlled by changes in pressure, temperature and concentrations of chemical species. Precipitation occurs when chemical species in solution react to produce a solid that does not remain in solution. Crystallization is the process of producing pure crystals of an element, molecule or mineral from a fluid or solution undergoing a cooling process.

Screening Analysis

The geochemical environment within the region of interest is such that there are unlikely to be marked regions of change in environmental conditions that could lead to dissolution, precipitation and/or crystallization. The only potential region of interest could be the region of transition from high pH conditions (within the cemented NPDDF) to the background geochemical conditions occurring in the geosphere. While this may affect the mobility of radionuclides, it is not expected to be sufficiently demarcated to lead to any of the abovementioned processes. Furthermore, the contaminants of interest are present in low concentrations.

Screening Decision

Screen Out.

C 6.3.1.6 FEP # 4.3.1.6 Speciation and Solubility [Geosphere]

Description

The chemical speciation and solubility processes affecting the migration of contaminants through the geosphere under prevailing geosphere conditions.

The concentration of an element in aqueous solution (at equilibrium) reflects the solubility of the solid compounds which contain the element. Factors such as temperature, gas partial pressure, ionic strength, the presence of complexing agents and pH and Eh conditions affect solubility. These factors affect the chemical form and speciation of the element. Thus, different solids of the same element may have different solubilities in a particular solution.

Screening Analysis

The majority of radionuclides in the geosphere will be present at very low concentrations and as such solubility will not be a factor that constrains their migration. For radioisotopes of an element that is naturally abundant in the geology and which is subject to solubility limitation, there may be some effects. In addition, where elemental solubility is strongly dependent on the pH the difference between porewater in the NPDDF and the surrounding geosphere might mean that solubility limitation occurs at the transition to near neutral conditions in the geosphere. Arcadis & Quintessa (2020a) indicates this may be the case for lead.

Screening Decision

All post-closure scenarios.

C 6.3.1.7 FEP # 4.3.1.7 Sorption and Desorption [Geosphere]

Description

The sorption/desorption processes affecting the migration of contaminants through the geosphere under prevailing geosphere conditions.

Sorption describes the physical-chemical interaction where dissolved species adhere to a solid phase. Desorption is the opposite. Two sorption-desorption processes are commonly considered: ion-exchange processes involving an electrostatic or ionic attraction between charged dissolved species and oppositely charged surfaces; and chemisorption involving the formation of a chemical bond. Neutral species and (usually) anions are generally not strongly sorbed.

Screening Analysis

Sorption represents an intrinsic feature of aqueous contaminant transport and as such must be represented in the postclosure safety assessment. Sorption varies with material and geochemical conditions, and it will be necessary to represent differing degrees of sorption in the safety analysis.

Reduced sorption in overburden and bedrock are examined in sensitivity analyses.

Screening Decision

All post-closure scenarios, Sensitivity (Reduced Far-Field Sorption).

C 6.3.1.8 FEP # 4.3.1.8 Colloid Transport [Geosphere]

Description

The transport of colloids and interaction of contaminants with colloids migrating through the geosphere under prevailing geosphere conditions.

Colloids (particles with diameters typically less than 10 µm) may influence contaminant migration in a variety of ways: retarding migration by sorption of aqueous radionuclide species and subsequent filtration; or, enhancing migration by sorption and migration with flowing groundwater. Sources can include materials in the waste package (e.g., organic wastes), the Facility (e.g., bentonite and cementitious materials) and the geosphere (e.g. naturally occurring organics).

Screening Analysis

The presence of colloidal material is unclear at present. While the relatively permeable overburden may permit colloids to move in groundwater without filtering them significantly there is not known to be a significant organic source except for the thin layer of surface soil. Colloidal transport in the bedrock is less likely. Furthermore, the migration of contaminants with colloids is unlikely to be a significant process anyway, as transport through the geosphere is expected to be rapid for all radionuclides, compared with the containment offered by the Facility. It is normally within the geosphere that colloidal transport is considered to be a factor of potential interest, but the analysis of performance of the NPDDF indicates that the geosphere is not a significant barrier. Although colloids could potentially penetrate some low porosity spaces, their transport is retarded - experiments have shown that even colloids that were deliberately introduced into rock fractures have shown no breakthrough at observation points although other tracers have reached the observation points in the expected time scales, indicating that colloid transport through fractured media acted more as a filter than a conduit for colloids (Vandergraaf *et al.*, 2011).

Finally, examining uncertainties in sorption coefficients will provide a perspective on the implications of more rapid transport for sorbed radionuclides. Colloidal transport is often modelled by applying a modifying factor to the retardation equation used in advective transport, and the planned approach for exploring sensitivity to Kd values will adopt essentially the same approach, with a “sensitivity factor” being applied to the Kd values. In this way, the results of the analysis can reasonably be assumed to capture the potential consequences of colloidal transport. On this basis, colloidal transport is not considered to be significant.

Screening Decision

Screen Out.

C 6.3.2 FEP # 4.3.2 Gas-mediated Migration [Geosphere]

Description

The migration of contaminants in gas or vapour phase or as fine particulate or aerosol in gas or vapour through the geosphere.

Gases may be generated from the wastes and Facility materials (FEP 3.2.4.4) or might be naturally present in the geosphere (FEP 4.1.3). Aerosols or particulates may be transported along with non-radioactive gases, or gases may expel contaminated water ahead of them. Furthermore, gases might volatilize out of groundwater due to chemical and biochemical processes occurring in the geosphere. The rate of volatilization is controlled by changes in pressure, temperature and concentration of volatiles in the geosphere.

Screening Analysis

There are no significant sources of gas in the NPDDF (see FEP 2.4.2) or the geosphere itself, therefore the FEP is screened out on the basis of having no consequence.

Screening Decision

Screen Out.

C 6.3.3 FEP # 4.3.3 Solid-mediated Migration [Geosphere]

Description

The migration of contaminants in solid phase in the geosphere.

This might result from processes such as the fluvial erosion of the geosphere (FEP 1.2.8), the glacial erosion of the geosphere (FEP 1.3.5) or magmatic/volcanic activity affecting the geosphere (FEP 1.2.5). Human action mediated migration [geosphere] is handled under FEP 4.3.4.

Screening Analysis

The movement of solids is not expected to occur as a continuous process as there are no drivers for any significant erosion or sedimentation. However, some events could result in movement of contaminated materials with solids, including: erosion as a result of a catastrophic flood, glacial erosion and mass excavation. Glacial erosion is not credible within the 10,000-y assessment timeframe (see discussion under FEP 1.3.5). Erosion from a catastrophic flood or from mass excavation are not represented within the normal evolution scenario as they are not certain to occur, but are represented as Disruptive Events and a What If scenario.

Screening Decision

Disruptive Events – Surface Erosion, Excavation of Above-Bedrock Facility, and What If (Facility Mass Excavation).

C 6.3.4 FEP # 4.3.4 Human-action-mediated Migration [Geosphere]

Description

The migration of contaminants from the geosphere as a direct result of human actions.

This might result from processes such as drilling into or excavation of the geosphere (FEPs 1.4.5 and 1.4.6) and might result in the migration of contaminants directly from the geosphere into the biosphere.

Screening Analysis

Excavation to the base of the overburden could result in moving contaminants to the surface. Various activities could be envisaged, with the most likely being excavation of aggregates of the excavation of a shallow well. The former would result in the contaminants becoming mixed with large volumes of uncontaminated material and is thus not of consequence. The latter could be more localized and is associated with an identified Disruptive Event scenario (FEP 1.4.9).

Screening Decision

Disruptive Events – Site Investigation (Inadvertent Human Intrusion), Excavation of Above-Bedrock Facility, Overburden Well, Bedrock Well, and What If (Facility Mass Excavation).

C 7 BIOSPHERE FACTORS

The factors related to the biosphere (the surface environment, humans and non-human biota) and the associated migration of contaminants.

Includes the geosphere-biosphere interface such as water abstraction wells, near-surface aquifers, and unconsolidated sediments, and groundwater discharge zones.

The four subcategories under Biosphere Factors are:

5.1 Surface Environment
5.2 Human Characteristics and Behaviour
5.3 Contaminant Migration [biosphere]
5.4 Exposure Factors

C 7.1 Surface Environment

The features and processes within the surface environment and their potential future evolution.

There are 14 subcategories under Surface Environment:

5.1.1 Topography and morphology
5.1.2 Biomes
5.1.3 Soil and sediment
5.1.4 Near-surface aquifers and water-bearing features
5.1.5 Terrestrial surface water bodies
5.1.6 Coastal features
5.1.7 Marine features
5.1.8 Atmosphere
5.1.9 Vegetation
5.1.10 Animals
5.1.11 Climate and weather
5.1.12 Hydrological regime and water balance (near-surface)
5.1.13 Erosion and deposition
5.1.14 Ecological/biological/microbial systems

C 7.1.1 FEP # 5.1.1 Topography and Morphology

Description

The relief and shape of the surface environment and the processes affecting its potential evolution.

Topography defines surface water flows, the location of groundwater recharge and discharge locations, and the magnitude of hydraulic heads that drive local and regional groundwater flows.

Changes covered within this category are limited to short-term processes, such as wind erosion and river meandering that could occur over a few centuries. Changes resulting from processes acting on a geologic timescale, such as mountain building, are described under FEP 1.2 (Geological Factors). Other changes resulting from evolution of the climate (such as denudation and deposition from ice sheets) and human actions are discussed under FEP 1.3 (Climatic Factors) and FEP 1.4 (Future Human Actions).

Screening Analysis

The site is situated on the Ottawa River, at an elevation of approximately 125 mASL (above sea level). The site is situated on a regionally relatively flat area, dipping from a topographic high beginning on the north side of Tee Lake (approximately 225 mASL), to highway 17, which has an approximate elevation of 160 mASL, continuing to the Ottawa River, which has an average elevation of 111 mASL (MacLarentech, 1990). The surrounding terrain, except for the Laurentian Hills directly north and east across the river, consists of gently rolling hills, interspaced with many small lakes. The Ottawa River flows northwest to southeast (Seto, 2015).

For the purposes of the postclosure safety assessment, the local topography requires representation as it has implications for land use, groundwater flow, etc.

Screening Decision

All post-closure scenarios.

C 7.1.2 FEP # 5.1.2 Biomes

Description

The mixed community of animals and plants (a biotic community) occupying a major geographical area on a continental scale and the processes affecting their potential evolution.

Each biome is characterized by similarity of vegetation structure or physiognomy rather than by similarity of species composition, and is usually related to climate. Within a particular biome, the animals and plants are regarded as being well adapted to each other and to broadly similar environmental conditions, especially climate.

Important factors influencing biome classification include temperature, precipitation, latitude and altitude. Anthropogenic activities may also influence the classification.

Screening Analysis

The safety assessment addresses effects on Valued Ecosystem Components that represent the environment at the site. It will therefore focus on specific, representative species of importance rather than complete ecosystems.

Screening Decision

Screen Out – Out of Scope.

C 7.1.3 FEP # 5.1.3 Soil and Sediment

Description

The characteristics of the soils and sediments that overlie the rock of the geosphere and the processes affecting their potential evolution.

The properties (including existence) of soil and sediment will evolve because of natural weathering processes (including hydration and dehydration, freeze-thaw cycles, dissolution and leaching, oxidation, acid hydrolysis and complexation), erosion (wind and water), and anthropogenic management practices (e.g. deforestation and dredging).

The following more specific factors are discussed under separate entries:

5.1.3.1 Surface soils
5.1.3.2 Overburden
5.1.3.3 Aquatic sediments

The first two categories involve terrestrial soils found on the surface and at depth. The third category involves aquatic sediments found at the bottom of surface water bodies such as lakes and rivers.

C 7.1.3.1 FEP # 5.1.3.1 Surface Soils

Description

The soils that are within a few metres of the land surface and typically underlain by unconsolidated overburden.

The soil type, such as loam, sand, clay and organic, can be characterized by parameters such as particle-size distribution and organic matter content. These will have different physical and chemical properties, different land management properties, and different contaminant migration properties. Microbial populations (or their absence) are an important component of soils.

Typically, the top 0.2 to 0.3 m is the active surface soil region that contains the bulk of the plant roots, as well as being the region most directly affected by agricultural practices such as ploughing.

Screening Analysis

Surface soils are used to grow plants for human and animal foods (garden and forage field), to grow trees for the provision of wood for building and heating fuel (woodlot), and to obtain peat for heating fuel (peat lot). Contaminant concentrations in surface soil may be affected by processes such as irrigation, leaching, radioactive decay, radioactive ingrowth, groundwater discharge, precipitation, surface runoff, etc. while soil propertied may also evolve over time due to weathering processes. This FEP is relevant to the Facility long-term performance and safety as it provides a medium for the accumulation of contaminants and transfer to humans. In the case of the NPDDF system, direct contamination of soils is only likely to result from irrigation

by well water or river water, or as a consequence of excavation of contaminated material. Under normal evolution conditions, the river water is likely to be the primary source.

Screening Decision

All post-closure scenarios.

C 7.1.3.2 FEP # 5.1.3.2 Overburden

Description

The unconsolidated material, excluding the surface soils, that overlies the rock of the geosphere.

The transition from soil/sediment to overburden and from overburden to bedrock may not be abrupt. The overburden will change in time. These changes will be driven by the same processes affecting soils.

Screening Analysis

The overburden may serve as a pathway for contaminated groundwater flows from the geosphere and as a source of diluting contaminant-free water. Overburden with high clay content can be relatively impermeable, and groundwater flow might be restricted or confined to channels and fractures. A localized discharge from the geosphere might be dispersed over a larger area by the effects of this overburden, resulting in more widespread sorption and possibly more numerous discharges (and smaller contaminant concentrations) into the surface environment.

As contaminants can be absorbed in the overburden, the overburden affects the concentrations of contaminants in the groundwater discharging into the biosphere. Changes driven by weathering processes, climate change, and human activities will occur in the overburden over time which in turn will affect the quality of discharging groundwater. Thus, this FEP is relevant to the Facility long-term performance and safety.

For the purposes of this study, the overburden has been classified as a geosphere component (see FEP group 4), recognizing that it contains the main near-surface aquifer and has a direct connection to the NPDDF.

Screening Decision

All post-closure scenarios.

C 7.1.3.3 FEP # 5.1.3.3 Aquatic Sediments

Description

The sediments formed by the deposition of particulates from surface water.

Aquatic sediments are found at the bottom of surface water bodies and are generally composed of fine-grained sand, clays, and organic material. They can be differentiated into upper sediments which can have

high biological activity and lower sediments that are covered by the upper sediments and become more compacted. The former are subject to wave action and currents and can be eroded and reformed relatively easily. Sediments may eventually form surface soil when, for instance, a river changes its course or a lake dries up. They can be dredged for use as soil conditioners.

Screening Analysis

The site is located on the south bank of the Ottawa River, about 3 km downstream form the Des Joachims Dam. Aquatic sediments can play an important role in contaminant transport through sorption processes. While sorption onto sediments can remove contaminants from the aqueous environment, it can also contribute to exposure routes involving contaminated sediments, e.g., accumulation on riverbanks. This FEP is relevant to the Facility long-term performance and safety.

Screening Decision

All post-closure scenarios.

C 7.1.4 FEP # 5.1.4 Near-surface Aquifers and Water-bearing Features

Description

The aquifers and water-bearing features within a few tens of metres of the land surface and the processes affecting their potential evolution.

Aquifers are water-bearing features, geological units or near-surface deposits, which yield significant amounts of water to wells or springs. The presence of aquifers and other water-bearing features will be determined by the geological, hydrological and climatic factors.

Screening Analysis

The near-surface aquifer running through the base of the overburden is the key transport pathway for contaminants released into groundwater. Its characteristics, relevant flow paths and processes are discussed in FEP group 4.

Screening Decision

All post-closure scenarios, except Disruptive Event – Site Investigation (Inadvertent Human Intrusion), and What If (Facility Mass Excavation).

C 7.1.5 FEP # 5.1.5 Terrestrial Surface Water Bodies

Description

The characteristics of terrestrial surface water bodies, such as rivers, lakes, wetlands and springs, and the processes affecting their potential evolution.

Streams, rivers and lakes often act as boundaries on the hydrogeological system. They usually represent a significant source of dilution for materials (including) contaminants entering these systems, but in hot dry environments, where evaporation dominates, concentration is possible.

Discharge points for groundwater are often found at the margin or base of surface-water bodies. Springs are also discharge points where the water table intersects the surface and groundwater flows out into the surface environment.

The following more specific factors are discussed under separate entries:

5.1.5.1 Wetlands
5.1.5.2 Lakes and rivers
5.1.5.3 Springs and discharge zones

C 7.1.5.1 FEP # 5.1.5.1 Wetlands

Description

The land areas where the water table is at or near the surface.

Wetlands (including marshes, fens and peat bogs) may be underlain by, or lead to formation of, thick deposits of organic material (e.g., peat). Wetlands may also be drained to provide agricultural land and excavated for peat which is then used as a fuel or soil supplement.

Screening Analysis

Wetland areas on the site are mainly found on the western half of the property. Three main deciduous swamp communities exist, one smaller community immediately southeast of Landfill 2 and two larger communities to the northwest of Landfill 2. Discharge of contaminated groundwater will not occur to the wetlands, therefore it is not necessary to consider wetlands in the postclosure safety analysis.

Screening Decision

Screen Out – Out of Scope.

C 7.1.5.2 FEP # 5.1.5.2 Lakes and Rivers

Description

The surface water bodies that are large enough to persist for many years.

Surface water bodies will evolve through a number of processes such as gradual infill, meandering and braiding. Lakes may also be drained to use their sediments for farming, or sediments might be dredged to enrich poor soils. Lakes can also undergo eutrophication and other geochemical changes (e.g. acidification), significantly affecting their ecology. Rivers can change their beds exposing sediments for farming or changing land-use options.

Screening Analysis

The Ottawa River is the dominant drainage feature in the area and all surface drainage on the site ultimately drains to the Ottawa River. Thus, contaminants released from the Facility will travel in groundwater to the Ottawa River (discharge point). Lakes and rivers can involve a variety of contaminant transport mechanisms and exposure pathways. This FEP is relevant to the Facility long-term performance and safety.

Screening Decision

All post-closure scenarios.

C 7.1.5.3 FEP # 5.1.5.3 Springs and Discharge Zones

Description

The locations where the water table intersects the surface, allowing groundwater to flow out onto the surface.

Springs may also be found at various elevations depending on factors such as the lithology and stratigraphy of the geosphere and the location of outcropping geological units. Discharge zones are often low-lying areas such as at the margin or bottoms of lakes and wetlands (bogs and marshes). Spring and discharge zones can be affected by changes in the water table caused by local climate changes, human activities, or changes in topography.

Screening Analysis

Discharge zones could be local or regional, with regional discharges likely resulting in greater dispersion and longer travel times. Discharge zones can be affected by changes in the water table caused by local climate, human activities, or changes in topography. Springs and discharge zone should be considered in the context of regional groundwater flows. For contaminants released from the NPDDF into shallow groundwater, the discharge zone is expected to be to the river bed close (perhaps within metres of) the shore. This interface is important to represent as it determines the dilution and dispersion characteristics of contaminants in the biosphere.

Screening Decision

Normal Evolution, What If (River Level Fall).

C 7.1.6 FEP # 5.1.6 Coastal Features

Description

The characteristics of coasts and the near shore, and processes affecting their potential evolution.

Coastal features include headlands, bays, beaches, spits, cliffs and estuaries. The processes operating on these features, e.g., active erosion, deposition, longshore transport, determine the development of the coastal system.

Screening Analysis

The site is not located near an ocean, sea or large lake.

Screening Decision

Screen Out – Out of Scope.

C 7.1.7 FEP # 5.1.7 Marine Features

Description

The characteristics of seas and oceans, including the sea bed, and the processes affecting their potential evolution.

Marine features include oceans, ocean trenches, shallow seas, and inland seas. Processes operating on these features such as erosion, deposition, thermal stratification and salinity gradients, determine the development of the marine system.

Screening Analysis

The site is not located near an ocean or sea.

Screening Decision

Screen Out – Out of Scope.

C 7.1.8 FEP # 5.1.8 Atmosphere

Description

The characteristics of the atmosphere, including capacity for transport, and their evolution.

Screening Analysis

Relevant processes include physical transport of gases, aerosols and dust in the atmosphere. Contaminants may enter the atmosphere as gases, particulates, or aerosols, and exposure to humans and non-human biota may occur due to inhalation. However, airborne contaminants can be directed, diluted and dispersed by convection, turbulence and diffusion, which can influence the predicted dose to the critical group.

Climate is an important driving force for contaminant transport through the atmosphere. This FEP is relevant to the Facility long-term performance and safety.

Screening Decision

All post-closure scenarios.

C 7.1.9 FEP # 5.1.9 Vegetation

Description

The characteristics of terrestrial and aquatic vegetation, including algae and fungi, both as individual plants and in mass, and the processes affecting their potential evolution.

Particular consideration is often given to any local endangered or valued species.

Screening Analysis

The site is mainly wooded with the exception of open wetland areas. Forests are largely mixed or deciduous, dominated by white pine, red maple, poplar, and red pine (Morin, 2015). Natural coniferous forest, characterized by pine and cedar species, is more prevalent on downward slopes approaching the river. Three main deciduous wetland (swamp) communities exist at the site, southeast and northwest of the former Landfill 2. No nationally or provincially endangered or threatened species of vascular plants have been identified or recorded on the site although no formal survey for such species has been conducted.

At present, there is no agricultural use of the land, but domestic properties can cultivate land for homegrown vegetables, and this might represent a future pathway if the site were to be inhabited. Pathways involving wild foods and berries may also be relevant.

Contaminants may be taken up by terrestrial and aquatic vegetation through contaminated groundwater and surface water; contaminants may then be transferred through the food chain, leading to exposure pathways (ingestion) affecting humans and non-human biota. External and inhalation exposure may also result from forest fires involving contaminated vegetation or form using contaminate vegetation as a source of fuel and/or building materials. The uptake of contaminants by aquatic vegetation will also affect the movement of contaminants in surface water. The FEP is relevant to the Facility long-term performance and safety.

Screening Decision

All post-closure scenarios.

C 7.1.10 FEP # 5.1.10 Animals

Description

The characteristics of the terrestrial and aquatic animals both as individual animals and as populations, and the processes affecting their potential evolution.

Particular consideration is often given to any local endangered or valued species.

Screening Analysis

Wildlife species found on the site would be typical of a boreal region in Ontario. A list of species at risk that are present, potentially present, or known to be in close vicinity to the plant was compiled. Targeted surveys were conducted for species on this list, and nine of these species have been found to be present at the site.

The site is located in the reach of the Ottawa River extending approximately 90 km between La Passe and the Des Joachims Dam. More specifically, the property is directly adjacent to the Joachims Dam. This reach of the river consists of several lakes separated by short rapids and supports diverse warm water and cool water fish communities. Typical catches from the river include walleye, northern pike, channel catfish, smallmouth bass, and lake sturgeon (Morin, 2015).

In the future, it is possible that contaminated land and water might be taken up by smallholding animals and thus provide a foodchain pathway. Animals may be exposed to contaminants that have been released and transported from the Facility by groundwater pathways. Some members of the local animal population represent potential human food sources, and thus are components of contaminant transport through the human food chain. This FEP is relevant to the Facility long term performance and safety.

Screening Decision

All post-closure scenarios.

C 7.1.11 FEP # 5.1.11 Climate and Weather

Description

The characteristics of weather and climate, and the processes affecting their potential evolution.

They are characterized by precipitation, temperature, pressure and wind speed and direction. Their variability should be considered so that extremes such as drought, flooding, storms and snow melt are identified. In addition to long-term variations (FEPs 1.3.1 and 1.3.2), daily and seasonal variations can have a wide influence. For example, these variations affect irrigation requirements for agricultural crops, habitat for animal populations and the source of drinking water.

Screening Analysis

The weather and climate affects the ecosystems and land use of the site and surrounding area. The climate of the area is classified as humid continental, with warm summers, cold winters, and no distinct dry season. It is expected to remain largely as such in the future, although climate change effects might result in some modest warming, Glaciation is not expected to result in significant climate change for 100,000 y or more, but cooling might occur towards 100,000 y as the Earth enters a proglacial phase. It may therefore be appropriate to represent such a climate state as part of the normal evolution projection.

Climate is an important driving force for contaminant transport through the soil and the atmosphere by both hydrological processes and by wind and wind-induced erosion. It also determines land use and human activities and thus exposure pathways. The FEP is relevant to the Facility long-term performance and safety.

Screening Decision

All post-closure scenarios.

C 7.1.12 FEP # 5.1.12 Hydrological Regime and Water Balance (Near-surface)

Description

The near-surface hydrology at a catchment scale and soil water balance, and the processes affecting its potential evolution.

Screening Analysis

The hydrological regime includes movement of water and associated materials (e.g., sediments and particulates) through the near-surface environment and consideration of extremes such as drought, flooding, storms and snow melt. Key components are run-off (precipitation water that flows laterally over the top of the soil into a water body), and interflow (precipitation water that flows laterally through the soil into a water body). They are important in determining the flushing rate of surface-water bodies and, together with precipitation and evapotranspiration, determine irrigation water needs. Run-off and interflow may also carry contaminants, scavenged from the atmosphere or leached from the soil, to water bodies.

Extremes such as drought, flooding, storms and snow melt may be relevant. Therefore, this FEP is relevant to the Facility long-term performance and safety.

Screening Decision

All post-closure scenarios.

C 7.1.13 FEP # 5.1.13 Erosion and Deposition

Description

The erosional and depositional processes that operate in the surface environment, and their potential evolution.

Relevant processes may include fluvial and glacial erosion and deposition, denudation, aeolian erosion and deposition. These processes will be controlled by factors such as the climate, vegetation, topography and geomorphology.

Screening Analysis

Erosion of soil, overburden and bedrock by wind, water and ice may move contaminants laterally away from a discharge area or it may bring uncontaminated soil and overburden into the area, and thereby reduce local contamination concentrations. Alternatively, erosion may deposit contaminated material into a previously uncontaminated area. Erosion and deposition processes can redistribute contaminants between terrestrial and aquatic areas. This FEP is relevant to the Facility long-term performance and safety.

As discussed under FEP # 1.4.9 (water management – groundwater and surface water), under certain circumstances, severe erosion might occur over a short period due to a catastrophic flood (CNL, 2017). A catastrophic flood is extremely unlikely, but could possibly occur and result in a surge of river water up to

the elevation of the NPDDF surface structures (CNL, 2017). The floodwaters would likely disturb the ground surface (even if not down to the level that is contaminated).

This issue is appropriately captured with a Disruptive Event to examine surface erosion.

Screening Decision

Disruptive Event (Surface Erosion).

C 7.1.14 FEP # 5.1.14 Ecological/biological/microbial Systems

Description

The relations between populations of animals, plants and microbes and the processes affecting their potential evolution.

Characteristics of the ecological system in the vicinity of the Facility include the vegetation regime, and natural cycles such as forest fires or flash floods that influence the development of the ecology. The animal and plant populations occupying the surface environment are an intrinsic component of its ecology. Their behaviour and population dynamics are regulated by the wide range of processes that define the ecological system. Human activities have significantly altered the natural ecology of most environments.

Screening Analysis

The ecosystems of the surface environment provide the background within which contaminant migration may occur, should such contaminants be released into the biosphere. These include natural (forest, wetland, aquatic) and man-made (agricultural) ecosystems. The ecosystem might change in response to changing climate (see FEP 5.1.11). Contaminants may migrate through these systems, for example via root uptake into vegetation (bioconcentration) and subsequent movement through the food chain.

The ecosystems therefore provide a potential exposure route for humans, but also provide the system within which exposure of non-human biota may occur. This FEP is thus relevant to the Facility long-term performance and safety, although it is not necessary to include a comprehensive representation of the ecosystem.

Screening Decision

All post-closure scenarios.

C 7.2 Human Characteristics and Behaviour

The characteristics and habits of the individuals or populations, e.g., exposure groups, to whom exposures from the emplacement of the waste are calculated.

There are 5 subcategories under Human Characteristics and Properties:

5.2.1 Physical characteristics
5.2.2 Community characteristics
5.2.3 Diet and fluid intake
5.2.4 Habits (excluding diet)
5.2.5 Food preparation and water processing

C 7.2.1 FEP # 5.2.1 Physical Characteristics

Description

The physical characteristics of humans, including metabolism, physiology, age, gender and ethnicity.

Screening Analysis

Humans vary in their metabolism (chemical and biochemical reactions that occur in connection with the production and use of energy) and physiology (body and organ form and function). Susceptibility to contaminants varies with age, sex and reproductive status. Children and infants, although similar to adults, often have characteristic differences (e.g., respiratory rates, food types, ingestion of soil) that may lead to different exposure characteristics. For the purposes of radiological assessment, generalized human physiology is implicitly assumed through the use of ICRP dose coefficients. Age-dependency will, be represented by using dose coefficients for infants, children and adults.

Screening Decision

All post-closure scenarios.

C 7.2.2 FEP # 5.2.2 Community Characteristics

Description

The characteristics, behaviour and lifestyle of groups of humans that might be considered as exposure groups in an assessment.

The following more specific factors are discussed under separate entries:

5.2.2.1 Community type
5.2.2.2 Community location
5.2.2.3 Water source
5.2.2.4 Dwellings

C 7.2.2.1 FEP # 5.2.2.1 Community Type

Description

The general nature and size of the community, and in particular their degree of self-sufficiency and their use of land and water.

Screening Analysis

A range of community types can be considered including rural/agricultural, urban/industrial, and hunter-gatherer. Hunter/gathering describes a subsistence lifestyle employed by nomadic or semi-nomadic groups who roam relatively large areas of land hunting wild game and/or fish, and gathering native fruits, berries, roots and nuts, to obtain their dietary requirements. The community characteristics determine the exposure pathways and rates. In order to ensure that all exposure pathways have been captured, a set of different communities will be considered to ensure that the highest exposures to all pathways have been determined.

Screening Decision

All post-closure scenarios.

C 7.2.2.2 FEP # 5.2.2.2 Community Location

Description

The location of the community relative to areas which might be contaminated by the effects of the Facility.

Consideration should be given to the potential locations at which Facility-derived contaminants might be released into the surface environment and the potential for humans to make use of the land for a range of activities such as food production and leisure activities.

Screening Analysis

Dose rates to groups living downstream of the Facility will be lower than for groups living near the Facility, because contaminants would be diluted and dispersed as they travel to downstream locations or affected by other processes such as retardation, decay, etc. The community locations will therefore be chosen to result in exposure to the highest environmental concentrations.

Screening Decision

All post-closure scenarios.

C 7.2.2.3 FEP # 5.2.2.3 Water Source

Description

The origin of water used by the humans.

Humans require water for domestic purposes (drinking, cooking, washing and bathing), irrigating gardens and large agricultural fields used for crops and forage, to provide drinking water for livestock, and to serve

other purposes such as supply and maintenance of water for fish hatcheries or process water for industry. Different sources might be used for different purposes; for instance, water used for domestic purposes might derive from a dedicated water-supply well whereas water for irrigation may be taken from a nearby lake or from a different water-supply well. In addition, the volume of water required, and hence the type of water source will be affected by the size, lifestyle and occupations of the community, and additional sources might be required for a large community.

Screening Analysis

Potential water sources include municipal mains water, lakes, rivers, streams, wells and springs. Different sources might be used for different purposes; for instance, water used for domestic purposes might be obtained from a dedicated water-supply well whereas water for irrigation may be taken from a nearby lake or from a different water-supply well. In addition, the volume of water required, and hence the type of water source will be affected by the size, lifestyle and occupation of the community, and additional volumes and sources might be required for a growing community.

The different water sources could be contaminated to different degrees, with factors such as volume of diluting water, sedimentation and sorption affecting contaminant concentrations in the water. Moreover, the ingestion of contaminated drinking water could involve a relatively direct exposure route, with few delay and dilution processes. Consequently, radiological and chemical toxicity impacts on the critical group could depend strongly on their source of water.

In relation to the Facility, the key sources of potentially contaminated water include a well downgradient of the Facility and the river in the vicinity of the groundwater discharge zone. Installation of a well downgradient of the facility is a very unlikely situation for several reasons:

- Many downstream communities – including Deep River, Petawawa, and Pembroke – utilize the Ottawa River for their municipal drinking water supplies, rather than wells.
- Among those households that do use wells, most wells observed in the area obtain their water from much deeper formations that the depth of the Facility.
- The topography of the NPD site includes a large, steep slope between the facility and the river (i.e., along the downgradient groundwater path). This terrain would make installation of a well impractical.

Thus, the potential effects associated with use of a contaminated well are assessed as Disruptive Event scenarios.

Screening Decision

Normal Evolution, Disruptive Events – Overburden Well, Bedrock Well.

C 7.2.2.4 FEP # 5.2.2.4 Dwellings

Description

The houses or other structures or shelter in which humans spend time.

Materials used in their construction, the nature of their construction and their location are important factors in affecting potential human exposure to contaminants.

Screening Analysis

Several factors may affect the occupants' exposure mode and levels including dwelling location, construction materials (e.g., wood, stone and ashes), design elements for improved energy efficiency and air tightness and size, heating source (e.g., wood, peat, biogas, trapped methane), the likelihood of infiltration of water or gases into basements or flooding of basements from surface or groundwater sources, creation of household dust and fumes from indoor and outdoor sources and activities, and the introduction into the dwelling of contaminated furniture, household plant, etc. Many of these factors are important because they could affect contaminant concentrations in air, affecting exposures from inhalation and could enhance external irradiation (if located on contaminated ground). If the exposure group lives on site (in some cases they may not), the dwelling will be assumed to be located in such a way as to maximize exposures.

Screening Decision

All post-closure scenarios.

C 7.2.3 FEP # 5.2.3 Diet and Fluid Intake

Description

The intake of food and water by humans and the composition and origin of intake.

The diet of humans can vary greatly, both qualitatively and quantitatively. Potential food types include vegetables and fruit (e.g., grains, legumes, cultivated and wild fruits and berries), terrestrial animal products (e.g., meat and milk), and aquatic animal products (e.g., fish, crustaceans and molluscs). Humans may inadvertently ingest soil with food or from their hands, or they may have a craving for soil ingestion due to mineral deficiency. The total amount of food consumed can also vary with factors such as age and degree of physical activity.

The following more specific factors are discussed under separate entries:

5.2.3.1 Farming diet
5.2.3.2 Hunter/gatherer diet
5.2.3.3 Other diets

The two main diets are for a farming household and hunter/gatherer lifestyle. An aboriginal diet, for example may be particular relevance for a Facility located on the Canadian Shield. Depending on the lifestyle, it might be sufficiently covered within the reference farming and hunting/gatherer diets, or may require a third community-specific diet.

C 7.2.3.1 FEP # 5.2.3.1 Farming Diet

Description

The food and water intake characteristics of persons living a farming lifestyle.

For instance, the community's food intake may have a high proportion of plant food grown on local (and potentially contaminated) soil, as well as domesticated animals and fish. Water would come from wells or surface water bodies. The type of farming household can vary from self-sufficient to an "industrial" or monoculture operation.

Screening Analysis

Of the various plausible critical group lifestyles (Zach *et al.*, 1996), it is expected that doses to a self-sufficient farm group would be the highest because such a group is assumed to reside and grow their food in areas where contaminant concentrations are expected to be highest, particularly if they use contaminated river water or a well and irrigate their crops.

Screening Decision

All post-closure scenarios, except Disruptive Events – Site Investigation (Inadvertent Human Intrusion), and What If (Facility Mass Excavation).

C 7.2.3.2 FEP # 5.2.3.2 Hunter/gatherer Diet

Description

The food and water ingested by persons living a hunter/gatherer lifestyle.

Screening Analysis

Typically, the community's food intake would have a high proportion of fish and wild game, with little agriculture, water would come from springs or other surface water bodies, and a high percentage of their time may be spent outdoors. Such a community may be relevant under certain climate conditions (e.g. periglacial), and is also relevant due to values from stakeholder groups. This type of community could also be affected by the Facility and is thus relevant to the study.

Screening Decision

All post-closure scenarios, except Disruptive Events – Site Investigation (Inadvertent Human Intrusion), and What If (Facility Mass Excavation).

C 7.2.3.3 FEP # 5.2.3.3 Other Diets

Description

Other diets that cannot be adequately represented by a farming household diet or a hunter/gatherer diet.

Screening Analysis

The postclosure safety assessment includes a variety of receptors including an onsite resident and Indigenous receptors with two different diets. One diet is based on a self-sufficient lifestyle; this diet was also assessed in the previous 3rd Iteration of the PostSA (Arcadis & Quintessa, 2020c). The other diet is based on the findings of a diet survey performed by the Algonquins of Pikwàkanagàn First Nation (AOPFN) (Fediuk *et al.*, 2021).

Screening Decision

Normal Evolution, including Sensitivity cases.

C 7.2.4 FEP # 5.2.4 Habits (excluding diet)

Description

The non-diet related behaviour of humans, including time spent in various environments, pursuit of activities and uses of materials.

Screening Analysis

Habits will be influenced by agricultural practices and human factors such as culture, religion, economics and technology. Ploughing, fishing, and swimming are examples of behaviour that might give rise to particular modes of exposure to environmental contaminants. Human habits will influence the exposure pathways to humans.

The habits and characteristics that are assumed for the human critical group will be based on reasonable conservative and plausible assumptions that consider current lifestyles and available site-specific or region-specific information. As it is not possible to predict future human behavior with any certainty, it is generally assumed that humans in the future will have similar habits to present humans, except where such an assumption is clearly inconsistent with assumed variations in climatic conditions at a site (IAEA, 2012).

This FEP is relevant to the Facility long-term performance and safety.

Screening Decision

All post-closure scenarios.

C 7.2.5 FEP # 5.2.5 Food Preparation and Water Processing

Description

The treatment of food stuffs and water between raw origin and consumption.

Screening Analysis

Once a crop is harvested or an animal slaughtered it may be subject to a variety of storage, processing and preparation activities prior to human or livestock consumption, changing the contaminant distribution and content in the product. Water sources may be treated prior to human or livestock consumption, e.g., chemical treatment and/or filtration. Contaminants in food and water are usually lost as a result as processing and preparation. Cautiously, food preparation losses will be ignored.

Screening Decision

Screen Out.

C 7.3 Contaminant Migration [Biosphere]

The processes that directly affect the migration of contaminants in the biosphere.

There are 6 subcategories under Contaminant Migration [biosphere]:

5.3.1 Water-mediated migration [biosphere]
5.3.2 Gas-mediated migration [biosphere]
5.3.3 Solid-mediated migration [biosphere]
5.3.4 Human-action-mediated migration [biosphere]
5.3.5 Uptake of contaminants by animals and plants
5.3.6 Radioactive decay and ingrowth [biosphere]

C 7.3.1 FEP # 5.3.1 Water-mediated Migration [Biosphere]

Description

The processes related to migration of contaminants in surface water in the aqueous phase (including dissolved gases) and as particulate matter in surface water bodies.

Particulate matter includes colloids and suspended sediment in surface water bodies. The movement of sediment by erosion is covered by FEP 5.3.3.

The following more specific factors are discussed under separate entries:

5.3.1.1 Groundwater discharge to biosphere
5.3.1.2 Migration associated with surface soil and overburden
5.3.1.3 Migration associated with surface water bodies
5.3.1.4 Dissolution and precipitation [biosphere]

5.3.1.5 Speciation and solubility [biosphere]
5.3.1.6 Sorption and desorption [biosphere]
5.3.1.7 Colloid transport [biosphere]

C 7.3.1.1 FEP # 5.3.1.1 Groundwater Discharge to Biosphere

Description

The discharge of contaminants in groundwater into surface water bodies and soils/sediments.

Screening Analysis

Contaminated groundwater can discharge to a range of different locations depending upon site-specific geological, hydrological and climatic factors. Discharge is most likely to occur to the river and is only expected to discharge to dry land if the river level were to decrease significantly (possible Disruptive Event scenario, see FEP 1.3.7). These aspects will be considered in the safety analysis as the point of discharge represents the location where the highest environmental concentrations are encountered.

Screening Decision

All post-closure scenarios.

C 7.3.1.2 FEP # 5.3.1.2 Migration Associated with Surface Soil and Overburden

Description

The migration of contaminants in water through the surface soil and overburden.

Screening Analysis

Contaminant migration by advection, diffusion and dispersion in soil pore water will be affected by characteristics such as soil texture, mineralogy and porewater pH and composition. Contaminants may also move through the soil profile via processes such as infiltration and interflow, and across the soil via surface runoff. This FEP is relevant to the study.

Screening Decision

All post-closure scenarios.

C 7.3.1.3 FEP # 5.3.1.3 Migration Associated with Surface Water Bodies

Description

The migration of contaminants in surface water bodies such as rivers, lakes and seas.

Screening Analysis

Contaminant migration by advection, diffusion and dispersion in surface water bodies will be affected by characteristics such as water flow rates, water temperature and chemical gradients. This FEP is relevant to the study as a key point of discharge will be the Ottawa River. Reduced river dilution is considered in a sensitivity analysis.

Screening Decision

All post-closure scenarios.

C 7.3.1.4 FEP # 5.3.1.4 Dissolution and Precipitation [Biosphere]

Description

The dissolution and precipitation of contaminants in the biosphere under prevailing environmental conditions.

Dissolution is the process by which constituents of a solid dissolve into solution. Dissolution is controlled by changes in pressure, temperature and gas concentrations in the biosphere.

Precipitation occurs when chemical species in solution react to produce a solid that does not remain in solution. Contaminants entering the biosphere from the geosphere will likely encounter different chemical and physical conditions, such as atmospheric concentrations of oxygen and carbon dioxide in water. These conditions may lead to precipitation in the near-surface zone.

Contaminants moving through the biosphere could be subjected to precipitation or dissolution as a result of different local conditions, or by active microbial processes. These processes can change in response to processes such as daily and seasonal changes in meteoric precipitation, temperature, and land use change.

Screening Analysis

Many of the contaminant biosphere parameter values used in the model (e.g., plant concentration factors, soil Kd values, etc.) are based on field or laboratory experiments. These biosphere parameter values could, in theory, be affected by dissolution and precipitation processes. Thus, such processes, if important, would be implicitly included in the model, although it would not be possible to ascertain the importance of such processes on the calculated impacts. This FEP is therefore implicitly included in the study through foodchain transfer factors.

Screening Decision

Screen Out.

C 7.3.1.5 FEP # 5.3.1.5 Speciation and Solubility [Biosphere]

Description

The chemical speciation and solubility of contaminants in the biosphere under prevailing environmental conditions.

The concentration of an element in aqueous solution (at equilibrium) reflects the solubility of the solid compounds which contain the element. Factors such as temperature, gas partial pressure, ionic strength, the presence of complexing agents and pH and Eh conditions affect solubility. These factors affect the chemical form and speciation of the element. Thus, different solids of the same element may have different solubilities in a particular solution.

Speciation of contaminants in the biosphere can be particularly important because of the relatively large concentrations of oxygen and carbon dioxide dissolved in rain water and the soil pore water and the presence of organic complexes and compounds. Bacteria and microbes may chemically transform contaminants and thereby change their sorption and solubility properties.

Screening Analysis

Neglecting solubility limits in the biosphere is reasonable as contaminant concentrations will be far lower in the biosphere than the Facility due to dispersion and dilution of contaminants as they move towards the surface. If solubility controls exist, they will act to limit the release from the source term. In relation to speciation, this aspect is implicit in empirical biosphere concentration factors.

Screening Decision

Screen Out.

C 7.3.1.6 FEP # 5.3.1.6 Sorption and Desorption [Biosphere]

Description

The sorption/desorption processes affecting the migration of contaminants through the biosphere under prevailing environmental conditions.

Sorption describes the physico-chemical interaction where dissolved species adhere to a solid phase. Desorption is the opposite. Two sorption-desorption processes are commonly considered: ion-exchange processes involving an electrostatic or ionic attraction between charged dissolved species and oppositely charged surfaces; and chemisorption involving the formation of a chemical bond. Neutral species and (usually) anions are generally not strongly sorbed.

Screening Analysis

Factors affecting sorption in the biosphere include soil/sediment texture and composition, pH and Eh conditions, and temperature. Sorption is an important aspect of contaminant transport in the biosphere as it can lead to selective accumulation in certain exposure media, and will control the rate of migration of

contaminants. For some elements (e.g., silver and lead), site-specific sorption information has been determined based on the sediment and surface water samples from the Ottawa river (Manolopoulos, 2020).

Screening Decision

All post-closure scenarios.

C 7.3.1.7 FEP # 5.3.1.7 Colloid Transport [Biosphere]

Description

The transport of colloids and interaction of contaminants with colloids migrating through the biosphere under prevailing environmental conditions.

Colloids (particles with diameters typically less than 10 μm) may influence contaminant migration in a variety of ways: retarding migration by sorption of aqueous radionuclide species and subsequent filtration; or, enhancing migration by sorption and migration with flowing water.

Screening Analysis

In the biosphere, colloids (or suspended particles) may be an important contributor to contaminant movement, in part because of the higher porosity of biosphere media and the presence of organic materials. Colloidal transport of contaminants from the soil layer could be important if colloids are mobile and contaminants are strongly sorbed to them. However, data for parameters such as the Kd and transfer factors are usually derived from experiments under conditions in which contaminants may be present in colloidal and/or dissolved form. Therefore, the effect of colloids is implicitly included in these biosphere data. For these reasons, colloidal interactions and transport in the biosphere do not need to be explicitly modelled.

Furthermore, enhanced mobility of key radionuclides in the biosphere due to colloidal processes is not expected to have a significant influence on the assessed doses, because the biosphere itself does not otherwise act as a “barrier” to exposure to contaminants. Rather, increased mobility of contaminants is actually more likely to result in their more rapid dispersion, and thus lower environmental concentrations and thus doses.

Screening Decision

Screen Out.

C 7.3.2 FEP # 5.3.2 Gas-mediated Migration [Biosphere]

Description

The migration of contaminants in gas or vapour phase or as fine particulate or aerosol in gas or vapour through the biosphere.

Contaminants may enter the atmosphere as a result of a variety of processes including transpiration, suspension of soil/sediment, volatilization from water bodies (including near-surface aquifers), production of radon gas from the decay of natural and/or Facility-derived uranium, thorium and radium, and direct discharge of gases from the geosphere. Contaminants may also enter the indoor atmosphere from: use of contaminated water in showers; suspension of dust brought in on clothing or footwear; or from infiltration of contaminated water and gases into basements.

The atmospheric system may represent a significant source of dilution for these contaminants. For example, advection and dispersion by wind can move contaminants from local to more dispersed regional areas.

Screening Analysis

The significance of seepage of contaminated gas into dwellings from contaminated soils or the underlying Facility depends on the potential for contaminated gas generation (see FEP 2.4.2). This has been assessed as not being significant except under certain Disruptive Event conditions (drilling), which themselves preclude a building in which they can accumulate. However, C-14 in soil can be transferred into air and can subsequently be absorbed by plants which themselves may be eaten. This pathway is only of relevance to C-14 but is relevant to include in the postclosure safety assessment model.

Screening Decision

All post-closure scenarios.

C 7.3.3 FEP # 5.3.3 Solid-mediated Migration [Biosphere]

Description

The transport of contaminants in solid phase in the biosphere.

This might result from processes such as the glacial/fluvial erosion, landslide, solifluction, bioturbation and sedimentation.

The processes of most interest are large-scale erosion/sedimentation processes that are associated with External factors, such as regional erosion and sedimentation (FEP 1.2.8) and glacial and ice-sheet effects (FEP 1.3.5). However, smaller-scale processes can also occur that affect the local distribution of contaminants on shorter timescales. These include the bioturbation of soils and the silting of water bodies.

Screening Analysis

Contaminant migration in solids can occur in the aquatic environment as a result of sediment erosion and deposition and is relevant to consider. Erosion of contaminated media in the terrestrial environment is most

likely to constitute a mechanism for the loss of contaminants from soils. Both processes are relevant to consider and thus incorporate in the postclosure safety assessment.

Screening Decision

All post-closure scenarios.

C 7.3.4 FEP # 5.3.4 Human-action-mediated Migration [Biosphere]

Description

The transport of contaminants in the biosphere as a direct result of human actions.

Screening Analysis

Includes processes such as the dredging of contaminated sediments from lakes, rivers and estuaries and placing them on land, the ploughing of soils, which result in the mixing of the top layers of agricultural soil, and irrigation of soils, which could involve contaminated water.

These processes are most likely to act to dilute and disperse contaminants in the environment through mixing processes. Nevertheless, they represent expected aspects of the environmental system and are therefore relevant to include in the analysis.

Screening Decision

All post-closure scenarios.

C 7.3.5 FEP # 5.3.5 Uptake of Contaminants by Animals and Plants

Description

The incorporation of contaminants into animal and plant species.

Screening Analysis

Plants may become contaminated either as a result of direct deposition onto their surfaces or indirectly as a result of uptake from contaminated soils or water via the roots. Animals may become contaminated as a result of ingesting contaminated plants, or directly as a result of ingesting contaminated soils, sediments and water sources, or via inhalation of contaminated particulates, aerosols or gases. Consumption of contaminated plants and animals will introduce contaminants into the human food chain. This FEP is relevant to the study and needs to be included in the safety assessment.

Screening Decision

All post-closure scenarios.

C 7.3.6 FEP # 5.3.6 Radioactive Decay and Ingrowth [Biosphere]

Description

The spontaneous transformation of an unstable nucleus into a lighter one, in which radiation is released in the form of alpha particles, beta particles, gamma rays, or other particles. The increase in activity of radionuclides due to decay of their parent radionuclide.

Screening Analysis

Radioactive decay and ingrowth affect the concentration of radionuclides and therefore needs to be included in the assessment.

Screening Decision

All post-closure scenarios.

C 7.4 Exposure Factors

The processes and conditions that directly affect the health or give rise to other impacts on human beings and the environment, from given contaminant concentrations in environmental media.

Human beings and other living organisms exposed to a contaminant concentration in an environmental medium will be subject to a possible impact. Various modes of exposure ranging from external exposure to inhalation and ingestion are possible. The level of impact is a function of the properties of the contaminant, the contaminant concentration in the environmental medium and various human and non-human biota behavioural and physiological characteristics related to the mode of exposure.

There are 7 subcategories under Exposure Factors:

5.4.1 Contaminated drinking water and food
5.4.2 Contaminated non-food products
5.4.3 Other contaminated environmental media
5.4.4 Exposure mode
5.4.5 Dosimetry and biokinetics
5.4.6 Radiological toxicity/effects
5.4.7 Chemical toxicity/effects

C 7.4.1 FEP # 5.4.1 Contaminated Drinking Water and Food

Description

The presence of contaminants in drinking water, foodstuffs or drugs that may be consumed by humans.

Screening Analysis

Contaminants may be incorporated into the food chain through contaminated soil, water and air (see for example FEP 5.3.5). Water used for drinking is particularly important because it can provide a direct pathway of contaminant ingestion, with few delays. However, factors such as bioconcentration, bioaccumulation and biomagnification can increase concentrations of some contaminants in foodstuffs (e.g., fish, plants, meat and milk products), and may result in more significant exposures to particular contaminants. The nature of the source of contaminated water and food is scenario dependent, and some scenarios (e.g., Disruptive Event, drilling) might not include foodchain pathways, but it is relevant to consider in normal evolution scenarios.

Screening Decision

All post-closure scenarios.

C 7.4.2 FEP # 5.4.2 Contaminated non-food Products

Description

The presence of contaminants in human manufactured materials or environmental materials that have special uses.

Screening Analysis

Examples of materials that could be contaminated include: wood and rock used as building material and household furnishings; natural fibres and animal skins used in clothing; and peat, charcoal and biogas (from plant materials, feces and refuse, or from trapping methane from garbage disposal sites, bogs and sediments) for use in house heating. This pathway might be relevant in providing external irradiation pathways in circumstances where it is unlikely that a house could be situated on contaminated soil and is therefore included.

Screening Decision

All post-closure scenarios.

C 7.4.3 FEP # 5.4.3 Other Contaminated Environmental Media

Description

The presence of contaminants in environmental media other than drinking water, foodstuffs, drugs or non-food products, i.e., soil, water, sediment and air.

Screening Analysis

Environmental media such as indoor and outdoor air, well and surface water, soil, plants and non-human biota will be considered in the model. All can represent a potential external exposure pathway for people, and some may also have intake pathways (e.g., inhalation of suspended soil and inadvertent ingestion of soil).

Screening Decision

All post-closure scenarios.

C 7.4.4 FEP # 5.4.4 Exposure Modes

Description

The exposure of humans and other organisms to contaminants.

Exposure modes can be broadly categorized as internal and external with respect to the human body or affected non-human biota. Internal exposure means the contaminant enters and may temporarily or permanently reside in the affected organism. External exposure means the contaminant is outside the organism at all times, although radiation and energy might be transferred into the organism.

Radiotoxic and chemotoxic species differ in their ability to affect organisms. Radiotoxic materials can lead to impacts through internal or external exposure. Chemotoxic species are generally only of concern from internal exposure. Chemicals may be sorbed through skin or surfaces of non-human biota, but subsequent impacts are usually from internal exposure. However, there may be exceptions, for example allergic skin reactions that occur with nickel.

The following more specific factors are discussed under separate entries:

5.4.4.1 Exposure of humans
5.4.4.2 Exposure of non-human biota

C 7.4.4.1 FEP # 5.4.4.1 Exposure of Humans

Description

Exposure modes affecting humans.

Screening Analysis

Human exposures to internal and external radiation doses need to be explicitly considered in the model. The most important modes of exposure to radionuclides are: ingestion (internal exposure) from drinking or eating contaminated water or foodstuffs; inhalation (internal exposure) from inhaling gaseous or particulate radioactive materials; external exposure as a result of direct irradiation from radionuclides deposited on, or present on, the ground, buildings or other objects. Exposure can also come from immersion in contaminated water bodies, direct radiation from airborne plumes of radioactive materials, injection through wounds, and absorption of some species through the skin. This FEP is relevant to the study.

Screening Decision

All post-closure scenarios.

C 7.4.4.2 FEP # 5.4.4.2 Exposure of Non-human Biota

Description

Exposure modes affecting animals and plants.

Screening Analysis

Non-human biota can be divided into two broad groups: domesticated and cultivated species, and wild and Indigenous species. The exposure pathway would be similar to those for humans: ingestion, inhalation, external irradiation and skin absorption. However, the relative importance of these pathways would likely be quite different from humans and also between species. It is established practice to evaluate the potential exposure of non-human species in radiological assessment, with a view to demonstrating that the environment is adequately protected. As such, the FEP is included in the postclosure safety assessment.

Screening Decision

All post-closure scenarios.

C 7.4.5 FEP # 5.4.5 Dosimetry and Biokinetics

Description

The dependence between radiation or chemotoxic effect and amount and distribution of radiation or chemical agent in the organs, tissues and whole body.

The following more specific factors are discussed under separate entries:

5.4.5.1 Dosimetry and biokinetics for humans
5.4.5.2 Dosimetry and biokinetics for non-human biota

C 7.4.5.1 FEP # 5.4.5.1 Dosimetry and Biokinetics for Humans

Description

The dependence between radiation and chemical toxicity effect and the amount of radiation or chemical agent in human organs, tissues, and whole body.

Screening Analysis

Doses from radioactive contaminants depend on factors that include the exposure mode (e.g., internal or external exposure), the metabolism of the radiotoxic and chemotoxic species, the residence time in the tissue or organ, the energy and type of radioactive emissions of the radionuclide and any progeny, and the age of the human at exposure and the lifetime commitment to the exposure.

Similar comments apply to chemotoxic effects, except that chemical and biochemical disruption of cell functions, not radioactive emissions, affect the tissues of the body. The chemical form of a compound plays an important role in determining whether and how the toxic component interacts with cells and tissues.

Radiological impacts and impacts from chemically toxic elements on humans need to be considered in the model. For radionuclides, standard models of biokinetics and dosimetry are recommended by ICRP (based on epidemiology and supporting experiments) for the prospective assessment of human exposures, and will be used in the study. For chemicals, exposure standards take account of biokinetics by being based on epidemiological or experimental data.

Screening Decision

All post-closure scenarios.

C 7.4.5.2 FEP # 5.4.5.2 Dosimetry and Biokinetics for Non-human Biota

Description

The dependence between radiation or chemical toxicity effect and the amount of radiation or chemical agent in animal organs, tissues and the whole body and/or plant tissues and the whole plant.

Screening Analysis

Dose factors for non-human biota take account of dosimetry in a simplified fashion. Specifically, absorbed dose is determined on the basis of simple phantoms that take account of the organism's mass and shape. Biokinetics are not generally represented, although uptake factors used to determine concentrations in the organism represent this to some extent. These factors are therefore taken into account in the study.

Screening Decision

All post-closure scenarios.

C 7.4.6 FEP # 5.4.6 Radiological Toxicity/Effects

Description

The effect of radiation on humans and other organisms.

Radiation effects can be classified in several different ways. For example: somatic or genetic, occurring in the exposed individual or in the offspring of the exposed individual, respectively; and stochastic or non-stochastic (deterministic) where the probability of the effect is a function of dose received) or the severity of the effect is a function of dose received and no effect may be observed below some threshold, respectively. Another issue of potential concern is synergistic (combined) effects of two or more radiotoxic or chemotoxic species.

The following more specific factors are discussed under separate entries:

5.4.6.1 Radiological toxicity/effects for humans
5.4.6.2 Radiological toxicity/effects for non-human biota

C 7.4.6.1 FEP # 5.4.6.1 Radiological Toxicity/Effects for Humans

Description

The effects of radiation on humans.

Screening Analysis

Radiation exposure can have a wide variety of effects depending upon the exposure levels. At low exposure levels, cancer induction (carcinogenesis) and genetic effects are of main concern, possibly because of mutations that may lead to cancer or, if the reproductive cells are affected, hereditary effects that may be detrimental and transmitted to future generations. These effects are incorporated into ICRP's dose coefficients through radiation- and tissue- weighting factors and in the epidemiologically-derived risk coefficients for various forms of cancer and hereditary disease.

Screening Decision

All post-closure scenarios.

C 7.4.6.2 FEP # 5.4.6.2 Radiological Toxicity/Effects for Non-human Biota

Description

The effects of radiation on animals and plants.

Screening Analysis

For non-human biota the goal is to evaluate potential effects at a population or community level. This involves assessing the potential exposure for the representative populations of species. If the effects are

widespread throughout a population of some non-human biota, there could also be consequential effects, such as disruption of food webs or ecosystems. Radiological protection standards for non-human species are not, however, in terms of effective dose but rather in terms of absorbed dose (i.e., expressed in units of Gray). This does not account for radiotoxicity because there is insufficient epidemiological data for plants and animals other than humans to establish the radiation sensitivity to different types of radiation and radioisotope.

Screening Decision

All post-closure scenarios.

C 7.4.7 FEP # 5.4.7 Chemical Toxicity/Effects

Description

The effects of chemotoxic species on humans and other organisms.

Some components of radioactive waste can be chemically toxic to humans and other organisms, including plants. The waste will include a wide range of radiologically stable, but potentially toxic species, including heavy metals and persistent organic species. Chemical toxicity also relates to some radioactive elements, for example naturally occurring uranium is a heavy metal and as such is chemically toxic. Another issue of potential concern is synergistic (combined) effects of two or more radiotoxic or chemotoxic species.

The following more specific factors are discussed under separate entries:

5.4.7.1 Chemical toxicity/effects for humans
5.4.7.2 Chemical toxicity/effects for non-human biota

C 7.4.7.1 FEP # 5.4.7.1 Chemical Toxicity/Effects for Humans

Description

The effects of chemically toxic species on humans.

Screening Analysis

Chemical toxicity can involve a wide range of effects, including teratogenic (developmental disturbances), mutagenic effects (mutations that may lead to cancer or hereditary changes transmitted to future generations) and carcinogenic (cancer inducing) effects and thus interfere with reproduction, growth and survival.

The release of potentially chemically toxic elements to humans from the Facility needs to be considered.

Screening Decision

All post-closure scenarios.

C 7.4.7.2 FEP # 5.4.7.2 Chemical Toxicity/effects for Non-human Biota

Description

The effects of chemically toxic species on animals and plants.

Screening Analysis

Chemical toxicity has the same range of effects on non-human biota as it does on humans, although toxicity may alter between species.

The releases of potentially chemically toxic elements from the Facility and their effects on non-human biota need to be considered.

Screening Decision

All post-closure scenarios.

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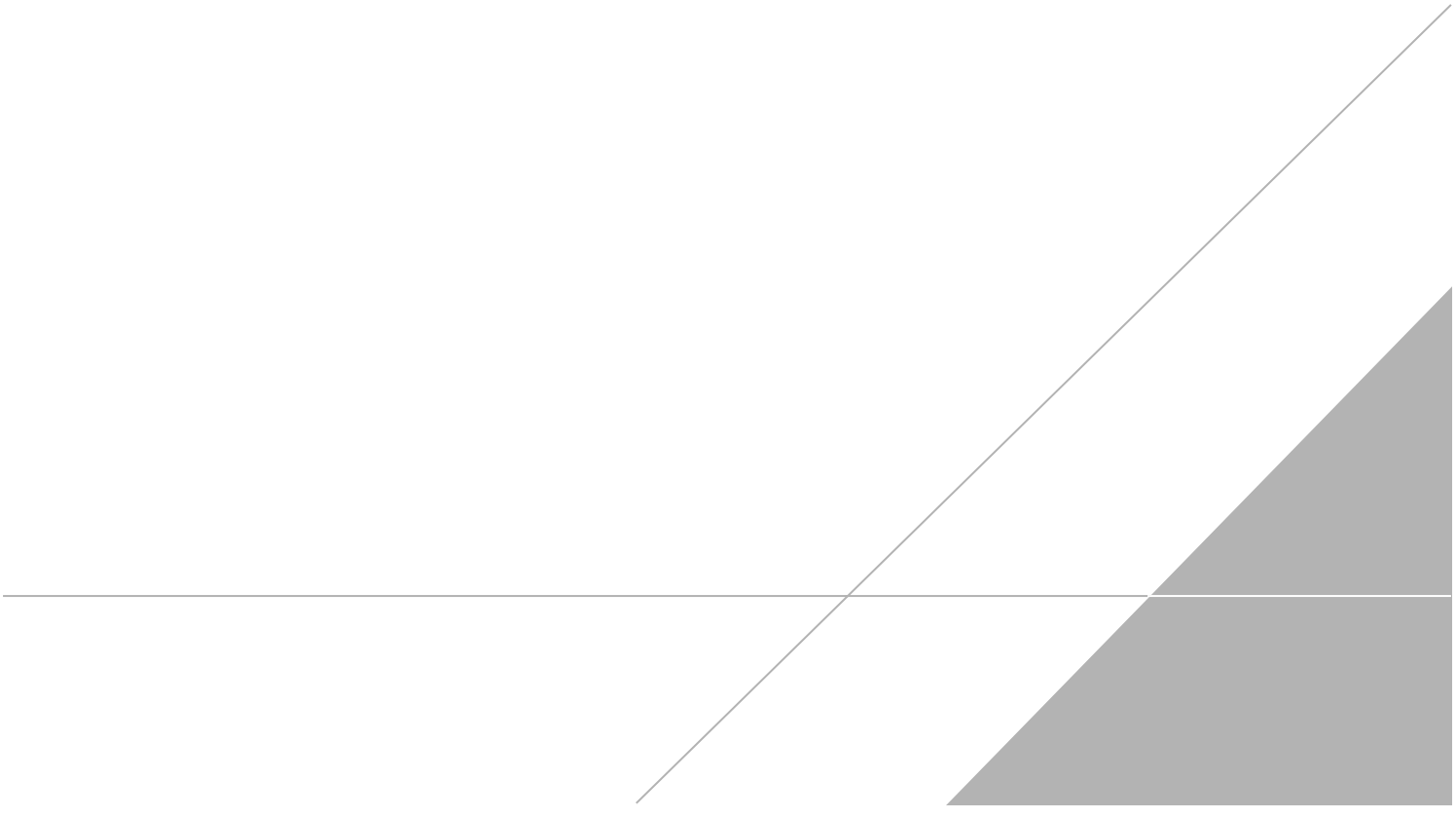
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APPENDIX D: SCENARIOS AND CALCULATION CASES



APPENDIX D – SCENARIOS AND CALCULATION CASES

D 1 INTRODUCTION

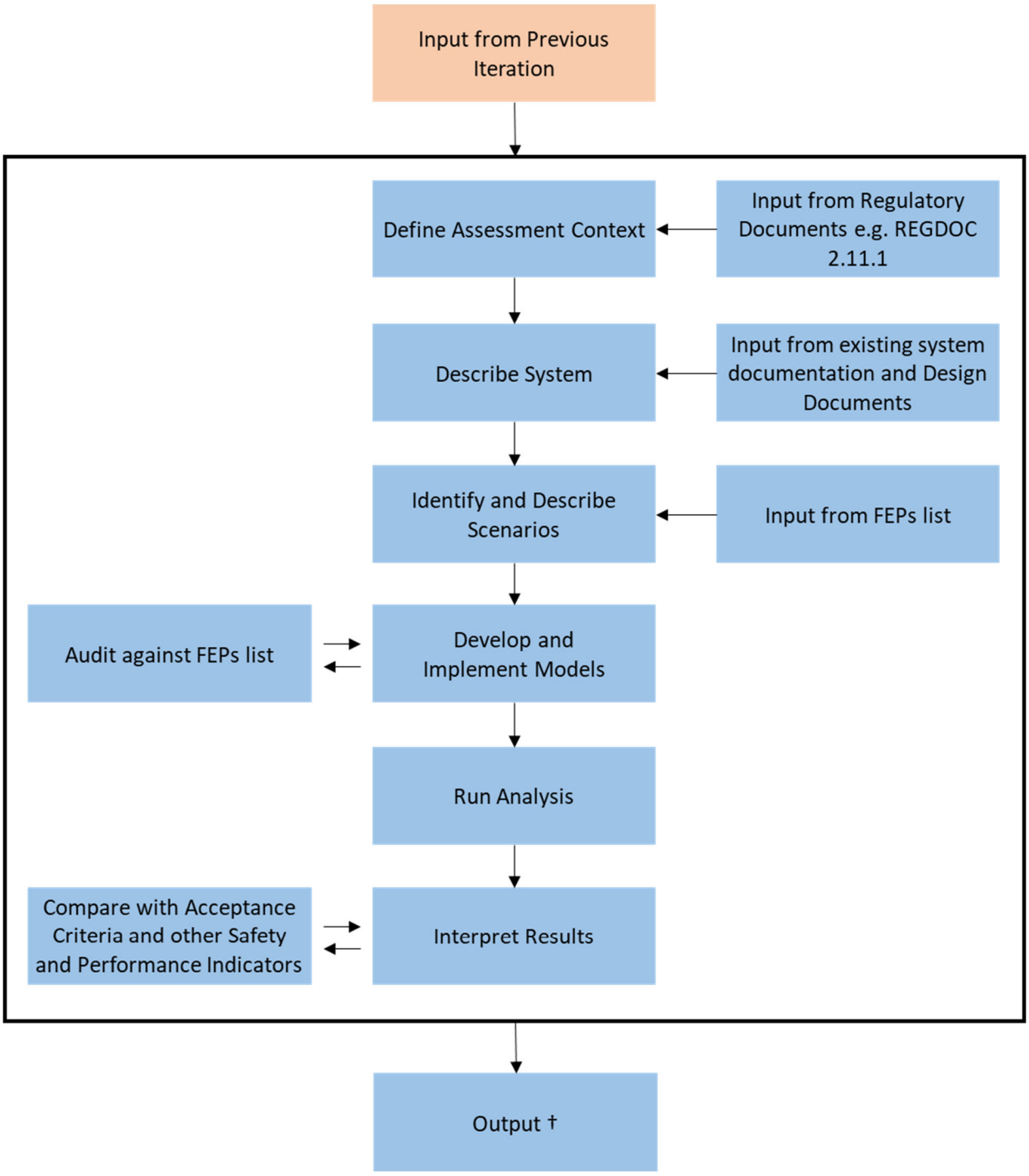
D 1.1 Background

Canadian Nuclear Laboratories (CNL, acting on behalf of Atomic Energy of Canada Limited, AECL) is proposing in-situ disposal of the Nuclear Power Demonstration Waste Facility (NPDWF), thereafter referred to as the Nuclear Power Demonstration Disposal Facility (NPDDF). This 4th Iteration Postclosure Safety Assessment (PostSA) will support the final EIS submission.

This 4th Iteration PostSA has been undertaken using international best practice, specifically the International Atomic Energy Agency's (IAEA's) Improving Safety Assessment Methodologies (ISAM) guidance (IAEA, 2004). This is a systematic, stepwise approach, the main stages of which are illustrated in Figure D-1. This PostSA has been documented in a way that corresponds to the ISAM approach, with a main report describing the key elements of the assessment and its outcomes.

This appendix addresses the third step in the ISAM approach, that of defining "scenarios". Each scenario needs to represent a set of conditions that might plausibly occur in the future. The scenarios selected for assessment also need to represent those that are likely to lead to the highest exposures that can be reasonably anticipated. A key tool in the process of defining scenarios is the list of potentially important "Features, Events and Processes" (FEPs) presented in Appendix C.

Figure D-1 Approach to Postclosure Safety Assessment, Adapted from ISAM (IAEA, 2004)



† Includes output to Environmental Impact Statement (EIS), Safety Case, and next iteration (if necessary).

D 2 SCENARIO DEFINITION PROCESS

D 2.1 Scenarios

Scenarios are descriptions of alternative, but internally consistent, future evolution pathways. Scenarios therefore provide a method by which uncertainties in the future can be taken into account in a postclosure safety analysis. Other types of uncertainties (e.g., uncertainties in the properties of rocks through which contaminated groundwater may flow) are addressed in different ways, namely by using a range of values for a parameter in an assessment, or even by using a different model to represent the process.

The scenarios selected for assessment need to reflect the assessment context and the specific environment and disposal facility under assessment. They do this by drawing on an assessment of the relevance of FEPs to the Facility and its surrounding environment (the “system”). For the Facility, these FEPs are documented in Appendix C.

The scenarios themselves need to provide a narrative description of a specific set of future conditions for the NPDDF system. Within this, key aspects include an identification of the factors that cause the scenario to occur, their timing and nature, their likelihood, and the impact on the system. The scenario does not have to describe the system as a whole in detail; this is the purpose of the next task, that of developing conceptual models (covered in detail in Appendix E). The development of conceptual models follows the scenario identification stage because it needs a defensible point of reference with conservative bias built into the assumptions for evolution of the system.

A summary of the Scenarios is provided in Table D-1.

Table D-1 Scenarios Summary

#	Scenario Name	Description
-	**Normal Evolution**	-
1	Normal Evolution Scenario (NES)	See Section D 3
-	***Sensitivity Cases***	-
1a	*NES Sensitivity Case: Measured Radionuclide Inventory*	*See Section D 4.1*
1b	*NES Sensitivity Case: Increased Modelled Radionuclide Inventory*	*See Section D 4.2*
1c	*NES Sensitivity Case: Reduced Near-Field Sorption*	*See Section D 4.3*
1d	*NES Sensitivity Case: Reduced Far-Field Sorption*	*See Section D 4.4*
1e	*NES Sensitivity Case: Reduced Sorption in Near-field and Far-field*	*See Section D 4.5*
1f	*NES Sensitivity Case: Rapid Degradation*	*See Section D 4.6*
1g	*NES Sensitivity Case: Increased Geosphere Bedrock Hydraulic Conductivity*	*See Section D 4.7*
1h	*NES Sensitivity Case: Increased Geosphere Overburden Hydraulic Conductivity*	*See Section D 4.8*
1i	*NES Sensitivity Case: Increased Dilution in the River*	*See Section D 4.9*
1j	*NES Sensitivity Case: Self-Sufficient Indigenous Receptor*	*See Section D 4.10*
-	**Disruptive Events**	
2	Site Investigation (Inadvertent Human Intrusion)	See Section D 5.1
3	Surface Erosion	See Section 0
4	Extreme Degradation	See Section D 5.3
5	Faut Zone Reactivation	See Section D 5.4
6	Excavation of Above-Bedrock Facility	See Section D 5.5
7	Overburden Well	See Section D 5.6
8	Bedrock Well	See Section 0
	Defence-in-Depth Cases	
9	Role of Existing Facility Concrete Structure	See Section D 6.1
10	Role of Grout	See Section D 6.2
	“What-If” Cases	
11	Facility Mass Excavation	See Section D 8.1
12	River Level Fall	See Section D 8.2
13	Undetected Fracture Zone	See Section 0

D 2.2 Link to FEPs

Not all FEPs are relevant to the definition of scenarios. Scenarios are concerned with future uncertainty in the way the system evolves. Where FEPs within the system influence its evolution (e.g., the timing of the degradation of the Facility structure and grout) these can be captured within the subsequently developed model (e.g., as a range of degradation timescales). By contrast, scenarios capture FEPs that are not directly included in the model, but could affect it. An example is climate change. It would be impractical and disproportionate to include in the assessment a model for climate change. Instead, it sits outside of the model itself and modelling decisions make reference to a set of assumptions about climate evolution. Climate related FEPs are therefore categorized as "External" FEPs (being external to the modelled system). It is these External FEPs that are the factors that typically generate scenarios.

The development of scenarios therefore focuses on External FEPs, although reference can be made to other FEPs where they are significantly affected by the External FEP. For example, periglacial conditions would have a significant effect on Human Characteristics and Behavior (FEP group 5.2 Appendix C).

D 2.3 Categories of Scenario and Calculation Case

The FEP list (Appendix C) includes a categorization scheme which identifies the relevance of FEPs to the postclosure safety assessment context.

- FEPs screened out of the assessment:
  - the FEP is outside the scope of the assessment context, or is simply not relevant to the system (e.g., it refers to something that is simply not present, such as a sea).
  - the FEP not significant on the basis of insignificant consequence to the system and its impacts (e.g., diffusion is dominated by advection in the groundwater transport through highly conductive media).
  - not significant on the basis of low probability.
- FEPs included in the assessment:
  - FEPs considered in Normal Evolution Scenario (NES) are by default also included in other scenarios.
  - FEPs giving rise to Disruptive Event (DE) scenarios, or of very low probability but provide useful information on system performance.
  - FEPs that are at the bounds of plausibility, but a "What If" (WI) calculation may be of interest to examine its implications for the performance of the system.

The resulting FEPs that lead to scenarios are those categorized as NES and DE. In order to distinguish them from a level of expectation, What If cases are referred to as "calculation cases". In addition, FEPs that represent factors that have a strong bearing on facility performance are selected for analysis as Defence-in-Depth cases, and FEPs in which there are significant uncertainties are identified for analysis in Sensitivity/Uncertainty cases.

D 3 NORMAL EVOLUTION SCENARIO

The Normal Evolution scenario is a reference description of the most likely evolution of the system. It is a defensible scenario with conservative bias built into the assumptions of the evolution of the Facility and its surrounding environment. The scenario description is a narrative summary of the FEP analysis presented in Appendix C and should be regarded in these qualitative terms. It is not an exhaustive description of all of the possible components of a system model; for this reference should be made to the FEP analysis report. A summary of the External FEPs that have been screened in and out of the Normal Evolution scenario is provided below in Table D-2.

The detailed assessment considers timescales from closure to 10,000 y (see the assessment context assumptions in Section 2 of the main report, and in Appendix A), with calculations run until 100,000 y to demonstrate that the peak has been captured. However, it is important to recognize that the reliability of quantitative predictions diminishes with increasing time. Therefore, the long-term quantitative estimates of impacts, such as dose rate, presented in this report should be seen as indicators rather than absolute measures of impact.

Table D-2 Status of FEPs for the Normal Evolution of the NPDDF System

Category	FEP No.	FEP	Screening for Normal Evolution Scenario *(see FEPs – Appendix C – for further details)*
1 EXTERNAL FACTORS			
1.1	Facility Factors		
	1.1.1	Quality assurance and control	In
	1.1.2	Site investigations	In
	1.1.3	Design	In
	1.1.4	Schedule and planning	In
	1.1.5	Construction	In
	1.1.6	Operation	In
	1.1.7	Closure	In
	1.1.8	Accidents and unplanned events	Out – not relevant to long-term performance and safety.
	1.1.9	Administrative control	In
	1.1.10	Monitoring	Out – monitoring will not affect long-term performance and safety.
	1.1.11	Records and markers	In
1.2	Geological Factors		
	1.2.1	Tectonic movement	Out – the most recent tectonic event to affect the region was about 66 million years ago. Tectonics are not relevant on the timescale of concern.
	1.2.2	Orogeny	Out – the most recent tectonic event to affect the region was about 66 million years ago. Tectonics are not relevant on the timescale of concern.
	1.2.3	Deformation (elastic, plastic, or brittle)	Out – tectonic/orogenic deformation unlikely to occur on timescale.

Category	FEP No.	FEP	Screening for Normal Evolution Scenario *(see FEPs – Appendix C – for further details)*
	1.2.4	Seismicity	In – in region with some seismic activity. Certain seismic events are encompassed within Normal Evolution, while others are addressed using a Disruptive Event scenario.
	1.2.5	Magmatic and volcanic activity	Out – no known regions of current volcanism in Ontario.
	1.2.6	Metamorphism	Out – facility in near the surface so will not be impacted by metamorphism.
	1.2.7	Hydrothermal activity	Out – the facility is not deep enough to be impacted by hydrothermal activity.
	1.2.8	Regional erosion and sedimentation	Out – the next glaciation is not expected within the timescale of the assessment.
	1.2.9	Diagenesis	Out – As the Facility is shallow, no significant physical and chemical changes are expected in the bedrock.
	1.2.10	Pedogenesis	In
	1.2.11	Salt diapirism and dissolution	Out – there are no salt deposits at the site.
	1.2.12	Hydrological/Hydrogeological response to geological changes	Out – large-scale geological changes are not relevant for the site.
	1.2.13	Geomorphological response to geological changes	Out – large-scale geological changes inducing geomorphological changes are not relevant for the site.
1.3	Climatic Factors		
	1.3.1	Global climate change	In
	1.3.2	Regional and local climate change	In
	1.3.3	Sea level change	Out – the site is not close to the sea.
	1.3.4	Periglacial effects	In
	1.3.5	Glacial and ice-sheet effects	Out – glaciation is not expected to occur within the timeframe of the assessment (see Appendices A and C).
	1.3.6	Warm climate effects (tropical and desert)	Out - the development of warm tropical or desert climate around the site is not considered to be plausible over the timescales of concern. This FEP is not relevant for the site geographical setting.
	1.3.7	Hydrological response to climate change	In
	1.3.8	Ecological response to climate change	In

Category	FEP No.	FEP	Screening for Normal Evolution Scenario *(see FEPs – Appendix C – for further details)*
	1.3.9	Human response to climate change	In
	1.3.10	Geomorphological response to climate changes	Out – glaciation is not expected to occur within the timeframe of the assessment.
1.4	Future Human Actions		
	1.4.1	Human influences on climate	In
	1.4.2	Social and institutional developments	In
	1.4.3	Technological developments	Out – it is difficult to predict technological developments so conservative assumptions are made with no technological development.
	1.4.4	Knowledge and motivational issues (Facility)	Out - It is an accepted basis of PostSA that deliberate intrusion is beyond the scope of the safety analysis as the intruders would be responsible for their own safety.
	1.4.5	Drilling activities	Out – Unlikely to occur with no knowledge of the site, but considered in Disruptive Event scenarios and a What If calculation case.
	1.4.6	Mining and other underground activities	Out – no known mineral occurrences, but included as Disruptive Event scenarios and a What If calculation case.
	1.4.7	Un-intrusive site investigation	Out – un-intrusive investigations would have no impact on long term performance and safety.
	1.4.8	Surface activities	In
	1.4.9	Water management (groundwater and surface water)	In
	1.4.10	Explosions and crashes	Out – very low probability of occurring.
	1.4.11	Remedial actions	Out – any remedial actions will be undertaken with knowledge of the facility and will improve long term performance and safety.
	1.4.12	Deliberate human intrusion	Out – deliberate actions are assumed to be carried out after consideration of the safety aspects.
1.5	Other External Factors		
	1.5.1	Meteorites and human space debris	Out – very low probability
	1.5.2	Evolution of biota	Out – ICRP 2000 recommends assessing dose based on current human physiology.

Category	FEP No.	FEP	Screening for Normal Evolution Scenario *(see FEPs – Appendix C – for further details)*
2 WASTE PACKAGE FACTORS			
2.1	Waste Forms		
	2.1.1	Contaminant inventory	
	2.1.1.1	Radionuclide content	In
	2.1.1.2	Chemical content	In
	2.1.2	Waste form characteristics and properties	
	2.1.2.1	Metals	In
	2.1.2.2	Organics	Out - There is no significant source of bulk organic material in the Facility, so this aspect is not considered in terms of Postclosure safety at this stage is it will have trivial consequence for radionuclide mobility. Hazards associated with the contaminants themselves are covered in FEP #2.1.1.2.
	2.1.2.3	Non-metals, inorganics	Out - Asbestos materials such as pipe insulation, floor tiles and transite building cladding will be present. The potential effects of these materials on the release, migration and fate of associated radionuclides are not considered to be significantly different from other wastes present in the Facility. Hazards associated with the contaminants themselves are covered in FEP #2.1.1.
	2.1.2.4	Immobilization matrix	In
	2.1.2.5	Deposits on surfaces	In
2.2	Waste Packaging Characteristics and Properties		
	2.2.1	Containers	Out of scope
	2.2.2	Overpacks	Out of scope
2.3	Waste Package Processes		
	2.3.1	Thermal processes (waste form/waste package)	
	2.3.1.1	Radiogenic heat production and transfer	Out - The radioactive waste in the NPDDF generates a negligible amount of heat.
	2.3.1.2	Chemical heat production and transfer	Out - Heat production from chemical processes within the waste form is expected to be low. Heat generated from curing of the grout is discussed in FEP #3.2.1.
	2.3.1.3	Biological heat production and transfer	Out - No significant quantities of organic material are located in the Facility.

Category	FEP No.	FEP	Screening for Normal Evolution Scenario *(see FEPs – Appendix C – for further details)*
	2.3.2	Hydraulic processes (waste form/waste package)	
	2.3.2.1	Saturation/desaturation	In
	2.3.2.2	Thermal effects	Out - No significant thermal processes are expected at the Facility
	2.3.2.3	Mechanical effects	Out - No significant swelling is expected in the waste forms over time.
	2.3.2.4	Chemical effects	Out - Metal components will corrode over time. This will not affect hydraulic processes but is important for radionuclide releases into water (see FEPs #2.4.1, #2.4.2 and #2.4.3).
	2.3.2.5	Gas effects	Out - Gas could be produced by e.g. corrosion of the carbon steel waste form, however the rate, and volume generated will be such that it is not expected to limit the re-saturation of the Facility.
	2.3.3	Mechanical processes (waste form/waste package)	
	2.3.3.1	Deformation	Out - For the post-closure phase, it is assumed that the grouted structure is stabilized and deformation of the waste form will not have any effect.
	2.3.3.2	Material volume changes (waste form/waste package)	Out - Corrosion of metals within the reactor vault will increase their volume. Although the BFS grout selected for the NPDDF is not designed to accommodate expansion of metals due to corrosion, there will be sufficient void space in the reactor and associated piping to provide space for the corrosion. Corrosion of the Al by the grout will also provide some void spaces in the grout from formation of bubbles due to hydrogen generation.
	2.3.3.3	Movement	Out - In the far future, the corrosion of the metal wastes in the Reactor Vault will reduce their structural integrity and ultimately, they will collapse. Earthquakes could also cause the material to collapse. This will not, however, have any significant consequence for the long-term performance of the Facility.

Category	FEP No.	FEP	Screening for Normal Evolution Scenario *(see FEPs – Appendix C – for further details)*
	2.3.3.4	Stress corrosion cracking	Out - While the process might occur within the Reactor Vessel it does not have any containment function therefore there is no significant consequence. No other containers are used in the Facility.
	2.3.3.5	Gas explosion (waste Form)	Out – Conditions needed to accumulate and ignite hydrogen gas are highly unlikely to occur in the post-closure period.
	2.3.4	Chemical processes (waste form/waste package)	
	2.3.4.1	Evolution of pH conditions (waste form/waste package)	Out - The pH of the waste forms in the Facility will be influenced by the alkaline conditions in and around the grout. The pH of the wastes themselves will not change, but the pH of the surrounding water will influence corrosion rates. This aspect is covered in FEP 3.2.4.
	2.3.4.2	Evolution of Eh conditions (waste form/waste package)	In
	2.3.4.3	Migration of chemical species (waste form/waste package)	In
	2.3.4.4	Corrosion (waste form/waste package)	In
	2.3.4.5	Alteration (waste form/waste package)	In
	2.3.4.6	Precipitation (waste form/waste package)	In
	2.3.4.7	Complexation (waste form/waste package)	Out - The inflowing water is expected to be conditioned by the upstream engineered barrier (concrete) and thus not contain any significant amount of complexants. There will not be a source of complexants within the reactor vault, so, the process is screened out.
	2.3.4.8	Colloid formation (waste form/waste package)	Out - The low hydraulic conductivity of the Facility will prevent any significant colloidal transport.
	2.3.5	Biological processes (waste form/waste package)	
	2.3.5.1	Microbial growth and poisoning (waste form/waste package)	Out - Microbial activity is expected to be low or non-existent in the waste form because of the limited organic and nutrient sources present.
	2.3.5.2	Microbially/biologically mediated processes (waste form/waste package)	Out - Microbial activity is expected to be low or non-existent in the waste form because of the limited organic

Category	FEP No.	FEP	Screening for Normal Evolution Scenario *(see FEPs – Appendix C – for further details)*
			and nutrient sources present.
	2.3.6	Radiological processes (waste form/waste package)	
	2.3.6.1	Radioactive decay and ingrowth (waste form/waste package)	In
	2.3.6.2	Radiolysis (waste form/waste package)	Out - Radionuclide concentrations within the reactor structures are not sufficiently high to cause any significant degree of radiolysis within the waste form.
	2.3.6.3	Helium production	Out - Due to the low inventories of alpha-emitting radionuclides in the Facility, this production can be neglected.
	2.3.6.4	Radon production (waste form/waste package)	Out - Radon gas generation is expected, but the quantities of radon precursor radionuclides within the inventory is small, and thus over the assessment timescales radon production rates will always be very low.
	2.3.6.5	Radiation damage (waste form/waste package)	Out - The concentration of radionuclides in the Facility is not sufficiently high that radiation damage will occur.
	2.3.6.6	Criticality (waste form/waste package)	Out - The Facility does not contain any significant quantity of nuclear fuel that could result in a nuclear criticality.
2.4	Contaminant Release (waste form)		
	2.4.1	Liquid-mediated release	
	2.4.1.1	Dissolution (waste form)	In
	2.4.1.2	Diffusion (waste form)	In
	2.4.1.3	Speciation and solubility (waste form)	In
	2.4.1.4	Sorption and desorption (waste form)	In
	2.4.2	Gas-mediated release	Out – See Appendix C: there is limited potential for gas generation and gas-mediated transport of contaminants.
	2.4.3	Solid-mediated release	Out – The mechanisms by which there may be a solid-mediated release are: by site investigation (inadvertent human intrusion), excavation of above-bedrock facility, and surface erosion (assessed as Disruptive Event Scenarios), and,

Category	FEP No.	FEP	Screening for Normal Evolution Scenario *(see FEPs – Appendix C – for further details)*
			glacial disruption (not credible based on the 10,000 y assessment timeframe), or mass excavation (which is considered to be a What If FEP (FEP #1.3.5)).
	2.4.4	Human-action-mediated release	Out – Human intrusion is assessed as Disruptive Event scenarios (Site Investigation and Excavation of Above-Bedrock Facility), and as What If (Facility Mass Excavation).
2.5	Contaminant Migration (waste package)		
	2.5.1	Water-mediated migration (waste package)	Out of scope
	2.5.2	Gas-mediated migration (waste package)	Out of scope
3 FACILITY FACTORS			
3.1	Facility Characteristics and Properties		
	3.1.1	Buffer/backfill	In
	3.1.2	Room/tunnel seals	In
	3.1.3	Shaft/ramp seals	Out of scope
	3.1.4	Borehole seals	Out of scope
	3.1.5	Other engineered features	In
	3.1.6	Excavation damaged and disturbed zones	In
3.2	Facility Processes		
	3.2.1	Thermal processes (Facility)	Out - heat from grout curing is expected to have dissipated by the end of the institutional control period. It will not be of consequence to post-closure performance.
	3.2.2	Hydraulic processes (Facility)	
	3.2.2.1	Desaturation/resaturation	In
	3.2.2.2	Piping/hydraulic erosion	Out - There are no features that could lead to any significant piping effects and therefore the FEP is not considered to be of any consequence to the postclosure performance of the Facility.
	3.2.3	Mechanical processes (Facility)	
	3.2.3.1	Material volume changes (Facility)	Out – Insofar as it is plausible that some material expansion may occur, consequent effects on material properties (principally the hydraulic conductivity) can be considered to be covered by the Sensitivity case (Rapid Degradation) and Disruptive Event scenarios that consider the extreme degradation and fault zone

Category	FEP No.	FEP	Screening for Normal Evolution Scenario *(see FEPs – Appendix C – for further details)*
			activation (see FEP 1.1.1).
	3.2.3.2	Creep	Out - The effects of grout creep are expected to be minor. It is assumed to have stabilized by the time of closure and is thus screened out as being of no consequence to post-closure safety.
	3.2.3.3	Collapse of openings	Out – The grout backfill will occupy voids in the waste, thus there will be no significant openings. If any collapse occurs, it would affect hydraulic properties and so is assessed via the Disruptive Event – Extreme Degradation of Engineered Barriers and Fault Zone Activation.
	3.2.3.4	Gas-induced dilation (Facility)	Out – Gas generation in the Facility is not a significant process in the long term.
	3.2.3.5	Gas explosion (Facility)	Out - Conditions needed to accumulate and ignite hydrogen gas are highly unlikely to occur in the post-closure period.
	3.2.4	Chemical processes (Facility)	
	3.2.4.1	Evolution of pH conditions (Facility)	In
	3.2.4.2	Evolution of Eh conditions (Facility)	In
	3.2.4.3	Migration of chemical species (Facility)	In
	3.2.4.4	Corrosion (Facility)	In
	3.2.4.5	Alteration (Facility)	In
	3.2.4.6	Precipitation (Facility)	Out - As precipitation decreases contaminant concentrations in fluids and thus contaminant fluxes out of the Facility, neglecting to account for contaminant precipitation in the Facility is conservative.
	3.2.4.7	Complexation (Facility)	In
	3.2.4.8	Colloid formation (Facility)	Out - The low hydraulic conductivity of the Facility will prevent any significant colloidal transport.
	3.2.5	Biological processes (Facility)	
	3.2.5.1	Microbial growth and poisoning (Facility)	Out - Microbial growth will not be a significant process due to lack of nutrients in the Facility.
	3.2.5.2	Microbially/biologically mediated processes (Facility)	Out - Microbial growth will not be significant due to lack of nutrients in the Facility.
	3.2.6	Radiological processes (Facility)	

Category	FEP No.	FEP	Screening for Normal Evolution Scenario *(see FEPs – Appendix C – for further details)*
	3.2.6.1	Radioactive decay and ingrowth (Facility)	In
	3.2.6.2	Radiolysis (Facility)	Out - Radionuclide concentrations within the Facility will be insufficient for any significant radiolysis effects, therefore the FEP is screened out.
	3.2.6.3	Radon production (Facility)	Out - Radon gas generation is expected, but the quantities of radon precursor radionuclides within the inventory is small, and thus over the assessment timescales radon production rates will always be very low.
	3.2.6.4	Radiation damage (Facility)	Out - The concentration of radionuclides in the Facility is not sufficiently high that radiation damage will occur.
	3.2.6.5	Criticality (Facility)	Out - The Facility does not contain any significant concentrations of nuclear fuel that could result in a nuclear criticality.
3.3	Contaminant Migration (through Facility)		
	3.3.1	Water-mediated migration (through Facility)	
	3.3.1.1	Advection (Facility)	In
	3.3.1.2	Dispersion (Facility)	In
	3.3.1.3	Diffusion (Facility)	In
	3.3.1.4	Dissolution, precipitation, and crystallization (Facility)	In
	3.3.1.5	Speciation and solubility (Facility)	In
	3.3.1.6	Sorption and desorption (Facility)	In
	3.3.1.7	Colloid transport (Facility)	Out - Colloids will be effectively filtered out by the cement. Therefore, colloidal transport within the Facility is not considered to be significant.
	3.3.2	Gas-mediated migration (through Facility)	Out – the only situation by which this could occur is considered to be by site investigation (DE scenario), and by facility mass excavation (What If calculation).
	3.3.3	Solid-mediated migration (from Facility)	Out – The only mechanisms by which there may be a solid-mediated release is by glacial disruption (not credible, see Appendices A and C), human intrusion and excavation of above-bedrock facility (assessed via other DE scenarios), and facility mass excavation (What If calculation case).

Category	FEP No.	FEP	Screening for Normal Evolution Scenario *(see FEPs – Appendix C – for further details)*
	3.3.4	Human-action-mediated migration (from Facility)	Out – assessed under separate scenarios: Disruptive Events – Site Investigation (Inadvertent Human Intrusion), Excavation of Above-Bedrock Facility, Overburden Well, Bedrock Well, and What If (Facility Mass Excavation).
4 GEOSPHERE FACTORS			
4.1	Geosphere Characteristics and Properties		
	4.1.1	Stratigraphy	In
	4.1.2	Large-scale discontinuities	Out – See Appendix C: the presence of a large-scale discontinuity feature (such as a shear zone or similar feature) is not credible. However, the impact of the increased hydraulic conductivity (and thus flow) in bedrock is considered in a sensitivity case, and the undetected fracture zone is considered in a “What If” case.
	4.1.3	Geological resources	Out - assessed under separate scenarios: Disruptive Events – Site Investigation (Inadvertent Human Intrusion), Excavation of Above-Bedrock Facility, Overburden Well, Bedrock Well, and What If (Facility Mass Excavation).
	4.1.4	Undetected features	Out – See Appendix C: the presence of an undetected large-scale feature (such as a shear zone or similar feature) is not credible. However, the impact of the increased hydraulic conductivity (and thus flow) in bedrock is considered in a sensitivity case, and the undetected fracture zone is considered in a “What If” case.
	4.1.5	Geothermal characteristics and properties	Out - There is no geothermal activity in the vicinity of the site.
	4.1.6	Hydraulic characteristics and properties	In
	4.1.7	Mechanical characteristics and properties	In
	4.1.8	Geochemical characteristics and properties	In

Category	FEP No.	FEP	Screening for Normal Evolution Scenario *(see FEPs – Appendix C – for further details)*
	4.1.9	Biological characteristics and properties	Out – microbial processes may be present, but there will not be a substantial organic component at depth and thus the chemical conditions will be controlled primarily by inorganic processes.
4.2	Geosphere Processes		
	4.2.1	Thermal processes (geosphere)	In
	4.2.2	Hydraulic processes (geosphere)	In
	4.2.3	Mechanical processes (geosphere)	In
	4.2.4	Chemical processes (geosphere)	In
	4.2.5	Biological processes (geosphere)	Out - screened out due to insignificant consequences.
	4.2.6	Radiological processes (geosphere)	In
4.3	Contaminant Migration (Geosphere)		
	4.3.1	Water-mediated migration (geosphere)	
	4.3.1.1	Advection (geosphere)	In
	4.3.1.2	Dispersion (geosphere)	In
	4.3.1.3	Diffusion (geosphere)	Out - While it is likely to be relevant (at least for a period) within the Facility, the hydraulic conductivity of the geological materials is expected to be such that advection always dominates diffusion.
	4.3.1.4	Matrix diffusion	Out - Although the bedrock is fractured, for the purposes of the post-closure safety assessment it can readily be represented as an equivalent porous medium. As such, matrix diffusion, as a process, is not necessary to represent as it will not have significant consequence in the overall description of contaminant transport.
	4.3.1.5	Dissolution, precipitation, and crystallization (geosphere)	Out – Concentrations of contaminants in releases are low. The only potential area could be the transition from high pH (within the facility) to lower levels at the geosphere interface. Still, it is not expected to be sufficiently demarcated to cause e.g., dissolution, precipitation or crystallization.
	4.3.1.6	Speciation and solubility (geosphere)	In
	4.3.1.7	Sorption and desorption (geosphere)	In

Category	FEP No.	FEP	Screening for Normal Evolution Scenario *(see FEPs – Appendix C – for further details)*
	4.3.1.8	Colloid transport (geosphere)	Out – See Appendix C: not considered to be significant within the geosphere.
	4.3.2	Gas-mediated migration (geosphere)	Out - There are no significant sources of gas in the NPDDF (see FEP 2.4.2) or the geosphere.
	4.3.3	Solid-mediated migration (geosphere)	Out - Assessed as Disruptive Events – Site Investigation (Inadvertent Human Intrusion), Surface Erosion, Excavation of Above-Bedrock Facility, and a What If calculation case (Facility Mass Excavation).
	4.3.4	Human-action-mediated migration (geosphere)	Out – Assessed as Disruptive Events – Site Investigation (Inadvertent Human Intrusion), Excavation of Above-Bedrock Facility, Overburden Well, Bedrock Well, and a What If calculation case (Facility Mass Excavation).
5 BIOSPHERE FACTORS			
5.1	Surface Environment		
	5.1.1	Topography and morphology	In
	5.1.2	Biomes	Out - The safety assessment addresses effects on Valued Ecosystem Components that represent the environment at the site. It will therefore focus on specific, representative species of importance rather than complete ecosystems.
	5.1.3	Soil and sediment	
	5.1.3.1	Surface soils	In
	5.1.3.2	Overburden	In
	5.1.3.3	Aquatic sediments	In
	5.1.4	Near-surface aquifers and water-bearing features	In
	5.1.5	Terrestrial surface water bodies	
	5.1.5.1	Wetlands	Out - Discharge of contaminated groundwater is northward toward the river, not toward the wetland west of the Facility.
	5.1.5.2	Lakes and rivers	In
	5.1.5.3	Spring and discharge zones	In
	5.1.6	Coastal features	Out of scope
	5.1.7	Marine features	Out of scope
	5.1.8	Atmosphere	In
	5.1.9	Vegetation	In
	5.1.10	Animals	In
	5.1.11	Climate and weather	In

Category	FEP No.	FEP	Screening for Normal Evolution Scenario *(see FEPs – Appendix C – for further details)*
	5.1.12	Hydrological regime and water balance (near-surface)	In
	5.1.13	Erosion and deposition	In
	5.1.14	Ecological/biological/microbial systems	In
5.2	Human Characteristics and Behaviour		
	5.2.1	Physical characteristics	In
	5.2.2	Community characteristics	
	5.2.2.1	Community type	In
	5.2.2.2	Community location	In
	5.2.2.3	Water source	In
	5.2.2.4	Dwellings	In
	5.2.3	Diet and fluid intake	
	5.2.3.1	Farming diet	In
	5.2.3.2	Hunter/gatherer diet	In
	5.2.3.3	Other diets	In
	5.2.4	Habits (excluding diet)	In
	5.2.5	Food preparation and water processing	Out - food preparation losses will be ignored (conservative).
5.3	Contaminant Migration (Biosphere)		
	5.3.1	Water-mediated migration (biosphere)	
	5.3.1.1	Groundwater discharge to biosphere	In
	5.3.1.2	Migration associated with surface soil and overburden	In
	5.3.1.3	Migration associated with surface water bodies	In
	5.3.1.4	Dissolution and precipitation (biosphere)	Out - implicitly included in the study through foodchain transfer factors.
	5.3.1.5	Speciation and solubility (biosphere)	Out - Neglecting solubility limits in the biosphere is reasonable as contaminant concentrations will be far lower. In relation to speciation, this aspect is implicit in empirical biosphere concentration factors.
	5.3.1.6	Sorption and desorption (biosphere)	In
	5.3.1.7	Colloid transport (biosphere)	Out - data for parameters such as the Kd and transfer factors are usually derived from experiments under conditions in which contaminants may be present in colloidal and/or dissolved form. Therefore, the effect of colloids is implicitly included in these biosphere data and do not need to be explicitly modelled.
	5.3.2	Gas-mediated migration (Biosphere)	In
	5.3.3	Solid-mediated migration	In

Category	FEP No.	FEP	Screening for Normal Evolution Scenario *(see FEPs – Appendix C – for further details)*
		(biosphere)	
	5.3.4	Human-action-mediated migration (biosphere)	In
	5.3.5	Uptake of contaminants by animals and plants	In
	5.3.6	Radioactive decay and ingrowth (biosphere)	In
5.4	Exposure Factors		
	5.4.1	Contaminated drinking water and food	In
	5.4.2	Contaminated non-food products	In
	5.4.3	Other contaminated environmental media	In
	5.4.4	Exposure modes	
	5.4.4.1	Exposure of humans	In
	5.4.4.2	Exposure of non-human biota	In
	5.4.5	Dosimetry and biokinetics	
	5.4.5.1	Dosimetry and biokinetics for humans	In
	5.4.5.2	Dosimetry and biokinetics for non-human biota	In
	5.4.6	Radiological toxicity/effects	
	5.4.6.1	Radiological toxicity/effects for humans	In
	5.4.6.2	Radiological toxicity/effects for non-human biota	In
	5.4.7	Chemical toxicity/effects	
	5.4.7.1	Chemical toxicity/effects for humans	In
	5.4.7.2	Chemical toxicity/effects for non-human biota	In

D 3.1 External Factors

The Facility is assumed to be closed as planned, with no unforeseen events. A period of institutional control is initiated and lasts for 100 y during which the Facility remains under surveillance and passive control. No human intrusion occurs within this timeframe or thereafter. The potential exposures that could occur following human intrusion are examined as Disruptive Event Scenarios (Section D 5.1). The engineered barriers are assumed to gradually degrade as a result of the natural evolution of cement and corrosion of metals.

Seismic Events

In the surrounding environment, minor design-basis earthquakes may occur. These include events with magnitudes of up to 1-in-2250 return period. An event with a 1-in-2250 return period has a corresponding magnitude of between 5.5 and 6.5, with a probability of approximately 1-in-2250 y, and a peak ground acceleration (PGA) of approximately 0.24 g (CNL, 2021a). This is the value used as the CRL DBE, and it is the value recommended by the 2015 National Building Code of Canada (NBCC). It is assumed that the facility will experience one or more events of this nature.

Given that the facility will remain in place long into the future, it may experience a seismic event of even greater magnitude. Therefore, Normal Evolution assumes that the facility will also experience a 1-in-10,000 y event, in addition to DBE events. The 1-in-10,000 earthquake was developed by obtaining the seismic hazard for NPD using the seismic hazard calculator provided by Natural Resources Canada (NRC). Following the recommendation given by NRC for low probability earthquakes, the 1-in-10,000 y earthquake was characterized by extrapolating on a log-log scale using the PGAs of the 1-in-1,000 y earthquake and the 2% exceedance in 50 y earthquake (0.000404 probability). NRC recommends extrapolation using this method to determine an earthquake hazard which may not necessarily be accurate but is likely conservative. The PGA representing this extrapolation is 0.623 g, which is conservative when compared with the NRC unpublished data for the CRL Site (which shows a PGA of ~0.55 g). The ground response spectra (GRS) for PGA of 0.623 g was then characterized as a standard-shaped-spectra defined by CSA N289.3.

CNL's updated (2021a) *NPD Underground Structure Seismic Assessment* report selected and examined the effects of a 1-in-2,250 y event, a 1-in-10,000 y event, and a 1-in-50,000 y event, on the NPDDF. For a 1-in-2250-y event, results of CNL (2021a) indicate that the facility will experience cracking in the above-bedrock portion of the facility (particularly at the interface between the above-bedrock and below-bedrock portions of the facility), but no cracking in the below-bedrock portion of the facility. For a 1-in-10,000-y event, results of CNL (2021a) again indicate that the above-bedrock portion of the facility will experience more extensive cracking while the below-bedrock portion of the facility will not. Results of CNL (2021a) are again similar for the 1-in-50,000-y event, where the portion of the facility above-bedrock will experience significant cracking while the below-bedrock portion of the facility will not. The reader is referred to the original CNL (2021a) assessment for further information on the selection, definition, and assessment of seismic events and their impacts on the facility.

Cracking is not expected to occur in the lower portion of the facility socketed into the bedrock as it is expected that when the NPD structure experiences a DBE or the BDBE, the upper portion of the NPD structure will be subjected to very high shear stresses and separate from the lower part of the NPD structure. This is a consequence of the shear failure between the upper portion of the structure and the lower portion of the structure. The shear failure would likely start some nominal distance above the horizontal plane where horizontal shear forces could be transferred to the rock that provides restraint to the lower section as an inclined diagonal crack that gradually changes to a near horizontal shear failure plane.

The reaction of the shear forces from the upper part of NPD will produce a bearing reaction on the rock surfaces at the top of the lower part of the NPD structure. As the shear strength of the upper grouted structure is much lower in strength than the bearing capacity of the reinforced concrete walls of the lower part of the structure or the bearing capacity of the rock adjacent to the lower structure, a shear failure will occur and the upper and lower portions of the NPD structures will physically separate. For these reasons cracking of the bedrock socketed portion of the facility will not occur.

The preliminary slope stability assessment (Arcadis & Geofirma, 2021) that considers earthquake-induced soil liquefaction, shows that the North Slope under current water level conditions is stable under static loading conditions and under loading conditions associated with a 1:2,250-y earthquake. Parts of the North Slope are stable, while some parts of the North Slope are unstable under a 1:10,000-y earthquake. The North Slope is likely to fail during a 1:50,000-y earthquake. It is unlikely that the predicted failures of the North Slope will result in the direct exposure of groundwater to a new ground surface that would be established following earthquake induced slope failures. Slope failures at the North Slope are expected to result in accumulations of failed granular materials on the lower half of the North Slope. Given the permeable nature of all soils that comprise the North Slope, the expected redistribution of soils following slope failure is unlikely to change groundwater flows from the NPDDF to the Ottawa River. For more details, the reader is referred to the preliminary slope stability assessment (Arcadis & Geofirma, 2021).

Therefore, based on the findings of CNL (2021a) and Arcadis & Geofirma (2021), the Normal Evolution Scenario assumes that 1-in-2,250-y events occur, as well as a 1-in-10,000-y event at 1,000 y past closure; these produce cracks in the above-grade portion of the facility. The below-bedrock portion of the facility is assumed to remain undamaged.

The timing and severity of these events is uncertain, and so the significance of both aspects of the assumptions is explored with alternative calculation cases. An earlier occurrence of the 1-in-10,000 y earthquake is examined with a Sensitivity Case that examines more rapid degradation of engineered barriers (see Section D 4.6). The effects of seismic events with greater magnitudes, damaging the facility (above and below bedrock) as well as creating a fracture zone, are assessed as Disruptive Event Scenarios (see Sections D 5.3 and D 5.4).

Erosion

The ground surface may be subject to erosion by various mechanisms including variations in river level, biotic weathering and aeolian erosion. In the Normal Evolution Scenario, it is assumed that there is a net balance of erosion and deposition of fresh soil/sediment from upgradient. Net erosion of the surface, down to bedrock, is considered in a Disruptive Event scenario (see Section 0). There are no other significant geological events or developments that affect the Facility and its surrounding environment.

Climate Change

The climate is assumed to evolve according to the currently central interpretation of anthropogenically-forced climate change. This is anticipated to include global warming of several degrees centigrade for a period of up to 100,000 y from the present. This is sufficient to defer the next scheduled ice age to beyond 100,000 y from now (Ganopolski *et al*., 2016). For this 4th Iteration PostSA, because glaciation is not

expected to occur for over 100,000 y, it is not credible over the 10,000 y assessment timeframe and has therefore been screened out (see FEPs Appendix C)). Note though, that the potential effects of glaciation were assessed in an earlier iteration of the PostSA (Arcadis & Quintessa, 2017a).

Aside from glaciation, climate change may still alter the regional and local meteorology, particularly affecting temperature, precipitation (and duration of snow cover), and frequency of storm events.

For temperature, future climate predictions were described in CNL (2019) using four representative concentration pathways (RCPs), which are outputs accepted by the Intergovernmental Panel on Climate Change (IPCC). RCPs are future radiative forcing scenarios based on the full range of published emissions scenarios. Among the four RCP scenarios the lowest and highest represent the most extreme emissions scenarios, whereas the two more central RCP estimates were selected to be roughly equally spaced between the other two extremes (IPCC, 2013). Table D-3 presents the four RCP scenarios and their corresponding temperature increase estimates.

Table D-3 Projected Increases in Temperature (°C) for RCPs (Zickfeld *et al.*, 2013)

Representative Concentration Pathway	Net Temperature Increase (°C)
RCP2	0.6
RCP4.5	2.2
RCP6	3.9
RCP8.5	7.8

The two more central RCP estimates range from 2.2°C to 3.9°C. These are assumed to be part of Normal Evolution. This range of temperature increase is expected to have no significant impacts on facility characteristics and sorption coefficients.

For precipitation, IPCC (2013) predicts that global precipitation is expected to increase by 1% to 3%, per degree (Celsius) of increased temperature, over the period from the year 2100 to 3000. As noted in IPCC (2013), the distribution of this precipitation increase will vary spatially. For simplicity, this range of precipitation increase has been applied to the area surrounding NPD. Table D-4 shows the projected precipitation (in mm) for the NPD site, calculated using the current annual precipitation of 852 mm (current ECCC climate normal, 1981- 2006) and the range of potential increases in temperature (from Table D-3) and precipitation.

Table D-4 Projected Annual Precipitation at NPD Based on Temperature and Precipitation Percent Changes (mm)

		Net Temperature Increase			
		0.6°C	2.2°C	3.9°C	7.8 °C
Increase in precipitation per degree Celsius	**1%**	857 mm	871 mm	885 mm	918 mm
	2%	862 mm	889 mm	918 mm	985 mm
	3%	867 mm	908 mm	952 mm	1051 mm

So, for Normal Evolution, the value of 952 mm is used, which represents a conservatively higher percent-per-degree increase (3%), based on a conservative (but not extreme) temperature increase (3.9°C).

It is assumed that the resulting effects of increased precipitation (and storm events) do not change the local hydrology significantly. A “What-if” case also examines the consequences of significant river level change (Section D 8.2), which encompasses the effects of storm events.

On the basis of present-day practice, people may obtain water from either the river (such as the communities at Deep River) or from a groundwater well. Wells are generally drilled into deep aquifers and would not, therefore, intercept any contamination originating from the NPD. However, a hypothetical well into contaminated groundwater in the bedrock is considered as a Disruptive Event case (Section 0). Similarly, another Disruptive Event case examines a hypothetical overburden well intersecting water in the pipe trench (Section D 5.6).

D 3.2 Wastes

The waste inventory in the Facility is based on current information summarized in the NPD System Description (Appendix B). This includes the reactor vessel and internals, together with some contaminated material (e.g., the primary heat transfer circuit). Several key non-radioactive contaminants are also assessed, with inventories based on the currently available information from decommissioning works.

For a period of time the wastes are unsaturated and will corrode gradually in the presence of residual moisture, but there will be no pathway for the release of contaminants.

The NPDDF will gradually resaturate and the water table within the Facility will eventually be higher than outside the Facility (see the discussion in Section D 3.3). Once the Facility has become saturated with groundwater the radionuclides will begin to be released into the groundwater. Radionuclides present within neutron-activated metal structures will be released as the metals corrode. Please note that the influence of corrosion rate is examined in Arcadis & Quintessa (2020a) and CNL (2021b). In the NES, cautiously, no credit is taken for any containment of radionuclides in drums or sealed structures (such as pipework). Also, all radionuclides present as surface contamination within the NPDDF (including fission products and actinides) will become instantly available for dissolution. In the saturated environment contaminants will distribute between solid surfaces (e.g., the concrete) and groundwater according to their sorption properties.

Over time it is possible that corrosion processes may generate gases, some of which may be radioactive. Depending on the rate of resaturation and corrosion, free gas may be evolved, or the gas may simply be dissolved in groundwater. Because the Facility is expected to resaturate quickly, any small quantities of radioactive gas that might be evolved from the aluminum would be released while the Facility remains under Institutional Control. This could migrate through the pores of the grout ultimately to be released to the open air and a portion may dissolve in groundwater. Any radioactive gas from the corrosion of other metals would be generated at such a slow rate that it would be dissolved in groundwater rather than accumulate as a bulk gas. Because the gas from the aluminum oxidation will be evolved quickly and be

released during the institutional control period when exposures can be prevented, it is not necessary to model. Because gas from corrosion of the other metals will evolve very slowly, and therefore will not migrate as a bulk gas but would be expected to dissolve in groundwater, it can be modelled in the same way as tritium in groundwater.

Parts of the NPDDF are *currently* above the local water table. The concrete cap and engineered barrier that will be emplaced over the nuclear area of the NPDDF will be designed to encourage run-off and reduce infiltration into the rooms of the NPDDF. A small amount of water is likely to infiltrate through the concrete cap and engineered barrier and as they degrade, infiltration will increase. This will result in an elevated water table inside the NPDDF compared to the local area. Radionuclides in rooms initially above the water table will leach into the groundwater and be transported with the groundwater through the facility (examined in Arcadis & Geofirma, 2023b), and ultimately towards the Ottawa River.

As mentioned in Appendix B (System Description), several studies have been completed to understand groundwater flow in and around the facility.

D 3.3 Facility

Initially the grout is expected to be close to fully saturated after curing, and facility concrete is expected to be unsaturated. After closure, groundwater will begin to flow through the pores of the concrete and grout "resaturating" the facility. The rate of resaturation will be controlled by the hydraulic conductivity of the Facility walls and the rate of flow through the concrete cap and engineered barrier. Hydrogeological calculations (from Arcadis & Geofirma, 2023c) indicate that resaturation may take several decades to complete; further discussion of the process is presented in Appendix B. During the resaturation period contaminants will only be released from the Facility by diffusion, because water will be flowing *into* the facility and this flow would not lead to any contaminant releases from the facility; additional cracking of the facility will have no effect during the resaturation period except some minor possible movement of inventory between rooms. When the engineered barrier and concrete cap begins to degrade, rainfall and snowmelt will percolate down through the Facility towards the water table. Once the water levels in the NPDDF have risen to a steady level, contaminants will begin to migrate through the grout backfill and concrete walls of the Facility. Initially, this may be dominated by diffusive transport due to the low hydraulic conductivity of the Facility structure and grout. The porewater will be alkaline due to the conditioning effect of the cement. Radionuclides will sorb to the cement consistent with these conditions.

Groundwater contact with the Facility structure and grout will gradually degrade it as the cement constituents are slowly leached. As it degrades, the pH of the cement will fall and its porosity will increase. The cement and concrete will gradually loose strength and may begin to crack and fracture, e.g., as a result of corrosion of rebar. Close to the surface, freeze-thaw effects will degrade the concrete cap.

Degradation of the Facility structure and grout will increase their hydraulic conductivity and consequently groundwater flows through the Facility will increase. This in turn will increase the rate of leaching and subsequent degradation. This process will continue until the cement phases are largely removed and the remaining material is inert. At this point, the Facility will be largely indistinguishable from loose aggregate.

The timescales for the evolution of the Facility are dependent on the detailed properties of the constituent materials, but it is unlikely to be complete for several thousand years, perhaps tens of thousands.

As mentioned in Appendix B (System Description), several studies have been completed to understand the degradation process of the BFS:PC grout blend and the resaturation of the facility.

D 3.4 Geosphere

Information from the construction of the Facility and from recent field measurements has been compiled in the Geosynthesis Report (Arcadis & Geofirma, 2022) and used to inform subsequent groundwater modelling (in Arcadis & Geofirma, 2023a). Groundwater flow upgradient of the facility flows primarily through the overburden-bedrock interface. Groundwater flow through bedrock is less, due to its lower hydraulic conductivity, but is still a significant component. Bedrock topography generally slopes down toward the facility and the river, and so directs groundwater flow in this general direction.

Initially, before there is any significant degradation of the NPDDF structure, groundwater arriving at the NPDDF structure will be deflected and flow around the Facility. The tile drains will promote this regime, collectively they capture over 90% of overburden groundwater and direct it toward the river. Groundwater downgradient of the Facility which has not been captured by the tile drains will flow towards the river. Here the cooling pipe trench is expected to act as a preferential pathway for most (but not all) of the groundwater travelling to the river. The pipe trench discharges under the riverbed, close to the shore. The tile drains discharge to the shore, 1-2 m from the river.

Over time the facility will gradually resaturate and begin to degrade. The tile drains are expected to degrade more quickly; however, they may still continue to influence flows though not to the same extent as when the tile drains were fully functioning. The manner in which they are included in the PostSA model is discussed in Appendix E and F. However, several key changes will occur at this time, based on modelling performed in Arcadis & Geofirma (2023b):

- The volume of water previously captured by the tile drains will now also travel through the overburden, some of this additional flow will emerge as springs along the northern slope in the land, some will travel through to the pipe trench.

- There is increased flow through the facility itself. Groundwater that flows through the upper portions of the facility that lie above bedrock will exit and preferentially travel through the pipe trench to the river. Groundwater that flows through the lower portions of the facility that lie within bedrock will exit and travel through the bedrock to the river. It is also important to note that no significant faults or fractures have been found which interact with the NPDDF structure or its groundwater flow field.

As degradation gradually increases the Facility's hydraulic conductivity, a greater proportion of the groundwater will begin to flow through the Facility and subsequently into the Ottawa River. Contaminants will be released from the concrete and cement into the groundwater and migrate through the overburden and bedrock (as mentioned above), towards the river. Supporting calculations (in Arcadis & Quintessa,

2020c) show that there will be sufficient dilution that there will be no significant increase in groundwater pH downstream of the facility. Contaminants will sorb to the geosphere media, which will retard their transport. There may also be some precipitation due to differences in solubility in the near neutral pH groundwater; however, this is conservatively neglected in the models. The transport will be primarily by advection and dispersion.

D 3.5 Biosphere

The primary point of contaminant release into the biosphere is taken to be the riverbed close to the shore of the Ottawa River. In the aquatic environment, the contaminants may sorb to sediments or be taken up by aquatic flora and fauna. The dominant process will, however, be advection, dispersion and subsequent dilution in the water. However, contaminants may also be released directly into soils; groundwater modelling in (Arcadis & Geofirma, 2023b) suggests that it is possible, once the tile drains have ceased to function, for springs to form close to the river from which potentially contaminated groundwater may be released from the overburden. Spring water is intermittent and considered inappropriate for use as drinking water etc. in preference to the very large volume of clean river water close to the discharge zone. However, residents can spend time in the area where the spring water has contaminated soils and receive exposure from those soils. It is also possible that, once the Facility has resaturated and the tile drains have failed, a small fraction of the contaminated water in the upper part of the NPDDF might enter the cap overlying it (e.g., as a result of seasonal variations in water table). This area of soil may also become contaminated, and subsequently expose people using that area of land.

In the vicinity of the NPDDF, there is evidence of the use of wells to extract water for domestic and agricultural use. If the site of the Facility were to be inhabited in the future, it is possible that a water well could be drilled nearby. However, the facility is located in close proximity to the Ottawa River with a steep slope adjacent to it. Beyond the slope there is only a small low piece of flat land before the river, and this piece of land is only a meter or two above the river's water level. Thus, the area along flow path from the facility to the river is not desirable for a well installation. Wells are generally drilled into deep aquifers, in which case the water would be uncontaminated. On this basis drinking water would not be obtained from a contaminated aquifer, even if it were obtained from a well. The potential use of contaminated well water is considered in Disruptive Event scenarios (Sections D 5.6 and 0).

River water is also used by people downstream of the NPDDF; for example, Deep River obtains its water from the Ottawa River. This is a more likely route by which contaminated drinking water could be obtained. Indeed, as the river serves many communities downstream, any contaminants entering the river could expose people at some point. The most conservative assumption is that water is extracted from close to the point of groundwater discharge into the river and used by a small settlement or farm. The water could be used for drinking by people and livestock, and also to irrigate soil for crops that are subsequently consumed. Irrigation water would transfer contaminants to soil where a portion would remain for a period before being slowly leached out by rainwater and returned to the geosphere. The contaminated soil would constitute a source of external irradiation, inhalation (suspended soil) and ingestion pathways to the community living there.

Members of the community may also use the river in other ways. It is a significant source of fish, which could take up contaminants from the water and then be ingested. A person fishing the river would also be exposed to contaminants sorbed onto bank sediments. They may swim in the river and would be likely to use it for washing.

In addition, as a result of Indigenous stakeholder feedback, the NES examines the Indigenous receptor, which is based on a new study of the diet and harvest of the Algonquins of Pikwàkanagàn First Nation (AOPFN) (Fediuk *et al*., 2021). The study shows that today, the Algonquins are more likely to supplement their diet with additional groceries purchased from local shops. The Indigenous receptor does not live on the NPD site but uses the land surrounding the facility for some traditional activities such as hunting, fishing and gathering wild plants.

In summary, the receptors for NES include:

1. Resident (infant, child, adult); and,
2. Hunter / Recreational (infant, child, adult); and,
3. Offsite Receptor(s), based on Deep River and Ottawa (infant, child, adult); and,
4. Indigenous Receptor(s) (adult) based on the new AOPFN study (Fediuk *et al*., 2021).

The Self-sufficient Indigenous Receptor(s) (infant, child, adult) are based on the results of lifestyle surveys in SENES (2014) (adult) and are considered in a sensitivity case (Section D 4.10).

See Appendix E (Models & Data) for details and parameter values for each receptor group.

D 4 NES SENSITIVITY CALCULATIONS

NES sensitivity calculations examine the effect on key performance measures of important uncertainties in the models and data used in the PostSA's NES. As many modelling aspects can in practice be expressed through parameter values (e.g., the importance of a particular pathway can be emphasized by assigning a greater proportion of groundwater flow to it), these cases are all characterized by alternative parameter value choices. The alternative parameter values assigned need not represent specific bounds on uncertainty (as in some cases these cannot easily be established). Rather, they are used to test the effect of uncertainty; for example, if parameter x is increased by a factor of 10, by what factor does the dose increase by?

Key parameters have been identified by:

- Identifying key areas of uncertainty as part of the System Description (Appendix B);
- Reviewing Features, Events and Processes relevant to the long-term safety of the NPDDF (Appendix C);
- Determining model and data uncertainties (see Appendix E); and,
- Performing multi-variate sensitivity analyses in Arcadis & Quintessa (2018).

Uncertainties vary in significance, and therefore the outcomes of prior iterations of the PostSA calculations, and the multi-variate sensitivity analyses in Arcadis & Quintessa (2018), have been used to identify those most important to the performance of the NPDDF.

The sensitivity calculations related to inventory and rate of release of contaminants relate to radiological impacts on local residents and users of the environment around the NPDDF.

The following sensitivity calculations have therefore been defined.

D 4.1 Measured Radionuclide Inventory

The reference radionuclide inventory used in the NES is based on modelling and sample analyses, ultimately producing estimates that include various conservatisms and are intended to be bounding. So, in order to gain perspective on the uncertainties in the radionuclide inventory, this case involves using only measured data on radionuclide concentrations, without any uncertainty factors, where possible.

D 4.2 Increased Modelled Radionuclide Inventory

In order to further gain perspective on uncertainties in the radionuclide inventory, this second sensitivity case considers a radionuclide inventory twice that of the reference radionuclide inventory used in NES.

D 4.3 Reduced Near-field Sorption

The sorption coefficient is the ratio of the concentration on solid to that in solution in a saturated medium, and controls the rate by which contaminants can travel relative to groundwater. This parameter can be

very uncertain as it is sensitive to groundwater chemistry and the minerals present to which sorption can occur. Data reviews (e.g., Ochs *et al.,* 2016) show the values vary by differing amounts, sometimes in excess of an order of magnitude. In order to provide a transparent analysis of sensitivity, all sorption coefficients for the near field (grout and concrete) have been reduced. Lower limit values from Ochs *et al*. (2016) have been used, where possible. Where no lower limit data were available, the values were reduced by an order of magnitude (this will lead to a more rapid release of contaminants to the surface environment).

D 4.4 Reduced Far-field Sorption

To capture the uncertainty in sorption parameters, all sorption coefficients for the far field (geosphere – overburden and bedrock) were reduced by an order of magnitude. The near field sorption coefficients were taken as in NES.

D 4.5 Reduced Sorption in Near-field and Far-field

To provide a transparent analysis of sensitivity and capture the uncertainty in both the near field and far field, the two sensitivity cases described above (Sections D 4.3 and D 4.4) were combined.

D 4.6 Rapid Degradation

The timing of the facility's degradation is an important aspect of the postclosure performance of the NPDDF, because as the facility degrades seepage into the facility, and releases from the facility, generally increase. This sensitivity case examines poorer performance of the facility, based on more rapid degradation of the grout and concrete than that used in the NES. Various factors might lead to poor performance of the grout and concrete. For example, unexpected cracking in the concrete could occur, or there could be poorer than anticipated grout performance, in addition to damage as a result of seismic activity (see, for example, CNL (2021a)).

It can be assumed that if issues of this nature were to arise before the end of the institutional control period, then the damage would be mitigated in some way, so this scenario is only relevant on timescales outside of the institutional control period. So, cautiously, the scenario examines the facility reaching its degraded condition instantly at the end of the institutional control period.

D 4.7 Increased Geosphere Bedrock Hydraulic Conductivity

The regional and site hydrogeological framework for the NPDDF site is described based on historical and 2019 local investigation and site characterization work completed at and in the vicinity of the NPD site and at the CRL site, review of Ontario Ministry of Environment, Conservation and Parks (OMECP) water well records, and review of the scientific literature (Arcadis & Geofirma, 2022). The presence and hydrogeological properties of the permeable fluvial sand and gravel layer that subparallels the Ottawa River and extends tile drain capture of overburden groundwater northwest of the NPDDF is identified as an uncertainty in modeling of groundwater flow at the NPDDF site (Arcadis & Geofirma, 2022).

However, uncertainty in the extent and hydrogeological properties of the fluvial sand and gravel layer located northwest of the NPDDF will have a negligible effect on the rate and location of overburden groundwater discharge from the NPDDF to the Ottawa River and hence the NPD closure and post-closure phases. Resolving the uncertainty on the location and hydrogeological properties of this fluvial sand and gravel layer would enhance the confidence in the 3-D groundwater flow model and the volumes of tile drain water, but that uncertainty primarily concerns the completeness of the site characterization work and not the fate of overburden groundwater discharge from the NPDDF to the Ottawa River (Arcadis & Geofirma, 2022).

Overall, the Geosynthesis Report (Arcadis & Geofirma, 2022) outlines the hydraulic conductivity best estimates for each of the hydrostratigraphic units based on site characterization data, and compares these values to the final calibrated values generated by the groundwater model. The discussions indicate that the calibrated values generated by the groundwater flow model are reasonable. However, to reflect the uncertainties in hydrogeological properties, a sensitivity study is considered here.

This case therefore examines increased hydraulic conductivity (and thus flow) in bedrock compared to NES, based on the information provided in the Arcadis & Geofirma (2023a) Groundwater Modelling Report.

D 4.8 Increased Geosphere Overburden Hydraulic Conductivity

Aligned with the “Increased Geosphere Bedrock Hydraulic Conductivity”, this case therefore examines increased hydraulic conductivity (and thus flow) in the overburden fill material between the facility and the river, compared to NES. Information provided in the Arcadis & Geofirma (2023a) Groundwater Modelling Report) is used, which assumes the highest hydraulic conductivity value for till (from the Arcadis & Geofirma (2022) Geosynthesis Report).

D 4.9 Increased Dilution in the River

This sensitivity scenario examines the impact of the river dilution factor, by applying a lesser dilution factor of 0.35 (similar to the ratio used for CNL’s NSDF project) as opposed to the factor of 0.658 used in NES. This approach is adopted to reflect the uncertainty in river flows, as river characteristics may vary throughout the year due to seasonal patterns and climate changes.

D 4.10 Self-Sufficient Indigenous Receptor

A self-sufficient indigenous receptor group, intended to represent traditional Indigenous lifestyles, is examined in a sensitivity case. The exposure characteristics outlined for this hypothetical receptor group, which is referred to as the Self-sufficient Indigenous receptor are quite conservative, and they bound the dietary and lifestyle of Indigenous communities in the area (based on the results of lifestyle surveys in SENES (2014), which found no distinct difference between the two demographic groups (Indigenous vs non-Indigenous communities)).

D 5 DISRUPTIVE EVENT SCENARIOS

D 5.1 Site Investigation (Inadvertent Human Intrusion)

In postclosure safety assessment a key scenario that requires consideration is one that could result in inadvertent but direct exposure to the waste itself. Key scenarios are categorized as future human actions and FEP group 1.4 deals with these.

In relation to the Facility, the most important aspect to consider is the resilience offered by the NPDDF structure. This will be covered with a robust concrete cap and engineered barrier once the facility has been decommissioned. Such a construction would be highly robust and would require specialist engineering to intrude into it. Specifically, until such a time that the concrete cap, engineered barrier and Facility structure becomes substantially degraded, the only plausible method of intrusion that would reach the wastes themselves would be to drill and core the Facility. This type of activity is, however, not uncommon as a method for investigating an unusual feature, which the Facility could readily be established as. The intrusion could, for example, be motivated by archaeological interests without knowledge of the nature of the Facility and its contents. Intrusion into the Facility *with prior knowledge* of its content is excluded from the scope of the postclosure safety assessment (see the assumptions in Appendix A and supporting references).

It is assumed that any site investigation would occur after the end of the institutional control period and to be conservative, the site is assumed to be disturbed at 100 y. More extensive excavation is considered much less likely due to the size and robustness of the structure. Moreover, it is assumed that investigation of the retrieved cores would reveal the nature of the Facility and prevent further intrusion.

The process of drilling, extracting and examining a core sample could lead to external and internal exposures. The drill crew would only be on site for a short period of time, however, while the investigation is undertaken. After this is complete it is assumed that drilling waste is left on the site and subsequently becomes mixed with soil. It could then result in exposures to a site resident using the soil for small-scale farming. An estimate of the mass of Zircaloy in the core sample was made, being 0.437 kg in 16.25 kg of grout, dictated by the core sample size of 4.5 m. Therefore, the 5 kg value of metal used is a factor of 10 more conservative than would be expected.

A related human intrusion scenario is excavation of the above-bedrock facility (considered as a Disruptive Event Scenario – see Section D 5.5). Full excavation of the facility (e.g., FEP #1.4.6) is evaluated as a What If case (see Section D 8.1).

Related FEPs are outlined in Table D-5 below.

Table D-5 Controlling FEPs for the Site Investigation Scenario

FEP #	Name	Comment
FEPs Included in All Scenarios (including Disruptive Events) *(See Appendix C)*		
1.1.1, 1.1.2, 1.1.3, 1.2.10, 1.3.2, 1.3.4, 1.3.8, 1.3.9, 1.4.8, 2.1.1.1, 2.1.1.2, 2.1.2.1, 2.1.2.4, 2.1.2.5, 2.3.6.1, 3.2.6.1, 4.1.1, , 4.1.6, 4.1.8, 4.2.2, 4.2.6, 4.3.1.1, 4.3.1.2, 4.3.1.6, 4.3.1.7, 5.1.1, 5.1.3.1, 5.3.1.2, 5.1.3.3, 5.1.5.2, 5.1.8, 5.1.9, 5.1.10, 5.1.11, 5.1.12, 5.1.14, 5.2.1, 5.2.2.1, 5.2.2.2, 5.2.2.4, 5.2.4, 5.3.1.1, 5.3.1.2, 5.3.1.3, 5.3.1.6, 5.3.2, 5.3.3, 5.3.4, 5.3.5, 5.3.6, 5.4.1, 5.4.2, 5.4.3, 5.4.4.1,5.4.5.1, 5.4.5.2, 5.4.6.1, 5.4.6.2, 5.4.7.1, 5.4.7.2.		
FEPs Drivers for this Disruptive Event – Site Investigation (Inadvertent Human Intrusion) Scenario		
1.1.4	Schedule and planning	
1.1.9	Administrative control	
1.1.11	Records and markers	
1.4.2	Social and institutional developments	
1.4.5	Drilling activities	Drilling may be unintentional or intentional, although given the obvious structure of the NPDDF the latter is more likely.
1.4.6	Mining and other underground activities	
2.4.3	Solid-mediated release	
2.4.4	Human-action-mediated release	
3.3.2	Gas-mediated migration (through Facility)	
3.3.3	Solid-mediated migration (from Facility)	
3.3.4	Human-action-mediated migration (from Facility)	
4.1.3	Geological resources	
4.3.3	Solid-mediated migration (geosphere)	
4.3.4	Human-action-mediated migration (geosphere)	

D 5.2 Surface Erosion

The Ottawa River is the receptor for potentially contaminated groundwater from the NPDDF, but as a major environmental feature close to the Facility, it may also impact it directly. There is limited variation in the river level at the present day, due to its extremely large catchment and flow rate. However, under certain circumstances it has been shown that a major flood is possible. Specifically, the combination of a major storm in the north and a catastrophic series of dam failures could lead to a surge in the river. This has been assessed and the maximum flood level at the NPDDF location is 132.2 mASL (i.e., a water level increase of 23.5 m), compared to the facility's elevation at 129 mASL (OPG, 1999). While this might not overtop the cap and earthen cover, it could denude surrounding ground by removing some of the overburden and thus change the pathways to the surface. This might be of significance and so this is relevant to consider as a Disruptive Event scenario, though noting the extreme nature of the assumptions required to generate the event (which are unlikely to occur within the 10,000 y assessment timeframe).

The consequences of a flood for the NPDDF are likely to involve a short period of very high flows of water through the geosphere. The effect of a sudden increase in flows through the overburden will be to dilute and decrease the concentration of contaminants in groundwater. Such a situation is not of interest from the perspective of the PostSA as it will result in a reduction in the environmental concentrations of contaminants compared with the Normal Evolution Scenario. Direct exposure of someone living on the site after the flood could consequently give rise to higher doses than the Normal Evolution Scenario, in which contamination is not discharged to the surface environment until it reaches the river, where it is diluted.

This situation is represented by assuming that a flood scours the surface and exposes contaminated overburden and rock through which groundwater flows, and that a person subsequently lives next to, and uses, the contaminated area in the same way as a site resident is assumed to in the Normal Evolution Scenario. The key difference is that in this scenario, contaminant concentrations will be significantly higher as contaminated groundwater will flow directly through the soil/sediment used by the resident.

This scenario also covers the consequences of other events that could erode the overburden and leave the area through which contaminated groundwater flows denuded. It therefore covers situations like a small ice-sheet advance and retreat, and even long-term aeolian erosion.

Related FEPs are outlined in Table D-6 below.

Table D-6 Controlling FEPs for the Surface Erosion Scenario

FEP #	Name	Comment
FEPs Included in All Scenarios (including Disruptive Events) *(See Appendix C)*		
1.1.1, 1.1.2, 1.1.3, 1.2.10, 1.3.2, 1.3.4, 1.3.8, 1.3.9, 1.4.8, 2.1.1.1, 2.1.1.2, 2.1.2.1, 2.1.2.4, 2.1.2.5, 2.3.6.1, 3.2.6.1, 4.1.1, , 4.1.6, 4.1.8, 4.2.2, 4.2.6, 4.3.1.1, 4.3.1.2, 4.3.1.6, 4.3.1.7, 5.1.1, 5.1.3.1, 5.3.1.2, 5.1.3.3, 5.1.5.2, 5.1.8, 5.1.9, 5.1.10, 5.1.11, 5.1.12, 5.1.14, 5.2.1, 5.2.2.1, 5.2.2.2, 5.2.2.4, 5.2.4, 5.3.1.1, 5.3.1.2, 5.3.1.3, 5.3.1.6, 5.3.2, 5.3.3, 5.3.4, 5.3.5, 5.3.6, 5.4.1, 5.4.2, 5.4.3, 5.4.4.1,5.4.5.1, 5.4.5.2, 5.4.6.1, 5.4.6.2, 5.4.7.1, 5.4.7.2.		
FEPs Drivers for this Disruptive Event - Surface Erosion Scenario		
1.3.7	Hydrological response to climate change	
1.4.9	Water management (groundwater and surface water)	
2.4.3	Solid-mediated release	
4.3.3	Solid-mediated migration (geosphere)	
5.1.13	Erosion and deposition	

D 5.3 Extreme Degradation

Damage to the Facility structure and grout could occur from a number of causes, and might result in the engineered structures not performing as anticipated (for example, unnoticed problems while pouring grout in the NPDDF rooms; issues with grout curing; extreme seismic event; etc.). This Extreme Degradation scenario captures these and other situations.

The Scenario is based on the anticipated effects of a 1:50,000-y seismic event. This could be 2 orders of magnitude more severe than the most degraded state in the NES. Conservatively, it is assumed to happen early in the postclosure period. However, it can be assumed that if issues of this nature were to arise before the end of the institutional control period, then the damage would be mitigated in some way, so this scenario is only relevant on timescales considerably outside of the institutional control period. Consequently, this scenario is assumed to occur at 1000 y past closure. After this period in time the facility enters an extremely degraded state – two orders of magnitude more severe than the most degraded stage in the NES. All other aspects of this scenario are the same as the Normal Evolution Scenario.

Given the nature of this scenario it would mainly impact FEPs #3.1.1 (facility buffer/backfill properties) and #3.1.2 (facility room/tunnel seals). Extreme degradation of the engineered barriers would then affect the associated hydraulic processes (FEP #3.2.2) and contaminant migration (FEP group 3.3). Other FEPs that could lead to conditions in which there is extreme degradation of the structure are also shown in Table D-7.

Related FEPs are outlined in Table D-7 below.

Table D-7 FEPs Related to Extreme Degradation Scenario

FEP	Name	Comment
FEPs Included in All Scenarios (including Disruptive Events) *(See Appendix C)*		
1.1.1, 1.1.2, 1.1.3, 1.2.10, 1.3.2, 1.3.4, 1.3.8, 1.3.9, 1.4.8, 2.1.1.1, 2.1.1.2, 2.1.2.1, 2.1.2.4, 2.1.2.5, 2.3.6.1, 3.2.6.1, 4.1.1, , 4.1.6, 4.1.8, 4.2.2, 4.2.6, 4.3.1.1, 4.3.1.2, 4.3.1.6, 4.3.1.7, 5.1.1, 5.1.3.1, 5.3.1.2, 5.1.3.3, 5.1.5.2, 5.1.8, 5.1.9, 5.1.10, 5.1.11, 5.1.12, 5.1.14, 5.2.1, 5.2.2.1, 5.2.2.2, 5.2.2.4, 5.2.4, 5.3.1.1, 5.3.1.2, 5.3.1.3, 5.3.1.6, 5.3.3, 5.3.4, 5.3.5, 5.3.6, 5.4.1, 5.4.2, 5.4.3, 5.4.4.1,5.4.5.1, 5.4.5.2, 5.4.6.1, 5.4.6.2, 5.4.7.1, 5.4.7.2.		
FEPs Drivers for this Disruptive Event – Extreme Degradation		
1.1.1	Quality assurance and control	Facility structure and grouted rooms are assumed to be built as designed. Unforeseen circumstances could result in poorer than anticipated performance.
1.1.5	Construction	Facility structure and grouted rooms are assumed to be built as designed. Unforeseen circumstances could result in poorer than anticipated performance.
1.1.6	Operation	Facility structure and grouted rooms are assumed to be built as designed. Unforeseen circumstances could result in poorer than anticipated performance.
1.1.7	Closure	Facility structure and grouted rooms are assumed to be built as designed. Unforeseen circumstances could result in poorer than anticipated performance.
1.2.4	Seismicity	Facility structure and grouted rooms are assumed to be built as designed. Unforeseen circumstances could result in poorer than anticipated performance.
3.1.1	Facility Characteristics & properties – Buffer/Backfill	Facility structure and grouted rooms are assumed to be built as designed. Unforeseen circumstances could result in poorer than anticipated performance.
3.1.2	Facility Characteristics & properties – Room/tunnel seals	Facility structure and grouted rooms are assumed to be built as designed. Unforeseen circumstances could result in poorer than anticipated performance.
3.1.5	Other engineered features	Facility structure and grouted rooms are assumed to be built as designed. Unforeseen circumstances could result in poorer than anticipated performance.
3.2.3.1	Material volume changes (Facility)	Facility structure and grouted rooms are assumed to be built as designed. Unforeseen circumstances could result in poorer than anticipated performance.
3.2.3.3	Collapse of openings	Facility structure and grouted rooms are assumed to be built as designed. Unforeseen circumstances could result in poorer than anticipated performance.
3.2.4.3	Migration of chemical species (Facility)	Facility structure and grouted rooms are assumed to be built as designed. Unforeseen circumstances could result in poorer than anticipated performance.
3.2.4.4	Corrosion (Facility)	Facility structure and grouted rooms are assumed to be built as designed. Unforeseen circumstances could result in poorer than anticipated performance.
4.2.3	Mechanical processes (geosphere)	Facility structure and grouted rooms are assumed to be built as designed. Unforeseen circumstances could result in poorer than anticipated performance.

D 5.4 Fault Zone Activation

It is assumed in the NES that the Facility will experience one or more 1-in-2,250-y events. Furthermore, given that the facility will remain in place long into the future, it is assumed to experience seismic events of even greater magnitudes, such as a 1-in-10,000-y event.

Seismic events of even greater magnitudes (such as a 1-in-50,000 y event) may have further impacts on the Facility's long-term performance and safety due to early degradation of engineered barriers (CNL, 2021a). Such events may also induce a fault zone of higher conductivity in the geosphere (specifically, bedrock near river) and this requires evaluation.

This Disruptive Event Scenario therefore examines the impact of an extreme seismic event occurring, damaging the facility (in the same manner as in the Extreme Degradation Case, see Section D 5.3), but also creating a fracture zone, which will be represented using a higher conductivity in the bedrock between the facility and the river compared to that of the NES.

Related FEPs are outlined in Table D-8 below.

Table D-8 FEPs Related to Fault Zone Activation Scenario

FEP	Name	Comment
FEPs Included in All Scenarios (including Disruptive Events) *(See Appendix C)*		
1.1.1, 1.1.2, 1.1.3, 1.2.10, 1.3.2, 1.3.4, 1.3.8, 1.3.9, 1.4.8, 2.1.1.1, 2.1.1.2, 2.1.2.1, 2.1.2.4, 2.1.2.5, 2.3.6.1, 3.2.6.1, 4.1.1, , 4.1.6, 4.1.8, 4.2.2, 4.2.6, 4.3.1.1, 4.3.1.2, 4.3.1.6, 4.3.1.7, 5.1.1, 5.1.3.1, 5.3.1.2, 5.1.3.3, 5.1.5.2, 5.1.8, 5.1.9, 5.1.10, 5.1.11, 5.1.12, 5.1.14, 5.2.1, 5.2.2.1, 5.2.2.2, 5.2.2.4, 5.2.4, 5.3.1.1, 5.3.1.2, 5.3.1.3, 5.3.1.6, 5.3.3, 5.3.4, 5.3.5, 5.3.6, 5.4.1, 5.4.2, 5.4.3, 5.4.4.1, 5.4.5.1, 5.4.5.2, 5.4.6.1, 5.4.6.2, 5.4.7.1, 5.4.7.2.		
FEPs Drivers for this Disruptive Event – Fault Zone Activation Scenario		
1.1.5	Construction	Facility structure and grouted rooms are assumed to be built as designed. Unforeseen circumstances could result in poorer than anticipated performance.
1.1.6	Operation	Facility structure and grouted rooms are assumed to be built as designed. Unforeseen circumstances could result in poorer than anticipated performance.
1.1.7	Closure	Facility structure and grouted rooms are assumed to be built as designed. Unforeseen circumstances could result in poorer than anticipated performance.
1.2.4	Seismicity	Under external conditions (e.g., seismic, glaciation) the mechanical properties of the geosphere will become important. Unforeseen circumstances could also impact the mechanical evolution of the geosphere.
3.1.1	Facility Characteristics & properties – Buffer/Backfill	Facility structure and grouted rooms are assumed to be built as designed. Unforeseen circumstances could result in poorer than anticipated performance.
3.1.2	Facility Characteristics & properties – Room/tunnel seals	Facility structure and grouted rooms are assumed to be built as designed. Unforeseen circumstances could result in poorer than anticipated performance.

FEP	Name	Comment
3.1.5	Other engineered features	Facility structure and grouted rooms are assumed to be built as designed. Unforeseen circumstances could result in poorer than anticipated performance.
3.2.3.1	Material volume changes (Facility)	Facility structure and grouted rooms are assumed to be built as designed. Unforeseen circumstances could result in poorer than anticipated performance.
3.2.3.3	Collapse of openings	Facility structure and grouted rooms are assumed to be built as designed. Unforeseen circumstances could result in poorer than anticipated performance.
3.2.4.3	Migration of chemical species (Facility)	Facility structure and grouted rooms are assumed to be built as designed. Unforeseen circumstances could result in poorer than anticipated performance.
3.2.4.4	Corrosion (Facility)	Facility structure and grouted rooms are assumed to be built as designed. Unforeseen circumstances could result in poorer than anticipated performance.
4.2.3	Mechanical processes (geosphere)	Under external conditions (e.g., seismic, glaciation) the mechanical properties of the geosphere will become important. Unforeseen circumstances could also impact the mechanical evolution of the geosphere.

D 5.5 Excavation of Above-Bedrock Facility

The mass excavation of the entire Facility is too unlikely to be considered to be a plausible Disruptive Event Scenario because the concrete structure would retain sufficient structural integrity to preclude it. In addition to the existing structure, it will be backfilled with grout and a concrete cap will be placed over the nuclear area as well as an engineered barrier over the entire facility. More limited examination (as considered in Section D 5.1) would be sufficient to reveal the characteristics of the Facility and deter any more large-scale disruption. Hence, this has been discussed in the context of “What If” calculations (see Section D 8.1).

Nevertheless, the consequences of the partial disruption and excavation of the NPDDF is of interest. This Disruptive Event scenario examines the impacts of the above-bedrock portion of the facility being excavated and mixed with soil (at a ratio of 1:10 grout and concrete to soil). The assumption is that there is no house built inside of the excavated hole and only the resident receptor is assumed to be exposed. Other aspects are similar to the “What if” Mass Excavation Scenario (see Section D 8.1).

Related FEPs are outlined in Table D-9 below.

Table D-9 Controlling FEPs for the Excavation of Above-Bedrock Facility Scenario

FEP #	Name	Comment
FEPs Included in All Scenarios (including Disruptive Events) *(See Appendix C)*		
1.1.1, 1.1.2, 1.1.3, 1.2.10, 1.3.2, 1.3.4, 1.3.8, 1.3.9, 1.4.8, 2.1.1.1, 2.1.1.2, 2.1.2.1, 2.1.2.4, 2.1.2.5, 2.3.6.1, 3.2.6.1, 4.1.1, , 4.1.6, 4.1.8, 4.2.2, 4.2.6, 4.3.1.1, 4.3.1.2, 4.3.1.6, 4.3.1.7, 5.1.1, 5.1.3.1, 5.3.1.2, 5.1.3.3, 5.1.5.2, 5.1.8, 5.1.9, 5.1.10, 5.1.11, 5.1.12, 5.1.14, 5.2.1, 5.2.2.1, 5.2.2.2, 5.2.2.4, 5.2.4, 5.3.1.1, 5.3.1.2, 5.3.1.3, 5.3.1.6, 5.3.2, 5.3.3, 5.3.4, 5.3.5, 5.3.6, 5.4.1, 5.4.2, 5.4.3, 5.4.4.1,5.4.5.1, 5.4.5.2, 5.4.6.1, 5.4.6.2, 5.4.7.1, 5.4.7.2.		
FEPs Drivers for this Excavation of Above-Bedrock Facility Scenario		
1.1.4	Schedule and Planning	Influences the earliest time at which inadvertent human intrusion can occur, based on the time at which institutional controls end.
1.1.9	Administrative Control	Influences the earliest time at which inadvertent human intrusion can occur, based on the time at which institutional controls end.
1.1.11	Records and Markers	Influences the earliest time at which inadvertent human intrusion can occur, based on the time at which institutional controls end.
1.4.2	Social and institutional developments	Influences the earliest time at which inadvertent human intrusion can occur, based on the time at which institutional controls end.
1.4.5	Drilling Activities	A very cautious assumption would be to assume the above-bedrock Facility structure was excavated, crushed and used.
1.4.6	Mining and other underground activities	A very cautious assumption would be to assume the above-bedrock Facility structure was excavated, crushed and used.
2.4.3	Solid-mediated release	A very cautious assumption would be to assume the above-bedrock Facility structure was excavated, crushed and used.
2.4.4	Human-action-mediated release	A very cautious assumption would be to assume the above-bedrock Facility structure was excavated, crushed and used.
3.3.3	Solid-mediated migration (from Facility)	A very cautious assumption would be to assume the above-bedrock Facility structure was excavated, crushed and used.
3.3.4	Human-action-mediated migration (from Facility)	A very cautious assumption would be to assume the above-bedrock Facility structure was excavated, crushed and used.
4.1.3	Geological resources	A very cautious assumption would be to assume the above-bedrock Facility structure was excavated, crushed and used.
4.3.3	Solid-mediated migration (geosphere)	A very cautious assumption would be to assume the above-bedrock Facility structure was excavated, crushed and used.
4.3.4	Human-action-mediated migration (geosphere)	A very cautious assumption would be to assume the above-bedrock Facility structure was excavated, crushed and used.

D 5.6 Overburden Well

In the vicinity of the NPDDF some properties use wells to extract water for domestic and agricultural use. Such wells extract water from formations in the rock well below the limited region that could become contaminated with releases from the Facility. It is therefore concluded to be very unlikely that a well in a desirable location, with sufficient productivity, reliability and quality, could intercept the contaminated groundwater. Nevertheless, the potential for exposure to well water for domestic use is clearly of interest in constraining the potential exposures that could arise from exposure to contaminated groundwater. This situation is therefore examined as a Disruptive Event case.

The well is assumed to be drilled after 100 y and be immediately downstream of the Facility, into the overburden intersecting the pipe trench. A well into the Facility itself would not be practical as the very low water flows through the Facility would mean that it is not productive. If a well were to be located between the Facility and the river so as to capture radionuclides in (overburden) groundwater, it could provide a pathway for a variety of exposure pathways including drinking water, vegetables (by irrigation), animals (by drinking water) and external irradiation from irrigated soil. The well pathway would effectively remove the geosphere and river from these pathways, leading to exposures with substantially less dilution.

The instigating FEP (see Table D-10) is within the future human actions group (FEP #1.4.9). It primarily impacts on FEP #5.3.1.1, groundwater discharge to biosphere, and consequent human exposure pathways.

Related FEPs are outlined in Table D-10 below.

Table D-10 Controlling FEPs for the Overburden Well Case

FEP	Name	Comment
FEPs Included in All Scenarios (including Disruptive Event Cases) *(See Appendix C)*		
1.1.1, 1.1.2, 1.1.3, 1.2.10, 1.3.2, 1.3.4, 1.3.8, 1.3.9, 1.4.8, 2.1.1.1, 2.1.1.2, 2.1.2.1, 2.1.2.4, 2.1.2.5, 2.3.6.1, 3.2.6.1, 4.1.1, , 4.1.6, 4.1.8, 4.2.2, 4.2.6, 4.3.1.1, 4.3.1.2, 4.3.1.6, 4.3.1.7, 5.1.1, 5.1.3.1, 5.3.1.2, 5.1.3.3, 5.1.5.2, 5.1.8, 5.1.9, 5.1.10, 5.1.11, 5.1.12, 5.1.14, 5.2.1, 5.2.2.1, 5.2.2.2, 5.2.2.4, 5.2.4, 5.3.1.1, 5.3.1.2, 5.3.1.3, 5.3.1.6, 5.3.3, 5.3.4, 5.3.5, 5.3.6, 5.4.1, 5.4.2, 5.4.3, 5.4.4.1, 5.4.5.1, 5.4.5.2, 5.4.6.1, 5.4.6.2, 5.4.7.1, 5.4.7.2.		
FEPs Drivers for this Disruptive Event – Overburden Well Case *(see Appendix C)*		
1.4.9	Water management (groundwater and surface water)	There are drains surrounding the Facility which will ultimately degrade. A well might be excavated downgradient of the Facility.
4.3.4	Human-action-mediated migration (geosphere)	After the reference institutional control period, there is a potential that the groundwater or surface water in the vicinity of the Facility could be used as a source of water for human use and/or industrial purposes. This water use could introduce pathways for contaminant movement and may impact the Facility long-term performance and safety. This requires representation in a Disruptive Event scenario involving a well.
5.2.2.3	Water source	Installation of a well downgradient of the facility is very unlikely (see Appendix C). However, the potential effects associated with use of a well intersecting water in the pipe trench are assessed as a Disruptive Event case.

D 5.7 Bedrock Well

In the vicinity of the NPDDF some properties use wells to extract water for domestic and agricultural use. Such wells extract water from formations in the rock well below the limited region that could become contaminated with releases from the Facility. It is therefore concluded to be very unlikely that a well in a desirable location, with sufficient productivity, reliability and quality, could intercept the contaminated groundwater. Nevertheless, the potential for exposure to well water for domestic use is clearly of interest

in constraining the potential exposures that could arise from exposure to contaminated groundwater. This situation is therefore examined as a Disruptive Event case.

The well is assumed to be drilled after 100 y and be immediately downstream of the Facility, into the bedrock intersecting the bedrock release plume between the Facility and the river. A well into the Facility itself would not be practical as the very low water flows through the Facility would mean that it is not productive. If a well were to be located between the Facility and the river so as to capture radionuclides in (bedrock) groundwater, it could provide a pathway for a variety of exposure pathways including drinking water, vegetables (by irrigation), animals (by drinking water) and external irradiation from irrigated soil. The well pathway would effectively remove the geosphere and river from these pathways, leading to exposures with substantially less dilution.

The instigating FEP (see Table D-11) is within the future human actions group (FEP #1.4.9). It primarily impacts on FEP #5.3.1.1, groundwater discharge to biosphere, and consequent human exposure pathways.

Related FEPs are outlined in Table D-11 below.

Table D-11 Controlling FEPs for the Bedrock Well Case

FEP	Name	Comment
FEPs Included in All Scenarios (including Disruptive Event Cases) *(See Appendix C)*		
1.1.1, 1.1.2, 1.1.3, 1.2.10, 1.3.2, 1.3.4, 1.3.8, 1.3.9, 1.4.8, 2.1.1.1, 2.1.1.2, 2.1.2.1, 2.1.2.4, 2.1.2.5, 2.3.6.1, 3.2.6.1, 4.1.1, , 4.1.6, 4.1.8, 4.2.2, 4.2.6, 4.3.1.1, 4.3.1.2, 4.3.1.6, 4.3.1.7, 5.1.1, 5.1.3.1, 5.3.1.2, 5.1.3.3, 5.1.5.2, 5.1.8, 5.1.9, 5.1.10, 5.1.11, 5.1.12, 5.1.14, 5.2.1, 5.2.2.1, 5.2.2.2, 5.2.2.4, 5.2.4, 5.3.1.1, 5.3.1.2, 5.3.1.3, 5.3.1.6, 5.3.2, 5.3.3, 5.3.4, 5.3.5, 5.3.6, 5.4.1, 5.4.2, 5.4.3, 5.4.4.1,5.4.5.1, 5.4.5.2, 5.4.6.1, 5.4.6.2, 5.4.7.1, 5.4.7.2.		
FEPs Drivers for this Disruptive Event – Bedrock Well Case *(see Appendix C)*		
1.4.9	Water management (groundwater and surface water)	There are drains surrounding the Facility which will ultimately degrade. A well might be excavated downgradient of the Facility.
4.3.4	Human-action-mediated migration (geosphere)	After the reference institutional control period, there is a potential that the groundwater or surface water in the vicinity of the Facility could be used as a source of water for human use and/or industrial purposes. This water use could introduce pathways for contaminant movement and may impact the Facility long-term performance and safety. This requires representation in a Disruptive Event scenario involving a well.
5.2.2.3	Water source	Installation of a well downgradient of the facility is very unlikely (see Appendix C). However, the potential effects associated with use of a contaminated well penetrating the bedrock are assessed as a Disruptive Event case.

D 6 DEFENCE-IN-DEPTH CASES

An important regulatory requirement for the PostSA is to build confidence in the performance of the NPDDF. There are a variety of confidence building activities, such as the application of a systematic approach to developing the PostSA. At the quantitative level, a key method for confidence building is the analysis of engineered barrier performance. This provides important information on the overall envelope of safety performance and the importance of specific design aspects.

The key barriers in the NPDDF are the facility as a whole, the grout planned to be added, the existing structure, and the wasteforms themselves. Each of these have been developed into calculation cases in order to examine their individual influence on the performance of the system.

It is important to note that the role of the facility *as a whole* (i.e., the existing structure and the grout fill) can be quantified by examining the consequences if it performed altogether less well than expected, i.e., as examined in: Disruptive Event Scenarios - Extreme Degradation, and Fault Zone Activation (see Sections D 5.3 and D 5.4); Sensitivity Case – Rapid Degradation (see Section D 4.6) or if the structure were simply bypassed, or not present. Assuming that the facility is not present is naturally a limiting situation that could not occur in practice (e.g., it would require the complete disruption/excavation of the Facility). Nevertheless, such a situation is examined in the 'What-If' Mass Excavation Scenario (see Section D 8.1).

There are a number of other engineered barriers that can be tested with less extreme assumptions.

- The strategy of grouting the internal spaces of the NPDDF can be explored to show the extent to which the performance of the Facility relies on the grout.
- The waste form itself is a potentially important barrier. Contamination is cautiously assumed to be dispersed in such a way that the radionuclides present are available for release from the point of closure. However, radionuclides in the most active wastes (the Calandria) are present within the matrix of highly corrosion-resistant components. These provide a barrier function, by limiting the rate of release of the radionuclides. The importance of this element of the disposal system is a suitable area for confidence building.

On this basis, there are two confidence building calculation cases:

- The role of the existing NPDDF concrete structure in safety performance; and
- The role of the grout within the NPDDF, as a whole, in safety performance.

It should be noted that the role of the wasteform in safety performance has been considered in the 3rd Iteration PostSA (Arcadis & Quintessa, 2020b), which demonstrated that although the corrosion rates were increased by a factor of 10 (compared to the NES), the highest increase in the rate of release of contaminants into the geosphere was a factor of 3.

D 6.1 Role of Existing Facility Structure

As mentioned in Appendix B, the NPDDF is represented in the PostSA as a series of cuboidal grout-filled "rooms", with walls on each face. The walls represent the existing concrete structure of the NPDDF. Similar to the grout fill, the existing facility structure is comprised mainly of concrete and so shares similar characteristics in that it is relatively porous (though less porous than the grout fill), and provides a substrate for sorption.

In order to provide a quantitative indication of the role of the existing structure, this calculation case examines the performance of the NPDDF *with* the following properties assigned to the existing concrete structure:

- In terms of chemical properties, structural concrete is modelled as being fully degraded, beginning at 0 y post-closure; and
- In terms of physical properties, structural concrete is modelled as being extremely degraded, beginning at 0 y post-closure.

In this hypothetical case the structural properties of the existing structure are assumed to remain (i.e., structural destabilization of the facility is not examined). All other aspects of the model are the same as the Normal Evolution Scenario.

Related FEPs are outlined in Table D-12 below.

Table D-12 Controlling FEPs for the Role of Existing Facility Structure Calculation Case

FEP	Name	Comment
FEPs Included in All Scenarios (including Defence-in-Depth) *(See Appendix C)*		
1.1.1, 1.1.2, 1.1.3, 1.2.10, 1.3.2, 1.3.4, 1.3.8, 1.3.9, 1.4.8, 2.1.1.1, 2.1.1.2, 2.1.2.1, 2.1.2.4, 2.1.2.5, 2.3.6.1, 3.2.6.1, 4.1.1, , 4.1.6, 4.1.8, 4.2.2, 4.2.6, 4.3.1.1, 4.3.1.2, 4.3.1.6, 4.3.1.7, 5.1.1, 5.1.3.1, 5.3.1.2, 5.1.3.3, 5.1.5.2, 5.1.8, 5.1.9, 5.1.10, 5.1.11, 5.1.12, 5.1.14, 5.2.1, 5.2.2.1, 5.2.2.2, 5.2.2.4, 5.2.4, 5.3.1.1, 5.3.1.2, 5.3.1.3, 5.3.1.6, 5.3.2, 5.3.3, 5.3.4, 5.3.5, 5.3.6, 5.4.1, 5.4.2, 5.4.3, 5.4.4.1,5.4.5.1, 5.4.5.2, 5.4.6.1, 5.4.6.2, 5.4.7.1, 5.4.7.2.		
FEPs Drivers for this Defence-in-Depth – Role of Existing Facility Structure Case *(see Appendix C)*		
1.1.1	QA and Control	Poor construction techniques could impact on the performance of the Facility.
1.1.3	Design	All of the above grade structures will be removed during decommissioning and most will be disposed in the subsurface vaults beneath the Main building. Hence, the facility design is an essential component of the Safety Assessment and so needs to be included.
3.1.5	Other engineered features	The existing facility is one of the engineered barriers. All engineered barriers need to be represented in the PostSA.

D 6.2 Role of Grout

The NPDDF is represented in the PostSA as a series of cuboidal "rooms", with walls on each face. In the Normal Evolution Scenario, each room is assumed to be completely filled with a homogeneous grout. In order to provide a quantitative indication of the significance of the grout as a substrate this calculation case examines the performance of the NPDDF with the grout having the following properties:

- In terms of chemical properties, the grout is modelled as being fully degraded, beginning at 0 y post-closure; and
- In terms of physical properties, the grout is modelled as being extremely degraded, beginning at 0 y post-closure.

All other aspects of the model are the same as the Normal Evolution Scenario.

Related FEPs are outlined in Table D-13 below.

Table D-13 Controlling FEPs for the Role of Grout Calculation Case

FEP	Name	Comment
FEPs Included in All Scenarios (including Defence-in-Depth) *(See Appendix C)*		
1.1.1, 1.1.2, 1.1.3, 1.2.10, 1.3.2, 1.3.4, 1.3.8, 1.3.9, 1.4.8, 2.1.1.1, 2.1.1.2, 2.1.2.1, 2.1.2.4, 2.1.2.5, 2.3.6.1, 3.2.6.1, 4.1.1, , 4.1.6, 4.1.8, 4.2.2, 4.2.6, 4.3.1.1, 4.3.1.2, 4.3.1.6, 4.3.1.7, 5.1.1, 5.1.3.1, 5.3.1.2, 5.1.3.3, 5.1.5.2, 5.1.8, 5.1.9, 5.1.10, 5.1.11, 5.1.12, 5.1.14, 5.2.1, 5.2.2.1, 5.2.2.2, 5.2.2.4, 5.2.4, 5.3.1.1, 5.3.1.2, 5.3.1.3, 5.3.1.6, 5.3.2, 5.3.3, 5.3.4, 5.3.5, 5.3.6, 5.4.1, 5.4.2, 5.4.3, 5.4.4.1,5.4.5.1, 5.4.5.2, 5.4.6.1, 5.4.6.2, 5.4.7.1, 5.4.7.2.		
FEPs Drivers for this Defence-in-Depth – Role of Grout Case *(see Appendix C)*		
1.1.1	QA and Control	Issues with QA and Control could lead to the grout not performing as planned.
1.1.3	Design	Application of the grout as a backfill to rooms is a design choice aimed at providing an additional engineered barrier, which is examined with this case.
3.1.1	Buffer/backfill	Application of the grout as a backfill to rooms is a design choice aimed at providing an additional engineered barrier, which is examined with this case.

D 7 ALTERNATIVE STRATEGY CASES

Regulatory guidance requires that the principle of optimization be applied to disposal facilities for radioactive wastes. An accepted method of optimizing the disposal system design is to examine alternative strategies for the closure of the Facility, and evaluate the effects on safety performance. The reference strategy for the closure of the NPDDF involves backfilling the Facility with grout with the Calandria and other wastes within the Facility. Alternative strategies for the closure of the NPDDF could focus on two aspects: a different approach to engineering the closed facility and, a strategy option for increasing the length of the Institutional Control Period. These are discussed further in the subsections below.

D 7.1 Engineered Approach

Earlier iterations of the PostSA (Arcadis & Quintessa, 2017a,b) as well as scoping calculations (Arcadis & Quintessa, 2019) did collectively assess a range of different alternative strategies, such as potential removal of the calandria, alternative backfill materials, and upgradient barrier walls. In the 3rd iteration PostSA (Arcadis & Quintessa, 2020b), in respect of engineering, the Defence-in-Depth scenarios illustrated the potential implications of not grouting the Facility. However, at the time of this 4th iteration PostSA, engineering options/variants are no longer being contemplated. Hence, the Defence-in-Depth scenario in this 4th Iteration PostSA considers grout as being fully degraded (chemically) and extremely degraded (physically).

D 7.2 Longer Institutional Control

In the Normal Evolution scenario, the period of institutional control is 100 y. An alternative strategy could be to have a longer period of institutional control. 300 y is considered the longest time over which institutional controls could reasonably be assumed to be in place. The main impact of a longer institutional control period is that site investigation will not be able to occur for 300 y. The 2nd iteration of the Postclosure Safety Assessment (Arcadis *et al.,* 2017) included a scenario examining this, and the results showed that extending the period of institutional control from 100 y to 300 y does not substantially reduce the dose rate to an inadvertent human intruder. Hence, this 4th Iteration PostSA considers that the period of institutional control is 100 y.

D 8 "WHAT IF" CASES

"What If" cases represent a deliberately extreme set of assumptions that can be used to understand the absolute limits to safety performance. These have been identified as potentially of interest in the same way as other scenarios and calculation cases, but discounted from the main set of assessment calculations on the basis that they are of very low or negligible likelihood. Nevertheless, they inform on the underlying bounds to postclosure safety and, as such, provide valuable perspective. However, due to their very low likelihood they are not for comparison to any criteria.

D 8.1 Facility Mass Excavation

The mass excavation of the entire Facility is too unlikely to be considered to be a plausible Disruptive Event Scenario because the concrete structure would retain sufficient structural integrity to preclude it. In addition to the existing structure, it will be backfilled with grout and a concrete cap will be placed over the nuclear area as well as an engineered barrier over the entire facility. More limited examination (as considered in Section D 5.1) would be sufficient to reveal the characteristics of the Facility and deter any more large-scale disruption.

Nevertheless, in the context of "What If" calculations, the consequences of the complete disruption and excavation of the NPDDF is of interest. This calculation case provides a basic perspective on the intrinsic hazard of the radioactive material in the Facility. A suitably stylized calculation case can consider the potential consequences to a site resident if the entire inventory of the Facility is dispersed in surface soils that are subsequently used, e.g., for cultivating foods. It is conservatively assumed to occur after 100 y.

Related FEPs are outlined in Table D-14 below.

Table D-14 Controlling FEPs for the Mass Excavation Case

FEP	Name	Comment
FEPs Included in All Scenarios (including What-If Cases) *(See Appendix C)*		
1.1.1, 1.1.2, 1.1.3, 1.2.10, 1.3.2, 1.3.4, 1.3.8, 1.3.9, 1.4.8, 2.1.1.1, 2.1.1.2, 2.1.2.1, 2.1.2.4, 2.1.2.5, 2.3.6.1, 3.2.6.1, 4.1.1, , 4.1.6, 4.1.8, 4.2.2, 4.2.6, 4.3.1.1, 4.3.1.2, 4.3.1.6, 4.3.1.7, 5.1.1, 5.1.3.1, 5.3.1.2, 5.1.3.3, 5.1.5.2, 5.1.8, 5.1.9, 5.1.10, 5.1.11, 5.1.12, 5.1.14, 5.2.1, 5.2.2.1, 5.2.2.2, 5.2.2.4, 5.2.4, 5.3.1.1, 5.3.1.2, 5.3.1.3, 5.3.1.6, 5.3.2, 5.3.3, 5.3.4, 5.3.5, 5.3.6, 5.4.1, 5.4.2, 5.4.3, 5.4.4.1,5.4.5.1, 5.4.5.2, 5.4.6.1, 5.4.6.2, 5.4.7.1, 5.4.7.2.		
FEPs Drivers for this What If – Mass Excavation Case *(see Appendix C)*		
1.4.6	Mining and other underground activities	An extremely cautious assumption would be to assume the entire Facility structure were excavated, crushed and used.
1.1.4	Schedule and planning	Influences the earliest time at which inadvertent human intrusion can occur, based on the time at which institutional controls end.
1.1.9	Administrative control	Influences the earliest time at which inadvertent human intrusion can occur, based on the time at which institutional controls end.
1.1.11	Records and markers	Influences the earliest time at which inadvertent human

FEP	Name	Comment
		intrusion can occur, based on the time at which institutional controls end.
1.4.2	Social and institutional developments	Influences the earliest time at which inadvertent human intrusion can occur, based on the time at which institutional controls end.
1.4.5	Drilling activities	An extremely cautious assumption would be to assume the entire Facility structure were excavated, crushed and used.
2.4.3	Solid-mediated release	An extremely cautious assumption would be to assume the entire Facility structure were excavated, crushed and used.
2.4.4	Human-action-mediated release	An extremely cautious assumption would be to assume the entire Facility structure were excavated, crushed and used.
3.3.2	Gas-mediated migration [through Facility]	If a gas phase exists in the Facility, e.g., before saturation of the Facility or as a result of gas generation, the gaseous contaminants may move through the gas phase (by diffusion), or be transported with the gas phase (by convection or advection), out of the Facility. Alternatively, gas pressures could be sufficiently high to form an unsaturated phase where two-phase flow is important, or to expel contaminants dissolved in groundwater from parts of the Facility and geosphere. The only situation that this could occur in is considered to be site investigation drilling that penetrates the facility.
3.3.3	Solid-mediated migration [from Facility]	An extremely cautious assumption would be to assume the entire Facility structure were excavated, crushed and used.
3.3.4	Human-action-mediated migration [from Facility]	An extremely cautious assumption would be to assume the entire Facility structure were excavated, crushed and used.
4.1.3	Geological resources	An extremely cautious assumption would be to assume the entire Facility structure were excavated, crushed and used.
4.3.3	Solid-mediated migration [geosphere]	An extremely cautious assumption would be to assume the entire Facility structure were excavated, crushed and used.
4.3.4	Human-action-mediated migration [geosphere]	An extremely cautious assumption would be to assume the entire Facility structure were excavated, crushed and used.

D 8.2 River Level Fall

In the future, the Ottawa River is the main receptor for groundwater containing contaminants from the NPDDF. It is unlikely that the river level would change very substantially from its current position; this would require major changes to precipitation and runoff in the overall catchment of the Ottawa River. However, future environmental conditions are a source of uncertainty. This calculation case provides an

indication of the consequences of river level fall, conservatively assuming that the situation occurs after only 100 y, when the inventory of the NPDDF is higher.

This “What If” case considers a fall in the river level of several metres, sufficient to permit groundwater to be released directly to the shore. The case primarily involves an effect on FEP #5.3.1.1 (groundwater discharge to biosphere). It can be represented in the PostSA by directing all groundwater to the shoreline sediments rather than the river bed, resulting in significantly higher activity concentrations in the terrestrial environment. The same exposure groups assessed in the Normal Evolution Scenario are used to assess the potential effects of this case.

Related FEPs are outlined in Table D-15 below.

Table D-15 Controlling FEPs for the River Level Fall Case

FEP	Name	Comment
FEPs Included in All Scenarios (including What-If Cases) *(See Appendix C)*		
1.1.1, 1.1.2, 1.1.3, 1.2.10, 1.3.2, 1.3.4, 1.3.8, 1.3.9, 1.4.8, 2.1.1.1, 2.1.1.2, 2.1.2.1, 2.1.2.4, 2.1.2.5, 2.3.6.1, 3.2.6.1, 4.1.1, , 4.1.6, 4.1.8, 4.2.2, 4.2.6, 4.3.1.1, 4.3.1.2, 4.3.1.6, 4.3.1.7, 5.1.1, 5.1.3.1, 5.3.1.2, 5.1.3.3, 5.1.5.2, 5.1.8, 5.1.9, 5.1.10, 5.1.11, 5.1.12, 5.1.14, 5.2.1, 5.2.2.1, 5.2.2.2, 5.2.2.4, 5.2.4, 5.3.1.1, 5.3.1.2, 5.3.1.3, 5.3.1.6, 5.3.2, 5.3.3, 5.3.4, 5.3.5, 5.3.6, 5.4.1, 5.4.2, 5.4.3, 5.4.4.1,5.4.5.1, 5.4.5.2, 5.4.6.1, 5.4.6.2, 5.4.7.1, 5.4.7.2.		
FEPs Drivers for this What If – River Leve Fall Case *(see Appendix C)*		
1.2.12	Hydrological/hydrogeological response to geological changes	Large-scale geological changes are not relevant for the site and the timescale of concern. However, if river levels were to drop due to changes in the catchment, discharge from the NPDDF could arise on the shore rather than beneath the river.
1.3.1	Global climate change	Climate change will be represented in all scenarios; however, glaciation is not considered to be likely earlier than 100,000 y.
1.3.7	Hydrological response to climate change	In the onset of a glacial episode, ice sheet development to the north of the site could result in less precipitation entering the Ottawa River, as it accumulates as snow and ice. Similarly, a change leading to dryer conditions over much of Canada could have similar consequences. In either case, the result could be a reduction in the level of the river and adjustment of the hydrogeology local to the NPDDF. This could lead to a larger proportion of the contaminated groundwater discharging through surface springs rather than to the riverbed.
5.1.5.3	Springs and discharging zones	For contaminants released from the NPDDF into shallow groundwater, the discharge zone is expected to be to the river bed close (perhaps within metres of) the shore. This interface is important to represent as it determines the dilution and dispersion characteristics of contaminants in the biosphere.

D 8.3 Undetected Fracture Zone

The natural or man-made features within the geosphere that may not be detected during the site investigation (e.g., fracture zones, faults, brine pockets, old mine workings, and boreholes) could play a role in the transport of groundwater to and from the Facility and the associated migration of contaminants. Some physical features of the geological environment may remain undetected during site surveys and even during pilot tunnel excavations (Arcadis & Geofirma, 2022). The nature of the geological environment will indicate the likelihood that certain types of undetected features may be present, and the site investigation may be able to place bounds on the maximum size or minimum proximity to such features.

Hence, this case examines the impact of an undetected fracture zone being present. In this proposed case, the facility evolves as per the NES but the bedrock is assigned a higher hydraulic conductivity. This combination of conditions is the same as would be modelled in the "Sensitivity Case – Increased Geosphere Bedrock Hydraulic Conductivity" (see Section D 4.7).

Related FEPs are outlined in Table D-16 below.

Table D-16 Controlling FEPs for the Undetected Fracture Zone Case

FEP	Name	Comment
FEPs Included in All Scenarios (including What-If Cases) *(See Appendix C)*		
1.1.1, 1.1.2, 1.1.3, 1.2.10, 1.3.2, 1.3.4, 1.3.8, 1.3.9, 1.4.8, 2.1.1.1, 2.1.1.2, 2.1.2.1, 2.1.2.4, 2.1.2.5, 2.3.6.1, 3.2.6.1, 4.1.1, , 4.1.6, 4.1.8, 4.2.2, 4.2.6, 4.3.1.1, 4.3.1.2, 4.3.1.6, 4.3.1.7, 5.1.1, 5.1.3.1, 5.3.1.2, 5.1.3.3, 5.1.5.2, 5.1.8, 5.1.9, 5.1.10, 5.1.11, 5.1.12, 5.1.14, 5.2.1, 5.2.2.1, 5.2.2.2, 5.2.2.4, 5.2.4, 5.3.1.1, 5.3.1.2, 5.3.1.3, 5.3.1.6, 5.3.2, 5.3.3, 5.3.4, 5.3.5, 5.3.6, 5.4.1, 5.4.2, 5.4.3, 5.4.4.1,5.4.5.1, 5.4.5.2, 5.4.6.1, 5.4.6.2, 5.4.7.1, 5.4.7.2.		
FEPs Drivers for this What If – Well in Contaminated Plume Case *(see Appendix C)*		
4.1.2	Large-scale discontinuities	The presence of a large-scale discontinuity feature (such as a shear zone or similar feature) is not credible. However, the impact of the undetected feature is considered in a "What if" scenario.
4.1.4	Undetected features	The presence of a large-scale discontinuity feature (such as a shear zone or similar feature) is not credible. However, the impact of the undetected feature is considered in a "What if" scenario.

D 9 SUMMARY

In order to ensure that people and the environment are sufficiently protected from any residual radioactivity, postclosure assessment scenarios need to be selected so that they take account of the specific characteristics of the NPDDF. The scenarios selected for assessment also need to represent those that are likely to lead to the highest exposures that can be reasonably anticipated. Calculation cases are related to scenarios, but are more stylized calculations intended to illustrate the performance characteristics of the Facility.

This appendix has identified scenarios for the postclosure safety analysis of the Facility, based on an evaluation of the NPDDF FEPs, the findings of prior iterations of the PostSA (e.g., Arcadis & Quintessa, 2017a,b; 2020b), and taking into account the overall assessment context for this 4th iteration PostSA study. The following scenarios have been selected.

- Normal Evolution Scenario.
- Sensitivity Calculations:
  - Measured Radionuclide Inventory;
  - Increased Modelled Radionuclide Inventory;
  - Reduced Near-field Sorption;
  - Reduced Far-field Sorption;
  - Reduced Sorption in Near-field and Far-field;
  - Rapid Degradation;
  - Increased Geosphere Bedrock Hydraulic Conductivity;
  - Increased Geosphere Overburden Hydraulic Conductivity;
  - Increased Dilution in the River; and,
  - Self-sufficient Indigenous Receptor.
- Disruptive Event Scenarios:
  - Site Investigation (Inadvertent Human Intrusion);
  - Surface Erosion;
  - Extreme Degradation;
  - Fault Zone Activation;
  - Excavation of Above-Bedrock Facility;
  - Overburden Well; and,
  - Bedrock Well.

These scenarios are accompanied by a range of calculation cases.

- Defence-in-Depth Cases include:
  - Role of Existing Facility Structure (sensitivity to the properties attributed to the existing facility concrete structure); and,
  - Role of Grout (sensitivity to properties attributed to the grout).
- What If Cases comprise:
  - Facility Mass Excavation;
  - River Level Fall; and,
  - Undetected Fracture Zone.

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APPENDIX E: CONCEPTUAL MODELS AND DATA

APPENDIX E - CONCEPTUAL MODELS AND DATA

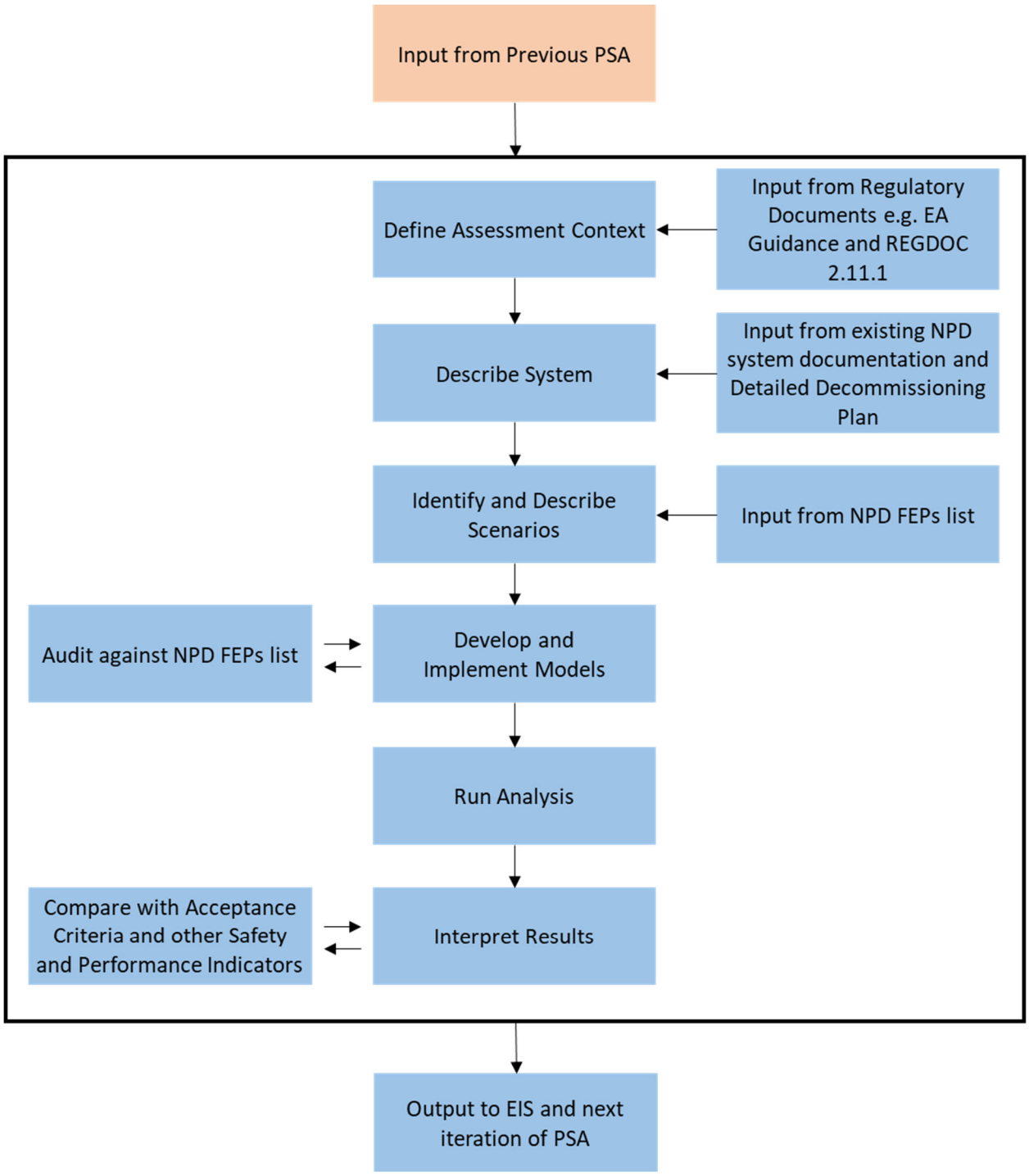
E 1 INTRODUCTION

Canadian Nuclear Laboratories (CNL, acting on behalf of Atomic Energy of Canada Limited, AECL) is proposing in-situ disposal of the Nuclear Power Demonstration Waste Facility (NPDWF), thereafter referred to as the Nuclear Power Demonstration Disposal Facility (NPDDF). This 4th Iteration Postclosure Safety Assessment (PostSA) will support the final EIS submission.

This 4th Iteration PostSA has been undertaken using international best practice, specifically the International Atomic Energy Agency's (IAEA's) Improving Safety Assessment Methodologies (ISAM) guidance (IAEA, 2004). This is a systematic, stepwise approach, the main stages of which are illustrated in Figure E-1. This PostSA has been documented in a way that corresponds to the ISAM approach, with a main report describing the key elements of the assessment and its outcomes.

This appendix addresses the definition of the conceptual models to represent the NPDDF and its surrounding environment (i.e., fourth step in ISAM approach), and specifies the data that are used to describe it. The conceptual models are described in Section E 2 and the data are presented in Section E 3. The corresponding mathematical models are presented in Appendix F.

Figure E-1 Approach to Postclosure Safety Assessment, Adapted from ISAM (IAEA, 2004)



E 2 CONCEPTUAL MODELS

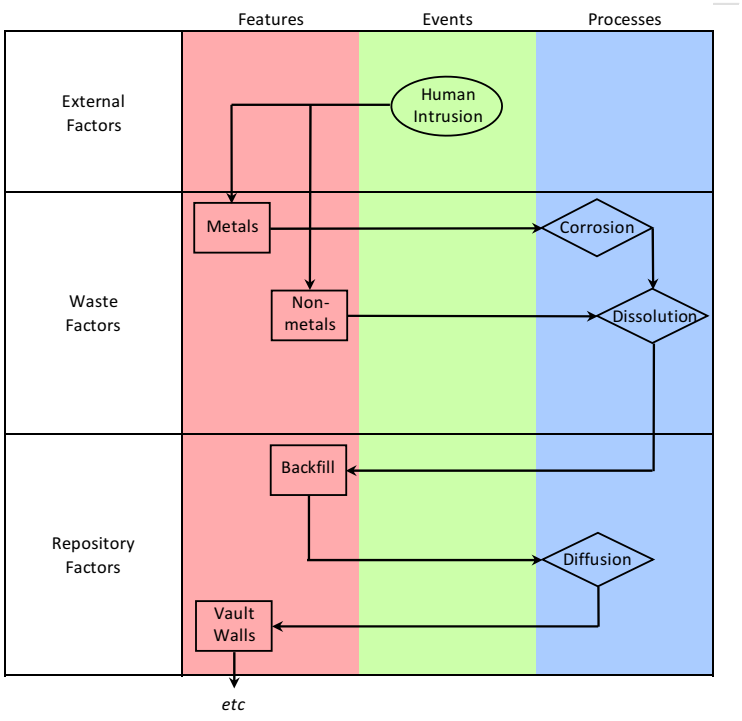
E 2.1 Model Development Process

The screened FEP list (Appendix C) provides a basis for the conceptual model of the Normal Evolution (and other) scenarios and calculation cases since it identifies the FEPs that need to be considered in the model. The conceptual model development process that has been used is based on IAEA's guidance (IAEA, 2004). This involves organising the significant FEPs and their linkages (see Figure E-2). FEPs are organised into those outside the modelled system (External FEPs, considered in generating scenarios), and those concerning:

- contaminants and waste;
- the facility;
- the geosphere; and
- the biosphere.

Although there are linkages between them, each part of the system has specific considerations and so it is common to develop conceptual models and associated data in terms of these main elements. This is the approach that has been used through this study, with the exception that the contaminants, waste and the facility have been treated together as they are intrinsically linked.

Figure E-2 Illustration of the development of an example conceptual model through the combination of Features, Events and Processes



The models themselves are then developed by taking those FEPs considered to be relevant to the system and using them to determine the physical components of the model, and their characteristics (referred to as the "media") and the processes that can act on them (primarily related to contaminant transport). It is also necessary to consider if (and if so how) the media and/or processes may change over the period of the assessment. The outcome, a network of media that are connected by processes, constitutes the conceptual model and provides the basis for the mathematical model. Conceptual models for other scenarios are described in terms of aspects that differ from the Normal Evolution scenario. The level of detail of the conceptual model is sufficient for representing the system over the assessment timescale considered in the PostSA (see Appendix A).

Accompanying the conceptual model is the specific information needed to describe it, the model data. Consistent with the assessment context, presented in Appendix A, an attempt to be realistic where possible, but often including deliberate cautious bias to manage uncertainty has been used to define parameters, noting that in many cases there are uncertainties. Site-specific model data have been drawn from the data sources referred to in the System Description (see Appendix B), supplemented with other data sources as required. There is also a range of data that are not site-specific which are drawn mainly from international compilations of data (e.g., radiation dose coefficients (ICRP, 2012)) and Canadian guidance (e.g., generic biosphere data such as edible crop yield (CSA, 2022)).

It is important to note that, for radionuclides, the assessment focuses primarily on determining a dose to people in suitably conservative hypothetical exposure groups. Whereas for non-radiological chemicals the assessment focuses on determining concentrations in environmental media for comparison against screening criteria.

E 2.2 Normal Evolution Scenario

E 2.2.1 Scenario Description

The Normal Evolution scenario is a reference description of a defensible scenario with conservative bias built into the assumptions of the evolution of the Facility and its surrounding environment. The scenario is developed in Appendix D and summarised below.

It assumes that the Facility is closed as planned with no unforeseen events, and a period of institutional control of 100 y follows.

Radionuclide releases from neutron-activated metal wastes in the Reactor Vault occur by corrosion once the NPDDF has resaturated. Contamination in other materials in the NPDDF, where located below the water table, is assumed to be instantly available once resaturation has occurred provided the aqueous solubility limit is not reached. Contaminants in solution may then migrate by diffusion and, as the concrete structure degrades, by advection. For a period, the porewater will be alkaline due to the conditioning effect of the cement. Contaminants will sorb to the cement and their migration will be retarded. Groundwater will gradually leach cement constituents and degrade the concrete and grout, increasing its permeability and ultimately reducing the pH to near neutral.

Initially, the rooms within the NPDDF are free of groundwater. However, as the Facility resaturates, and associated structures such as the Tile Drains that deflect groundwater away from the NPDDF degrade, the entire Facility is expected to become saturated.

Groundwater flows in the vicinity of the NPDDF are dominantly through the base of the overburden. The flow is determined largely by recharge up-gradient (westwards) of the Facility. Groundwater will be deflected by the NPDDF and flow around the facility and be captured by the tile drain, for a period. The tile drain is, however, expected to degrade and collapse whereupon its influence will cease. Groundwater downgradient of the facility will flow towards the river. Some water from the overburden may emerge as groundwater springs. Water flowing through the bedrock is expected to discharge under the riverbed, close to the shore. Contaminants will sorb to the geosphere media, which will retard their transport. The transport will be primarily by advection and dispersion.

Contaminants released to the river can sorb to sediments or be taken up by aquatic flora and fauna, but the dominant process will be advection, dispersion and subsequent dilution in the water. Cautiously, river water is assumed to be extracted for domestic and agricultural use. The most conservative situation that can be reasonably expected is that water is extracted from close to the point of groundwater discharge and used by a small settlement or farm. The water could be used for drinking by people, and also to irrigate soil for crops that are subsequently consumed.

Members of the community may also use the river in other ways. It is a significant source of fish, which could take up contaminants from the water and then be ingested. A person fishing the river would also be exposed to contaminants sorbed onto bank sediments. They may swim in the river and would be likely to use it for washing. In addition to such a community, wild animals could be exposed to contaminants by living in and drinking the river water. Other people, such as self-sufficient and Indigenous people following a traditional lifestyle, or recreational users of the land (including those fishing the river) may therefore be exposed to contaminants in the river water.

Based on the findings of CNL (2019a, 2021a), the Normal Evolution Scenario assumes that 1-in-2250-y seismic events occur, as well as a 1-in-10,000-y event at 1,000 y; these produce cracks in the above-grade portion of the facility.

The outcome of the NPD Underground Structure Seismic Assessment (CNL, 2021a) indicates that parts of the underground structure of NPDDF are not able to withstand a Chalk River Laboratories Design Basis Earthquake (CRL DBE), 1-in-10,000 y, and 1-in-50,000 y seismic event after grouting of the structure. As per the results obtained in this assessment, shear failures/cracks are the dominant failure modes for all cases. Below the bedrock elevation level, the NPDDF structure is socketed into surrounding bedrock on all sides and does not experience structural failure/cracking due to the continuous lateral support provided by the bedrock. The grouted structure, as well as the lateral support provided by the bedrock increases the stiffness of the NPDDF structure.

Groundwater modelling (Arcadis & Geofirma, 2023a) has investigated effects of cracking by representing an increased hydraulic conductivity in the affected above-bedrock portion of the facility.

The cracked above-bedrock region is modelled as an equivalent porous medium (EPM) – i.e., flow is through the whole volume of the NPDDF above the bedrock (this is overly conservative as the water "sees" all contaminants as it passes through the facility). An EPM representation is deemed suitable as the hydraulic conductivity of intact bedrock is several orders of magnitude lower than the lowest K value measured from straddle-packer testing, hence all of the reported K values are attributed to the presence of fractures, either as individual discontinuities or as part of small fracture zones (Arcadis & Geofirma, 2022). Given the ubiquitous occurrence of small-scale fractures and fracture zones, the bedrock in groundwater flow models is represented as an EPM with spatially variable, isotropic representation of the rock mass hydraulic conductivity (Arcadis & Geofirma, 2022). A sensitivity study undertaken during the second iteration of the PostSA (Arcadis & Quintessa, 2018) compared results from an EPM model with representations of the Facility in which the equivalent flows were modelled with either a dense or sparse network of cracks. This demonstrated that the EPM model was conservative, resulting in doses that were between 1.8 and 2.5 times greater than the models that explicitly represented transport in fractures.

E 2.2.2 Waste and Facility

The screened list of FEPs relating to wastes (FEP group 2) and the Facility (FEP group 3) is shown in Table E-1. This table also summarises the treatment of the FEP in the conceptual model. The following paragraphs provide a narrative description of the conceptual model and how the FEPs are represented.

Table E-1 Representation of Waste and Facility FEPs in the Conceptual Model

FEP	Title	Incorporation in Conceptual Model
2.1.1.1	Radionuclide content	Initial inventory of contaminants
2.1.1.2	Chemical content	Initial inventory of contaminants
2.1.2.1	Metals	Release of contaminants from corroding metals into water
2.1.2.4	Immobilization Matrix	Presence of grout in the facility
2.1.2.5	Deposits on surfaces	Instant release of surface contamination into water
2.3.2.1	Saturation/desaturation	Gradual resaturation of the Facility and Reactor Vault
2.3.4.2	Evolution of Eh conditions (waste form/waste package)	Cement degradation effects on sorption and solubility
2.3.4.3	Migration of chemical species (waste form/waste package)	Corrosion controlled release of activation products in metals, instant release of other contaminants
2.3.4.4	Corrosion (waste form/waste package)	Corrosion controlled release of activation products in metals
2.3.4.5	Alteration (waste form/waste package)	Cement degradation effects on sorption and solubility
2.3.4.6	Precipitation (waste form/waste package)	Cement degradation effects on sorption and solubility

FEP	Title	Incorporation in Conceptual Model
2.3.6.1	Radioactive decay and ingrowth (waste form/waste package)	Representation of decay and ingrowth
2.4.1.1	Dissolution (waste form)	Corrosion controlled release of activation products in metals, instant release of other contaminants
2.4.1.2	Diffusion (waste form)	Diffusion of contaminants through concrete and cement
2.4.1.3	Speciation and solubility (waste form)	Solubility controls on dissolution of contaminants into water
2.4.1.4	Sorption and desorption (waste form)	Cement degradation effects on sorption and solubility
2.4.3	Solid-mediated release	Erosion, human intrusion, excavation of above-bedrock facility and mass excavation considered in additional scenarios and cases
2.4.4	Human-action-mediated release	Human intrusion, excavation of above-bedrock facility and mass excavation assessed in additional scenarios and cases
3.1.1	Buffer/backfill	Representation of backfill in Facility voids, assumed to be cement grout
3.1.2	Room/tunnel seals	Pipes to Ottawa River assumed sealed
3.1.5	Other engineered features	Representation of the existing Facility structure and representation of an emplaced engineered cover.
3.1.6	Excavation damaged and disturbed zones	Representation of the grouted infill surrounding the Facility structure
3.2.2.1	Desaturation/resaturation	Gradual resaturation of the Facility after closure.
3.2.3.1	Material volume changes (Facility)	Rebar corrosion resulting in concrete cracking and degradation, increase in hydraulic conductivity (considered in sensitivity and disruptive event scenarios)
3.2.3.3	Collapse of openings (Facility)	Considered as enhanced degradation in disruptive events
3.2.4.1	Evolution of pH conditions (Facility)	Cement degradation effects on porosity, sorption and solubility (and potentially hydraulic conductivity)
3.2.4.2	Evolution of Eh conditions (Facility)	Chemical effects on sorption and solubility
3.2.4.3	Migration of chemical species (Facility)	Advection and diffusion of contaminants
3.2.4.4	Corrosion (Facility)	Rebar corrosion resulting in concrete cracking and degradation, increase in hydraulic conductivity
3.2.4.5	Alteration (Facility)	Cement degradation effects on porosity, sorption and solubility
3.2.4.7	Complexation (Facility)	Chemical effects on sorption and solubility
3.2.6.1	Radioactive decay and ingrowth (Facility)	Representation of radioactive decay and ingrowth
3.3.1.1	Advection (Facility)	Representation of advective transport of contaminants
3.3.1.2	Dispersion (Facility)	Representation of dispersion of contaminants
3.3.1.3	Diffusion (Facility)	Representation of diffusion of contaminants

FEP	Title	Incorporation in Conceptual Model
3.3.1.4	Dissolution, precipitation, and crystallization (Facility)	Contaminants dissolve in water
3.3.1.5	Speciation and solubility (Facility)	Solubility controls on dissolution of contaminants into water
3.3.1.6	Sorption and desorption (Facility)	Representation of sorption and desorption of contaminants
3.3.3	Solid-mediated migration (from facility)	Represented in Disruptive Event (Surface Erosion, Site Investigation (Inadvertent Human Intrusion), Excavation of Above-Bedrock Facility) and What If (Facility Mass Excavation) cases
3.3.4	Human-action-mediated migration (from facility)	Represented in Disruptive Event (Site Investigation (Inadvertent Human Intrusion), Excavation of Above-Bedrock Facility) and What If (Facility Mass Excavation) cases

Waste and Facility Media

The Facility comprises the radioactive material within the NPDDF structure, the grout backfill within the structure, and the structure itself. It also includes the infill between the NPDDF structure and the surrounding bedrock and overburden. These bulk materials will differ in properties that will influence the transport of radioactive contaminants through them (contaminants, listed in Section E 3.1, are present in much lower quantities or concentrations than the bulk materials).

The conceptual model therefore needs to distinguish between:

- the existing NPD concrete structure and any waste placed within it;
- the grout backfill added to the NPDDF; and
- infill surrounding the NPDDF (concrete where the NPDDF is within bedrock).

The groundwater flows that act on the materials differ in the overburden and bedrock regions, therefore structure and grout backfill above the bedrock needs to be treated differently from that below the bedrock. The overburden will also be largely unsaturated while tile drains function. For the purposes of the PostSA, the water table outside the Facility is assumed to sit just above the bedrock surface during this period, rising up to the surface when the tile drains cease to function. The water table inside the Facility is higher than outside. Arcadis & Geofirma (2023a) provides estimated water table contours based on groundwater flow modelling for various scenarios.

It is also necessary to distinguish the waste materials where their properties are significantly different from the NPDDF structure. As noted in the System Description (Appendix B), the majority of the radioactivity is assumed to be associated with the pressure tubes, Calandria, and associated structures. This includes activation products which are present within the matrix of materials. Consequently, the different types of metals, concrete, and other surface contamination need to be represented separately, as the contaminants will be released at different rates from each.

With reference to the Reactor Vault structures, the following materials can be identified as requiring representation in the conceptual model:

- aluminum;
- carbon steel;
- stainless steel;
- Zircaloy.

Radioactive activation products are assumed to be present within the structural walls of the Reactor Vault but are freely available to dissolve upon contact with water. Radioactivity associated with the heat transfer system, spent fuel storage and handling, and other parts of the Facility is largely in the form of contamination. Contaminants in these wastes are cautiously assumed to be free to dissolve instantly and become available for migration. As the closure plan is to grout the rooms the contaminants are assumed to become dispersed within the grout, to which they can adsorb.

The exception to this approach is the large mass of lead shielding present, mainly in the Fuelling Room and Reactor Vault. The mass of bulk lead is such that its release will be controlled by solubility limits. Furthermore, as a substantial fraction of the lead is present as solid metal, a surface release model is more appropriate than assuming the entire amount is instantaneously available for dissolution.

Geometry of the Waste and Facility

For the purposes of the PostSA, the main geometrical aspect of the wastes to represent is the surface area from which corrosion can take place for those metals in the Reactor Vault. This can be derived from the mass of metal, its density and a nominal wall thickness of the structures. For wastes represented as contamination, the inventory is conservatively assumed to be dispersed in the grout infill in the relevant room.

The geometry of the surrounding NPDDF structures is complicated. It has a significant bearing on the timing and rate of release of contaminants from different rooms. A simplified geometry (see Figure E-3) based on a conceptual 3D model derived from the design drawings (AECL, 1958a-d; AECL, 2013a-d) is adopted for the PostSA in which the main components of the NPDDF are represented by a number of cuboids (in some cases multiple cuboids joined together) that represent the main voids in the structure:

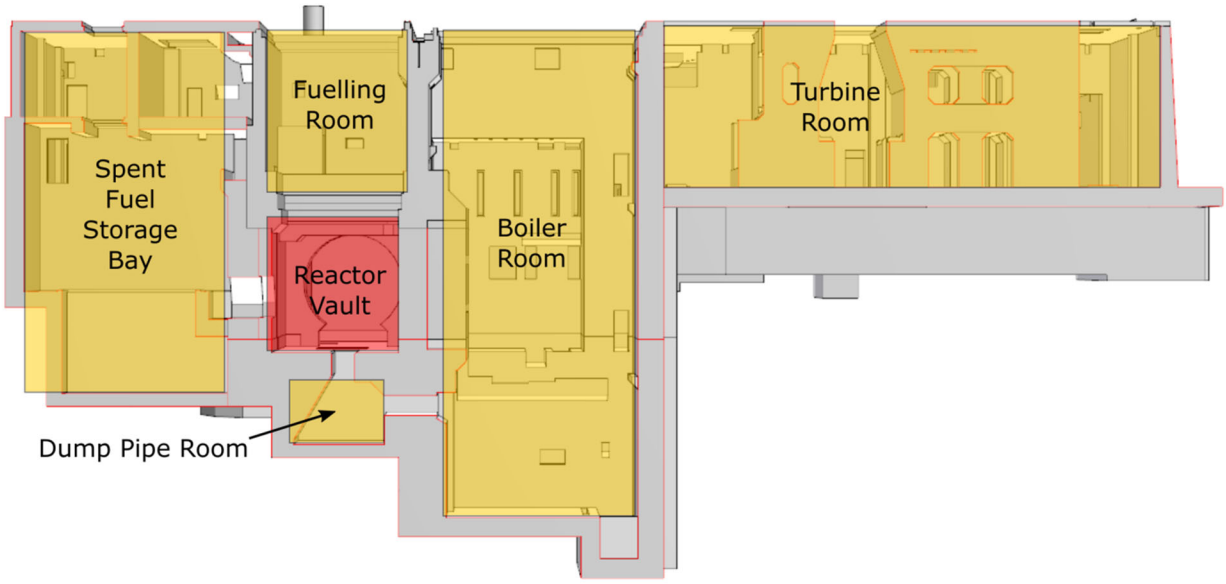
- Fuel Storage Room;
- Fuelling Room;
- Reactor Vault;
- Room to the east of the Reactor Vault;
- Room to the west of the Reactor Vault;
- Dump Pipe Room;
- Boiler Room; and
- Turbine Room.

As noted above, for the Reactor Vault it is also necessary to represent the solid waste metal from which contaminants are gradually released as they dissolve. This is the Calandria and internal components. In the Fuelling Room and Reactor Vault the dissolution of bulk lead is assumed to be controlled by its solubility, which is dependent on the prevailing pH.

The location of the components also determines their connectivity. Each is assumed to be surrounded by "walls" (including roof and floor) of varying thickness (AECL, 1958a). For simplicity, it is assumed that the top of the Fuel Storage Room, Fuelling Room, Boiler Room and Turbine Room is at the same elevation, which is taken to be ground level. The base of the Fuelling Room and Turbine Room is assumed to be at the same elevation as the bedrock surface. The geometrical arrangement is shown on an engineering cross-section in Figure E-3.

The nuclear area of the NPDDF will be covered with a concrete cap, which is assumed to be profiled and overlain with layers of natural materials to provide a vegetated surface.

Figure E-3 Key Components of the NPDDF (Cross-Section)



Metal Corrosion

Metal corrosion is a process that controls the release of radioactive activation products in irradiated metals such as pressure tubes and the Calandria, and the lead from lead shielding material (primarily in the Fuelling Room). A controlling factor will be the surface area presented by the various metals present. Corrosion rates (in m y^{-1}) depend on the presence of groundwater, the redox conditions in the groundwater, and the pH, all of which may vary as the system evolves after closure. Metal corrosion in the cementitious conditions will be sufficiently slow not to result in any significant build up of bulk gas.

Degradation of the Facility Structures

Over time, all cementitious materials (the existing structure as well as cementitious grout backfill added during decommissioning) will degrade as the cement constituents are removed, leading to an increase in porosity, increase in hydraulic conductivity, and decrease in alkalinity. The materials will also degrade physically through cracking, which could result from internal forces (e.g., rebar corrosion) or external forces (e.g., seismic events).

Chemical degradation of cementitious materials follows a characteristic mechanism. In typical cements, there is an initial increase in pH through hydrolysis of portlandite (calcium hydroxide) and incongruent dissolution of the C-S-H gel. The pH will decrease with time in accordance with leaching of progressively less-soluble solids. In the long term, pH in concrete pore fluids is controlled by the incongruently soluble C-S-H gel, with pH progressively decreasing from 12.5 to <10. For such materials, three characteristic phases can be identified for typical cements (see Berner (1992)):

- Stage I, which is representative of 'fresh' cementitious barriers and cement pore fluid conditions of pH 12.5-13. Portlandite [$(CaOH)_2$] and CSH gel are present in the system.
- Stage II, which is representative of partially degraded cementitious barriers, corresponding to cement pore fluid conditions controlled by the solubility of portlandite (pH 12.5). Partial removal of portlandite is assumed to have occurred.
- Stage III, which is representative of partially degraded cementitious barriers, corresponding to cement pore fluid conditions controlled by CSH gel (pH < 12). Portlandite has been removed. Partial removal of CSH gel is assumed to have occurred.
- Stage IV, in which all the cement solids have been leached, leaving secondary calcite (pH ~8).

These stages can be used to represent the evolution of the structural concrete of the NPDDF.

The BFS/PC grout anticipated to be used in backfilling the NPDDF evolves differently due to its formulation. Stage I does not occur as there are no alkali (Na and K) species present to be leached. Stage II does not occur either, as there is no portlandite. Therefore, only Stage III behaviour occurs, which lasts until depletion of CSH gel, at which point, secondary solids (such as calcite) or residual materials determine pH (referred to as Stage IV (Ochs *et al.*, 2016)). For BFS-PC grout (from Wilson, 2020) these are subdivided so as to represent more subtle variation in pH. The pH is initially 11.9, decreasing as follows: pH 11.5 at flush 107, 11.2 at flush 228. By flush 644 the pH has dropped to 10.2, with C-S-H having a Ca/Si ratio of 0.7 (lowest Ca/Si C-S-H composition). By flush 1979, C-S-H has been completely lost, with pH being buffered at 8.2 by secondary calcite, which reaches a maximum concentration at this time. Between ~2000 to 4386 flushes, calcite is dissolved by the groundwater (pH 5.8, Stage IV cement leaching, e.g. Ochs *et al*., 2016) and by 4387 flushes, the alkalinity provided by the grout and secondary calcite is completely lost and pH returns to background values.

For the grout, therefore, an alternative pattern of chemical evolution is modelled, with six rather than four stages (referred to as Stages A – F), with Stages A-D for the grout corresponding to Stage III for the structural concrete in terms of removal of C-S-H gel, Stage E corresponding to Stave IV where calcite is the main mineral influencing pH and Stage F corresponding to background pH values. For both structural

concrete and the BFS-PC grout Wilson (2020) shows how these phases can be related to the integrated flow of water through the cement, and this can be used to determine the timescales for the degradation of the cement. Concrete and grout properties, including porosity and sorption coefficients, can be assigned to each stage. In the PostSA the transitions in values that depend on these stages (e.g., sorption) is modelled as being instantaneous at the end of each stage.

The characteristic number of pore flushes for the structural concrete are:

- Stage I: 0-100 flushes
- Stage II: 101 – 1000 flushes
- Stage III: 1001 - 7450 flushes
- Stage IV: >7450 flushes

The characteristic number of pore flushes for the grout are:

- Stage A: 0 - 106 flushes
- Stage B: 107 - 227 flushes
- Stage C: 228 - 643 flushes
- Stage D: 644 - 1978 flushes
- Stage E: 1979 - 4386 flushes
- Stage F: > 4386 flushes

Overall, the number of pore flushes needed to degrade concrete and grout depends on the groundwater composition. In the NPD, some water entering a room has already passed through another room. This “conditioned” water is less effective in degrading concrete or grout than “fresh” groundwater and so more pore flushes would be needed to degrade the concrete or grout. This effect is conservatively neglected in the model calculations. Consequently:

- The duration of each Stage is underestimated in the model;
- Because pH decreases with time, the duration of high pH conditions is underestimated in the model; and
- Since high pH conditions correspond to high sorption, the sorption properties of the concrete or grout are underestimated in the model.

The corresponding timescales for the chemical evolution are calculated based on the integrated flow of water through each of the modelled components (NPDDF rooms), which is calculated during each model run, and depends on the hydraulic conductivity of the structure and the flows through the rooms calculated by the detailed groundwater flow model (Arcadis & Geofirma, 2023b). The results of these calculations are summarised in Table E-2 and Table E-3 for each of the cases.

Table E-2: Time at which Concrete Degradation Stages Begin

NOTE: Greyed-out times are outside of the assessment timeframe

Room	Stage I	Stage II	Stage III	Stage IV
Normal Evolution Scenario (NES)				
Above Bedrock				
Fuel Storage Room	0	25,000	>100,000	>100,000
Fuelling Room	0	15,000	>100,000	>100,000
Boiler Room	0	30,000	>100,000	>100,000
Turbine Room	0	15,000	>100,000	>100,000
Below Bedrock				
Fuel Storage Room	0	12,000	>100,000	>100,000
Reactor Vault	0	15,000	>100,000	>100,000
East of Reactor Vault	0	3,250	25,000	>100,000
West of Reactor Vault	0	7,000	60,000	>100,000
Dump Tank Pipe Room	0	8,750	80,000	>100,000
Boiler Room	0	9,900	90,000	>100,000
Boiler Room (deep)	0	7,000	60,000	>100,000
Rapid Degradation Case (NES(f))				
Above Bedrock				
Fuel Storage Room	0	25,000	>100,000	>100,000
Fuelling Room	0	12,000	>100,000	>100,000
Boiler Room	0	30,000	>100,000	>100,000
Turbine Room	0	12,000	>100,000	>100,000
Below Bedrock				
Fuel Storage Room	0	12,000	>100,000	>100,000
Reactor Vault	0	12,000	>100,000	>100,000
East of Reactor Vault	0	2,400	25,000	>100,000
West of Reactor Vault	0	6,000	60,000	>100,000
Dump Tank Pipe Room	0	8,000	80,000	>100,000
Boiler Room	0	9,000	90,000	>100,000
Boiler Room (deep)	0	6,000	60,000	>100,000
Extreme Degradation Case (DE(c))				
Above Bedrock				
Fuel Storage Room	0	1,900	9,700	70,000
Fuelling Room	0	1,700	8,000	60,000
Boiler Room	0	1,600	6,500	40,000
Turbine Room	0	2,200	15,000	90,000
Below Bedrock				
Fuel Storage Room	0	12,000	>100,000	>100,000
Reactor Vault	0	12,000	>100,000	>100,000
East of Reactor Vault	0	3,000	25,000	>100,000
West of Reactor Vault	0	8,000	70,000	>100,000
Dump Tank Pipe Room	0	8,000	70,000	>100,000
Boiler Room	0	8,500	80,000	>100,000
Boiler Room (deep)	0	7,000	70,000	>100,000

Table E-3: Time at which Grout Degradation Stages Begin

NOTE: Greyed-out times are outside of the assessment timeframe

Room	Stage A	Stage B	Stage C	Stage D	Stage E	Stage F
Normal Evolution Scenario (NES)						
Above Bedrock						
Fuel Storage Room	0	25,000	50,000	>100,000	>100,000	>100,000
Fuelling Room	0	15,000	30,000	80,000	>100,000	>100,000
Boiler Room	0	30,000	60,000	>100,000	>100,000	>100,000
Turbine Room	0	15,000	30,000	80,000	>100,000	>100,000
Below Bedrock						
Fuel Storage Room	0	15,000	30,000	80,000	>100,000	>100,000
Reactor Vault	0	15,000	30,000	80,000	>100,000	>100,000
East of Reactor Vault	0	3,250	6,000	15,000	50,000	>100,000
West of Reactor Vault	0	8,000	15,000	40,000	>100,000	>100,000
Dump Tank Pipe Room	0	9,200	20,000	60,000	>100,000	>100,000
Boiler Room	0	12,000	25,000	60,000	>100,000	>100,000
Boiler Room (deep)	0	7,000	15,000	40,000	>100,000	>100,000
Rapid Degradation Case (NES(f))						
Above Bedrock						
Fuel Storage Room	0	25,000	50,000	>100,000	>100,000	>100,000
Fuelling Room	0	15,000	30,000	80,000	>100,000	>100,000
Boiler Room	0	30,000	60,000	>100,000	>100,000	>100,000
Turbine Room	0	15,000	30,000	80,000	>100,000	>100,000
Below Bedrock						
Fuel Storage Room	0	12,000	25,000	70,000	>100,000	>100,000
Reactor Vault	0	15,000	30,000	80,000	>100,000	>100,000
East of Reactor Vault	0	2,400	5,000	15,000	50,000	100,000
West of Reactor Vault	0	6,500	15,000	40,000	>100,000	>100,000
Dump Tank Pipe Room	0	8,250	20,000	50,000	>100,000	>100,000
Boiler Room	0	9,475	25,000	60,000	>100,000	>100,000
Boiler Room (deep)	0	6,500	15,000	40,000	>100,000	>100,000
Extreme Degradation Case (DE(c))						
Above Bedrock						
Fuel Storage Room	0	2,000	3,000	7,000	20,000	50,000
Fuelling Room	0	1,700	2,600	5,500	15,000	40,000
Boiler Room	0	1,600	2,200	4,250	12,000	25,000
Turbine Room	0	2,400	3,750	8,500	25,000	60,000
Below Bedrock						
Fuel Storage Room	0	15,000	30,000	80,000	>100,000	>100,000
Reactor Vault	0	12,000	25,000	70,000	>100,000	>100,000
East of Reactor Vault		3,250	5,500	15,000	40,000	100,000
West of Reactor Vault		8,000	17,000	50,000	>100,000	>100,000
Dump Tank Pipe Room	0	8,000	17,000	50,000	>100,000	>100,000
Boiler Room	0	9,000	20,000	50,000	>100,000	>100,000
Boiler Room (deep)	0	8,000	15,000	40,000	>100,000	>100,000

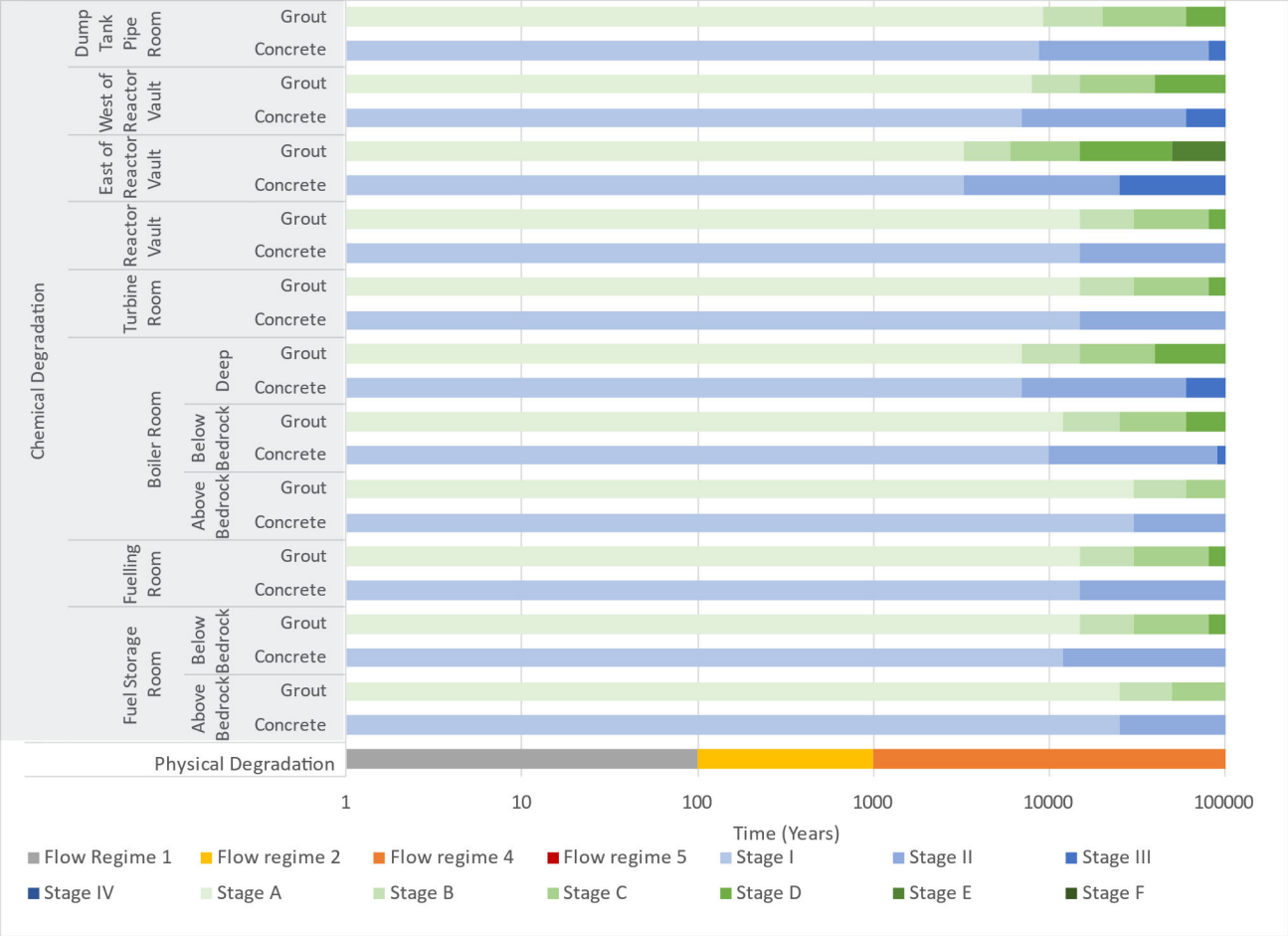
Hydraulic conductivity can also be related to these stages for mass concrete; although where internal or external stresses may apply a more rapid (physical) degradation, e.g., reflecting cracking due to rebar corrosion, physical degradation of the concrete is more appropriate to model. Corrosion of rebar is likely to be the fastest degradation process and the increase in volume of corrosion products will locally degrade the mechanical and hydrological properties. On this basis, the hydraulic conductivity of Facility structures is assumed to change from a "fresh" to "cracked" state over a shorter period of time, not based on the cement stages. In practice, CNL (2019a, 2021a) suggests that moderate seismic activity could also lead to some degradation of the structures and grout. Although probabilities can be estimated, the precise timing of such an event is impossible to predict. Cautiously, in the Normal Evolution Scenario it has been assumed that a significant seismic event occurs after 1,000 y and results in cracking of the structures and grout and a consequent increase in their hydraulic conductivity. The patterns of physical degradation are presented in Table E-4, with the corresponding assumptions for the hydraulic conductivity of the structures. Figure E-4 illustrates the timelines of chemical and physical degradation in each of the three cases.

Table E-4: Physical Degradation Timescales

Flow regime	Time at which flow regimes begin			Hydraulic conductivity of grout (m/s)
	Normal Evolution Scenario	Rapid Degradation	Extreme Degradation / Fault Zone	
Flow regime 1 (undegraded facility with tile drains)	0 y	0 y	0 y	6.3E-11(below bedrock) 6.3E-10(above bedrock)
Flow regime 2 (undegraded facility with degraded cap and tile drain failure)	100 y	-	100 y	6.3E-11(below bedrock) 6.3E-10(above bedrock)
Flow regime 4 (degraded facility with tile drain failure)	1000 y	100 y	-	1E-08
Flow regime 5 (extremely degraded facility with tile drain failure)	-	-	1000 y	1E-08 (below bedrock) 1E-06 (above bedrock)

Note: *All other scenarios and calculation cases have the same pattern of physical degradation as the Normal Evolution Scenario. Although some cases have alternative flows determined by hydraulic conductivities for some materials or the presence of a well, they still represent the flow regimes listed above in terms of the degradation state of the facility, cap and tile drains.

Figure E-4 Timeline of Chemical and Physical Degradation in the NES



Contaminant Release and Transport

Contaminants will be released from the waste materials in different ways and/or at different rates depending on the properties of the material.

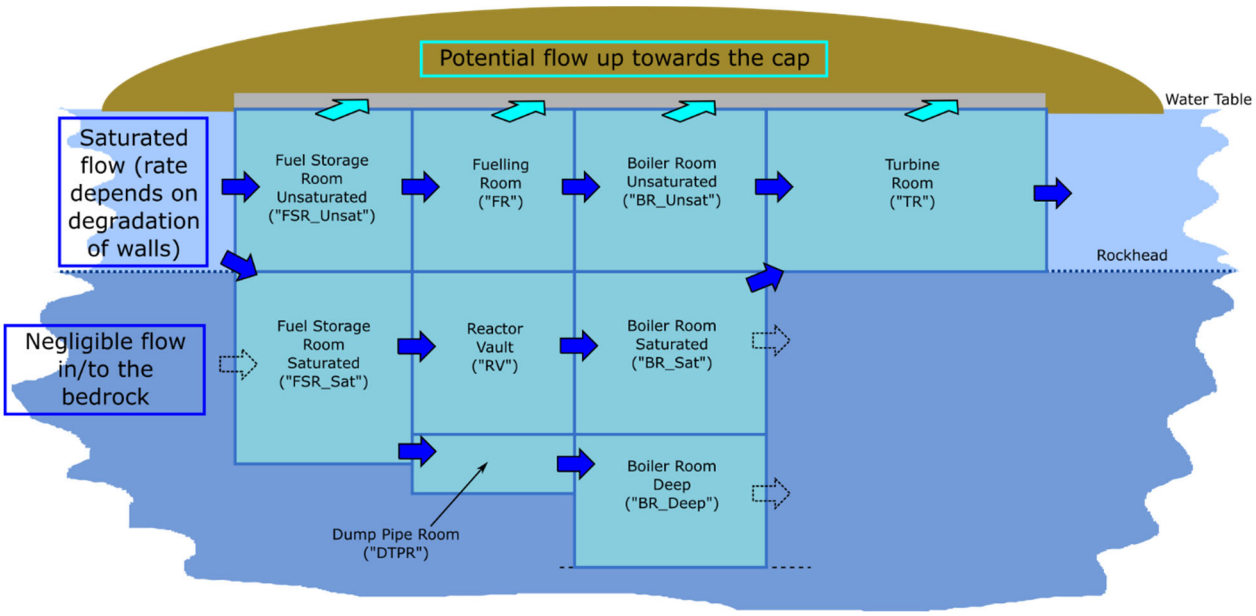
Contaminants present as surface contamination (e.g., within the heat transfer system, or present as contamination in fuel handling areas) are cautiously assumed to be instantaneously released into solution once contacted by water. Radionuclides present in activated metals and lead will be released gradually according to a corrosion rate (see above). Due to its porous nature, contaminants present in concrete surrounding the Reactor Vault are most appropriately represented as being instantaneously released upon saturation of the concrete.

Contaminant releases into groundwater will commence once water is present in the NPDDF rooms. Sorption will occur within the grout backfill and Facility structure, determined by the prevailing chemical

conditions. While the vault is resaturating there will be a net inflow of water and releases from the NPDDF will only occur via diffusion through the wetted surface of the structure's outer walls. Once saturated, there may be advection and diffusion in already-saturated regions. Diffusion will occur radially from the source of contaminants.

Advective flows are shown conceptually in Figure E-5 for the initial phase of the assessment, whilst engineered barriers are degrading.

Figure E-5 Illustration of Advective flows of Water through the NPDDF while Engineered Barriers are Degrading



Advection in the saturated regions will principally follow the hydraulic gradient (see Figure E-5). This means that the advective transfers will flow from one room towards another, before leaving the Boiler Room and Turbine Room and joining the groundwater flows orientated towards the Ottawa River. The rate of flow will be determined by the hydraulic conductivity of the NPDDF walls.

E 2.2.3 Geosphere

The screened list of FEPs relating to the geosphere (FEP group 4) is listed in Table E-5. This table also summarises the treatment of the FEP in the conceptual model.

This shows that the geosphere is represented with relatively few components and processes which is as expected for a system that is very close to the surface. The key element of the model is the representation of the contaminant transport pathways in terms of geometry, and the specification of the water flows through and between them.

The following paragraphs provide a narrative description of the conceptual model and how the FEPs are represented.

Table E-5 Representation of Geosphere FEPs in the Conceptual Model

FEP	Title	Incorporation into the Conceptual Model
4.1.1	Stratigraphy	Representation of the bedrock and overburden, as well as disturbed areas of ground (e.g., drain runs)
4.1.2	Large-scale discontinuities	Presence of large-scale discontinuities considered in a sensitivity case (Increased hydraulic conductivity in bedrock), and the What if case (Undetected fracture zone)
4.1.3	Geological resources	Exploitation of gravel considered in Disruptive Event (Site Investigation (Inadvertent Human Intrusion), Excavation of Above-Bedrock Facility) and What If (Facility Mass Excavation) cases.
4.1.6	Hydraulic characteristics and properties	Representation of the hydraulic conductivity of the main geosphere components
4.1.7	Mechanical characteristics and properties	Cracking due to seismic activity affects hydraulic properties of grout and concrete
4.1.8	Geochemical characteristics and properties	Representation of sorption in the main geosphere components
4.2.1	Thermal processes (geosphere)	Representation of degradation of facility structures which is in part caused by freeze-thaw cycles.
4.2.2	Hydraulic processes (geosphere)	Representation of advection and dispersion in geosphere components
4.2.3	Mechanical processes (geosphere)	Geosphere expected to be mechanically stable, but an earthquake could affect mechanical stability, in turn affecting hydraulic properties of the facility.
4.2.4	Chemical processes (geosphere)	Representation of sorption in geosphere components
4.2.6	Radiological processes (geosphere)	Representation of radioactive decay and ingrowth during transport through the geosphere
4.3.1.1	Advection (geosphere)	Representation of advection in geosphere components
4.3.1.2	Dispersion (geosphere)	Representation of dispersion in geosphere components
4.3.1.6	Speciation and solubility (geosphere)	Representation of solubility limits at boundary between facility and geosphere.
4.3.1.7	Sorption and desorption (geosphere)	Representation of sorption in the main geosphere components
4.3.3	Solid-mediated migration (geosphere)	Represented in Disruptive Event (Site Investigation (Inadvertent Human Intrusion), Surface Erosion, Excavation of Above-Bedrock Facility) and What If (Facility Mass Excavation) cases
4.3.4	Human-action-mediated migration (geosphere)	Represented in Disruptive Event (Site Investigation (Inadvertent Human Intrusion), Overburden Well, Bedrock Well, Excavation of Above-Bedrock Facility) and What If (Facility Mass Excavation) cases

Geosphere Media

The geosphere within which the Facility sits is simple in terms of its structure, with a relatively homogeneous loosely compacted overburden of sand, gravel and larger cobbles overlying weathered bedrock. It is noted that within this there are regions that have been disturbed as a result of the NPD construction (e.g., along pipe and tile drain runs) as well as the pipes and drains themselves. A comprehensive description of the geological and hydrogeological system is presented in Arcadis & Geofirma (2023a) and the Geosynthesis report (Arcadis & Geofirma, 2022). The conceptual model includes:

- undisturbed overburden;
- disturbed overburden;
- weathered bedrock;
- pipe trench;
- tile drains.

Geometry of the Geosphere

The undisturbed geosphere consists of bedrock that dips towards the Ottawa River, overlain by unconsolidated drift (i.e., overburden). At the site, the overburden has been reworked extensively resulting in an area of disturbed ground arising from the NPD construction. The bedrock has also been excavated to accommodate the NPD structure and cooling pipes, then backfilled. This disturbed material around the cooling pipes is assumed to be more conductive than undisturbed overburden. A detailed discussion and synthesis of geologic information for the site and the surrounding region is presented in the 2021 update of the Geosynthesis Report (Arcadis & Geofirma, 2022).

The geometry to be represented in the PostSA is informed by the anticipated groundwater flow pathways, as this is the dominant process in the geosphere. Detailed groundwater flow modelling (Arcadis & Geofirma, 2023a), therefore, has a major role in informing the geometric representation of the geosphere.

A calibrated groundwater model has been built which represents groundwater flows in the vicinity of the NPDDF (Arcadis & Geofirma, 2023a). This model shows that the bulk of the groundwater flows through the overburden, including fill, just above the bedrock surface, and the tile drains.

Based on the work by Arcadis & Geofirma (2023a), there are four groundwater pathways that could transport contamination from the facility towards the river. These are:

1. tile drains;
2. infill around cooling pipes (pipe trench);
3. overburden; and
4. weathered bedrock.

The location of these pathways is illustrated in Figure E-6 and Figure E-7. Arcadis & Geofirma (2023a) indicates that both the overburden and the bedrock conduct water originating from the NPDDF; the former likely to emerge as springs close to the shore, and the latter discharging through the river bed. Figure E-8 shows the concept of the seal, the pipe trench, and the cooling pipes therein. It also reflects CNL's decision to grout-fill the cooling pipes.

Figure E-6 Location of Groundwater Pathways (Plan)

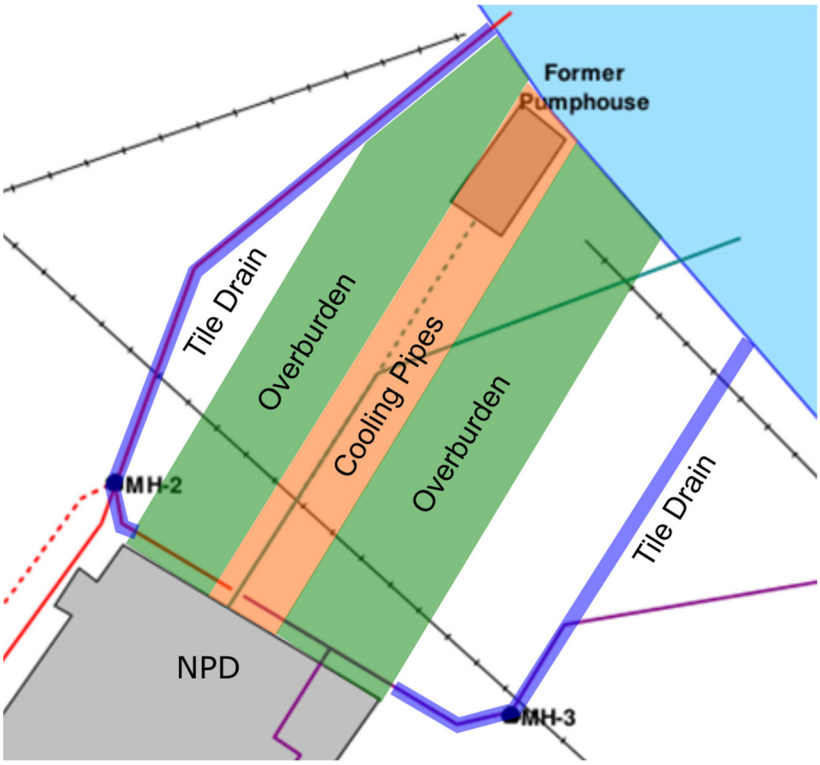
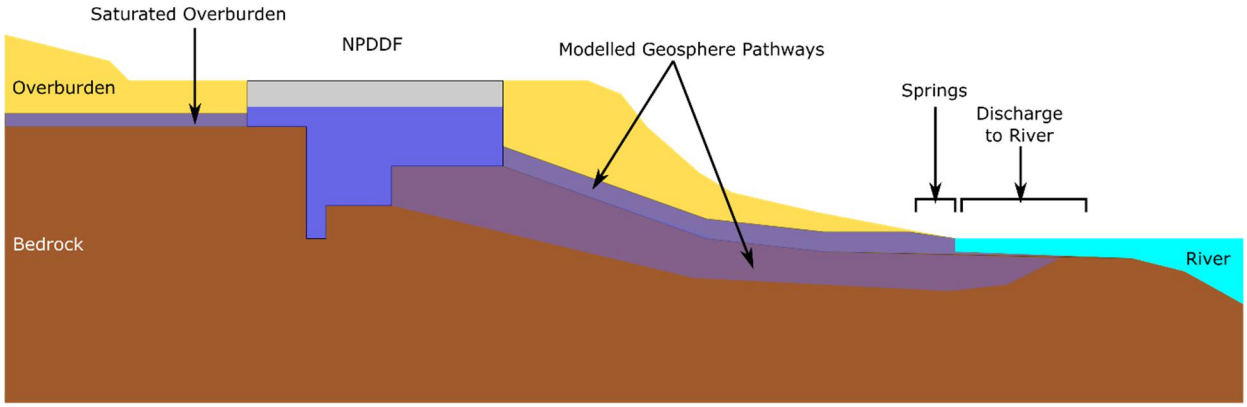
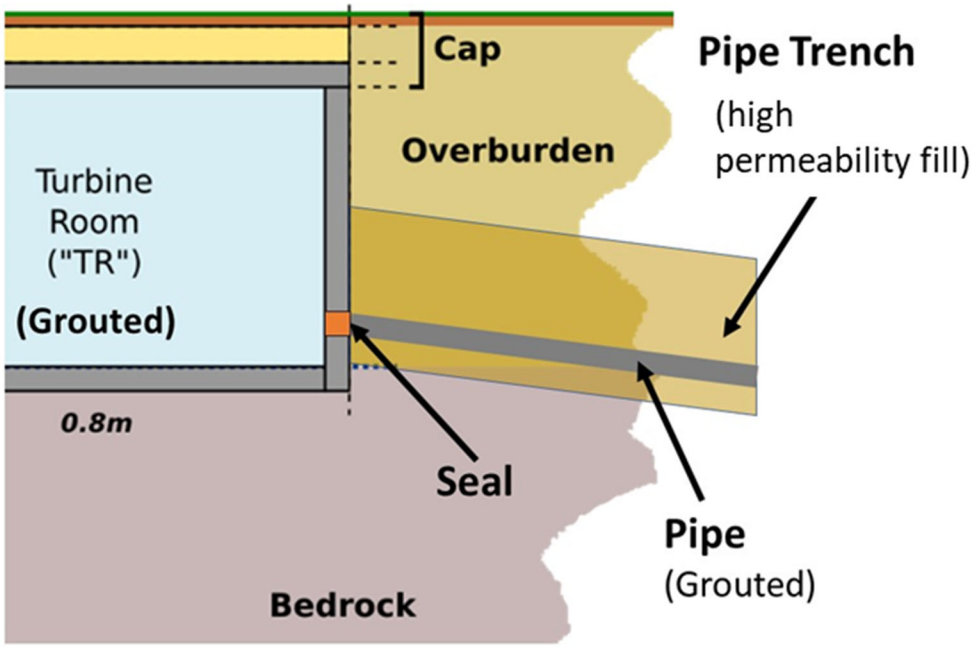


Figure E-7 Location of Groundwater Pathways (Cross-Section)



(Approximate scale, with vertical exaggeration x2)

Figure E-8 Concept of Seal, Pipe Trench, and Cooling Pipes



Tile drains

There are a number of elements to the subsurface drainage system surrounding the Facility and linking it to the river (Taylor, 2014). Collector pipes run around the perimeter of the Facility, including beneath some buildings (although not beneath the Reactor Vault). These collector pipes feed water into two tile drains that take water to the river. The two tile drains, considered part of the geosphere system despite being man-made, are different diameter corrugated ARMCO pipe and drain to the north and east of the Facility.

It is known that the tile drain extending from MH-2 is breached between MH-2 and the river bank (there has been subsidence into the drain line). Although their condition suggests that the drains are connected to the surrounding groundwater, it is conservative to assume that there are no perforations in the tile drains since this will reduce dilution of contaminants in the tile drains.

While the tile drains are open, any contaminants that enter the drains in the near-field will be rapidly advected along the pathway to the shoreline of the river, where the tile drains flow out onto the shoreline rock/cobblestone. It is cautious to assume no sorption along this pathway. There will be considerable dilution in the tile drains due to the large volumes of uncontaminated water captured by the drains up-stream of the Facility.

The tile drains may fail at some point after the end of the period of institutional control. If a tile drain collapses, it will be infilled with surrounding materials, most likely fill from above the drain. The material properties will be very similar to that of the surrounding overburden. Arcadis & Geofirma (2023a) suggests that if the effect of the tile drains is lost the flows through the Facility may change.

Cooling pipes

Cooling pipes run from the Facility to the river, installed in a large trench which was then backfilled. The cooling pipes will be sealed with concrete at the Facility end so will not provide a flow path in themselves. The trench, which was cut into the bedrock, will provide a preferential flow path for contaminants rising in the fill surrounding the NPDDF since the elevation of the bedrock surface is lower in the trench. Advection is likely to be the dominant transport mechanism and there will be sorption to the fill.

Overburden

Away from the Facility, groundwater flow is expected to occur in the overburden, close to the top of the bedrock. Construction of the Facility and the tile drains means that close to the Facility much of this groundwater flow has been diverted, but there will still be some flow at the base of the overburden. Contaminants released from the parts of the NPDDF that lie in the overburden are assumed to be released into this pathway, unless they are captured in the tile drains. Transport in the overburden will be mainly by advection with sorption to the associated sediments. Contaminants are expected to be released into the river through the river bed sediments, where the top of the bedrock outcrops in the river. However, Arcadis & Geofirma (2023a) also indicates that there is the potential for some release via springs close to the shore. Conservatively, this is chosen to be the main pathway for the discharge of water originating in the NPDDF and flowing through the overburden.

Weathered bedrock

There may be a weathered zone at the top of the bedrock whose permeability is higher than for unweathered bedrock, such that it could act as a flow pathway for contaminants. The pathway will have a similar spatial extent to the overburden pathway, with a different flow depth. Advection will be the dominant transport process but will be significantly slower than in the overburden. This could retard migration of contaminants through the geosphere leading to release of contaminants at the river being over a longer timescale. The bedrock is nevertheless considered to be a significant pathway based on the modelling by Arcadis & Geofirma (2023a) which suggests that it may conduct about half for the total flow of water out of the NPDDF. The modelling also indicates that the groundwater travelling in the bedrock is expected to be released through the riverbed. Based on the modelling by Arcadis & Geofirma (2023a), contaminants in the parts of the NPDDF that lie in the bedrock will be released into the bedrock pathway.

The preliminary slope stability assessment (Arcadis & Geofirma, 2021a) that considers earthquake-induced soil liquefaction, shows that the North Slope under current water level conditions is stable under static loading conditions and under loading conditions associated with a 1:2,250-y earthquake. Parts of the North Slope are stable, while some parts of the North Slope are unstable under a 1:10,000-y earthquake. The North Slope is likely to fail during a 1:50,000-y earthquake. It is unlikely that the predicted failures of the North Slope will result in the direct exposure of groundwater to a new ground surface that would be established following earthquake induced slope failures. Slope failures at the North Slope are expected to result in accumulations of failed granular materials on the lower half of the North Slope. Given the permeable nature of all soils that comprise the North Slope, the expected redistribution of soils following slope failure is unlikely to change groundwater flows from the NPDDF to the Ottawa River. For more details, the reader is referred to the preliminary slope stability assessment (Arcadis & Geofirma, 2021a).

E 2.2.4 Biosphere

The screened list of FEPs relating to the biosphere (FEP group 5) is listed in Table E-6. This table also summarises the treatment of the FEP in the conceptual model.

For the Normal Evolution scenario, the contaminant release pathway to the biosphere is via groundwater discharge to springs close to the shore and river bed sediments adjacent to the site, from where contamination may pass into the river water. The biosphere conceptual model therefore includes a wide range of FEPs that encompass a wide range of biosphere media, processes, and exposure pathways.

Gas release from the NPDDF to the biosphere is not considered in the Normal Evolution scenario as the grouting of the facility will seal possible pathways to the surface. Release of contaminated material in solid form is also not represented in the Normal Evolution scenario as only disruptive events could lead to such conditions. The release of radionuclides in solid material is represented, hypothetically, through Disruptive Event cases (Site Investigation (Inadvertent Human Intrusion), Excavation of Above-Bedrock Facility) (Sections E 2.4.1 and E 2.4.5) and a What If case (Facility Mass Excavation) (Section E 2.6.1).

The following paragraphs provide a narrative description of the conceptual model and how the FEPs are represented.

Table E-6 Representation of Biosphere FEPs in the Conceptual Model

FEP	Title	Incorporation into the Conceptual Model
5.1.1	Topography and morphology	Considered in the assignment of land uses
5.1.3.1	Surface soils	Representation of surface soils as a biosphere component
5.1.3.2	Overburden	Incorporated into the geosphere model
5.1.3.3	Aquatic sediments	Representation of river sediments as a biosphere component
5.1.4	Near-surface aquifers and water-bearing features	Incorporated into the geosphere model
5.1.5.2	Lakes and rivers	Representation of the Ottawa River as a biosphere component
5.1.5.3	Spring and discharge zones	Discharge of groundwater to surface springs and to river sediments
5.1.8	Atmosphere	Representation of resuspension of contaminated soil and dust
5.1.9	Vegetation	Representation of uptake of contaminants to vegetables
5.1.10	Animals	Representation of uptake of contaminants to animals
5.1.11	Climate and weather	Implications considered in terms of effects on river, growing periods, and human habits
5.1.12	Hydrological regime and water balance (near-surface)	Incorporated into the geosphere model
5.1.13	Erosion and deposition	Surface erosion from steep banks is represented Erosion and deposition of river sediments is represented

FEP	Title	Incorporation into the Conceptual Model
5.1.14	Ecological/biological/microbial systems	A farmed and semi-natural system is considered in defining exposure pathways
5.2.1	Physical characteristics	Human physiology is included in dose factors and habits data
5.2.2.1	Community type	A range of communities is assessed
5.2.2.2	Community location	Communities located closest to the NPD and river will be most affected
5.2.2.3	Water source	The Ottawa River is the primary water source. Intermittent springs are considered to be too small and inappropriate for drinking
5.2.2.4	Dwellings	The presence of dwellings on site is represented
5.2.3.1	Farming diet	A farming diet is represented
5.2.3.2	Hunter/gatherer diet	A hunter diet is represented
5.2.3.3	Other diets	Recreational use of the river is represented
5.2.4	Habits (excluding diet)	Representation of exposure location and duration
5.3.1.1	Groundwater discharge to biosphere	Discharge may occur to surface springs and to river sediments
5.3.1.2	Migration associated with surface soil and overburden	Discharge via springs, and contaminated water use (irrigation) can result in contaminant transfer to soils
5.3.1.3	Migration associated with surface water bodies	Representation of dispersion in the Ottawa River
5.3.1.6	Sorption and desorption (biosphere)	Representation of sorption and desorption
5.3.3	Solid-mediated migration (biosphere)	Representation of soil erosion on steep banks
5.3.4	Human-action-mediated migration (biosphere)	Representation of irrigation
5.3.5	Uptake of contaminants by animals and plants	Representation of uptake of contaminants by animals and plants
5.3.6	Radioactive decay and ingrowth (biosphere)	Decay and ingrowth is included
5.4.1	Contaminated drinking water and food	Representation of intake pathways for exposed groups
5.4.2	Contaminated non-food products	Representation of external irradiation pathways from environmental materials that have special uses
5.4.3	Other contaminated environmental media	Representation of contaminated soils and river shore/bed sediments
5.4.4.1	Exposure of humans	Assessment of radiation dose to a range of potentially exposed groups

FEP	Title	Incorporation into the Conceptual Model
5.4.4.2	Exposure of non-human biota	Assessment of radiation dose to non-human biota
5.4.5.1	Dosimetry and biokinetics for humans	ICRP reference models used in dose calculations for internal irradiation by biosphere media, reference external dose factors used for external radiation, taking into account source geometry.
5.4.5.2	Dosimetry and biokinetics for non-human biota	ERICA reference models used in dose calculations
5.4.6.1	Radiological toxicity/effects for humans	ICRP reference models used in dose calculations
5.4.6.2	Radiological toxicity/effects for non-human biota	ERICA reference models used in dose calculations
5.4.7.1	Chemical toxicity/effects for humans	Environmental concentrations of chemically toxic elements are calculated for comparison against suitable standards.
5.4.7.2	Chemical toxicity/effects for non-human biota	Environmental concentrations of chemically toxic elements are calculated for comparison against suitable standards.

Land Use and Exposed Groups

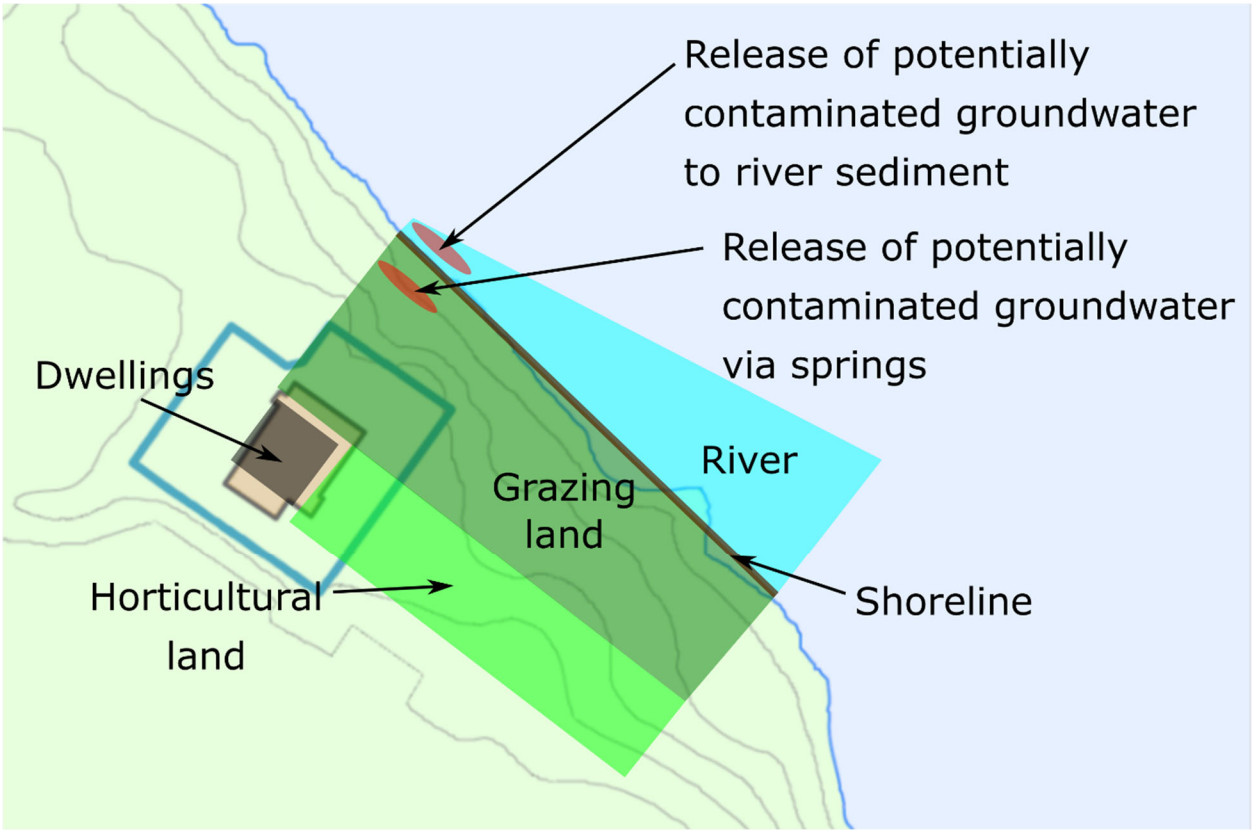
Beyond the period of institutional control, people may live in the vicinity of the Facility and use the area for recreational purposes and also, potentially, for small-scale agricultural production. Four potentially exposed groups are included in the conceptual model:

- A highly conservative group that maximises potential exposures. This is reflected by a small household (comprising two adults, a child and an infant) residing directly over the Disposal Facility and maximising use of local resources through a lifestyle that is reasonably self-sufficient, including growing crops in a garden, using potentially contaminated river water for domestic use and agricultural irrigation purposes and raising a small number, though broad range, of livestock.
- A hunting/recreational group, represented by a small number of adults, children and an infant, making hunting and/or recreational use of the river and the area surrounding the NPDDF.
- An offsite resident receptor group, represented by two households (adults, children, and an infant) that reside alongside the Ottawa River at Deep River and Ottawa/Gatineau. These households are assumed to use river water from the Ottawa River for domestic use and as drinking water, and to use the Ottawa River for recreational swimming.
- An Indigenous receptor group represented by adults, following a similar lifestyle to the self-sufficient receptor group (see Section E 2.3.6). The Indigenous receptor group does not live on the NPD site but uses the area around the NPDDF, including the Ottawa River, for hunting, fishing and gathering wild plants. This group is also assumed to supplement their diet with additional groceries purchased from shops, and to make use of medicinal plants. The receptor's habits are based on a new study of the diet and harvest of the Algonquins of Pikwàkanagàn First Nation (AOPFN) (Fediuk *et al.*, 2021).

Location

In principle, the exposed groups could be located anywhere near the Facility. However, it is conservatively assumed that the resident lives on the NPDDF and water is drawn close to the point of contaminated groundwater discharge to the river. The proximity of the river means that a well is not represented as a water source in the Normal Evolution scenario, although this is considered in Disruptive Event cases (Sections E 2.4.6 and E 2.4.7). If it is conservatively assumed that the group has a house on top of the Facility, then it is reasonable to assume that the land just to the east of the Facility is used for a garden and horticulture, with adjacent land being used for grazing (see Figure E-9). The river water is taken to be used for the small-scale agriculture required to support such a household. The group is referred to as the Site Resident group.

Figure E-9 Illustrative Location of the Site Resident House, Garden/Horticultural Area and Grazing/Forage Area



The Hunter group is assumed to use this same area, but spend different amounts of time in the various locations. For example, the hunter could spend longer on the riverbanks, fishing.

The Offsite Resident Receptor groups are assumed to be located along the Ottawa River, at Deep River and Ottawa/Gatineau. They use river water for drinking water, and for domestic use, as well as recreational swimming.

The Indigenous receptor group is assumed to use the same area as the Site Resident group but does not live on the NPD site and spends different amounts of time in the various locations. For example, this group could spend longer on the riverbanks, fishing.

For the Normal Evolution scenario, potential wildlife exposures are limited to those that may occur in the river and at the shoreline. The radionuclide concentrations in the surface environment are expected to be highest in these areas.

Exposure Pathways for the Site Resident Group

The lifestyle for the site resident group is taken to include:

- use of river water for domestic purposes, including drinking, bathing and washing;
- use of river water to irrigate garden crops, including fruit, vegetables (including potatoes) and forage (for animals);
- use of river water as drinking water for livestock, including chickens, pigs, sheep, goats and dairy and beef cattle; and
- fishing from the river adjacent to the Facility.

Spring water is intermittent and considered inappropriate for use as drinking water etc. in preference to the very large volume of clean river water close to the discharge zone. However, residents can spend time in the area where the spring water has contaminated soils and receive exposure from those soils.

These exposure pathways are consistent with CSA (2022) from which mathematical models and data can be obtained. The site resident group is taken to maximise its occupancy in the area of the Facility, including the shoreline, to support these activities.

Exposure Pathways for the Hunting/Recreational Group

The exposure pathways for the hunting/recreational group are taken to include:

- time spent on the shoreline for recreation and fishing;
- time spent swimming in the river;
- ingestion of fish caught from the river; and
- hunting of game that uses the river for drinking water, foraging of wildfoods.

Exposure pathways and associated data for the Hunter group can be derived from CSA (2022).

Exposure Pathways for the Offsite Receptor Group

The lifestyle for the offsite resident group is taken to include:

- use of river water for domestic purposes, including drinking, bathing and washing;
- time spent swimming in the river.

Food obtained by the offsite receptor group is assumed not to be contaminated (e.g. obtained from a grocer).

Exposure Pathways for the Indigenous Receptor Group

The lifestyle for the Indigenous receptor group is taken to include:

- time spent on the shoreline for recreation and fishing;
- ingestion of fish caught from the river;
- hunting of game that uses the river for drinking water, foraging of wildfoods and honey;
- inhalation of smoke from burning medicinal plants; and
- rubbing medicinal plants into the skin.

It is assumed the Indigenous receptors supplement their diet with additional (uncontaminated) groceries purchased from local shops, which has been grown elsewhere (Fediuk *et al.*, 2021).

Biosphere Media

Given the groundwater source to the biosphere and the exposure pathways identified above, the following biosphere media are identified for the conceptual model of the biosphere:

- sediments: river bed/shoreline sediments;
- soils: garden soil, soil used for horticultural production, soil used for grazing and soil contaminated by groundwater springs;
- river water;
- atmosphere;
- plants: horticultural and garden plants, pasture, wildfoods; and
- animals: livestock, fish, game.

Biosphere processes

The conceptual model for contaminant migration in the biosphere is illustrated in Figure E-10. The numbered processes are listed below.

1. Discharge of potentially contaminated groundwater.
2. Infiltration/recharge to the geosphere.

3. Irrigation.
4. Erosion and interflow.
5. Loss to outside the region of interest due to river flow.
6. Interception of irrigation water.
7. Ingestion of river water by animals.
8. Uptake from river water into fish.
9. Gas volatilisation from soils.
10. Incidental ingestion of soil by animals.
11. Root uptake from garden soil to vegetables and fruit plants (note that external soil contamination is accounted for via inadvertent ingestion of soil by humans), and weathering losses/decay of plant into soil.
12. Root uptake from grazing soil to pasture (note that external soil contamination is accounted for via inadvertent ingestion of soil by humans), and decay of plant into soil.
13. Ingestion of plants by animals.
14. Uptake by plants from atmosphere (C-14), losses from plants to atmosphere (e.g., respiration).
15. Inhalation/exhalation, eructation etc.
16. Exchange between river water and atmosphere.
17. Loss to outside the region of interest due to air flow.

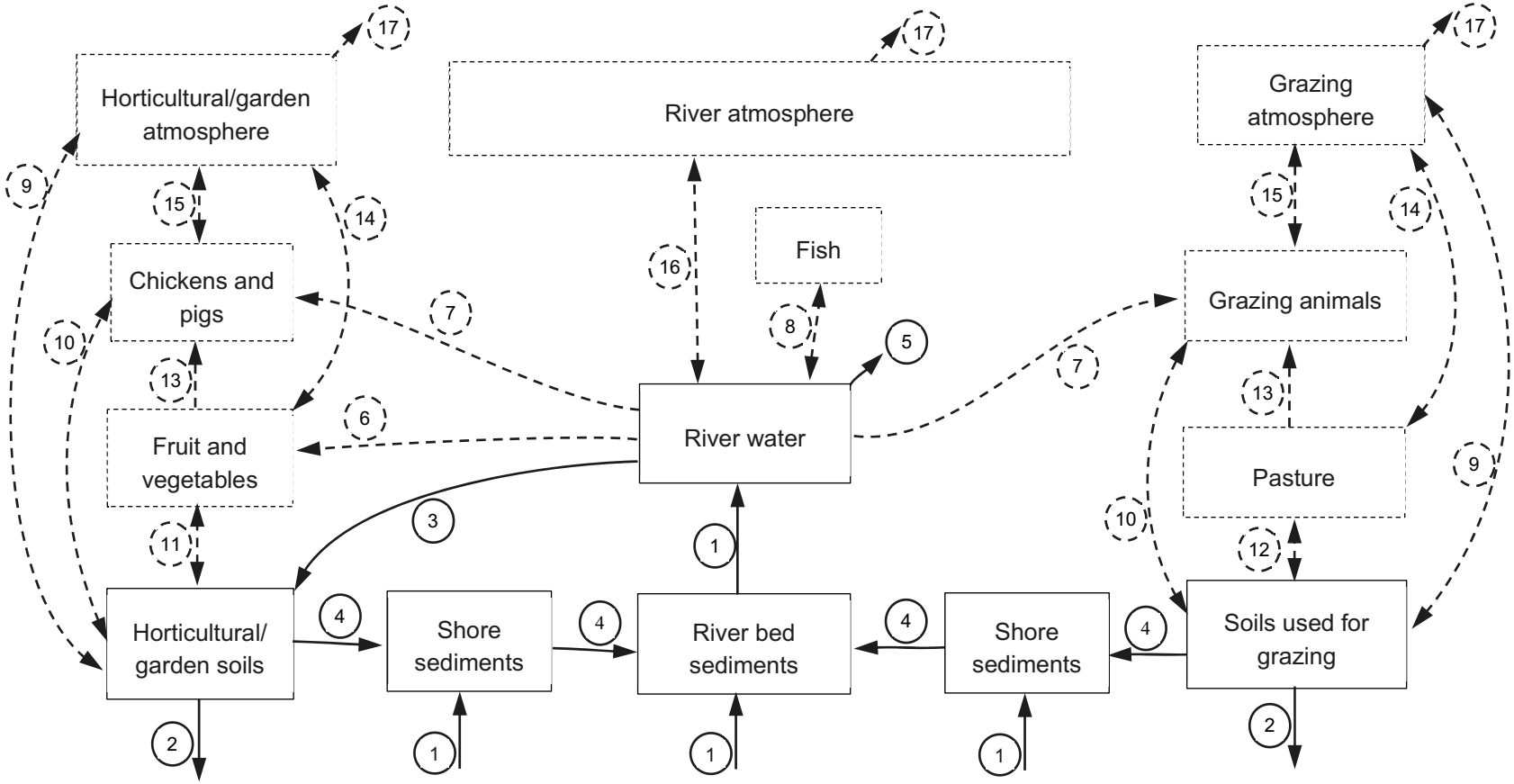
A summary of the potential exposure pathways considered for each of the potential exposure groups in the Normal Evolution scenario is given in Table E-7.

Table E-7 Summary of Potential Exposure Pathways for Each Exposure Group

Pathway	Site Resident	Offsite Resident	Hunter	Indigenous *(Using Fediuk et al., 2021)*
Drinking river water	✓	✓	✓	✓
Ingestion of garden produce, including honey	✓			✓
Ingestion of livestock produce	✓			
Ingestion of fish and shellfish from the river	✓		✓	✓
Ingestion of game (deer, geese and ducks)			✓	✓

Pathway	Site Resident	Offsite Resident	Hunter	Indigenous *(Using Fediuk et al., 2021)*
Incidental ingestion of soil from garden and grazing area	✓		✓	✓
Incidental ingestion of sediment from the shoreline	✓		✓	✓
External irradiation during time spent on the garden and in the grazing area	✓		✓	✓
External irradiation during time spent on the soils contaminated by springs	✓			✓
External irradiation due to time spent on the shore	✓		✓	✓
External irradiation from immersion in bath of river water	✓	✓		
External irradiation due to immersion in the river whilst swimming	✓	✓	✓	
Incidental ingestion of river water whilst swimming	✓	✓	✓	
Inhalation in the garden and grazing area	✓		✓	✓
Inhalation during time spent on the shore and swimming	✓		✓	✓
Inhalation of smoke from burning medicinal plants				✓
Rubbing medicinal plants into the skin				✓

Figure E-10 Conceptual Model of Contaminant Migration in the Biosphere. Dashed Lines indicate Equilibrium Assumptions



Climate

Climate change may alter the regional and local meteorology, in particular the temperature, annual rainfall, snowfall and duration of snow cover. It is anticipated that climate change will lead to increased temperature and increased precipitation in the vicinity of the NPD site (CNL, 2017a).

Projected future climate conditions were described in CNL (2017b) for the years 2100-3000 based on the Intergovernmental Panel on Climate Change (IPCC). The IPCC expects global precipitation to increase by 1-3% per degree Celsius of increased temperature over the period (IPCC, 2013). Based on this information, for the Normal Evolution Scenario, the temperature is assumed to increase by 3.9°C, and precipitation is assumed to increase from 852 to 952 mm/y, i.e., an increase of 100 mm/y. Although rainfall is anticipated to increase, higher temperatures will also lead to increased evapotranspiration (ET). Thus, hydrologically effective rainfall (HER), defined as rainfall minus ET, could increase, decrease or stay the same. Further consideration of ET indicates that it will balance the increase in rainfall so there is no net increase in HER (CNL, 2017a).

On this basis, overall, for the Normal Evolution Scenario, it is assumed that the effects of climate change are relatively small such that the present-day biosphere is adequately representative of future conditions (see the discussion in CNL (2017a) and Appendix D).

E 2.3 Sensitivity/Uncertainty Cases

The first category of calculation cases is concerned with examining the sensitivity of model results to uncertainties in key parameters. These cases involve applying alternative parameter values or data sets, to illustrate the bounds of the uncertainty. The parameters of interest have been identified on the basis of safety assessment modelling during the previous iterations of the PostSA study, and also draw on experience with other safety assessment studies concerning the most prominent uncertainties in the disposal system.

The uncertainties are focused on the properties of the NPDDF itself and the waste therein. This is because

- contaminant transport in the geosphere is relatively rapid, as the groundwater flows are high and the pathlength to the discharge point (the Ottawa River) is short, so the geosphere has a very limited containment function;
- the biosphere is inherently uncertain in the context of climate change and other factors such as human development and man's management of the environment. Rather than model a wide range of alternative biosphere states, the PostSA has taken a deliberately cautious and limiting interpretation of the biosphere, and people that might be exposed within it, so as to bound the potential radiological impacts on people in the future.

The key uncertainties that have been identified as candidates for calculation cases are follows.

E 2.3.1 Radioactive Inventory

The contaminant inventory of the NPDDF is fundamental to the potential health effects that might occur in the future. Recognising the importance of this, a cautious approach has been adopted in the Normal Evolution scenario, which uses an upper estimate of the inventory for the reference calculations. The importance of the inventory is illustrated with two alternative calculation cases.

The first sensitivity case takes into account the inventory based, where possible, on sampling data collected by CNL during the decommissioning works. Generally, these indicate a significantly lower inventory than theoretical estimates. Non-radioactive contaminant inventories are not included in this uncertainty/sensitivity case. This is because the bulk nature of the key non-radioactive contaminant (lead) is such that the inventory is not substantially uncertain.

The second sensitivity case uses the measured and modelled bounding inventory (i.e., the NES inventory) multiplied by a factor of two.

E 2.3.2 Sorption

Radionuclide sorption is a key mechanism in the containment of radionuclides within the NPDDF. Indeed, the key role of the grout as well as the overburden and bedrock is to provide conditions in which sorption of radionuclides is enhanced, reducing their mobility. However, sorption coefficients are both difficult to measure, and strongly influence the rate of release of contaminants. Three alternative calculation cases have therefore been considered to reflect the importance of radionuclide sorption. In the first and the second calculation cases, reference values used in the PostSA for grout and concrete, and for overburden and bedrock are reduced, respectively. The third calculation case combines the effects of the first two calculation cases. This is to illustrate the effects of greater than anticipated contaminant mobility.

E 2.3.3 Rapid Degradation

The NPDDF structure and grout play a key role in limiting the rate of release of contaminants into the environment. A sensitivity case therefore examines the potential consequences of less than anticipated physical performance by these engineered barriers. Various factors might lead to poor performance of the grout and concrete. For example, unexpected cracking in the concrete could occur, or there could be poorer than anticipated grout performance, in addition to damage as a result of seismic activity (see, for example, CNL (2021a)).

The consequences of such an event are modelled assuming an instantaneous increase in the hydraulic conductivity of the concrete and grout materials to a ‘degraded’ value immediately after the end of the institutional control period. Damage to the concrete structure of the NPDDF will result in higher flows of water through the Facility (as calculated by Arcadis & Geofirma, 2023b), which in turn will decrease contaminant transport times to the surrounding environment.

E 2.3.4 Hydraulic Conductivity

The regional and site hydrogeological framework for the NPDDF site is described based on historical and 2019 local investigation and site characterization work completed at and in the vicinity of the NPD site and at the CRL site, review of water well records from the OMECP (Ontario Ministry of Environment, Conservation and Parks), and review of the scientific literature (Arcadis & Geofirma, 2022). The presence and hydrogeological properties of the permeable fluvial sand and gravel layer that subparallels the Ottawa River and extends tile drain capture of overburden groundwater northwest of the NPDDF is identified as an uncertainty in modeling of groundwater flow at the NPDDF site (Arcadis & Geofirma, 2022).

However, uncertainty in the extent and hydrogeological properties of the fluvial sand and gravel layer located northwest of the NPDDF will have a negligible effect on the rate and location of overburden groundwater discharge from the NPDDF to the Ottawa River and hence the NPD closure and post-closure phases. Resolving the uncertainty on the location and hydrogeological properties of this fluvial sand and gravel layer would enhance the confidence in the 3-D groundwater flow model and the volumes of tile drain water, but that uncertainty primarily concerns the completeness of the site characterization work and not the fate of overburden groundwater discharge from the NPDDF to the Ottawa River (Arcadis & Geofirma, 2022).

Two alternative calculation cases have therefore been considered to account for the uncertainty in the hydraulic properties of the geosphere, using flow results from Arcadis & Geofirma (2023a):

- The first case examines increased hydraulic conductivity (and thus flow) in bedrock compared to NES. The bedrock hydraulic conductivity is increased to the maximum measured value of 6.6 x 10^{-6} m/s (see Arcadis & Geofirma (2023a) more additional information).

- The second case examines increased hydraulic conductivity (and thus flow) in the overburden fill material between the facility and the river, compared to NES. This case increases the fill conductivity by one order of magnitude greater than the calibrated value (Arcadis & Geofirma, 2023a). The calibrated hydraulic conductivity of the fill is at the maximum of the expected fill conductivity range, 10^{-3} m/s (Arcadis & Geofirma, 2023a). The conductivity of the fill in the high overburden hydraulic conductivity cases is 10^{-2} m/s, which is an extremely permeable value for the fill (Arcadis & Geofirma, 2023a).

E 2.3.5 River dilution

To reflect the uncertainty in river flows, as river characteristics may vary throughout the year due to seasonal patterns and climate changes, such a situation will be covered by a lesser dilution factor than the one used in Normal Evolution Scenario.

E 2.3.6 Self-sufficient Indigenous Receptor

The habits of people that may be exposed by contaminants released from the NPDDF define their level of exposure, but are uncertain. Reference assumptions are made for the Normal Evolution scenario. Other

people, such as Indigenous peoples may be exposed to contaminants released into the environment around NPDDF. This sensitivity case therefore considers a self-sufficient Indigenous receptor group following a traditional lifestyle. The group is represented by adults, children and infants using the area around the NPDDF, including the Ottawa River, for hunting and gathering. The exposure pathways for the self-sufficient Indigenous receptor group are taken to include:

- time spent on the shoreline for recreation and fishing;
- ingestion of water from the river;
- ingestion of fish caught from the river; and
- hunting of game that uses the river for drinking water, foraging of wildfoods and honey.

Exposure pathways and associated data for the self-sufficient Indigenous receptor group are derived from CSA (2022) and SENES (2014).

E 2.4 Disruptive Event Scenarios

Disruptive Event scenarios are represented as modifications to the Normal Evolution scenario described in Section E 2.2. As such, the underlying conceptual model is in most cases the same, but different values are selected for scenario-related parameters or there are some limited modifications to the model structure. The exposed groups (Site Resident, Hunter, Indigenous and Offsite receptor) are also the same in most cases. The following subsections summarise the way in which Disruptive Event Scenarios will be modelled. More details and description of each scenario is presented by Appendix D.

E 2.4.1 Site Investigation (Inadvertent Human Intrusion)

Inadvertent human intrusion into the NPDDF, as a result of site investigation, is considered in this scenario. The scenario concerns the drilling of an investigation borehole into the Facility structure without knowledge of its nature and contents. This could lead to exposure as a result of examining samples from the borehole. For the scenario, the primary exposure group is a person drilling the borehole. The driller could retrieve samples from any part of the Facility; it is most conservative to assume that the Reactor Vault is intercepted by the borehole as the majority and highest concentration of the radioactivity is located within this room, (McVeigh, 2019a; McVeigh, 2019b; Edwards & Adams, 2019; Porter, 2022). An estimate of the mass of Zircaloy in the core sample was made, being 0.437 kg in 16.25 kg of grout, dictated by the core sample size of 4.5 m. Therefore, the 5 kg value of metal assumed retrieved in the assessment of this scenario is a factor of 10 more conservative than would be expected.

Following drilling, some of the waste material may be left at the surface (this could be drilling mud, or even parts of core, if this were retrieved but discarded). To capture the potential exposures to this material, it is assumed to be discarded and in due course become mixed with soil. The use of the soil is then assessed in the same way as for the Site Resident, and a dose calculated to this exposure group.

It is assumed that human intrusion is prevented while there remain postclosure controls over the NPDDF site (e.g., access restrictions and signs). This calculation case can therefore be used to examine the implications of alternative periods of institutional control in terms of reduction in the potential dose due to human intrusion.

E 2.4.2 Surface Erosion

The presence of a significant depth of overburden over the groundwater surface is important in preventing the release of contaminants into soils or sediments that could be directly encountered by people. The possible consequences of this "barrier" being removed by some mechanism is therefore of interest.

A catastrophic flood is extremely unlikely, but could possibly occur and result in a surge of river water up to the elevation of the NPDDF surface structures. The floodwaters would likely disturb the ground surface (even if not down to the level that is contaminated). This was assessed by OPG in 1999, updated by OPG in 2016, and compared and summarized most recently by CNL in 2017 (CNL, 2017c). According to CNL (2017c), the 1999 OPG work identified the return period for such a flood based on a Probable Maximum Flood (PMF) involving a 1-in-10,000-y (i.e., 10^{-4} annual probability of occurrence) rainfall occurring (Probable Maximum Precipitation (PMP)) along with a 1-in-100-y snow accumulation. In total, this PMF is an event with a 10^{-6} annual return period (1-in-a-million years). When the PMF is used to determine dam failure scenarios, OPG's 1999 study concluded the frequency to be less than 1-in-10-million y. CNL (2017c) mentions that the purpose of OPG's 1999 work was "to establish flood limits for emergency planning", and further that "the conservatism inherent in this modelling was desirable and allowed Emergency Evacuation plans in heavily populated areas to be more conservative". CNL (2017c) compared the 1999 and 2016 results and noted that the basis for the PMF and its associated return period was the same, i.e., a 1-in-10,000-y PMP rainfall plus a 1-in-100-y snow accumulation, however, the 2016 predicted flood elevation levels are lower than those from 1999 (due to improvements in how topography is taken into account). For example, the 1999 flood elevation level estimated at Deep River was 131.1 mASL and at the NPD site was 132.2 mASL, whereas the 2016 estimate at Deep River was 117.8 mASL (a 2016 estimate was not provided specifically for the NPD site). The highest NPD estimate, 132.2 mASL, corresponds to a water level increase of 23.5 m), compared to the NPD's elevation at 129 mASL.

The conceptual model represents this scenario by assuming that, after the time of the event (assumed to be any time after the end of institutional control) the overburden is completely removed, leaving the contaminated infill and rock into which the groundwater from the NPDDF is directly released. Subsequently, a receptor is exposed directly to this material. Conservatively, they are assumed to have the same habits as the Site Resident in the Normal Evolution scenario. This includes food chain pathways (and using the exposed fill for farming), as well as direct irradiation.

It is possible that other mechanisms might lead to erosion of the ground surface, for example a loss of vegetation coupled with much greater rainfall and/or rapid snowmelt. The conceptual model representing this scenario also covers such situations.

E 2.4.3 Extreme Degradation

This disruptive event scenario addresses the potential effects of the facility experiencing a much more severe earthquake than that considered under Normal Evolution. This is assumed to correspond to a 1-in-50,000 y seismic event. Cautiously, this scenario is assumed to occur only 1,000 y after closure. The CNL (2019a, 2021a) NPD Underground Structure Seismic Assessment examined the effects of a 1-in-50,000 y event on the NPDDF. Results of CNL (2019a, 2021a) indicate that:

- the above-bedrock portion of the facility will experience substantial cracking (structural failure/cracking occurs); and
- the below-bedrock portion of the facility is not expected to experience cracking, as it is socketed into surrounding bedrock on all sides which provides continuous lateral support.

However, due to e.g., early degradation of engineered barriers, this scenario instead assumes that there is some cracking in the below-bedrock portion of the facility.

E 2.4.4 Fault Zone Activation

Seismic events of even greater magnitudes (such as a 1-in-50,000 y event) may have further impacts on the Facility's long-term performance and safety due to early degradation of engineered barriers (CNL, 2021a). Such events may also induce a fault zone of higher conductivity in the geosphere (specifically, the bedrock near the river).

This scenario therefore examines the impact of an extreme seismic event occurring 1000 y after closure, damaging the facility (in the same manner as in the Extreme Degradation Case, Section E 2.4.3), but also creating a fracture zone, which will be represented using a higher conductivity in the bedrock between the facility and the river compared to that of the NES.

E 2.4.5 Excavation of Above-Bedrock Facility

The mass excavation of the entire Facility is too unlikely to be considered to be a plausible Disruptive Event Scenario because the concrete structure would retain sufficient structural integrity to preclude it. In addition to the existing structure, it will be backfilled with grout and a concrete cap will be placed over the nuclear area as well as an engineered barrier over the entire facility. More limited examination (as considered in Section E 2.4.1) would be sufficient to reveal the characteristics of the Facility and deter any more large-scale disruption. Hence, this has been discussed in the context of "What If" calculations (see Section E 2.6.1).

Nevertheless, the consequences of the partial disruption and excavation of the NPDDF is examined in this case. This Disruptive Event scenario examines the impacts of the above-bedrock portion of the facility being excavated and mixed with soil (at a ratio of 1:10 grout and concrete to soil). The assumption is that there is no house built inside of the excavated hole and only the resident receptor is assumed to be exposed. Other aspects are similar to the "What if" Mass Excavation Scenario (Section E 2.6.1).

Similar to the Site Investigation Disruptive Event (Section E 2.4.1), it is assumed that human intrusion is prevented while there remain postclosure controls over the NPDDF site (e.g., access restrictions and signs). This calculation case can therefore also be used to examine the implications of alternative periods of institutional control in terms of reduction in the potential dose due to human intrusion.

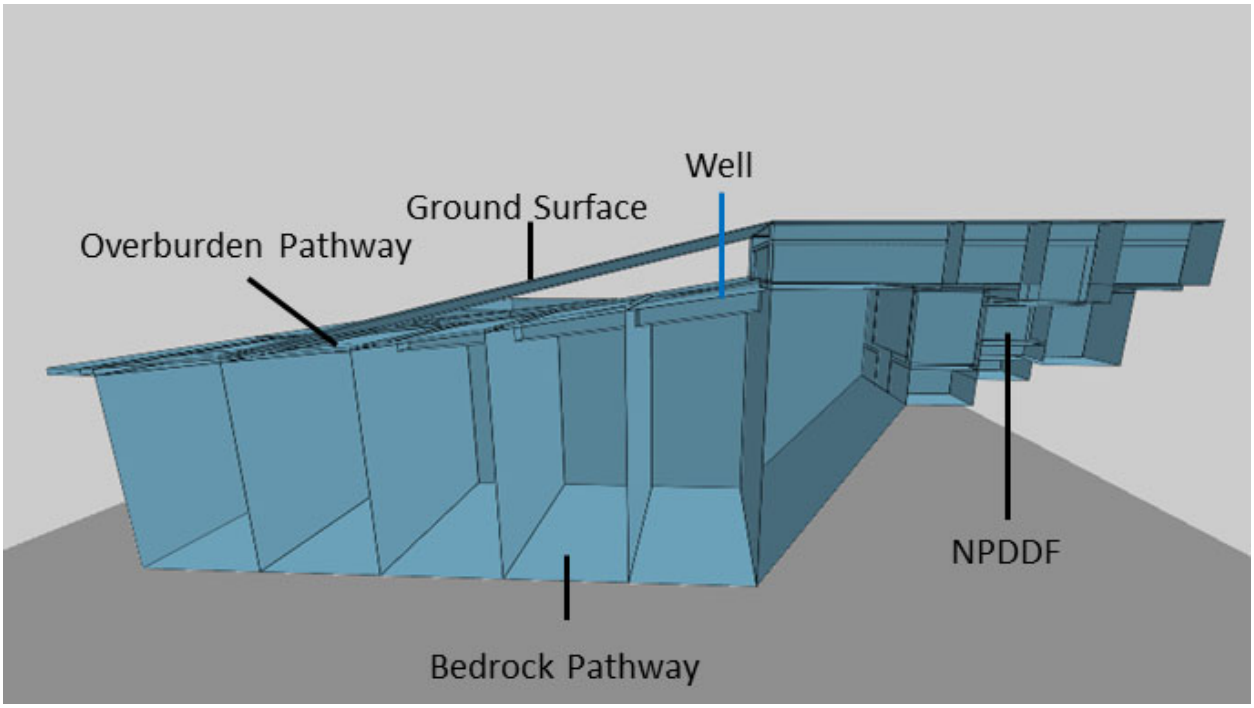
E 2.4.6 Overburden Well

This Disruptive Event case evaluates the potentially highest doses that could be received by a person exposed to contaminated groundwater released from the Facility.

As noted, wells are not uncommon in the vicinity of the NPDDF, but they are generally into deeper formations than the potentially contaminated aquifers, and would be very unlikely to be emplaced downstream of the Facility (see Figure E-11). This Disruptive Event case, however, assumes that an overburden well is placed between the Facility and the river and that the well intersects the water flow in the overburden immediately downstream of the Facility, i.e., in the pipe trench. The contaminated groundwater is pumped out and used for drinking and irrigation.

The model is based on the Normal Evolution scenario, but instead of modelling the extraction of river water by the Site Resident, in this case well water is used. This requires changing the irrigation transfer process to draw contaminants from the pipe trench rather than the river. As an input to the model, groundwater flow information from Arcadis & Geofirma (2023a,b) is used.

Figure E-11 Assumed Location of the Well, immediately Downstream of the NPDDF



E 2.4.7 Bedrock Well

This Disruptive Event case assumes that a well is placed between the Facility and the river and that the well intersects the bedrock release plume between the facility and the river. The contaminated groundwater is pumped out and used. As an input to the model, groundwater flow information from Arcadis & Geofirma (2023a,b) is used.

Other aspects are implemented in the same manner as in the Overburden Well Disruptive Event (Section E 2.4.6).

E 2.5 Defence-in-Depth Cases

Defence-in-depth cases are used to show the function of the barriers to contaminant release from the NPDDF. These demonstrate the postclosure safety performance benefits of the engineered barriers by quantifying the performance in their absence. As such, they are not “scenarios” in their own right as they involve somewhat artificial conditions. The defence-in-depth cases are discussed in more detail in Appendix D (scenarios).

E 2.5.1 Role of Existing Facility Structure

The reference strategy for the closure of the NPDDF is for all rooms to be infilled with cementitious grout. The grout and the existing facility concrete will act as barriers to contaminant release. This calculation case tests the significance of the existing facility concrete structure as part of the multi-barrier system. This is achieved using exactly the same conceptual models as the Normal Evolution scenario, but assigning the following properties to the existing facility structure:

- In terms of chemical properties, structural concrete is modelled as being fully degraded, beginning at 0 y post-closure; and
- In terms of physical properties, structural concrete is modelled as being extremely degraded beginning at 0 y post-closure.

E 2.5.2 Role of Grout

The reference strategy for the closure of the NPDDF is for all rooms to be infilled with cementitious grout. The grout provides an engineered barrier that confines radionuclides, primarily by providing conditions in which they are sorbed very effectively. This complements the properties of the existing engineered structure, while, in addition, limiting groundwater flows through the Facility. This calculation case tests the significance of the grout as part of the multi-barrier system. This is achieved using exactly the same conceptual models as the Normal Evolution scenario, but assigning the following properties to the grout:

- In terms of chemical properties, the grout is modelled as being fully degraded beginning at 0 y post-closure; and
- In terms of physical properties, the grout is modelled as being extremely degraded beginning at 0 y post closure.

E 2.6 What If Cases

What If cases are intended to explore key aspects of the disposal system and the limits of its performance. This is achieved with situations that are deliberately extreme. What If calculations have very low probability so are not for comparison with performance targets. The selection of What If cases is described in the Scenarios and Calculation Cases appendix (Appendix D).

E 2.6.1 Facility Mass Excavation

This calculation case represents an upper estimate to the concentrations of radionuclides to which people could be exposed in the surface environment. Rather than radionuclides being contained and only gradually released by groundwater, this case considers the complete excavation of the Facility and then the dispersal, in soil, of the excavated material. The excavated material is assumed to be spread on land with very limited dilution, then used for farming by a resident.

The calculation case is modelled by taking the total amount of radioactivity in the NPDDF at the time of disruption, dividing it by the volume of excavated material, and applying a simple dilution factor to account for the mixing of the material with soil.

E 2.6.2 River Level Fall

In the future, the Ottawa River is the main receptor for groundwater containing contaminants from the NPDDF. It is unlikely that the river level would change very substantially from its current position; this would require major changes to precipitation and runoff in the overall catchment of the Ottawa River. Future environmental conditions are uncertain, but such a major change would only be likely to be associated with a major environmental change episode such as a glaciation. A fall in the river level could permit all potentially contaminated groundwater to be released directly to the surface. Although very unlikely, this situation is of interest because the dilution with uncontaminated river water that occurs in the Normal Evolution scenario would not then occur. This calculation case evaluates the potential consequences of a release direct to surface of contaminated groundwater from the Facility. The conceptual model is the same as the Normal Evolution scenario, with the exception that the groundwater release from the geosphere is directed into the shoreline sediments, rather than the riverbed sediments.

E 2.6.3 Undetected Fracture Zone

The natural or man-made features within the geosphere that may not be detected during the site investigation (e.g., fracture zones, faults, brine pockets, old mine workings, and boreholes) could play a role in the transport of groundwater to and from the Facility and the associated migration of contaminants. Some physical features of the geological environment may remain undetected during site surveys and even during pilot tunnel excavations (Arcadis & Geofirma, 2022). The nature of the geological environment will indicate the likelihood that certain types of undetected features may be present, and the site investigation may be able to place bounds on the maximum size or minimum proximity to such features.

Hence, this case examines the impact of an undetected fracture zone being present. In this proposed case, the facility evolves as per the NES but the bedrock is assigned a higher hydraulic conductivity. This combination of conditions is the same as would be modelled in the “Sensitivity Case” which considers the increased hydraulic conductivity in the bedrock (see Section E 2.3.4).

E 3 DATA

This section presents the data used in the PostSA models, represented as a set of model parameters. These data have been selected from the most recently published and relevant information sources. Where possible, site specific data are used, drawing on the information sources presented in Appendix B (the System Description). If unavailable, data from well-established compilations (including other PostSA studies) have been adopted.

For each parameter, the basis for the data has been set out, together with an indication of the degree of uncertainty associated with the data. Other information presented includes the units and a parameter name (which is used in the AMBER assessment code). All data selected for the model are checked for their basis (with reference to the original source documents) and their incorporation into AMBER.

All data are assigned a “Version” number. The version corresponds to the iteration of the PostSA at which it was last updated. Consequently, some standard reference data, such as dose coefficients, refer to Version 1 as they have not been necessary to modify since, whereas other data (e.g., solubility limits) have been updated for the third iteration PostSA and are assigned “Version 3”. The data that have been updated in this 4th Iteration PostSA are assigned “Version 4”.

Prior to presenting the data by each component of the model, an initial section (Section E 3.1) identifies the contaminants of interest, recognising that those with short half-life, or very small quantity, are not of significance to the PostSA. A subsequent section (Section E 3.2) then presents fundamental data for the selected contaminants. Data are then presented according to each part of the system: the wastes, the facility, the geosphere, the biosphere and potential exposure groups. These sections (E 3.3 to E 3.7) of the appendix present the data used in the assessment of the Normal Evolution scenario. For alternative scenarios and cases, some of the parameters are modified in order to represent different assumptions. Data used in these alternative scenarios and calculation cases are presented in Sections E 3.8 to E 3.12.

E 3.1 Contaminants of Interest

E 3.1.1 Radionuclides

Radioactive inventory data are available from a number of supporting reports, and are discussed in the System Description (Appendix B). Inventory data are available for various radionuclides, not all of which are relevant to the postclosure period. Many have relatively short half-lives which mean they will not pose a hazard in the future. Other radionuclides are present with very low activity in the wastes. Clearly, there is no need to consider such radionuclides; resources are better directed at radionuclides likely to be of significance in terms of the postclosure performance of the NPDDF.

The radionuclide inventory derived by Porter (2022) has therefore been screened to reduce the number of radionuclides being considered to those that are relevant for the postclosure phase. The process for screening is the same as used in many other radioactive waste programmes, and takes account of both radioactive decay and a highly cautious measure of radiotoxicity. For the purposes of screening, the dominant component of the inventory of the NPDDF, the inventory of the Reactor Vault, has been used. This part of the inventory also considers the widest range of radionuclides; inventory data for other rooms is often based on a small number of measured radionuclides.

In relation to half-life effects, the radionuclide inventory has been decayed by 100 y, assuming that this is the minimum period before which exposure to radionuclides could occur (in the most conservative case, by human intrusion and direct exposure to the radioactivity). Noting that some radionuclides exhibit ingrowth of radioactive progeny, the inventory is also modelled beyond this point, as radiologically significant progeny may increase with time.

The steps in screening the inventory are as follows:

- radionuclides with a half-life of less than one year are screened out, on the basis that they will decay by more than a factor of $1x10^{30}$ in 100 y;
- a highly cautious measure of radiation dose to humans (both an adult and a child receptor) is then calculated for the remaining radionuclides. A screening criterion is then used to screen out radionuclides. Any radionuclide that contributes less than 0.001% of the total dose is screened out.

For the first step, radionuclide half-life data were obtained from ICRP (2008). The radionuclides screened out on this basis are shown in Figure E-12. In addition to these radionuclides, purely gaseous radionuclides (isotopes of Ar and Kr) were excluded from the inventory on the basis that they would have been released to air.

Figure E-12 Radionuclides Screened Out* from the Inventory on the Basis of Short Half-life of less than One Year

Radionuclide	Half-life (y)	Radionuclide	Half-life (y)
P32	3.91E-02	Po212	9.47E-15
Co60m	1.99E-05	Po213	1.33E-13
Y90	7.31E-03	Po215	5.64E-11
Ag108	4.51E-06	Po216	4.59E-09
Ag109m	1.25E-06	At217	1.02E-09
Sn121	3.08E-03	Fr221	9.32E-06
Te125m	1.57E-01	Rn220	1.06E-04
Sb126m	3.64E-05	Ra224	1.00E-02
Ba137m	4.85E-06	Ra225	4.08E-02
Ta182	3.13E-01	Ac225	2.74E-02
Re186	1.03E-02	Ac228	6.99E-04

Radionuclide	Half-life (y)	Radionuclide	Half-life (y)
Tl208	5.80E-06	Th231	2.91E-03
Pb209	3.71E-04	Th234	6.60E-02
Pb212	1.21E-03	Pa234	7.64E-04
Bi210	1.37E-02	Pa234m	2.22E-06
Bi211	4.07E-06	U237	1.85E-02
Bi212	1.15E-04	Am242	1.83E-03
Bi213	8.68E-05	Cm242	4.46E-01
Po210	3.79E-01		

* **Note**: Where these radionuclides are progeny of other, longer-lived radionuclides (e.g., Ba-137m from Cs-137, or Po-210 from Pb-210), they are represented in PostSA model, but only as daughters of longer-lived parents.

To calculate a simple measure of dose it is assumed that the entire reactor vault inventory is dispersed in water which is then drunk by a person. The volume of the Reactor Vault is used as the volume of water into which the radionuclides are mixed, with no additional dilution. Standard radiation dose coefficients for ingestion by a member of the public are used (ICRP, 2012). The dose from drinking this water is calculated as follows:

$$E_{Ing,n} = C_{w,n}\, I_w\, DC_{Ing,n}$$

where

$C_{w,n}$ is the activity of radionuclide *n* in Bq at times between 100 y and 100,000 y, divided by the volume water in the Reactor Vault (assumed to be 525.7 m^3);

I_w is the ingestion rate of water by an adult (0.6 $m^3\ y^{-1}$) and a child 10 years old (0.35 $m^3\ y^{-1}$) (Smith & Jones, 2003);

$DC_{Ing,n}$ is the dose coefficient for ingestion by an adult member of the public (ICRP, 2012).

The contributions of radioactive progeny of *n* (where present) have been added to the dose calculated for the parent. The AMBER code has been used to calculate the decay and ingrowth of radionuclides as a function of time, and the associated doses.

Input data required for the calculation include radionuclide half-lives and decay schemes, taken from ICRP (2008). Dose coefficients, including contributions from progeny, were taken from ICRP (2012). Table E-8 presents the calculated peak dose from those radionuclides in the initial inventory. Here, radionuclides are screened out from further consideration if the dose calculated under these extremely cautious assumptions contributes less than 0.001% of the total screening dose (calculated cumulatively, taking into account radionuclides with the highest percentage of the total dose).

Table E-8 Screening of Radionuclides on the Basis of a Cautious Calculation that the dose contributes to less than 0.001% of the total screening dose.

Radionuclide	Half-life (y)	Inventory (Bq)	Peak dose Adult* (Sv/y)	Peak dose Child* (Sv/y)	Screening Outcome
H3	1.23E+01	2.16E+12	1.60E-04	1.19E-04	
Be10	1.51E+06	2.34E+05	2.93E-07	3.73E-07	Out
C14	5.70E+03	1.59E+12	1.04E+00	8.37E-01	
Al26	7.17E+05	4.18E+06	1.67E-05	1.98E-05	Out
Si32	1.32E+02	5.13E+05	1.03E-06	1.31E-06	Out
Cl36	3.01E+05	2.98E+10	3.16E-02	3.76E-02	
Ca41	1.02E+05	1.01E+10	2.19E-03	3.23E-03	
Fe55	2.74E+00	3.51E+12	1.33E-11	2.58E-11	Out
Fe60	1.50E+06	4.27E+05	5.52E-05	7.41E-05	
Co60	5.27E+00	1.71E+13	1.29E-04	2.43E-04	
Ni59	1.01E+05	3.73E+11	2.68E-02	2.73E-02	
Ni63	1.00E+02	4.86E+13	4.17E+00	4.54E+00	
Se79	2.95E+05	1.84E+07	6.09E-05	1.71E-04	
Rb87	4.92E+10	3.29E+04	5.63E-08	6.79E-08	Out
Sr90	2.88E+01	6.43E+10	2.03E-01	2.54E-01	
Zr93	1.53E+06	2.40E+11	3.34E-01	1.36E-01	
Nb91	6.80E+02	2.22E+07	-	-	Out^
Nb93m	1.61E+01	1.95E+11	3.64E-04	4.78E-04	
Nb94	2.03E+04	1.58E+10	3.05E-02	3.55E-02	
Mo93	4.00E+03	2.65E+09	1.94E-06	2.54E-06	Out
Tc99	2.11E+05	5.67E+08	4.14E-04	4.91E-04	
Ru106	1.02E+00	4.91E+02	3.07E-25	3.84E-25	Out
Pd107	6.50E+06	6.08E+05	2.57E-08	3.28E-08	Out
Ag108m	4.18E+02	1.00E+11	2.23E-01	2.43E-01	
Cd109	1.26E+00	3.40E+05	1.64E-22	1.68E-22	Out
Cd113m	1.41E+01	2.90E+09	5.59E-04	4.11E-04	
Sn121m	4.39E+01	2.08E+11	4.26E-02	5.38E-02	
Sn126	2.30E+05	1.11E+06	9.08E-06	1.10E-05	Out
Sb125	2.76E+00	9.06E+10	6.12E-04	7.25E-04	
I129	1.57E+07	9.56E+04	1.20E-05	1.21E-05	Out

Radionuclide	Half-life (y)	Inventory (Bq)	Peak dose Adult* (Sv/y)	Peak dose Child* (Sv/y)	Screening Outcome
Ba133	10.52	1.03E+09	2.41E-06	4.32E-06	Out
Cs134	2.06E+00	7.62E+06	5.45E-19	2.34E-19	Out
Cs135	2.30E+06	2.15E+06	4.91E-06	2.44E-06	Out
Cs137	3.02E+01	1.33E+11	1.99E-01	8.91E-02	
La137	6.00E+04	1.46E+07	1.35E-06	1.55E-06	Out
Pm145	1.77E+01	2.47E+08	6.18E-07	7.54E-07	Out
Pm146	5.53E+00	1.84E+05	8.87E-13	9.50E-13	Out
Pm147	2.62E+00	1.93E+08	2.68E-13	2.04E-13	Out
Sm151	9.00E+01	3.11E+09	1.61E-04	1.91E-04	
Eu152	1.35E+01	1.34E+11	5.15E-02	5.58E-02	
Eu154	8.59E+00	2.69E+10	1.93E-05	2.31E-05	
Eu155	4.76E+00	2.01E+09	3.50E-10	4.34E-10	Out
Tb157	7.10E+01	4.24E+07	6.21E-07	7.24E-07	Out
Tb158	1.80E+02	8.26E+06	7.06E-06	7.86E-06	Out
Ho166m	1.20E+03	3.73E+07	8.04E-05	8.21E-05	
Hf182	9.00E+06	4.44E+06	2.28E-05	2.10E-05	
Re186m	2.00E+05	1.21E+06	5.11E-06	5.97E-06	Out
Pt193	5.00E+01	7.94E+08	7.02E-06	9.12E-06	Out
Pb205	1.53E+07	2.93E+05	9.37E-08	1.19E-07	Out
Pb210	2.22E+01	3.67E+01	3.53E-09	4.90E-09	Out
Ra228	5.75E+00	1.15E+07	6.91E-08	2.02E-07	Out
Th228	1.91E+00	2.43E+07	5.67E-18	1.00E-17	Out
Th229	7.34E+03	1.26E+06	8.71E-04	9.73E-04	
Th230	7.54E+04	1.26E+05	3.14E-04	4.26E-04	
Th232	1.41E+10	1.15E+07	1.40E-02	3.54E-02	
U232	6.89E+01	1.24E+07	2.47E-03	3.02E-03	
U233	1.59E+05	3.23E+08	2.10E-01	2.31E-01	
U234	2.46E+05	4.07E+07	5.79E-02	7.77E-02	
U235	7.04E+08	1.55E+06	3.07E-03	2.70E-03	
U236	2.34E+07	1.70E+05	9.11E-06	7.92E-06	Out
U238	4.47E+09	3.49E+07	1.04E-02	1.30E-02	

Radionuclide	Half-life (y)	Inventory (Bq)	Peak dose Adult* (Sv/y)	Peak dose Child* (Sv/y)	Screening Outcome
Np237	2.14E+06	6.06E+04	2.21E-05	2.05E-05	
Pu238	8.77E+01	2.30E+09	2.74E-01	1.67E-01	
Pu239	2.41E+04	2.10E+09	5.98E-01	3.77E-01	
Pu240	6.56E+03	1.49E+09	4.22E-01	2.66E-01	
Pu241	1.44E+01	2.96E+10	1.97E-01	1.27E-01	
Pu242	3.75E+05	1.21E+07	3.33E-03	2.10E-03	
Am241	4.32E+02	3.82E+09	7.42E-01	4.76E-01	
Am242m	1.41E+02	1.16E+07	2.68E-03	1.69E-03	
Am243	7.37E+03	1.74E+08	3.96E-02	2.55E-02	
Cm243	2.91E+01	1.01E+07	1.64E-04	1.02E-04	
Cm244	1.81E+01	1.67E+10	6.26E-02	4.20E-02	
Cm245	8.50E+03	1.94E+06	7.82E-04	5.01E-04	
Cm246	4.76E+03	5.61E+06	2.70E-03	1.68E-03	

Note:

* Doses for each radionuclide for which there is an initial inventory take account of ingrown radioactive progeny.

^No dose coefficient data have been calculated by ICRP (2012) for Nb-91, therefore no dose can be calculated and it has been screened out.

The list of 45 radionuclides for inclusion in the assessment is as follows.

- H-3, C-14, Cl-36, Ca-41, Fe-60, Co-60, Ni-59, Ni-63, Se-79, Sr-90, Zr-93, Nb-93m, Nb-94, Tc-99, Ag-108m, Cd-113m, Sn-121m, Sb-125, Cs-137, Sm-151, Eu-152, Eu-154, Ho-166m, Hf-182, Th-229, Th-230, Th-232, U-232, U-233, U-234, U-235, U-238, Np-237, Pu-238, Pu-239, Pu-240, Pu-241, Pu-242, Am-241, Am-242m, Am-243, Cm-243, Cm-244, Cm-245, Cm-246

These radionuclides are assigned an initial inventory at the beginning of the assessment. There are a further 10 radionuclides that are not in the initial inventory, but require inclusion as they are radioactive progeny of one or more of the included radionuclides of sufficient half-life to merit explicit inclusion in the PostSA model. Those radioactive progeny with a half-life of more than 100 days require explicit modelling; shorter lived radionuclides can be assumed to be constantly in secular equilibrium with their parents. The radionuclides requiring explicit modelling are:

- Ta-182, Pb-210, Po-210, Ra-226, Ra-228, Pa-231, Ac-227, Th-228, Cm-242, U-236

  [noting that Th-229, Th-230, Th-232, U-233, U-234, U-235, U-238, Am-241, Am-243, Np-237, Pu-238 Pu-239, Pu-240, Pu-241, Pu-242, Co-60, Nb-93m have initial inventory and will also grow in, thus are not double-counted in the list here]

This means that element-specific information will be required in the model for the following elements:

- H, C, Cl, Ca, Fe, Co, Ni, Se, Sr, Zr, Nb, Tc, Ag, Cd, Sn, Sb, Cs, Sm, Eu, Ho, Hf, Th, U, Np, Pu, Am, Cm, Ta, Pb, Po, Ra, Pa, Ac

E 3.1.2 Non-radioactive Contaminants

The inventory of non-radioactive contaminants includes:

- Lead;
- Mercury; and
- Asbestos.

Oils are not considered in the PostSA as they have been removed from systems during the Phase I decommissioning.

Schruder & Vickerd (2017) present the latest estimate of the inventory of hazardous substances. There is lead paint throughout the facility, and lead bricks, lead sheet and lead shot used as shielding. Small quantities of mercury are possible in the facility (Taylor, 2014), associated with thermometers etc. Gillespie (2016) states that there is an estimated 0.01 m^3 of mercury throughout the facility. Asbestos is present in the form of pipe insulation, floor tiles and building cladding. It is assumed that this will remain in the Facility once it is decommissioned, provided it can be grouted without negatively affecting the structural and hydrological properties of the Facility.

CNL will be removing all PCB ballasts from the facility before or during decommissioning work. Therefore, there will be no PCBs remaining in the facility.

There will be some organics in the waste disposed within the NPD building, including organic additives in cement grout, polythene (polyethylene) bags, and asphalt from the roof that will be collapsed into the disposal facility (Arcadis, 2021b). The available evidence suggests that the organic materials are unlikely to be significantly detrimental with respect to radiological risk. In addition, in safety assessments for radioactive waste disposal facilities in other countries, these (or similar) materials are not considered detrimental to safety. For more details the reader is referred to Arcadis (2021b).

The organic materials are therefore not explicitly considered in this safety assessment.

E 3.2 Fundamental Radionuclide Properties

E 3.2.1 Radioactive Decay

Name:	Radioactive Decay		
Version:	Version 4		
Symbol:	Half_Life		
Units:	Half-life is in y		
Description:	Radioactive decay schemes for use in the PostSA. Some shorter-lived radionuclides are taken to be present in secular equilibrium with their parent for the purpose of the PostSA modelling. The criterion is taken to be a half-life of less than 100 days. Those radionuclides with short-lived daughters are given in Table E-9 based on ICRP (2008). The contribution of the short-lived daughters is explicitly represented by including their contribution to the dose coefficient of the modelled parent radionuclide.		
Value(s):	Half-lives (parameter Half_Life) are shown in Table E-8. Table E-9 presents the radionuclides in secular equilibrium. Note: Branching fractions are given in brackets. Where none is stated, the fraction is 1. Table E-10 presents the decay chains modelled explicitly.		
Justification:	Radionuclide decay data are taken from ICRP (2008).		
Uncertainty:	Uncertainties in the decay of most radionuclides are very low. In some instances, however, half-lives have been subject to revision in the past decade.		
Source of uncertainty:	Difficulties in measuring decay rates for radionuclides that are rarely produced.		
References:	ICRP (2008). Nuclear Decay Data for Dosimetric Calculations. ICRP Publication 107. Ann. ICRP 38 (3).		
Author:	Louise Bruffell	**Date:**	2 December 2022
Checker (basis):	Kate Thatcher	**Date:**	21 December 2022
Checker (implementation):	Kate Thatcher	**Date:**	21 December 2022

Table E-9 Radionuclides with Progeny in Secular Equilibrium

Radionuclide	Progeny in Secular Equilibrium
Fe-60	→ Co-60m
Sr-90	→ Y-90
Ag-108m	→ (8.700E-2) Ag-108
Sn-121m	→ (7.76E-1) Sn-121
Sb-125	→ (2.314E-01) Te-125m
Cs-137	→ (9.440E-1) Ba-137m
Pb-210	→ Bi-210 → (1.320E-6) Tl-206 → (1.900E-8) Hg-206 → Tl-206
Ra-226	→ Rn-222 → Po-218 → (9.998E-1) Pb-214 → Bi-214 → (9.998E-1) Po-214 → (2.100E-4) Tl-210 → (2.000E-4) At-218 → (9.990E-1) Bi-214 (as above) → (1.000E-3) Rn-218 → Po-214
Ra-228	→ Ac-228
Ac-227	→ (9.862E-1) Th-227 → Ra-223→ Rn-219 → Po-215 → Pb-211 → Bi-211 → (9.972E-1) Tl-207 → (2.760E-3) Po-211 → (1.380E-2) Fr-223 → Ra-223 (as above) → (6.000E-5) At-219 → (9.700E-1) Bi-215 → Po-215 (as above)
Th-228	→ Ra-224 → Rn-220 → Po-216 → Pb-212 → Bi-212 → (6.406E-1) Po-212 → (3.594E-1) Tl-208
Th-229	→ Ra-225 → Ac-225 → Fr-221 → At-217 → (9.999E-1) Bi-213 → (9.791E-1) Po-213 → Pb-209 → (2.090E-2) Tl-209 ↗
U-235	→ Th-231
U-238	→ Th-234 → Pa-234m → (1.600E-3) Pa-234
Np-237	→ Pa-233
Pu-239	→ (9.994E-1) U-235m
Pu-241	→ (2.450E-5) U-237
Am-242m	→ (9.955E-1) Am-242 → (4.500E-3) Np-238
Am-243	→ Np-239

Note: Branching fractions are given in brackets. Where none is stated, the fraction is 1.

Table E-10 Radioactive Decay Chains

Radionuclide	Explicitly Modelled Progeny*
H3	
C14	
Cl36	
Ca41	
Fe60	(0.9976) Co60
Co60	
Ni59	
Ni63	
Se79	
Sr90	
Zr93	(0.975) Nb93m
Nb93m	
Nb94	
Tc99	
Ag108m	
Cd113m	Cd-113 daughter ignored due to low yield (0.14%) and low specific activity/extremely long half life
Sn121m	
Sb125	
Cs137	
Sm151	
Eu152	Gd-152 daughter ignored due to low specific activity/extremely long half life
Eu154	
Ho166m	
Hf182	Ta182
Th229	
Th230	Ra226 Pb210 Po210
Th232	Ra228 Th228
U232	Th228
U233	Th229
U234	Th230 Ra226 Pb210 Po210
U235	Pa231 Ac227
U236	Th232 Ra228 Th228
U238	U234 Th230 Ra226 Pb210 Po210
Np237	U233 Th229
Pu238	U234 Th230 Ra226 Pb210 Po210
Pu239	U235 Pa231 Ac227
Pu240	U236 Th232 Ra228 Th228
Pu241	Am241 Np237 U233 Th229
Pu242	U238 U234 Th230 Ra226 Pb210 Po210
Am241	Np237 U233 Th229
Am242m	(0.8233) Cm242 Pu238 U234 Th230 Ra226 Pb210 Po210
	(0.1722) Pu242 U238 U234 Th230 Ra226 Pb210 Po210

Radionuclide	Explicitly Modelled Progeny*
	(0.0045) Pu238 U234 Th230 Ra226 Pb210 Po210
Am243	Pu239 U235 Pa231 Ac227
Cm243	(0.0024) Am243 Pu239 U235 Pa231 Ac227
	(0.9976) Pu239 U235 Pa231 Ac227
Cm244	Pu240 U236 Th232 Ra228 Th228
Cm245	Pu241 Am241 Np237 U233 Th229
Cm246	Pu242 U238 U234 Th230 Ra226 Pb210 Po210

Note: Branching fractions are given in brackets. Where none is stated, the fraction is 1.

E 3.2.2 Internal Dose Coefficients

Name:	Internal Dose Coefficients		
Version:	Version 4		
Symbol:	DCF_f (ingestion), DCF_i (inhalation of particulate) and DCF_g (inhalation of gas)		
Units:	Sv Bq^{-1}		
Description:	Effective dose per unit inhalation and ingestion for adults, children (10 years) and infants (1 year). Values include contributions for short-lived radionuclides that are assumed to be in secular equilibrium with their parents, where data is available.		
Value(s):	See Table E-11(ingestion) and Table E-12 (inhalation). For inhalation of C-14 as CO_2 dose coefficients of 1.2E-11, 1.8E-11 and 3.8E-11 Sv/Bq are used for adults, children and infants.		
Justification:	The values are recommended by the CSA (2022) and ICRP (2012). For inhalation dose coefficients taken from ICRP (2012), the lung absorption type for each element is taken to be the same as used in CSA (2022), and otherwise the type given in ICRP (2012) for all or unspecified compounds.		
Uncertainty:	Committed effective doses are treated as reference values as they are specified in international guidance and Canadian regulatory guidance. Uncertainties vary with radionuclide but are likely to be less than one order of magnitude.		
Source of uncertainty:	Limited functional data on radiobiology for some radionuclides mean that there are uncertainties in the underlying biokinetic models and the radiation weighting and tissue weighting factors that are used to derive dose coefficients.		
References:	Canadian Standards Association (CSA). (2022). Guidelines for modelling radionuclide environmental transport, fate, and exposure associated with normal operation of nuclear facilities, N288.1:20, 2022 Errata, June. ICRP (2012). Compendium of Dose Coefficients based on ICRP Publication 60. ICRP Publication 119. Ann. ICRP 41(Suppl.).		
Author:	Russell Walke, James Penfold	**Date:**	2 July 2019
Checker (basis):	Louise Bruffell	**Date:**	5 December 2022
Checker (implementation):	Kate Thatcher	**Date:**	21 December 2022

Table E-11 Ingestion Dose Coefficients

Radionuclide	Infants (Sv Bq^{-1})	Children (Sv Bq^{-1})	Adults (Sv Bq^{-1})	Note
H-3	1.3E-10	6.3E-11	4.6E-11	3
C-14	1.6E-9	8.0E-10	5.8E-10	1
Cl-36	6.3E-9	1.9E-9	9.3E-10	1
Ca-41	5.2E-10	4.8E-10	1.9E-10	2
Fe-60*	2.7E-7	2.5E-7	1.1E-7	2
Co-60	2.7E-8	1.1E-8	3.4E-9	1
Ni-59	3.4E-10	1.1E-10	6.3E-11	2
Ni-63	8.4E-10	2.8E-10	1.5E-10	1
Se-79	2.8E-8	1.4E-8	2.9E-9	2
Sr-90*	9.3E-8	6.6E-8	3.1E-8	1
Zr-93	7.6E-10	5.8E-10	1.1E-9	2
Nb-93m	9.1E-10	2.7E-10	1.2E-10	2
Nb-94	9.7E-9	3.4E-9	1.7E-9	1
Tc-99	4.8E-9	1.3E-9	6.4E-10	1
Ag-108m*	1.1E-8	4.3E-9	2.3E-9	2
Cd-113m	5.6E-8	2.9E-8	2.3E-8	2
Sn-121m*	4.0E-9	1.2E-9	5.6E-10	2
Sb-125*	7.6E-9	2.5E-9	1.3E-9	1
Cs-137*	1.2E-8	1.0E-8	1.3E-8	1
Sm-151	6.4E-10	2.0E-10	9.8E-11	2
Eu-152	7.4E-9	2.6E-9	1.4E-9	1
Eu-154	1.2E-8	4.1E-9	2.0E-9	2
Ho-166m	9.3E-9	3.5E-9	2.0E-9	2
Hf-182	7.9E-9	4.0E-9	3.0E-9	2
Ta-182	9.4E-9	3.1E-9	1.5E-9	2
Pb-210*	3.6E-6	1.9E-6	6.9E-7	2
Po-210	8.8E-6	2.6E-6	1.2E-6	2
Ra-226*	9.6E-7	8.0E-7	2.8E-7	1
Ra-228*	5.7E-6	3.9E-6	6.9E-7	1
Ac-227*	4.3E-6	2.0E-6	1.2E-6	2

Radionuclide	Infants (Sv Bq^{-1})	Children (Sv Bq^{-1})	Adults (Sv Bq^{-1})	Note
Th-228*	1.1E-6	4.3E-7	1.4E-7	1
Th-229*	2.4E-6	1.2E-6	6.1E-7	1
Th-230	4.1E-7	2.4E-7	2.1E-7	2
Th-232	4.5E-7	2.9E-7	2.3E-7	1
Pa-231	1.3E-6	9.2E-7	7.1E-7	2
U-232	8.2E-7	5.7E-7	3.3E-7	1
U-233	1.4E-7	7.8E-8	5.1E-8	1
U-234	1.3E-7	7.4E-8	4.9E-8	1
U-235*	1.3E-7	7.2E-8	4.7E-8	1
U-236	1.3E-7	7.0E-8	4.7E-8	1
U-238*	1.5E-7	7.5E-8	4.8E-8	1
Np-237*	2.2E-7	1.1E-7	1.1E-7	1
Pu-238	4.0E-7	2.4E-7	2.3E-7	1
Pu-239*	4.2E-7	2.7E-7	2.5E-7	1
Pu-240	4.2E-7	2.7E-7	2.5E-7	1
Pu-241*	5.7E-9	5.1E-9	4.8E-9	1
Pu-242	4.0E-7	2.6E-7	2.4E-7	1
Am-241	3.7E-7	2.2E-7	2.0E-7	1
Am-242m*	3.0E-7	2.0E-7	1.9E-7	2
Am-243*	3.8E-7	2.2E-7	2.0E-7	1
Cm-242	7.6E-8	2.4E-8	1.2E-8	1
Cm-243	3.3E-7	1.6E-7	1.5E-7	2
Cm-244	2.9E-7	1.4E-7	1.2E-7	1
Cm-245	3.7E-7	2.3E-7	2.1E-7	2
Cm-246	3.7E-7	2.2E-7	2.1E-7	2

Notes: * Explicitly includes contribution of short-lived daughters, as listed in Table E-9, where data is available. (1) Table C.2 of CSA (2022). (2) Table F.1 of ICRP (2012). (3) Assumes organically bound tritium, with data from Table C.2 of CSA (2022).

Table E-12 Inhalation Dose Coefficients

Radionuclide	Infants (Sv Bq^{-1})	Children (Sv Bq^{-1})	Adults (Sv Bq^{-1})	Note
H-3	8.0E-11	3.8E-11	3.0E-11	3
C-14	6.6E-9	2.8E-9	2.0E-9	1
Cl-36	2.6E-8	1.0E-8	7.3E-9	1
Ca-41	2.6E-10	1.7E-10	9.5E-11	2
Fe-60*	1.7E-7	2.4E-7	1.4E-7	2
Co-60	3.4E-8	1.5E-8	1.0E-8	1
Ni-59	6.2E-10	2.1E-10	1.3E-10	2
Ni-63	1.9E-9	7.0E-10	4.8E-10	1
Se-79	1.3E-8	5.6E-9	1.1E-9	2
Sr-90*	1.2E-7	5.4E-8	3.8E-8	1,2
Zr-93	3.1E-9	4.1E-9	1.0E-8	2
Nb-93m	2.4E-9	8.2E-10	5.1E-10	2
Nb-94	3.7E-8	1.6E-8	1.1E-8	1
Tc-99	1.3E-8	5.7E-9	4.0E-9	1
Ag-108m*	2.7E-8	1.1E-8	7.4E-9	2
Cd-113m	2.7E-7	1.3E-7	1.1E-7	2
Sn-121m*	1.6E-8	6.7E-9	4.7E-9	2
Sb-125*	1.9E-08	7.9E-9	5.6E-09	1,2
Cs-137*	5.4E-9	3.7E-9	4.6E-9	1
Sm-151	1.0E-8	4.5E-9	4.0E-9	2
Eu-152	1.0E-7	4.9E-8	4.2E-8	1
Eu-154	1.5E-7	6.5E-8	5.3E-8	2
Ho-166m	2.5E-7	1.3E-7	1.2E-7	2
Hf-182	6.2E-7	3.6E-7	3.1E-7	2
Ta-182	3.4E-08	1.5E-08	1.0E-08	2
Pb-210*	4.0E-6	1.6E-6	1.2E-6	2
Po-210	1.1E-5	4.6E-6	3.3E-6	2
Ra-226*	1.1E-5	4.9E-6	3.5E-6	1,2
Ra-228*	1.0E-5	4.7E-6	2.6E-6	2
Ac-227*	1.7E-3	7.4E-4	5.7E-4	2
Th-228*	1.4E-4	5.9E-5	4.3E-5	1,2
Th-229*	2.2E-4	9.8E-5	7.8E-5	1,2
Th-230	3.5E-5	1.6E-5	1.4E-5	2
Th-232	5.0E-5	2.6E-5	2.5E-5	1

Radionuclide	Infants (Sv Bq^{-1})	Children (Sv Bq^{-1})	Adults (Sv Bq^{-1})	Note
Pa-231	2.3E-4	1.5E-4	1.4E-4	2
U-232	2.4E-5	1.1E-5	7.8E-6	1
U-233	1.1E-5	4.9E-6	3.6E-6	1
U-234	1.1E-5	4.8E-6	3.5E-6	1
U-235*	1.0E-5	4.3E-6	3.1E-6	1,2
U-236	1.0E-5	4.5E-6	3.2E-6	1
U-238*	9.4E-6	4.0E-6	2.9E-6	1,2
Np-237*	4.0E-5	2.2E-5	2.3E-5	1,2
Pu-238	7.4E-5	4.4E-5	4.6E-5	1
Pu-239*	7.7E-5	4.8E-5	5.0E-5	1
Pu-240	7.7E-5	4.8E-5	5.0E-5	1
Pu-241*	9.7E-7	8.3E-7	9.0E-7	1,2
Pu-242	7.3E-5	4.5E-5	4.8E-5	1
Am-241	6.9E-5	4.0E-5	4.2E-5	1
Am-242m*	5.3E-5	3.4E-5	3.7E-5	2
Am-243*	6.8E-5	4.0E-5	4.1E-5	1
Cm-242	1.8E-5	7.3E-6	5.2E-6	1
Cm-243	6.1E-5	3.1E-5	3.1E-5	2
Cm-244	5.7E-5	2.7E-5	2.7E-5	1
Cm-245	6.9E-5	4.1E-5	4.2E-5	2
Cm-246	6.9E-5	4.1E-5	4.2E-5	2

Notes: * Explicitly includes contribution of short-lived daughters, as listed in Table E-9, where data is available.
(1) Table C.1 of CSA (2022). (2) Table G.1 of ICRP (2012), assuming the lung class as in CSA (2022), where given, and otherwise the default ICRP lung class where specified, and where not taking the most conservative form.
(3) Assumes tritium as water vapour, with data from Table C.1 of CSA (2022).

E 3.2.3 External Dose Factors

Name:	Dose Coefficient for External Irradiation		
Version:	Version 4		
Symbol:	DCF_e, DCF_w, DCF_s, D_c, DCF_{sk}		
Units:	Sv s^{-1} per Bq m^{-3}		
Description:	Effective dose due to external irradiation from contaminated soils/sediments (based on contamination to an infinite depth) and water immersion, for adults, children (10 years) and infants (1 year). Values include contributions for short-lived radionuclides that are assumed to be in secular equilibrium with their parents. Values for exposure to contaminated shore sediments relate to contamination depth of 5 cm and apply a shore-width factor of 0.2 as defined by CSA (2022) (clause 7.10.3), except for essentially pure beta emitters. Values for skin contact are summed factors for beta and gamma (RCLEA, 2011), following the methodology of Oatway & Mobbs (2003).		
Value(s):	Table E-13 (external from soil and sediments) Table E-14 (immersion in contaminated water) Table E-15 (contaminated shore sediment) Table E-16 (skin contact)		
Justification:	CSA (2022) includes several assumptions in the calculation of dose coefficients, which are described in Clauses 4.3.6 and 4.3.7 of that report. These include screening-in or out inclusion of short-lived daughters depending on their overall contribution to the dose conversion factor and an appropriate time of exposure for each pathway. CSA (2022) goes on to state that "The progeny considered when calculating DRLs for a given facility should be based on the ingrowth times appropriate for that facility". Given the long-term nature of this assessment, in comparison to the DRL context, contributions from all short-lived daughters are conservatively included. CSA (2022) uses dose coefficient data from 1996. This PostSA uses the latest dose coefficients recommended by the US EPA (2019) by the same authors. Dose coefficients are taken from Table 4-5 for external irradiation from contaminated soil; Table 4-7 for contaminated water and Table 4-3 for shore sediment. Note that when external irradiation from immersion is calculated for a bathtub a correction factor of 0.7 is applied (parameter D_c, see CSA (2022) paragraph 6.16.1.2). For exposure to shoreline sediments, a conservative shoreline dilution factor (DF_s) of 1 is applied (clause 7.10.4 CSA (2022)).		
Uncertainty:	Committed effective doses are treated as reference values as they are specified in international guidance and Canadian regulatory guidance. Uncertainties vary with radionuclide but are likely to be less than one order of magnitude.		
Source of uncertainty:	There is natural variability and uncertainty in the geometries and physiological assumptions that support calculation of external dose coefficients.		
References:	Canadian Standards Association (CSA). (2022). Guidelines for modelling radionuclide environmental transport, fate, and exposure associated with normal operation of nuclear facilities, N288.1:20, 2022 Errata, June. United States Environmental Protection Agency (EPA). (2019). External Exposure to Radionuclides in Air, Water and Soil. External Dose Rate Coefficients for General Application. Federal Guidance Report No.15. EPA 402-R-19-002. RCLEA, 2011. The radioactively contaminated land exposure assessment methodology – Technical Report. CLR 14 v1.2 https://www.gov.uk/government/publications/rclea-software-application Oatway and Mobbs, 2003. Methodology for estimating the doses to members of the public from the future use of land previously contaminated with radioactivity. National Radiation Protection Board report NRPB-W36. ISBN 0 85951 508 7		
Author:	Louise Bruffell	**Date:**	5 December 2022
Checker (basis):	Kate Thatcher	**Date:**	12 December 2022
Checker (implementation):	Kate Thatcher	**Date:**	12 December 2022

Table E-13 Dose Coefficients for External Irradiation from Contaminated Soil/Sediment

Radionuclide	Adults (Sv s^{-1} per Bq m^{-3})	Children (Sv s^{-1} per Bq m^{-3})	Infants (Sv s^{-1} per Bq m^{-3})
H-3	3.41E-23	3.76E-23	4.19E-23
C-14	3.14E-20	3.46E-20	3.86E-20
Cl-36	4.21E-19	4.64E-19	5.17E-19
Ca-41	0.00E+00	0.00E+00	0.00E+00
Fe-60*	1.73E-19	1.91E-19	2.13E-19
Co-60	8.25E-17	9.08E-17	1.01E-16
Ni-59	4.52E-22	5.02E-22	5.65E-22
Ni-63	4.09E-21	4.51E-21	5.03E-21
Se-79	3.49E-20	3.85E-20	4.29E-20
Sr-90*	2.52E-18	2.76E-18	3.06E-18
Zr-93	4.84E-21	5.34E-21	5.95E-21
Nb-93m	3.04E-22	7.30E-22	9.33E-22
Nb-94	4.82E-17	5.33E-17	5.97E-17
Tc-99	1.01E-19	1.12E-19	1.24E-19
Ag-108m*	4.79E-17	5.31E-17	5.96E-17
Cd-113m	2.47E-19	2.72E-19	3.03E-19
Sn-121m*	1.34E-19	1.50E-19	1.69E-19
Sb-125*	1.23E-17	1.37E-17	1.54E-17
Cs-137*	1.72E-17	1.90E-17	2.14E-17
Sm-151	5.53E-21	6.10E-21	6.80E-21
Eu-152	3.61E-17	3.99E-17	4.44E-17
Eu-154	3.93E-17	4.34E-17	4.83E-17
Ho-166m	4.77E-17	5.29E-17	5.93E-17
Hf-182	6.11E-18	6.84E-18	7.68E-18
Ta-182	4.03E-17	4.45E-17	4.95E-17
Pb-210*	7.01E-19	7.73E-19	8.61E-19
Po-210	3.00E-22	3.32E-22	3.72E-22
Ra-226*	5.74E-17	6.32E-17	7.00E-17
Ra-228*	2.76E-17	3.04E-17	3.39E-17
Ac-227*	2.50E-17	2.79E-17	3.14E-17
Th-228*	5.06E-17	5.55E-17	6.08E-17
Th-229*	8.86E-18	9.89E-18	1.11E-17
Th-230	6.21E-21	7.37E-21	8.53E-21

Radionuclide	Adults (Sv s^{-1} per Bq m^{-3})	Children (Sv s^{-1} per Bq m^{-3})	Infants (Sv s^{-1} per Bq m^{-3})
Th-232	2.74E-21	3.37E-21	3.99E-21
Pa-231	8.50E-19	9.53E-19	1.07E-18
U-232	3.96E-21	4.85E-21	5.70E-21
U-233	4.93E-21	5.73E-21	6.57E-21
U-234	1.88E-21	2.44E-21	2.93E-21
U-235*	4.03E-18	4.55E-18	5.13E-18
U-236	9.32E-22	1.32E-21	1.62E-21
U-238*	2.62E-18	2.88E-18	3.21E-18
Np-237*	5.83E-18	6.54E-18	7.36E-18
Pu-238	5.29E-22	9.27E-22	1.18E-21
Pu-239*	1.47E-21	1.80E-21	2.10E-21
Pu-240	5.46E-22	9.29E-22	1.18E-21
Pu-241*	1.40E-22	1.58E-22	1.78E-22
Pu-242	3.08E-21	3.66E-21	4.16E-21
Am-241	2.20E-19	2.65E-19	3.19E-19
Am-242m*	5.30E-19	5.96E-19	6.71E-19
Am-243*	4.77E-18	5.41E-18	6.13E-18
Cm-242	5.93E-22	1.03E-21	1.30E-21
Cm-243	2.88E-18	3.24E-18	3.65E-18
Cm-244	1.00E-21	1.42E-21	1.71E-21
Cm-245	1.94E-18	2.20E-18	2.50E-18
Cm-246	1.25E-19	1.37E-19	1.52E-19

Notes: * Explicitly includes contribution of short-lived daughters, as listed in Table E-9.

Table E-14 Dose Coefficients for Immersion in Contaminated Water

Radionuclide	Adults ($Sv\ s^{-1}$ per $Bq\ m^{-3}$)	Children ($Sv\ s^{-1}$ per $Bq\ m^{-3}$)	Infants ($Sv\ s^{-1}$ per $Bq\ m^{-3}$)
H-3	6.15E-27	2.04E-26	2.79E-26
C-14	2.82E-21	2.91E-21	3.01E-21
Cl-36	1.89E-19	1.94E-19	2.02E-19
Ca-41	0.00E+00	0.00E+00	0.00E+00
Fe-60*	4.05E-19	4.60E-19	5.15E-19
Co-60	2.53E-16	2.82E-16	3.09E-16
Ni-59	1.40E-21	1.59E-21	1.79E-21
Ni-63	7.81E-24	1.32E-23	1.67E-23
Se-79	3.30E-21	3.40E-21	3.52E-21
Sr-90*	1.06E-18	1.10E-18	1.16E-18
Zr-93	9.75E-24	1.61E-23	2.02E-23
Nb-93m	6.12E-21	1.41E-20	1.63E-20
Nb-94	1.49E-16	1.68E-16	1.86E-16
Tc-99	3.09E-20	3.14E-20	3.21E-20
Ag-108m*	1.48E-16	1.68E-16	1.87E-16
Cd-113m	1.03E-19	1.06E-19	1.10E-19
Sn-121m*	1.21E-19	1.53E-19	1.89E-19
Sb-125*	3.85E-17	4.38E-17	4.93E-17
Cs-137*	5.24E-17	5.93E-17	6.60E-17
Sm-151	6.10E-23	1.05E-22	1.28E-22
Eu-152	1.12E-16	1.26E-16	1.40E-16
Eu-154	1.21E-16	1.36E-16	1.50E-16
Ho-166m	1.49E-16	1.69E-16	1.89E-16
Hf-182	1.99E-17	2.29E-17	2.65E-17
Ta-182	1.25E-16	1.41E-16	1.55E-16
Pb-210*	3.75E-19	4.12E-19	4.55E-19
Po-210	9.29E-22	1.05E-21	1.16E-21
Ra-226*	1.72E-16	1.91E-16	2.12E-16
Ra-228*	8.35E-17	9.38E-17	1.04E-16
Ac-227*	7.52E-17	8.56E-17	9.77E-17
Th-228*	1.51E-16	1.66E-16	1.83E-16
Th-229*	2.62E-17	2.96E-17	3.46E-17
Th-230	2.81E-20	3.70E-20	4.49E-20

Radionuclide	Adults (Sv s^{-1} per Bq m^{-3})	Children (Sv s^{-1} per Bq m^{-3})	Infants (Sv s^{-1} per Bq m^{-3})
Th-232	1.46E-20	2.09E-20	2.55E-20
Pa-231	2.81E-18	3.24E-18	3.77E-18
U-232	2.02E-20	2.93E-20	3.57E-20
U-233	2.00E-20	2.57E-20	3.11E-20
U-234	1.16E-20	1.87E-20	2.29E-20
U-235*	1.38E-17	1.60E-17	1.90E-17
U-236	7.31E-21	1.32E-20	1.61E-20
U-238*	3.17E-18	3.50E-18	3.96E-18
Np-237*	1.94E-17	2.20E-17	2.60E-17
Pu-238	6.60E-21	1.37E-20	1.63E-20
Pu-239*	7.26E-21	1.08E-20	1.30E-20
Pu-240	6.46E-21	1.31E-20	1.57E-20
Pu-241*	3.52E-22	3.96E-22	4.96E-22
Pu-242	1.32E-20	1.97E-20	2.26E-20
Am-241	1.20E-18	1.52E-18	1.88E-18
Am-242m*	1.31E-18	1.45E-18	1.81E-18
Am-243*	1.72E-17	1.95E-17	2.39E-17
Cm-242	7.52E-21	1.50E-20	1.77E-20
Cm-243	1.00E-17	1.12E-17	1.37E-17
Cm-244	7.86E-21	1.44E-20	1.69E-20
Cm-245	7.37E-18	8.08E-18	1.04E-17
Cm-246	3.75E-19	4.19E-19	4.61E-19

Notes: * Explicitly includes contribution of short-lived daughters, as listed in Table E-9. For exposure in a bathtub a correction factor (Dc) of 0.7 is applied.

Table E-15 Dose Coefficients for Exposure to Contaminated Shore Sediment

Radionuclide	Adults ($Sv\ s^{-1}$ per $Bq\ m^{-3}$)	Children ($Sv\ s^{-1}$ per $Bq\ m^{-3}$)	Infants ($Sv\ s^{-1}$ per $Bq\ m^{-3}$)
H-3	1.85E-23	2.02E-23	2.22E-23
C-14	1.70E-20	1.86E-20	2.04E-20
Cl-36	4.56E-20	4.98E-20	5.48E-20
Ca-41	0.00E+00	0.00E+00	0.00E+00
Fe-60*	4.00E-20	4.40E-20	4.86E-20
Co-60	8.60E-18	9.38E-18	1.03E-17
Ni-59	5.38E-23	5.94E-23	6.64E-23
Ni-63	2.21E-21	2.42E-21	2.67E-21
Se-79	1.89E-20	2.07E-20	2.27E-20
Sr-90*	1.38E-18	1.51E-18	1.64E-18
Zr-93	2.62E-21	2.87E-21	3.16E-21
Nb-93m	6.08E-23	1.46E-22	1.87E-22
Nb-94	5.42E-18	5.96E-18	6.58E-18
Tc-99	5.46E-20	5.98E-20	6.58E-20
Ag-108m*	5.58E-18	6.16E-18	6.84E-18
Cd-113m	1.33E-19	1.46E-19	1.60E-19
Sn-121m*	5.71E-20	6.30E-20	6.98E-20
Sb-125*	1.47E-18	1.63E-18	1.82E-18
Cs-137*	2.08E-18	2.29E-18	2.55E-18
Sm-151	2.99E-21	3.28E-21	3.61E-21
Eu-152	3.96E-18	4.34E-18	4.80E-18
Eu-154	4.28E-18	4.70E-18	5.18E-18
Ho-166m	5.54E-18	6.12E-18	6.80E-18
Hf-182	7.96E-19	8.90E-19	9.92E-19
Ta-182	4.36E-18	4.78E-18	5.24E-18
Pb-210*	7.72E-20	8.48E-20	9.35E-20
Po-210	3.36E-23	3.70E-23	4.10E-23
Ra-226*	6.10E-18	6.69E-18	7.32E-18
Ra-228*	3.02E-18	3.32E-18	3.66E-18
Ac-227*	3.07E-18	3.41E-18	3.81E-18
Th-228*	5.02E-18	5.47E-18	5.95E-18
Th-229*	1.22E-18	1.36E-18	1.51E-18
Th-230	9.90E-22	1.18E-21	1.36E-21

Radionuclide	Adults (Sv s^{-1} per Bq m^{-3})	Children (Sv s^{-1} per Bq m^{-3})	Infants (Sv s^{-1} per Bq m^{-3})
Th-232	4.68E-22	5.84E-22	6.86E-22
Pa-231	1.10E-19	1.23E-19	1.38E-19
U-232	6.28E-22	7.82E-22	9.22E-22
U-233	7.04E-22	8.24E-22	9.48E-22
U-234	3.14E-22	4.14E-22	5.00E-22
U-235*	5.59E-19	6.29E-19	7.06E-19
U-236	1.61E-22	2.36E-22	2.90E-22
U-238*	2.95E-19	3.24E-19	3.55E-19
Np-237*	7.69E-19	8.62E-19	9.63E-19
Pu-238	9.70E-23	1.75E-22	2.24E-22
Pu-239*	2.14E-22	2.68E-22	3.16E-22
Pu-240	9.90E-23	1.74E-22	2.22E-22
Pu-241*	1.89E-23	2.12E-23	2.39E-23
Pu-242	3.46E-22	4.32E-22	4.98E-22
Am-241	4.04E-20	4.88E-20	5.84E-20
Am-242m*	6.83E-20	7.68E-20	8.59E-20
Am-243*	6.86E-19	7.76E-19	8.74E-19
Cm-242	1.06E-22	1.92E-22	2.44E-22
Cm-243	3.98E-19	4.46E-19	5.00E-19
Cm-244	1.39E-22	2.16E-22	2.66E-22
Cm-245	2.90E-19	3.30E-19	3.72E-19
Cm-246	1.27E-20	1.39E-20	1.52E-20

Notes: * Explicitly includes contribution of short-lived daughters, as listed in Table E-9. The 0.2 shore-width factor is applied to all radionuclides, except for essentially pure beta emitters (H-3, C-14, Fe-60, Ni-63, Se-79, Sr-90, Zr-93, Tc-99, Cd-113m, Cs-137 and Sm-151; and Y-90, Sn-121 and Pb-209 of the radionuclides assumed to be in secular equilibrium with parents) (CSA, 2022).

Table E-16 Dose Coefficients for Skin Contact

Radionuclide	Adults and Children (Sv y^{-1} per Bq cm^{-3})	Notes
H-3	0	RCLEA, 2011
C-14	0.0079	RCLEA, 2011
Cl-36	0.0395	#C14 as analogue, multiplied by 5 as ~5 times higher decay energy
Ca-41	0.00014	#Fe55 as analogue
Fe-60	0	#Se79 as analogue
Co-60	0.0171	RCLEA, 2011
Ni-59	0	#H3 as analogue
Ni-63	0.00016	RCLEA, 2011
Se-79	0	RCLEA, 2011
Sr-90*	0.045	RCLEA, 2011
Zr-93	0	#Se79 as analogue
Nb-93m	1.00E-06	RCLEA, 2011
Nb-94	0.01983	RCLEA, 2011
Tc-99	0.014	RCLEA, 2011
Ag-108m*	0.00328	RCLEA, 2011
Cd-113m	0	#Sn121m as analogue
Sn-121m	0	RCLEA, 2011
Sb-125	0.01227	RCLEA, 2011
Cs-137*	0.02229	RCLEA, 2011
Sm-151	0.00025	RCLEA, 2011
Eu-152	0.0146	RCLEA, 2011
Eu-154	0.03065	RCLEA, 2011
Ho-166m	0.01677	#Cs134 as analogue
Hf-182	0.00818	#Sb125 as analogue, divided by 1.5 as ~ 1.5 lower decay energy
Ta-182	0	#Eu154 as analogue
Pb-210*	0.023073	RCLEA, 2011
Po-210	0.000954	#Pu238 as analogue
Ra-226*	0.05296	RCLEA, 2011
Ra-228*	0.02751	RCLEA, 2011
Ac-227*	0.05564	#Th229 as analogue
Th-228*	0.05688	RCLEA, 2011
Th-229*	0.05564	RCLEA, 2011

Radionuclide	Adults and Children (Sv y^{-1} per Bq cm^{-3})	Notes
Th-230*	0.000943	RCLEA, 2011
Th-232	0.0844	RCLEA, 2011
Pa-231	0.001325	RCLEA, 2011
U-232	8.90E-05	#U234 as analogue
U-233	6.10E-05	RCLEA, 2011
U-234	8.90E-05	RCLEA, 2011
U-235*	0.022095	RCLEA, 2011
U-236	4.08E-05	RCLEA, 2011
U-238*	0.033085	RCLEA, 2011
Np-237*	0.03048	RCLEA, 2011
Pu-238	0.000954	RCLEA, 2011
Pu-239	1.26E-05	RCLEA, 2011
Pu-240	9.10E-07	RCLEA, 2011
Pu-241*	4.36E-07	RCLEA, 2011
Pu-242	1.26E-05	#Pu239 as analogue
Am-241	0.00063	RCLEA, 2011
Am-242m	1.00E-05	#Nb93m as analogue, multiplied by 10 as ~10 times higher decay energy
Am-243	0.03048	#Np237 as analogue
Cm-242	0.000954	#Pu238 as analogue
Cm-243	0.03048	#Np237 as analogue
Cm-244	0.000954	#Pu238 as analogue
Cm-245	0.03048	#Np237 as analogue
Cm-246	0.000954	#Pu238 as analogue

Notes: * Explicitly includes contribution of short-lived daughters, as noted in RCLEA, 2011. Those in Table E-9 not included here are due to a lack of data for the daughter radionuclides.# Analogues chosen based on similar mode of decay and decay energy.

E 3.3 Waste and Repository

E 3.3.1 Normal Evolution Scenario - Radionuclide Inventory

Name:	Modelled Radionuclide Inventory
Version:	Version 4
Parameter Name:	i_{ActMat}, i_{BR}, i_{FR}, i_{TR}, $i_{cStruct}$
Units:	Bq and Bq g^{-1}
Description:	The modelled radionuclide inventory for the PostSA. • i_{ActMat} = inventory of activated metals in reactor vault • i_{BR} = inventory of boiler room • i_{FR} = inventory of fuelling room • i_{TR}, = inventory of turbine room • $i_{cStruct}$ = inventory of structure (concrete walls etc)
Value(s):	See Table E-17 (Reactor Vault) and Table E-18 (other rooms).
Justification:	The modelled inventory is primarily based on the data sources and assumptions presented in Porter (2022), Psotka (2021, 2022) and McVeigh (2018), and is discussed in detail in Appendix B. These data are used to define the inventory for the assessment as follows: • Reactor vault –values from Porter (2022) selected for the composite total activity. In general, this is the higher value from Edwards & Adams (2019) and NMNTI (2017). See Appendix B for more detail; • Reactor vault contamination –values from Porter (2022), multiplied by 3; • Boiler Room – values are the sum of activity in the moderator system, primary heat transport system and other minor systems (with the exception of the fuel handling system) as given in Porter (2022), multiplied by 3; • Fuelling Room – values are the activity associated with the fuel handling system multiplied by 3; • Turbine Room – values are the inventory associated with the non-nuclear area, above grade structure concrete multiplied by 3, with the addition of the tritium associated with asbestos; • General contamination – activity values associated with the below-grade facility structure are multiplied by 3, and then divided by the total mass of the NPDDF structure. The resulting activity concentrations are applied to all concrete in the model. Only those radionuclides not screened out are considered (see Section E 3.1.1). Note that the inventory of tritium for the Control Room has been assigned to the inventory of the Turbine Room for simplicity. Tritium is the only radionuclide recorded for this room, so it has not been represented directly in the model.

Name:	Modelled Radionuclide Inventory		
	For this case, an uncertainty factor of 3 has been applied to the inventories presented in Appendix B for the Reactor Vault Contamination, Boiler Room, Fuelling Room, Turbine Room, and Generic Contamination.		
Uncertainty:	Uncertainties in the inventory are discussed in Appendix B. For example, it is noted that the total activation product inventory estimated using Edwards & Adams (2019) is conservative by more than a factor of three in comparison to the total activation product inventory estimated by sample results alone (NMNTI, 2017). It is also noted that the most recent estimate of the Boiler Room inventory is around 2.5 times greater than the previous iteration estimate. A factor of 3 is therefore used to increase the inventory everywhere except the reactor vault to take into account the uncertainty in the inventory.		
Source of uncertainty:	The activation product inventory is calculated using neutron activation models that might not fully represent the geometry, material composition impurities and irradiation history of the facility, leading to some discrepancies. The inventory of other radionuclides is based on measurements and other estimates. Generally the key source of uncertainty relates to the assumptions made in scaling up the measured radionuclide concentration from a sample to the whole room.		
References:	Edwards and Adams (2019). Calculations of the Current NPD Reactor Vault Activation Source Term. CNL Ref #64-505100-ANL-001. February 2019. McVeigh, A. (2018). NPD Building Characterization Report, NPD Decommissioning, CNL No. 64-509410-REPT-011, R.0, November. NMNTI (2017). NPD Reactor Characterization Report, 64-509410-REPT-004, May 2017. Porter, G. (2022). Nuclear Power Demonstration Waste Facility (NPDWF) Waste Inventory Report. CNL No. 64-508600-REPT-001. Revision 1. Psotka, G. (2021). Report, General. Characterization Report for the NPDWF Primary Heat Transport and Moderator Systems. NPD Decommissioning. CNL No. 64-509410-REPT-002. Revision 2. Psotka, G. (2022). Characterisation Report for the NPDWF “Other Systems”. CNL No. 64-509410-REPT-015. Revision 1.		
Author:	Renato Zagorscak	**Date:**	10 November 2022
Checker (basis):	Kate Thatcher	**Date:**	21 December 2022
Checker (implementation):	Kate Thatcher	**Date:**	21 December 2022

Table E-17 Radionuclides in the Reactor Vault (i_{ActMat}, Bq)

Radionuclide	Aluminum	Concrete	Carbon Steel	Stainless Steel	Zircaloy	Contamination
H3	9.13E+09	1.41E+12	2.35E+08	2.04E+09	7.36E+11	2.29E+09
C14	1.00E+11	2.40E+10	1.25E+09	1.05E+11	1.36E+12	8.91E+09
Cl36	4.58E+09	1.74E+08	1.09E+07	2.64E+05	2.50E+10	8.37E+07
Ca41	9.21E+08	7.62E+09	5.80E+06	3.28E+08	1.25E+09	-
Fe60	7.25E+04	0.00E+00	0.00E+00	1.80E+05	1.74E+05	-
Co60	5.28E+11	3.18E+11	1.61E+11	1.34E+13	2.63E+12	7.56E+08
Ni59	2.17E+09	1.68E+06	8.37E+08	1.54E+11	2.16E+11	-
Ni63	5.22E+11	6.83E+10	3.96E+10	1.44E+13	3.36E+13	3.15E+09
Se79	1.06E+04	2.06E+00	6.08E+05	1.77E+07	1.04E+05	-
Sr90	3.11E+09	1.01E+06	1.68E+08	3.55E+10	2.55E+10	8.04E+10
Zr93	2.76E+06	2.80E+03	3.67E+03	2.06E+06	2.40E+11	-
Nb93m	4.97E+06	2.25E+03	2.55E+07	1.41E+09	1.94E+11	-
Nb94	0.00E+00	1.62E+05	5.84E+07	4.40E+09	1.13E+10	-
Tc99	2.17E+06	3.94E+02	7.53E+06	4.12E+08	1.45E+08	5.28E+07
Ag108m	3.42E+08	3.96E+03	8.63E+08	7.74E+10	2.16E+10	-
Cd113m	4.13E+07	2.15E+01	6.28E+08	2.21E+09	2.71E+07	-
Sn121m	6.19E+07	1.60E+02	1.94E+06	7.56E+07	2.08E+11	-
Sb125	2.67E+07	1.55E+01	1.15E+06	2.52E+07	9.05E+10	-
Cs137	6.91E+09	1.07E+06	1.87E+08	4.82E+10	7.79E+10	1.23E+11
Sm151	4.71E+08	5.51E+05	3.07E+08	2.25E+09	7.60E+07	-
Eu152	7.78E+09	1.23E+11	5.92E+07	1.26E+08	3.48E+09	-
Eu154	2.51E+10	1.38E+06	8.78E+05	6.75E+08	1.16E+09	4.80E+08
Ho166m	3.73E+07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	-
Hf182	0.00E+00	0.00E+00	0.00E+00	2.69E+03	4.44E+06	-
Th229	0.00E+00	2.25E+02	1.32E+04	1.24E+06	0.00E+00	-
Th230	0.00E+00	3.15E+03	9.66E+04	2.59E+04	0.00E+00	-
Th232	3.28E+04	3.14E+05	9.19E+06	1.98E+06	0.00E+00	-
U232	8.52E+05	0.00E+00	1.33E+03	1.15E+07	1.84E+03	-
U233	1.52E+06	5.72E+04	8.26E+06	3.13E+08	0.00E+00	-
U234	7.04E+05	4.35E+05	2.76E+07	1.18E+07	1.35E+05	-
U235	2.08E+04	2.02E+04	1.26E+06	2.45E+05	0.00E+00	-
U238	4.68E+05	4.40E+05	2.79E+07	6.04E+06	9.24E+04	-
Np237	0.00E+00	0.00E+00	0.00E+00	2.97E+04	3.09E+04	-
Pu238	8.96E+07	8.30E+08	7.26E+02	3.27E+08	1.05E+09	4.44E+08
Pu239	6.44E+07	2.06E+07	1.08E+08	1.49E+09	4.22E+08	2.99E+09
Pu240	4.24E+07	2.29E+01	1.39E+05	9.71E+08	4.80E+08	-
Pu241	1.12E+09	0.00E+00	1.50E+04	1.30E+10	1.56E+10	-
Pu242	6.73E+05	0.00E+00	0.00E+00	3.57E+05	1.11E+07	-
Am241	1.36E+08	0.00E+00	0.00E+00	1.88E+09	1.80E+09	4.47E+09
Am242m	3.37E+05	0.00E+00	0.00E+00	7.91E+06	3.39E+06	-
Am243	9.67E+06	0.00E+00	0.00E+00	3.48E+05	1.64E+08	-
Cm243	5.45E+05	0.00E+00	0.00E+00	3.10E+05	9.27E+06	-
Cm244	9.95E+08	0.00E+00	0.00E+00	1.19E+06	1.58E+10	-
Cm245	1.14E+05	0.00E+00	0.00E+00	0.00E+00	1.83E+06	-
Cm246	3.64E+05	0.00E+00	0.00E+00	0.00E+00	5.25E+06	-

Table E-18 Radionuclides in Other Rooms

Radionuclide	Boiler Room, i_{BR} (Bq)	Fuelling Room, i_{FR} (Bq)	Turbine Room, i_{TR} (Bq)	Generic Contamination, ic_{Struct} (Bq)*
H-3	1.76E+11	2.80E+08	1.97E+12	5.25E+12
C-14	9.99E+07	9.21E+05	8.15E+08	2.35E+11
Cl-36	1.10E+06	-	7.47E+07	5.07E+07
Co-60	1.51E+10	8.46E+07	1.09E+06	9.69E+06
Ni-63	1.16E+10	3.00E+08	3.55E+07	2.14E+07
Sr-90	1.88E+10	3.51E+09	1.44E+07	3.63E+07
Tc-99	-	4.35E+06	4.55E+06	1.02E+07
Cs-137	1.13E+09	6.18E+09	4.18E+06	1.38E+08
Eu-154	2.39E+08	1.31E+07	-	-
U-235	-	-	5.33E+06	5.79E+06
U-238	-	-	7.66E+07	9.36E+07
Pu-238	2.60E+08	8.07E+07	8.37E+06	2.91E+07
Pu-239	2.70E+09	3.21E+08	2.99E+06	6.45E+06
Pu-241	2.10E+10	3.81E+09	-	-
Am-241	2.86E+09	4.47E+08	4.31E+06	2.29E+06

Note: * Will be averaged over the total mass of the NPDDF structure as represented in the model: 9,769,100 kg

E 3.3.2 Chemical Inventory

Name:	Chemical Inventory
Version:	Version 4
Parameter Name:	i_{Pb}, i_{NR}
Units:	kg or m^3
Description:	The chemical inventory for the PostSA.

Value(s):	Lead (i_{Pb}):
	• Fuelling Room = 150,542 kg; as follows:
	  ○ Shielded cubicle rooms (2): 44,495 kg each, so 88,990 kg total;
	  ○ Lead shot in the roof of the shielded cubicle Rooms (2): 7,924 kg each, so 15,848 kg total;
	  ○ Floor Shield Gates (2): 22,852 kg each, so 45,704 kg total;
	• New Fuel Room – loose lead brick wall: 23,148 kg total *(Note: these lead bricks are located west of the Fuelling room, but are included within the Fuelling Room for modelling purposes, see Geometry section below)*.
	• Reactor Vault = 25,000 kg

Name:	Chemical Inventory		
	• Fuel Storage Room = 4,500 kg plus 2,800 kg from Active Auxiliaries Room (Room 307) • Boiler Room = 18,797 kg • Turbine Room = 335 kg associated with paint. • An additional 397 kg of lead in paint distributed throughout the facility below ground rooms. Mercury (i_{NR}): • <0.01 kg, assumed in the Boiler Room		
Justification:	The basis of the values is described in Schruder & Vickerd (2017) with the exception of the estimated mass of lead in the Fuelling Room, which is taken from Penfold & Watson (2019). The values are summarised in Porter (2022). The additional 397 kg of lead is proportioned by volume of the rooms below ground, namely BR_Sat, BR_Deep, DTPR_Sat, FSR_Sat, EastRV, WestRV and RV_Sat.		
Uncertainty:	There is low uncertainty in the chemical inventory because it is based on detailed walkdowns and drawings.		
Source of uncertainty:	Extent of non-radiological contamination surveys.		
References:	Penfold J & Watson S (2019). Scoping Calculations for Grouting Options and Refined Representation of Fuelling Room. Postclosure Safety Analysis. Prepared by Arcadis Canada Inc. for CNL. March 2019. Schruder K & Vickerd M (2017). Inventories and Locations of Hazardous Substances in the NPD Facility, 64-5092150021-000, Rev 1, June 2017. Porter, G. (2022). Nuclear Power Demonstration Waste Facility (NPDWF) Waste Inventory Report. CNL No. 64-508600-REPT-001. Revision 1.		
Author:	Renato Zagorscak	**Date:**	15 November 2022
Checker (basis):	Kate Thatcher	**Date:**	30 November 2022
Checker (implementation):	Kate Thatcher	**Date:**	30 November 2022

E 3.3.3 Mass of Wastes

Name:	Mass of Wastes		
Version:	Version 4		
Parameter Name:	M_{Waste}		
Units:	kg		
Description:	Mass of activated metal components.		
Value(s):	Aluminum: 10,560 kg Carbon steel: 38,110 kg Stainless Steel: 14,720 kg Zircaloy: 4,100 kg		
Justification:	The inventory for metals is based on the masses used by Edwards & Adams (2019) in neutron activation calculations for the determination of activation products in the NPD components. The actual mass of metal in the NPD may be greater, but other metals are assumed not to incorporate radionuclides and therefore do not require to be modelled . The same values are reported in the latest update to the inventory (Porter, 2022)		
Uncertainty:	Tens of percent. Note that Edwards & Adams (2019) estimated the mass using a numerical model of the main components of the Reactor Vault.		
Source of uncertainty:	The actual mass of metal in the NPD may differ from that assumed by Edwards & Adams (2019) depending on the accuracy of the numerical model of the vault.		
References:	Edwards & Adams (2019). Calculations of the Current NPD Reactor Vault Activation Source Term. CNL Ref #64-505100-ANL-001. February 2019. Porter, G. (2022). Nuclear Power Demonstration Waste Facility (NPDWF) Waste Inventory Report. CNL No. 64-508600-REPT-001. Revision 1.		
Author:	James Penfold	**Date:**	2 July 2019
Checker (basis):	Renato Zagorscak	**Date:**	15 November 2022
Checker (implementation):	Renato Zagorscak	**Date:**	15 November 2022

E 3.3.4 Thickness of Metals

Name:	Wall thickness		
Version:	Version 4		
Parameter Name:	L_{Corr}		
Units:	m		
Description:	Thickness of activated metal components. This determines the surface area of the metals and consequently the rate of release of activation products within the metals.		
Value(s):	$3x10^{-3}$ m for all materials		
Justification:	Although information is available concerning the detailed geometry of the reactor components it is appropriate to take a simple and cautious assumption for all materials. The value typical of the thickness of steel used in engineered components and structures is selected. The 3 mm thickness used in the model is conservative, as this is representative of the thinner metal components, i.e., pressure tubes. Using a thinner value such as this, considerably increases the resulting surface area and allows for the associated radionuclide inventory to be released sooner. All other metals in NPD are thicker. Further information on corrosion of metal components is also available in the Waste Form Synthesis Report (CNL, 2021b).		
Uncertainty:	It is unlikely that the average thickness of components is much lower than that assumed, but it could be a factor of a few greater.		
Source of uncertainty:	The value adopted is a cautious estimate based on broad assumptions about the structures and components.		
References:	Canadian Nuclear Laboratories (CNL). (2021b). Waste Form Synthesis Report. CNL No. 64-508760-REPT-017. Rev.1. July.		
Author:	James Penfold	**Date:**	26 August 2016
Checker (basis):	Kate Thatcher	**Date:**	25 October 2016
Checker (implementation):	Renato Zagorscak	**Date:**	26 January 2023

E 3.3.5 Density of Wastes

Name:	Density of Wastes		
Version:	Version 4		
Parameter Name:	rho_{stage}		
Units:	kg m^{-3}		
Description:	Density of activated metal and concrete components.		
Value(s):	Aluminum: 2700 kg m^{-3} (Lide, 2007)* Carbon steel: 7870 kg m^{-3} (Lide, 2007)* Stainless Steel: 7870 kg m^{-3} (Lide, 2007)* Zircaloy: 6520 kg m^{-3} (Lide, 2007)* * Densities of metals are based on their dominant component. The density of concrete is 2100 kg m^{-3} based on undegraded "structural concrete", and this value is presented in Section E 3.4.5.		
Justification:	Density values for waste materials are based on reference values.		
Uncertainty:	A few percent.		
Source of uncertainty:	The particular composition of alloying components will influence the density, but the uncertainty is trivial in the overall context of the PostSA.		
References:	Lide DR (ed) (2007). Handbook of Chemistry and Physics, 87th Edition, 2006 – 2007.		
Author:	James Penfold	**Date:**	26 August 2016
Checker (basis):	Kate Thatcher	**Date:**	25 October 2016
Checker (implementation):	Renato Zagorscak	**Date:**	26 January 2023

E 3.3.6 Corrosion Rates for Metals

Name:	Corrosion rate
Version:	Version 4
Parameter Name:	q_{corr}
Units:	m y^{-1}
Description:	Corrosion rate of metals in anticipated conditions in the NPDDF.
Value(s):	See Table E-19.
Justification:	Values for aluminum are based on those reported by Hoch *et al*. (2010). The value for high pH conditions is conservatively based on the initial acute corrosion rate. Even though this is recommended for a characteristic time of only 0.001 y, it is considered to be representative of the rate of oxidation that occurs if there is no passivated layer on the aluminum surface. The long-term average rate is appropriate for neutral or near-neutral conditions. Hoch *et al*. (2010) indicate that there is no dependence on oxygen availability. For stainless steel and Zircaloy, the corrosion rates used are the best estimate values presented in Appendix E of Walke *et al*. (2011). This report includes a review of the available corrosion rate data relevant to the long-term performance of disposed radioactive wastes in various chemical conditions. Corrosion rates for carbon steel are also presented in Appendix E of Walke *et al*. (2010). These values have been compared with more recent papers by King (2013) (with data for neutral conditions) and Kursten (2019) (corrosion rates in alkaline conditions). The best estimates recommended in Walke *et al*. (2010) are generally found to be conservative, for alkaline conditions and consistent with King (2013) for neutral conditions. The corrosion rate for lead is taken to be 1 µm y^{-1} based on the discussion in King & Watson (2010). However, lead is assumed conservatively to be instantaneously available for transport, although controlled by its solubility in water (see Section E 3.4.12).
Uncertainty:	A factor of a few; upper estimate values are presented in Table E-19.
Source of uncertainty:	Corrosion rates can be influenced by the specific local chemistry and its evolution as well as factors such as galvanic couplings etc. Nevertheless, all values are based on well established compilations of data and are suitable estimates for PostSA purposes. Ranges of values are available in Walke *et al*. (2010), King (2013) and Kursten (2019). A review of the expected corrosion behaviour of various metallic waste forms included in PostSA is given in the Waste Form Synthesis Report (CNL, 2021b), which concludes that none of the various factors that could lead to an enhanced rate of radionuclide release under disposal conditions have a significant impact on the release rate. Only once the concrete grout has been degraded and the pore-water pH decreases (perhaps after 100,000 y) is there a possibility of an increased rate of carbon steel corrosion when compared with either stainless steel or zirconium alloys.
References:	Hoch AR, Smart NR, Wilson JD and Reddy B (2010). A Survey of Reactive Metal Corrosion Data for use in the SMOGG Gas Generation Model, SERCO report SA/ENV-0895, Issue 2, September 2010.

Name:	Corrosion rate		
	King F and Watson SP (2010). Review of the Performance of Selected Metals as Canister Materials for UK Spent Fuel and/or HLW, QRS-1384J-1, Version 2.0, January 2010. King F (2013). Consequences of the general corrosion of C-steel used fuel containers for gas generation in a DGR, NWMO TR-2013-16. Kursten B (2019). Uniform corrosion evaluation of C-steel in cementitious environments relevant to the supercontainer design. Summary of corrosion rates from available literature and O/N funded RD&D programmes. SCK•CEN/26348152 ER-094, January 2019. Walke R, Humphreys P, King F, Little R, Metcalfe R, Penfold J, Towler G, Walsh R and Wilson J (2010). Postclosure Safety Assessment: Data, NWMO DGR-TR-2011-32, 2010. Canadian Nuclear Laboratories (CNL). (2021b). Waste Form Synthesis Report. NPD and WR-1 In Situ Disposal Projects. CNL No. 64-508760-REPT-017 Rev 1, July.		
Author:	James Penfold and Ryan Kovacs	**Date:**	10 May 2019
Checker (basis):	Emma Cairns	**Date:**	10 July 2019
Checker (implementation):	Renato Zagorscak	**Date:**	26 January 2023

Table E-19 Corrosion Rates

Material	Aerobic Conditions (μm y^{-1})		Anaerobic Conditions (μm y^{-1})	
	Neutral	High pH	Neutral	High pH
Aluminum	24.5	15,300	24.5	15,300
Carbon steel	40 (100)	0.1 (1)	2 (10)	0.1 (1)
Stainless Steel	0.1 (1)	0.1 (1)	0.1 (1)	0.1 (1)
Zircaloy	0.01 (0.05)	0.01 (0.05)	0.01 (0.05)	0.01 (0.05)
Lead	1 (7)	1 (7)	1 (7)	1 (7)

Note: Assessment calculations assumed aerobic high pH conditions. Best estimates are presented, with upper estimates given in brackets. No sensitivity values are given for aluminum as the corrosion rate is very rapid in the initial conditions of the grouted facility even with the best estimate values.

E 3.4 Facility

E 3.4.1 Geometry

Name:	Geometry		
Version:	Version 4		
Parameter Name:	Various		
Units:	m		
Description:	Simplified geometry of the NPDDF adopted for the PostSA		
Value(s):	The simplified geometry used to define the NPDDF model is shown in Figure E-13 and Figure E-14 with the key dimensions of rooms and walls marked. The total internal width of all the NPDDF rooms varies depending on the room and depth, as detailed in Figure E-14 and Figure E-15. Side walls are assumed to be 0.6 m thick on either side of the Facility. In addition, there is assumed to be a 0.6 m thick layer between the NPDDF outer walls and the native rock which has been infilled. The depth of the unsaturated parts of the NPDDF is taken to be the depth of the upper rooms, as shown in Figure E-13, noting that the Fuelling Room has a greater depth of 8.02 m. Penfold & Watson (2019) presents a more detailed geometrical representation of the lead sources in the Fuelling Room, which include: • Solid lead encased in the shielded room walls; • Lead shot in the roof of the Shielded Rooms; • Two shielded gates in the floor of the Fuelling Room; and Rather than assume that all of the lead is instantly available for dissolution and transport in groundwater, the updated lead corrosion and solubility model takes into account the geometry (i.e., the locations, areas and thicknesses) of the various components containing lead (Penfold & Watson, 2019). It is noted that the updated model includes the lead bricks assembled as a wall in the New Fuel Room, which is west of the Fuelling Room.		
Justification:	On the timescales considered in the PostSA, and taking account of its scope and context, a detailed representation of the NPD structure is inappropriate. However, the main components and their relative location do need to be represented. It is also necessary to distinguish between grout backfilled voids and the NPD structure. A conceptual 3D model of the NPD, in line with that used for groundwater modelling (Arcadis & Geofirma, 2023b), has been used to determine the dimensions and relative position of: the Fuel Storage Room, the Fuelling Room, Reactor Vault and adjacent rooms, Dump Pipe Room, Boiler Room and Turbine Room.		
Uncertainty:	Less than about 10%.		
Source of uncertainty:	Simplifications in the geometry.		
References:	Dimensions taken from the geometry used for the groundwater modelling (Arcadis & Geofirma, 2023b). Arcadis Canada Inc. & Geofirma Ltd. (2023b). 2023 Near-Field Groundwater Model at the Site of the Proposed Decommissioned Rolphton Nuclear Power Demonstration (NPD) Reactor. CNL No. 64-508760-REPT-013 Rev 1. June.		
Author:	Louise Bruffell	**Date:**	13 December 2021
Checker (basis):	Renato Zagorscak	**Date:**	16 December 2021
Checker (implementation):	Renato Zagorscak	**Date:**	16 December 2021

Figure E-13 Representation of the NPDDF used for the PostSA model (Cross-Section excluding the infilled concrete between the walls and geosphere)

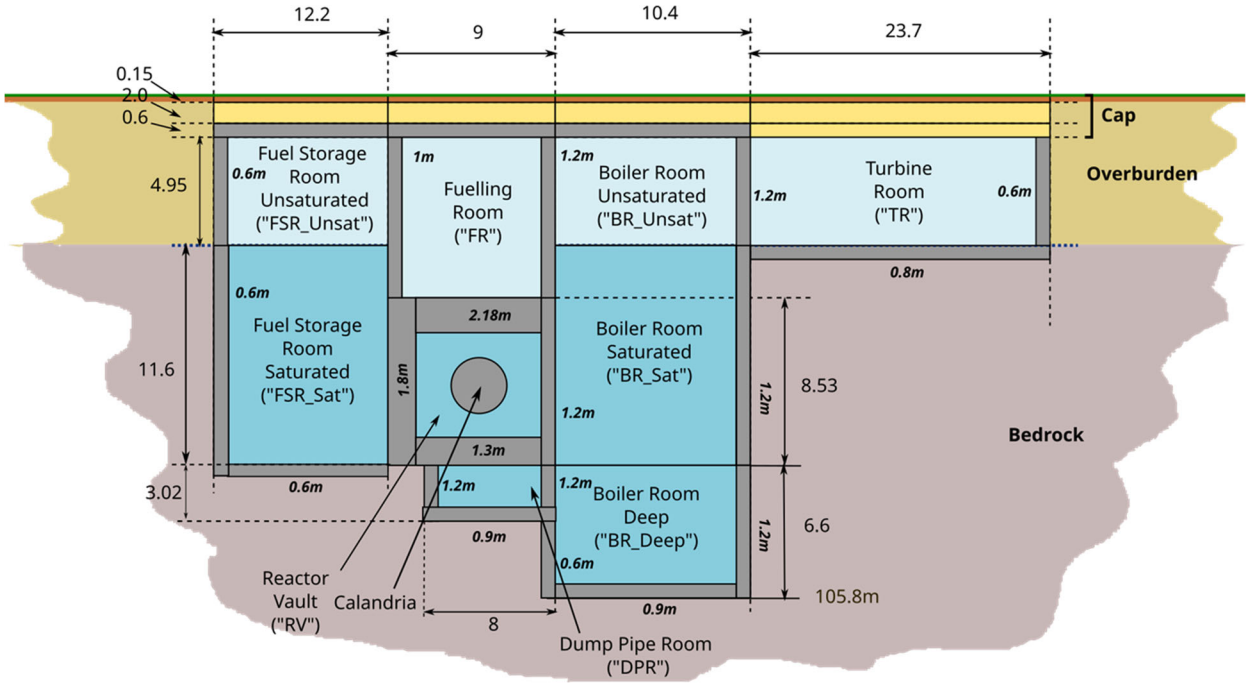


Figure E-14 Representation of the NPDDF used for the PostSA model (Plan view) at the three different levels

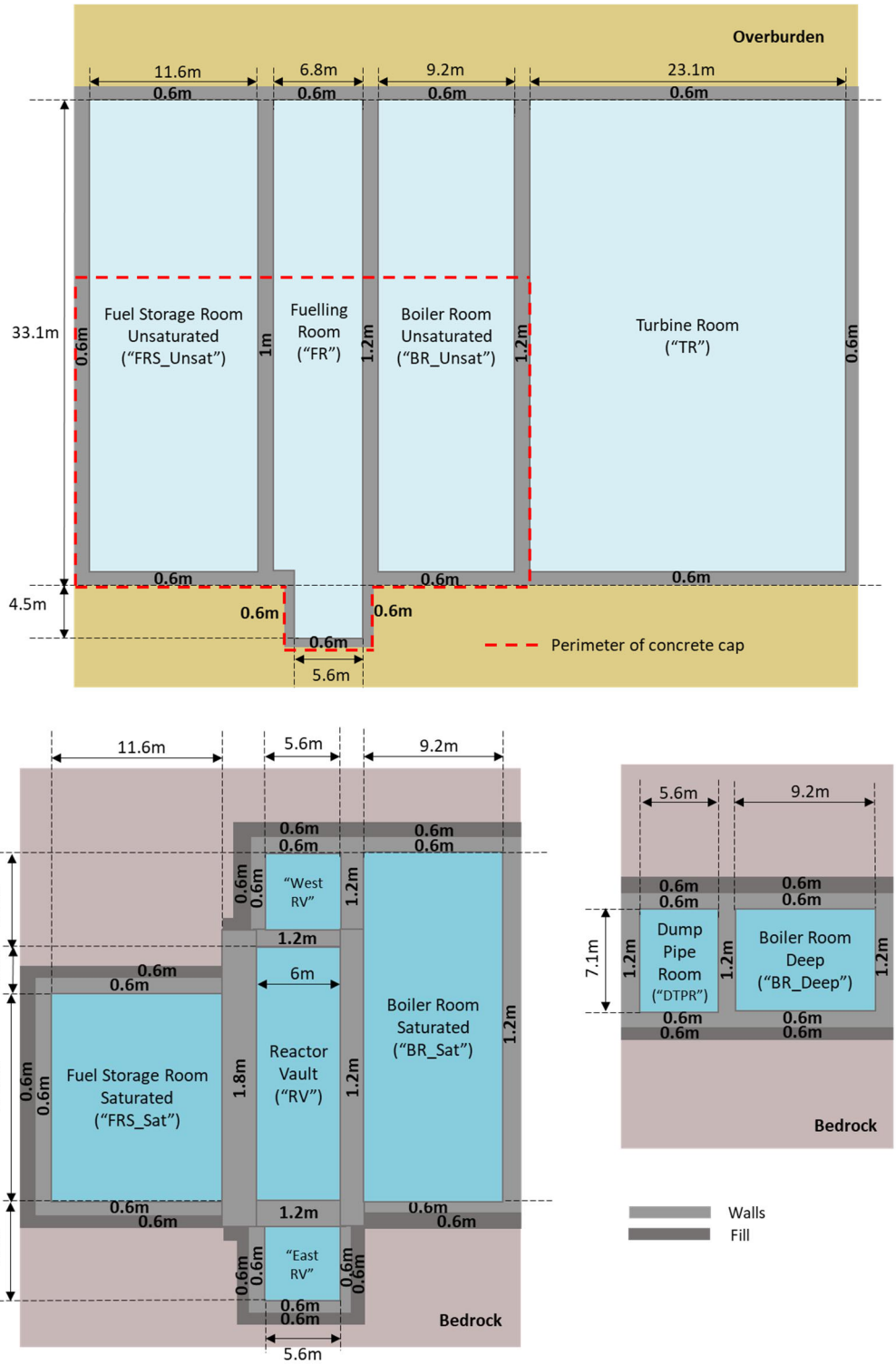
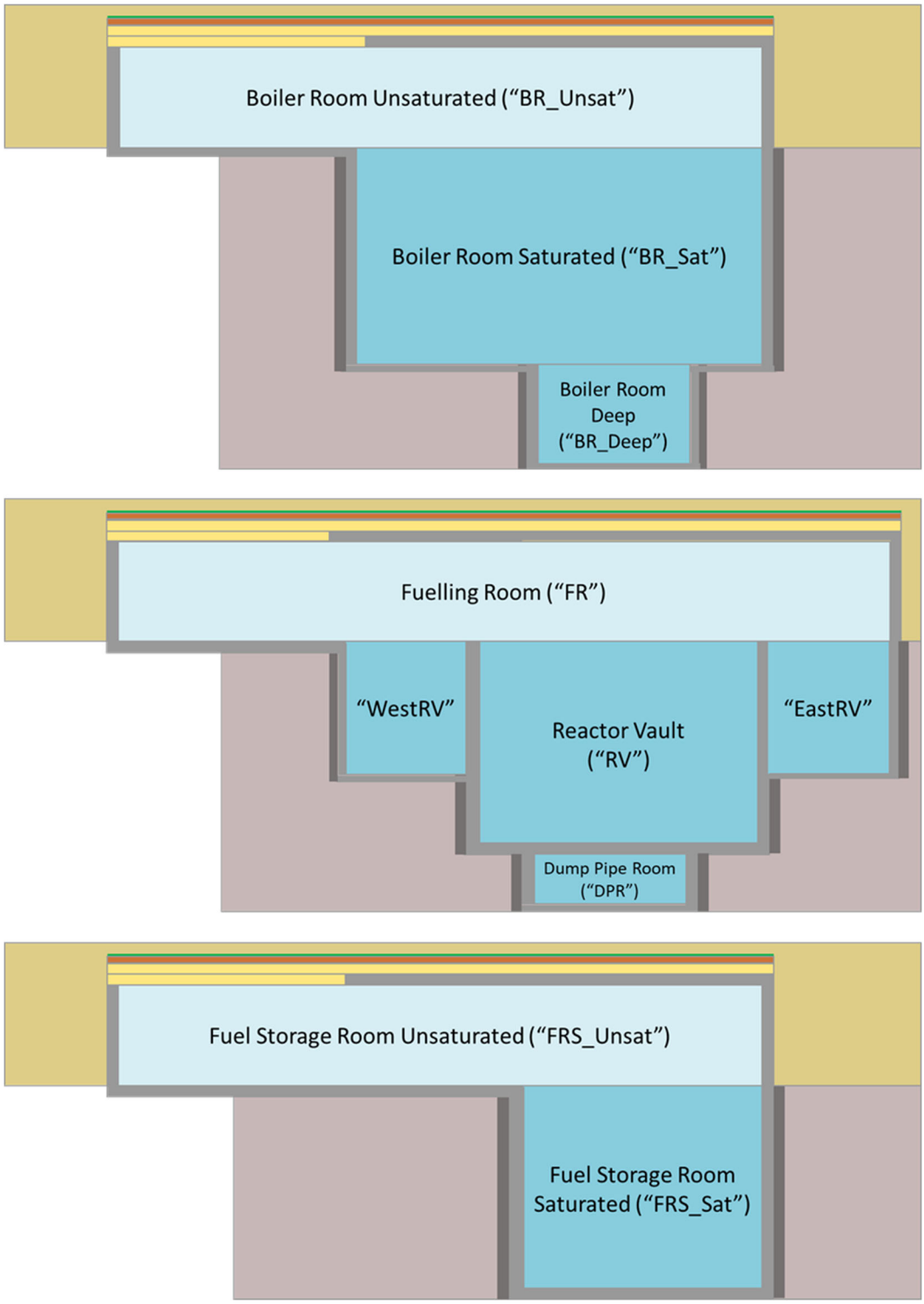


Figure E-15 Configuration with depth of the Components of the NPDDF Conceptual Model for the PostSA (facing downstream/north)



E 3.4.2 Porosity of Structures and Grout Backfill

Name:	Porosity of structures and grout backfill		
Version:	Version 4		
Parameter Name:	$theta_{stage}$		
Units:	none		
Description:	Total porosity of structures and grout backfill. Note that this is not the water-filled porosity which may be time-dependent, depending on resaturation.		
Value(s):	See Table E-20 and Table E-21.		
Justification:	The porosity of cementitious materials could change over time as the cement phases are leached and the material evolves. The approach to representing cement evolution is to treat the evolution as four characteristic stages for concrete, drawing on the approach developed by Berner (1992) and Ochs *et al*. (2016), and six for grout, as discussed in Wilson (2020). In the PostSA the transitions in values that depend on these stages is modelled as being instantaneous at the end of each stage. Savage & Stenhouse (2002) present recommended porosities for each stage based on a review of available data. Various types of material are considered including structural concrete and porous concrete. For the purposes of the PostSA the existing NPD structure is taken to be structural concrete, and the grout backfill throughout the facility is assumed to be blast-furnace slag/ Portland cement (BFS-PC), which is relatively porous. (Porosity is broadly related to the amount of water added to the fresh cement, so the grout, needing to be flowable, would be expected to be relatively porous when set.) The porosity of the NPDDF structure is based on Savage & Stenhouse (2002). The porosity of the grout, 0.4, is taken from Wilson (2019). This is conservative compared with the value from experimental testing of around 0.3.		
Uncertainty:	A few tens of percent. Savage & Stenhouse (2002) provide ranges.		
Source of uncertainty:	Variations in the cement/concrete formulation.		
References:	Berner UR (1992). Evolution of Porewater Chemistry during Degradation of Cement in a Radioactive Waste Repository Environment. Waste Management 12. 201-219. Ochs M, Mallants D and Wang L (2016). Radionuclide and Metal Sorption on Cement and Concrete. Topics in Safety, Risk, Reliability and Quality, Volume 29. Savage D and Stenhouse M (2002). SFR 1 Vault Database, SKI Report 02:53, April 2002. Wilson J (2019) Alkaline Plume Modelling – Grout Leaching. December 2019. Wilson, J. (2020) Grout Flushing Models Report – NPD Closure Project. 2019. 64-508760-REPT-009 Rev 1, March.		
Author:	James Penfold (structure) James Wilson (Grout)*	**Date:**	12 June 2017
Checker (basis):	Laura Limer (structure) Richard Metcalfe (Grout)*	**Date:**	12 June 2017
Checker (implementation):	Renato Zagorscak	**Date:**	26 January 2023

Note: * See Wilson (2019) for author and checker of grout values.

Table E-20 Total Porosity of Structure

Component	Stage I	Stage II	Stage III	Stage IV
Existing NPD structure	0.125	0.125	0.25	0.25
Concrete cap and infill between structure and bedrock	0.125	0.125	0.25	0.25
Cap Infill	As overburden*	As overburden*	As overburden*	As overburden*

Note: * see Section E 3.5. Unsaturated compartments are assumed to have 50% of the porosity saturated.

Table E-21 Total Porosity of Grout Backfill

Component	Stage A	Stage B	Stage C	Stage D	Stage E	Stage F
Grout Backfill	0.4	0.4	0.4	0.4	0.4	0.4

E 3.4.3 Resaturation Timescale

Name:	Resaturation Time		
Version:	Version 4		
Parameter Name:	t_{Resat}		
Units:	y		
Description:	The time take for the NPDDF to resaturate, based on the best estimate made by Arcadis & Geofirma (2023c).		
Value(s):	85 y		
Justification:	The reference resaturation time is 85 y, as estimated by Arcadis & Geofirma (2023c).		
Uncertainty:	From around 10 years to several hundred years. For example, the values taken from the range of resaturation times calculated by the groundwater flow models (Arcadis & Geofirma, 2023c) suggest faster resaturation (38 years) and slower resaturation (245 years). The values reflect the uncertainties in the water inflow rates which are in turn dependent on the material properties assigned to the NPDDF.		
Source of uncertainty:	Heterogeneity of materials and fluctuations in the water table depth through the complex NPDDF structure.		
References:	Arcadis Canada Inc. & Geofirma Ltd. (2023c). 2023 Resaturation Modelling for the Proposed Decommissioned Rolphton Nuclear Power Demonstration (NPD) Reactor. CNL No. 64-508760-REPT-015 Rev 3. June 2023.		
Author:	Louise Bruffell	**Date:**	27 January 2022
Checker (basis):	Renato Zagorscak	**Date:**	10 February 2022
Checker (implementation):	Renato Zagorscak	**Date:**	10 February 2022

E 3.4.4 Number of Pore Flushes

Name:	Number of Pore Flushes
Version:	Version 4
Parameter Name:	n_{Stage}
Units:	None
Description:	The number of times cement pores are flushed with groundwater, which determines the duration of the characteristic cement degradation stages described by Berner (1992).
Value(s):	For structural concrete (based on Berner (1992)): • Stage I: 0 to 100 • Stage II: 101 to 1000 • Stage III: 1001 to 7450 • Stage IV: > 7450 For BFS-PC grout (from Wilson, 2020) these are subdivided so as to represent more subtle variation in pH: • Stages A: 0 to 106 • Stage B: 107 to 227 • Stage C: 228 to 643 • Stage D: 644 to 1978 • Stage E: 1979 to 4386 • Stage F: > 4386 In the PostSA the transitions in values that depend on these stages (e.g., sorption) is modelled as being instantaneous at the end of each stage.
Justification:	The porosity, density and Kd of cementitious materials will change over time as the cement phases are leached and the material evolves. The approach to representing concrete evolution is to treat the evolution as four characteristic stages, drawing on the approach developed by Berner (1992) and Ochs *et al.* (2016). For BFS-PC grout six stages are used, based on Wilson (2020). For both, the duration of each of the stages is calculated based on the groundwater flow and the number of porewater flushes. After the end of Stage III (concrete) or Stage E (BFS-PC grout), there is no longer any chemical conditioning of the groundwater and it is assumed to have the same properties as overburden groundwater. Overall, the number of pore flushes needed to degrade concrete and grout depends on the groundwater composition. In the NPD, some water entering a room has already passed through another room. This “conditioned” water is less effective in degrading concrete or grout than “fresh” groundwater and so more pore flushes would be needed to degrade the concrete or grout. This effect is conservatively neglected in the model calculations. Consequently: • The duration of each Stage is underestimated in the model; • Because pH decreases with time, the duration of high pH conditions is underestimated in the model; and • Since high pH conditions correspond to high sorption, the sorption properties of the concrete or grout are underestimated in the model.
Uncertainty:	Around a factor of two.
Source of uncertainty:	Variations in the cement/concrete formulation.
References:	Berner UR (1992). Evolution of Porewater Chemistry during Degradation of Cement in a Radioactive Waste Repository Environment. Waste Management 12. 201-219.

Name:	Number of Pore Flushes		
	Ochs M, Mallants D and Wang L (2016). Radionuclide and Metal Sorption on Cement and Concrete. Topics in Safety, Risk, Reliability and Quality, Volume 29. Wilson J (2020) Grout Flushing Models Report – NPD Closure Project. Prepared for CNL. March.		
Author:	James Penfold, Farrah Cooper	**Date:**	16 April 2019
Checker (basis):	Renato Zagorscak	**Date:**	22 March 2022
Checker (implementation):	Renato Zagorscak	**Date:**	22 March 2022

E 3.4.5 Bulk Density of Structures and Grout Backfill

Name:	Density of Structures and Grout Backfill		
Version:	Version 4		
Parameter Name:	rho_{Stage}		
Units:	kg m^{-3}		
Description:	The dry bulk density of structures and grout backfill.		
Value(s):	See Table E-22 and Table E-23		
Justification:	The porosity of cementitious materials could change over time. The approach to representing cement evolution is to treat the evolution as four characteristic stages for concrete and six characteristic stages for grout, drawing on the approach developed by Berner (1992), Ochs *et al*. (2016) and discussed by Wilson (2019; 2020). For the purposes of the PostSA the existing NPD structure is taken to be structural concrete, with a density of 2100 kg m^{-3}. The density of the BFS-PC grout is from Wilson (2019).		
Uncertainty:	A few tens of percent at most. Savage & Stenhouse (2002) provide ranges.		
Source of uncertainty:	Variations in the cement/concrete formulation.		
References:	Berner UR (1992). Evolution of Porewater Chemistry during Degradation of Cement in a Radioactive Waste Repository Environment. Waste Management 12. 201-219. Wilson J (2019) Alkaline Plume Modelling – Grout Leaching, December 2019 Wilson J (2020) Grout Flushing Models Report – NPD Closure Project. Prepared for CNL. March.		
Author:	James Penfold, Farrah Cooper	**Date:**	16 April 2019
Checker (basis):	Emma Cairns	**Date:**	14 October 2019
Checker (implementation):	Renato Zagorscak	**Date:**	22 March 2022

Table E-22 Dry Bulk Density of Structure

Component	Stage I (kg m^{-3})	Stage II (kg m^{-3})	Stage III (kg m^{-3})	Stage IV and after Stage IV (kg m^{-3})
Existing NPD structure	2100	2100	1800	1800
Concrete cap and infill between structure and bedrock	2100	2100	1800	1800
Cap Infill	As overburden*	As overburden*	As overburden*	As overburden*

Note: * see Section E 3.5.

Table E-23 Dry Bulk Density of Grout Backfill

Component	Stage A (kg m^{-3})	Stage B (kg m^{-3})	Stage C (kg m^{-3})	Stage D (kg m^{-3})	Stage E (kg m^{-3})	Stage F and After Stage F (kg m^{-3})
BFS-PC Grout	1823	1823	1823	1823	1823	1823

E 3.4.6 Diffusion Properties of Structures and Grout Backfill

\	Effective diffusivity		
Version:	Version 4		
Parameter Name:	$D_{Eff,Stage}$		
Units:	$m^2\ y^{-1}$		
Description:	The effective diffusivity of structures and grout backfill.		
Value(s):	See Table E-24 and Table E-25.		
Justification:	Effective diffusivity is the product of the porosity, free-water diffusivity, and a geometrical factor relating to the network of narrow passages in the medium and the tortuosity of the pores. The porosity is defined in Section E 3.4.2, and free-water diffusivity can be assumed to be a constant, so the values depend on the ascribed "geometrical factor". For consistency with the other near-field parameters, Savage & Stenhouse (2002) is used as the main source of these values. This reference gives consideration to the effects of cement degradation in enhancing the connectivity of pores as a function of time and thus increasing the effective diffusivity. It is noted that Savage & Stenhouse (2002) compared the recommended ranges of values against those reported in other studies and found them to be consistent. For the purposes of the PostSA the existing NPD structure is taken to be structural concrete, and the BFS-PC backfill is assumed to be relatively porous concrete with values based in assumptions in Penfold & Watson (2019).		
Uncertainty:	A few tens of percent. Savage & Stenhouse (2002) provide ranges.		
Source of uncertainty:	Variations in the cement/concrete formulation.		
References:	Savage D and Stenhouse M (2002). SFR 1 Vault Database, SKI Report 02:53, April 2002. Penfold JSS and Watson SP (2019). Scoping Calculations for Grouting Options and Refined Representation of Fuelling Room, April 2019.		
Author:	James Penfold, Farrah Cooper	**Date:**	1 April 2019
Checker (basis):	Emma Cairns	**Date:**	14 October 2019
Checker (implementation):	Renato Zagorscak	**Date:**	26 January 2023

Table E-24 Effective Diffusivity of Structure

Component	Stage I ($m^2\ y^{-1}$)	Stage II ($m^2\ y^{-1}$)	Stage III and After Stage III ($m^2\ y^{-1}$)
Water^	$6x10^{-2}$	$6x10^{-2}$	$6x10^{-2}$
Existing NPD structure	$8x10^{-5}$	$8x10^{-4}$	$4x10^{-3}$

Note: ^ This is the free-water diffusion coefficient. * see Section E 3.5.

Table E-25 Effective Diffusivity of Grout Backfill

Component	Stage I (m^2 y^{-1})	Stage II (m^2 y^{-1})	Stage III (m^2 y^{-1})	Stage IV (m^2 y^{-1})	After Stage IV (m^2 y^{-1})
Backfill (BFS-PC grout)	$2x10^{-2}$	$2x10^{-2}$	$2x10^{-2}$	$2x10^{-2}$	$2x10^{-2}$ *

Note: * Diffusivity is assumed to be unchanged for completely degraded grout.

E 3.4.7 Flows through Structures and Grout Backfill

Name:	Flows through Structures and Grout Backfill		
Version:	Version 4		
Parameter Name:	Q_{NPD}		
Units:	m^3 y^{-1}		
Description:	The water flows through structures and grout backfill.		
Value(s):	Table E-26		
Justification:	The NPD model has been evolved to enable the latest groundwater flow modelling to be represented. This has entailed greater detail in the above-bedrock part of the model (previously "unsaturated") and implementation of a larger number of advective flow transfers (out of the face of each "room"). Based on the groundwater flow modelling, transfers are specified by Arcadis & Geofirma (2023b) out of each face of the main rooms and are then used in the AMBER model. Four of the five cases are used in the AMBER model: (1) Undegraded facility with tile drains. (2) Undegraded facility with degraded concrete cap and tile drain failure. (4) Degraded facility with tile drain failure. (5) Very degraded facility with tile drain failure. A time-dependent switch is used to switch between the specified flow rates in the calculation of the advective transfer rates. The flows emerging from the downstream face of the NPD are partitioned between a "shallow" geosphere pathway (in the overburden), a "deep" pathway (in the bedrock) and a pipe trench pathway (also in the overburden) based on Arcadis & Geofirma (2023b)). Some flow from the rooms are also directed to the tile drains.		
Uncertainty:	The variation in flows between the different groundwater flow modelling cases give an indication of the uncertainty, which can range up to several orders of magnitude depending on the condition of the engineered materials and external factors.		
Source of uncertainty:	The water flow rates are based on groundwater modelling (Arcadis & Geofirma, 2023b) and are therefore uncertain as a result of the uncertainties in the modelling.		
References:	Arcadis Canada Inc. & Geofirma Ltd. (2023b). 2023 Near-Field Groundwater Model at the Site of the Proposed Decommissioned Rolphton Nuclear Power Demonstration (NPD) Reactor. CNL No. 64-508760-REPT-013 Rev 1. June.		
Author:	Louise Bruffell	**Date:**	3 July 2023
Checker (basis):	Kate Thatcher	**Date:**	4 July 2023
Checker (implementation):	Kate Thatcher	**Date:**	4 July 2023

Table E-26 Flow Rates within the NPD (m^3 y^{-1})

Room, Face and Direction*	Flow Case (1)	Flow Case (2)	Flow Case (4)	Flow Case (5)
BRD_B_in	0.002524608	0.001325419	0.078894	2.15E-05
BRD_B_out	0.000293486	0.000946728	0.31242024	0.725825
BRD_E_in	0	0	0	0
BRD_E_out	0.011360736	0.011676312	1.8618984	1.767226
BRD_N_in	0	0	0	0
BRD_N_out	0.013885344	0.0157788	2.36682	1.830341
BRD_S_in	0.012307464	0.011991888	2.1143592	1.672553
BRD_S_out	0	0	0	0
BRD_T_in	0	0.001640995	0.27770688	1.199189
BRD_T_out	0.00224059	2.18E-05	0	0
BRD_W_in	0.01262304	0.013254192	2.0196864	1.45165
BRD_W_out	0	0	0	0
BRS_B_in	0.007258248	0.000725825	0.13254192	0.013885
BRS_B_out	0.003061087	0.008204976	1.7672256	4.418064
BRS_E_in	0	0	0	0
BRS_E_out	0.030610872	0.030926448	4.418064	5.995944
BRS_N_in	0.00157788	0.000568037	0.12307464	0
BRS_N_out	0.027770688	0.05364792	5.995944	4.102488
BRS_S_in	0.0315576	0.03786912	6.31152	4.418064
BRS_S_out	0	0	0	0
BRS_T_in	0.002650838	0.030926448	1.735668	8.836128
BRS_T_out	0.004418064	0.000173567	0.003471336	0
BRS_W_in	0.022405896	0.02209032	4.102488	1.70411
BRS_W_out	0	0	0	0
BRU_B_in	0	0.007573824	0.3471336	11.36074
BRU_B_out	0	0.029032992	2.051244	14.83207
BRU_E_in	0	0	0	0
BRU_E_out	0	0.014516496	0.3471336	50.49216
BRU_N_in[1]	**2.43E-05**	**0.002209032**	0.22405896	**13.25419**
BRU_N_out[1]	**0.000631152**	0.010729584	0.2682396	69.42672
BRU_S_in	0	0.01262304	0.5995944	88.36128
BRU_S_out	0	0.000378691	0.04102488	4.102488
BRU_T_in	0	0.024614928	0.8520552	15.7788
BRU_T_out	0	0.002145917	0.11676312	6.31152
BRU_W_in	0	0.013885344	0.9151704	26.50838
BRU_W_out	0	0.006627096	0.11360736	0.299797
DPR_B_in	0.001546322	0.000410249	0.027770688	0
DPR_B_out	0.000179878	0.001009843	0.2524608	0.568037

Room, Face and Direction*	Flow Case (1)	Flow Case (2)	Flow Case (4)	Flow Case (5)
DPR_E_in	0	0	0	0
DPR_E_out	0.001861898	0.002114359	0.30926448	0.315576
DPR_N_in	0	0	0	0
DPR_N_out	0.002808626	0.002682396	0.473364	0.347134
DPR_S_in	0.002398378	0.002209032	0.4418064	0.347134
DPR_S_out	0	0	0	0
DPR_T_in[2]	**0.000694267**	**0.005680368**	**0.8520552**	**1.735668**
DPR_T_out[2]	0.00066271	6.63E-06	**0.008204976**	**0.0006**
DPR_W_in	0.001230746	0.001388534	0.2524608	0.192501
DPR_W_out	0	0	0	0
ERV_B_in	0.000167255	0	0	0
ERV_B_out	0.001230746	0.00236682	0.315576	0.378691
ERV_E_in	0.004102488	0.00224059	0.315576	0.034713
ERV_E_out	0	1.01E-05	0	0.056804
ERV_N_in	0	0	0	0
ERV_N_out	0.01893456	0.014516496	2.4930504	2.429935
ERV_S_in	0.011676312	0.008836128	1.4832072	1.199189
ERV_S_out	0	0	0	0
ERV_T_in	0.011676312	0.011991888	1.6725528	2.398378
ERV_T_out	0.008520552	0.007573824	0.9151704	1.293862
ERV_W_in	0.001388534	0.001830341	0.28717416	0.599594
ERV_W_out	7.26E-05	0	0.026508384	0
FR_B_in	4.10E-06	0.00473364	0.24930504	7.258248
FR_B_out	0.016725528	0.0315576	4.102488	10.41401
FR_E_in	0.004102488	0.01104516	2.0196864	27.77069
FR_E_out	0.001136074	0.000757382	0.19881288	0.473364
FR_N_in	0	0	0	0
FR_N_out	0.009151704	0.0473364	4.102488	132.5419
FR_S_in	0.01262304	0.03786912	4.418064	91.51704
FR_S_out	0.001956571	0.000287174	0.26192808	0.883613
FR_T_in	0.010729584	0.022405896	1.1360736	7.258248
FR_T_out	6.00E-05	0.002461493	0.05049216	4.418064
FR_W_in	0.002272147	0.00946728	1.0729584	12.62304
FR_W_out	0.000441806	0.005049216	0.12938616	2.114359
FSRS_B_in	4.73E-05	0	0	0
FSRS_B_out	0.017041104	0.0236682	3.471336	4.102488
FSRS_E_in	0.01104516	0.002997972	0.9151704	0.020512
FSRS_E_out	0.001672553	0.004102488	0.473364	0.883613
FSRS_N_in	0	0	0	0
FSRS_N_out	0.01893456	0.017672256	3.15576	2.019686

Room, Face and Direction*	Flow Case (1)	Flow Case (2)	Flow Case (4)	Flow Case (5)
FSRS_S_in	0.013254192	0.015147648	2.5561656	1.483207
FSRS_S_out	0	0	0	0
FSRS_T_in	0.00946728	0.020196864	1.893456	7.573824
FSRS_T_out	0	0.000176723	0	0
FSRS_W_in	0.004418064	0.009151704	1.735668	1.230746
FSRS_W_out	0.00091517	3.06E-06	0	0
FSRU_B_in	0	0.003471336	0.23983776	3.471336
FSRU_B_out	0.00302953	0.0315576	3.15576	27.77069
FSRU_E_in	0.000441806	0.00473364	0.7573824	5.995944
FSRU_E_out	0	0.000280863	0.04102488	10.09843
FSRU_N_in	0	0	0	0
FSRU_N_out	0.003786912	0.020196864	0.8520552	63.1152
FSRU_S_in	0.00249305	0.025561656	1.8618984	66.27096
FSRU_S_out	0	0.002934857	0.14516496	0.820498
FSRU_T_in	0.003471336	0.019881288	1.0098432	13.56977
FSRU_T_out	0	0.002051244	0.02840184	1.388534
FSRU_W_in	6.00E-05	0.002934857	0.24930504	5.364792
FSRU_W_out	0.000116763	0.001072958	0.0473364	0.410249
NoFlowData	0	0	0	0
RV_B_in [2]	**0.00066271**	**6.63E-06**	0.008204976	0.0006
RV_B_out [2]	0.000694267	0.005680368	0.8520552	1.735668
RV_E_in	0.00018619	5.05E-05	0.000504922	0
RV_E_out	0.0078894	0.006942672	0.9782856	1.420092
RV_N_in	0	0	0	0
RV_N_out	0.020828016	0.019250136	3.15576	2.524608
RV_S_in	0.020196864	0.017987832	3.15576	2.303705
RV_S_out	0	0	0	0
RV_T_in	0.00473364	0.010729584	1.262304	3.02953
RV_T_out	4.10E-05	0	0	0
RV_W_in	0.00315576	0.002966414	0.6942672	0.315576
RV_W_out	0	0	0	0
TR_B_in	0	0.005049216	0.4418064	10.41401
TR_B_out	0.015147648	0.0315576	3.786912	37.86912
TR_E_in	0	0	0	0.000568
TR_E_out	0.022405896	0.0631152	10.098432	82.04976
TR_N_in	0	0.000378691	0.015147648	0
TR_N_out	0.000852055	0.004418064	0.29664144	16.09438
TR_S_in [1]	0.000631152	**0.010729584**	0.2682396	**69.42672**
TR_S_out [1]	2.43E-05	0.002209032	**0.22405896**	13.25419
TR_T_in	0.01104516	0.04102488	1.4832072	22.4059

Room, Face and Direction*	Flow Case (1)	Flow Case (2)	Flow Case (4)	Flow Case (5)
TR_T_out	0	0.00236682	0.15147648	3.471336
TR_W_in	0.028717416	0.06627096	13.254192	97.82856
TR_W_out	0.002209032	0.015463224	0.8836128	5.680368
WRV_B_in	0	0	0	0
WRV_B_out	0.001167631	0.001988129	0.31242024	0.410249
WRV_E_in	0	0	0	0
WRV_E_out	0.001893456	0.00170411	0.473364	0.167255
WRV_N_in	0.000410249	0.000473364	0.07258248	0.059959
WRV_N_out	0.002777069	0.003786912	0.5680368	0.504922
WRV_S_in	0.002934857	0.003471336	0.5680368	0.441806
WRV_S_out	0	0	0	0
WRV_T_in	0.001293862	0.002556166	0.4418064	0.631152
WRV_T_out	0.000883613	0.00157788	0.21143592	0.296641
WRV_W_in	0.002209032	0.002650838	0.5364792	0.246149
WRV_W_out	9.78E-05	9.47E-05	0.02209032	0.006943

Note: * The location of the flows are specified as follows.

Rooms are: BRD = Boiler Room (Deep), BRS = Boiler Room (Saturated), BRU = Boiler Room (Upper), DPR = Dump Pipe Room, FR = Fuelling Room, FSRS = Fuel Storage Room (Saturated), FSRU = Fuel Storage Room (Upper), ERV = East Room of the Reactor Vault, WRV = West Room of the Reactor Vault, RV = Reactor Vault, TR = Turbine Room

Face is: N = site north (direction of groundwater flow towards the river, all other directions relative to this), S = south, E = east, W = west, T = top, B = bottom

Direction is: in = flow into the relevant compartment through the relevant face, out = flow outwards through the face.

[1] For consistency, flows taken are maximum of flow in/out north of BRU and out/in south of TR (bold values those changed)

[2] For consistency, flows taken are maximum of flow in/out bottom of RV and out/in top of DPR (bold values those changed)

E 3.4.8 Flows to the Tile Drain

Name:	Flows to the Tile Drains		
Version:	Version 4		
Parameter Name:	$f_{TileDrain}$		
Units:	-		
Description:	The fraction of total water flow out of a room which goes to the tile drains.		
Value(s):	Room	Fraction of outflow going to tile drains	
	FR_Unsat	0.05	
	FSR_Sat	0.028	
	FSR_Usat	0.083	
	TR_Unsat	0.029	
Justification:	Based on the groundwater flow modelling; tracer results are specified in Appendix B of Arcadis & Geofirma (2023b) in terms of mass fractions of each room remaining in the rooms of the NPD and mass fractions reaching the tile drains. As the tile drains are assumed to fail at 100y, only the tracer results from the NES 0-100 y (undegraded facility with tile drains) case are used. The fraction of flow out of each room reaching the tile drains is taken to be the total mass fraction reaching the tile drains divided by the mass fraction leaving the room (1- mass fraction remaining in the room), at 100 y. The fraction reaching the tile drain is taken to be zero for rooms which result in flows less than 5E-04 m^3/y. A time-dependent switch is used in the calculation of the advective transfer rates to switch off the instantaneous flows to the tile drains after their assumed failure time (100y).		
Uncertainty:	The variation in flows between the different groundwater flow modelling cases give an indication of the uncertainty, which can range up to several orders of magnitude depending on the condition of the engineered materials and external factors.		
Source of uncertainty:	The results are obtained from groundwater modelling and are therefore uncertain as a result of the uncertainties in the modelling.		
References:	Arcadis Canada Inc. & Geofirma Ltd. (2023b). 2023 Near-Field Groundwater Model at the Site of the Proposed Decommissioned Rolphton Nuclear Power Demonstration (NPD) Reactor. CNL No. 64-508760-REPT-013 Rev 1. June		
Author:	Louise Bruffell	**Date:**	30 November 2022
Checker (basis):	Kate Thatcher	**Date:**	10 February 2023
Checker (implementation):	Kate Thatcher	**Date:**	10 February 2023

Rooms are: FR = Fuelling Room, FSR = Fuel Storage Room and TR = Turbine Room

E 3.4.9 Engineering Degradation

Name:	Engineering Degradation		
Version:	Version 4		
Parameter Name:	t_{NPD_Flow}		
Units:	y		
Description:	The condition of engineered barriers, represented through the timing at which different flow regimes through the facility are applied.		
Value(s):	Flow regime 1 (undegraded facility with tile drains) operates from 0 y Flow regime 2 (undegraded facility with degraded concrete cap and tile drain failure) operates from 100 y Flow regime 4 (degraded facility with tile drain failure) operates from 1000 y		
Justification:	The NPDDF structures and grout backfill provide multiple barriers to inflowing water but will ultimately degrade. Flow regimes through the structure assuming various degrees of degradation have been modelled by Arcadis & Geofirma (2023b) (see E 3.4.7) The lifetime of the engineered structures has been based on the performance of the engineering envisaged for the low-level waste repository (LLWR) near-surface disposal facility in the UK (LLWR, 2011)). The LLWR features concrete vaults with walls of comparable thickness to those of the NPDDF, and it is also constructed in a near-surface environment of relatively soft sediments comparable to the overburden of the NPD site. In the absence of any other information this is reasonably equivalent to the conditions of the above-bedrock NPDDF structure, while the below-bedrock structure can be expected to degrade more slowly as it is afforded greater protection and stability by the surrounding bedrock. Based on this, it is assumed that all concrete structures will have fully degraded (in terms of hydraulic performance) by 1000 y after decommissioning is complete (taken as the mean expected lifetime)		
Uncertainty:	Jackson *et al*. (2011) provide details of the anticipated uncertainties in cap performance. In the resaturation modelling (Arcadis & Geofirma, 2023c), the infiltration through the cap is found to be 10^{-4} mm/y once the Facility is saturated.		
Source of uncertainty:	The main source of uncertainty is in the timescales for degradation as represented by the variation of hydraulic conductivity with time.		
References:	Arcadis Canada Inc. & Geofirma Ltd. (2023b). 2023 Near-Field Groundwater Model at the Site of the Proposed Decommissioned Rolphton Nuclear Power Demonstration (NPD) Reactor. CNL No. 64-508760-REPT-013 Rev 1. June. Arcadis Canada Inc. & Geofirma Ltd. (2023c). 2023 Resaturation Modelling for the Proposed Decommissioned Rolphton Nuclear Power Demonstration (NPD) Reactor. CNL No. 64-508760-REPT-015 Rev 3. June. Jackson CP, Couch M, Yates H, Smith V, Kelly M and James M (2011). Elicitation of Uncertainties for LLWR, LLWR Environmental Safety Case report SERCO/TAS/E003796/010, Issue 2, April 2011. LLWR (2011). The 2011 Environmental Safety Case: Engineering Design, LLWR/ESC/R(11)10020, May 2011.		
Author:	James Penfold	**Date:**	16 February 2022
Checker (basis):	Renato Zagorscak	**Date:**	22 March 2022
Checker (implementation):	Renato Zagorscak	**Date:**	22 March 2022

E 3.4.10 Cap Effectiveness

Name:	Effectiveness of the cap		
Version:	Version 4		
Parameter Name:	q_{Cap}		
Units:	m y^{-1}		
Description:	The maximum flow through the concrete cap. The total effectiveness of the cap and its condition are represented through the timing at which different flow regimes through the facility are applied, and the flow into the tops of the rooms of the NPD.		
Value(s):	For all three flow regimes, the maximum infiltration though the concrete cap is 1E-03 mm/y. Any flow into the top of the room exceeding this is assumed to go through the area of the engineered cover where the concrete is not present. Flow regime 1 (undegraded facility with tile drains) operates from 0 y. Flow regime 2 (undegraded facility with degraded concrete cap and tile drain failure) operates from 100 y. Flow regime 4 (degraded facility with tile drain failure) operates from 1000 y.		
Justification:	The maximum infiltration rates for the concrete cap are based on those calculated in the resaturation model, and align with the assumptions made in the groundwater and near field models and (Arcadis & Geofirma, 2023a,b,c). The NPDDF is assumed to have a concrete cap in some areas and a multiple-layer engineered barrier emplaced over it at closure. These structures will be engineered to provide multiple barriers to inflowing water but will ultimately degrade. The lifetime of the capping structures has been based on the performance of the engineered cap envisaged for the LLWR near-surface disposal facility in the UK (LLWR, 2011). The LLWR features a multi-layered engineered cap and cover system at the surface. While the final design is yet to be finalised this is likely to be comparable to that used for NPDDF, and the assumptions concerning its performance lifetime are consistent with those used in other near-surface PostSA studies. Based on this, it is assumed to have fully degraded (in terms of hydraulic performance) by 1000 y after decommissioning is complete (taken as the mean expected lifetime)		
Uncertainty:	Jackson *et al*. (2011) provide details of the anticipated uncertainties in cap performance.		
Source of uncertainty:	The main source of uncertainty is in the timescales for degradation.		
References:	Arcadis Canada Inc. & Geofirma Ltd. (2023a). 2023 Groundwater Modelling at the Site of the Proposed Decommissioned Rolphton Nuclear Power Demonstration (NPD) Reactor. CNL No. 64-508760-REPT-012 Rev 1. June. Arcadis Canada Inc. & Geofirma Ltd. (2023b). 2023 Near-Field Groundwater Model at the Site of the Proposed Decommissioned Rolphton Nuclear Power Demonstration (NPD) Reactor. CNL No. 64-508760-REPT-013 Rev 1. June. Arcadis Canada Inc. & Geofirma Ltd. (2023c). 2023 Resaturation Modelling for the Proposed Decommissioned Rolphton Nuclear Power Demonstration (NPD) Reactor. CNL No. 64-508760-REPT-015 Rev 3. June. Jackson CP, Couch M, Yates H, Smith V, Kelly M and James M (2011). Elicitation of Uncertainties for LLWR, LLWR Environmental Safety Case report SERCO/TAS/E003796/010, Issue 2, April 2011. LLWR (2011). The 2011 Environmental Safety Case: Engineering Design, LLWR/ESC/R(11)10020, May 2011.		
Author:	Louise Bruffell	**Date:**	7 December 2022
Checker (basis):	Kate Thatcher	**Date:**	10 February 2023
Checker (implementation):	Kate Thatcher	**Date:**	10 February 2023

E 3.4.11 Distribution Coefficients of Structures and Grout Backfill

Name:	Distribution coefficients		
Version:	Version 4		
Parameter Name:	Kd_{cem}		
Units:	$m^3\ kg^{-1}$		
Description:	The distribution (or sorption) coefficients of cementitious structures and grout backfill.		
Value(s):	See Table E-27.		
Justification:	Sorption is an element-dependent empirical property that represents the distribution of an element between the solid and aqueous phase in a porous medium. It is represented with distribution coefficients. The sorption of some elements will depend on the pH of the material, which in turn evolves as cements degrade. The pH will initially be highly alkaline before decreasing as cement components are leached. Distribution coefficients therefore need to be defined for each of the cement degradation stages. The most recent compilation of sorption coefficients for cementitious environments is presented by Ochs *et al*. (2016) and this is the primary reference used here. Ochs *et al*. (2016) consider the same three-stage cement degradation model originally proposed by Berner (1992). In the PostSA the transitions in values that depend on these stages is modelled as being instantaneous at the end of each stage. For the purposes of the PostSA the existing NPD structure is taken to be structural concrete, and the backfill is BFS-PC grout. The values for stages I – III given by Ochs *et al*. (2016) are used for concrete, with Kds reverting to those of the overburden (see Section E 3.5.4) after the end of Stage III. The values for the grout in stages A-D are the same as the stage III values. Noting that Wilson (2020) suggests an additional "Stage IV" be considered for BFS-PC grout (i.e., a stage E), the value assigned for "> Stage III" by Ochs *et al*. (2016) is used for Stage IV/Stage E for the grout, before reverting to overburden values (for stage F). The distribution coefficients for the infill between the existing NPD structure and the bedrock is assumed to have the same properties as the concrete.		
Uncertainty:	An order of magnitude lower or higher.		
Source of uncertainty:	Sorption values are well accepted to be significantly dependent on local conditions and an important source of uncertainty.		
References:	Berner UR (1992). Evolution of Porewater Chemistry during Degradation of Cement in a Radioactive Waste Repository Environment. Waste Management 12. 201-219. Kaplan DI (2016). Geochemical data package for performance assessment calculations related to the Savannah River Site, SRNL-STI-2009-00473 Rev. 1, Savannah River National Laboratory, Aiken, SC. Ochs M, Mallants D and Wang L (2016). Radionuclide and Metal Sorption on Cement and Concrete. Topics in Safety, Risk, Reliability and Quality, Volume 29. Savage D and Stenhouse M (2002). SFR 1 Vault Database, SKI Report 02:53, April 2002. Skagius K, Pettersson M and Wiborgh M (1999). Compilation of data for the analysis of radionuclide migration from SFL 3-5. SKB Report: R-99-13. Wilson J (2020). Grout Flushing Models Report – NPD Closure Project. Prepared for CNL. March.		
Author:	James Penfold	**Date:**	12 June 2019
Checker (basis):	Renato Zagorscak	**Date:**	10 February 2022
Checker (implementation):	Renato Zagorscak	**Date:**	22 March 2022

Table E-27 Distribution Coefficients for Concrete and Grout (NES)

Element	Stage I	Stage II	Stage III/Stage A-D	Stage IV#/Stage E	Degraded~/Stage F	Notes
H	0	0	0	0	Overburden	
C	2	5	2	0.003*	Overburden	
Cl	0.02	0.05	0.02	0	Overburden	
Ca	0.007	0.001	0.01	0.04	Overburden	
Fe	0.065	0.4	0.4	0.005	Overburden	Assume as Ni (as per Savage & Stenhouse, 2002)
Co	0.065	0.4	0.4	0.005	Overburden	Assume as Ni
Ni	0.065	0.4	0.4	0.005	Overburden	
Se	0.003	0.003	0.0001	0.0001	Overburden	Se(VI) assumed, cautiously.
Sr	0.1	0.03	0.1	0.001	Overburden	
Zr	50	10	100	0.5	Overburden	Stage I, IV from analogy with Nb
Nb	50	50	50	0.5	Overburden	
Tc	0.001	0.001	0.001	0.001	Overburden	Tc(VII) assumed, cautiously
Ag	0.001	0.001	0.001	0.001	Overburden	
Cd	0.065	0.4	0.4	0.2	Overburden	Assume as Ni for Stage I, II, III, Stage IV as for “sandy sediment” estimated by Kaplan (2016)
Sn	20	20	0.5	0.28^	Overburden	Stage III from Skagius (1999)
Sb	20	20	0.5	0.28^	Overburden	Stage III from analogy with Sn
Cs	0.001*	0.002	0.02	0	Overburden	
Sm	5	5	1	0.14	Overburden	Assumed as Ac
Eu	5	5	1	0.14	Overburden	Assumed as Ac
Ho	5	5	1	0.14	Overburden	Assumed as Eu
Hf	50	10	100	0.5	Overburden	Assumed as Zr
Ta	50	50	50	0.5	Overburden	Assumed as Nb
Pb	0.3	3	30	0.8	Overburden	
Po	0.3	3	30	0.8	Overburden	Assume as Pb
Ra	0.3	0.1	0.8	0.001	Overburden	
Ac	5	5	1	0.14	Overburden	Savage & Stenhouse (2002)
Pa	10	10	10	3	Overburden	Assumes Pa(V), cautiously
Th	30	30	30	30	Overburden	
U	2	30	30	0.05	Overburden	
Np	30	30	30	0.3	Overburden	
Pu	2	30	30	0.05	Overburden	Assumes Pu (VI)
Am	10	10	10	10	Overburden	
Cm	5	5	1	0.14	Overburden	Savage & Stenhouse (2002)

Note: Data from Ochs *et al.* (2016) except where indicated. *No best estimate assigned, so the value selected is the geometric mean of the reported upper and lower limits given by Ochs *et al.* (2016). ^ Value based on Kd of overburden (see Section E 3.5). # Values only used for BFS-PC grout. ~ Same values as overburden, see E 3.5.4.

E 3.4.12 Solubility Limits for Lead in Structures and Grout Backfill

Name:	Solubility		
Version:	Version 4		
Parameter Name:	Sol_{Cement_Stages}, Sol_{Grout_Stages}		
Units:	Mol/kg		
Description:	The solubility of lead within the NPD. Only lead is subject to solubility limitation, as this hazardous material is present in the largest quantities in the NPDDF. As such, it is of most interest whether solubility limits will potentially be reached. Other contaminants are not solubility limited in the model; this is conservative in that there is no limitation on this aspect of their release from the Facility.		
Value(s):	For the concrete structure: • Stage I: 1 mol kg^{-1} • Stage II: 0.059 mol kg^{-1} • Stage III: $3.1x10^{-5}$ mol kg^{-1} • Stage IV: $2.4x10^{-5}$ mol kg^{-1} (fully degraded concrete). Lead solubility in BFS-PC grout is expected to vary in more complex ways than conventional grout. Wilson (2020), describes the evolution of solubility through five alternative phases, corresponding to the gradual decline of the pH from an initial condition of 11.9 to background conditions of pH 5.9. The following stages have been represented as described by Wilson (2020): • Stage A: 0 – 106: $2.5x10^{-4}$ mol kg^{-1} • Stage B: 107 – 227: $1.6x10^{-5}$ mol kg^{-1} • Stage C: 228 – 643 pore flushes: $2.8x10^{-6}$ mol kg^{-1}; • Stage D: 644 – 1978 pore flushes: $9.6x10^{-8}$ mol kg^{-1}; • Stage E: 1979 – 4386 pore flushes: $5.9x10^{-7}$ mol kg^{-1}; • Stage F: > 4386 pore flushes: $1.6x10^{-5}$ mol kg^{-1} According to Wilson (2020), the value for groundwater conditions is $1.6x10^{-5}$ mol kg^{-1}		
Justification:	The values for lead have been calculated with geochemical modelling (Wilson, 2017; Wilson, 2020). Reference should be made to the report for the basis for the selected values. In the PostSA the transitions in values that depend on these stages is modelled as being instantaneous at the end of each stage.		
Uncertainty:	Approximately an order of magnitude lower or higher.		
Source of uncertainty:	Solubility values are well accepted to be significantly dependent on local conditions and an important source of uncertainty. The values use local groundwater composition data to minimise uncertainties.		
References:	Wilson J (2017). Postclosure Safety Analysis of the NPD Waste Facility: Calculations of Lead Solubility Limits, May 2017. Wilson J (2020). Grout Flushing Models Report – NPD Closure Project. Prepared for CNL. March.		
Author:	James Penfold	**Date:**	12 June 2017
Checker (basis):	Emma Cairns	**Date:**	14 October 2019
Checker (implementation):	Renato Zagorscak	**Date:**	22 March 2022

E 3.4.13 Institutional Control Period

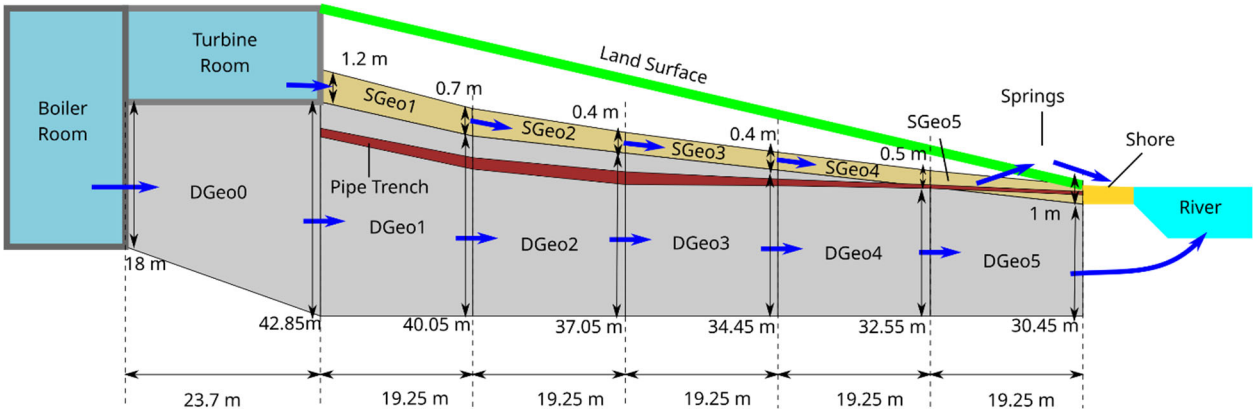
Name:	Institutional Control Period		
Version:	Version 4		
Symbol:	$t_{Control}$		
Units:	y		
Description:	The duration that the site remains under control for reasons related to the presence of radioactive material.		
Value(s):	100 y		
Justification:	In radioactive waste management it is generally assumed that the maximum period for which any residual controls could be assumed to be in place is 300 y, beyond which it would be inappropriate to put reliance on future society. The reference period of 100 y is assumed based on the assessment context (see Appendix A).		
Uncertainty:	Up to 300 y of institutional control could be considered.		
Source of uncertainty:	Variability in human habits and land use. In the model institutional control period defines the minimum time before the site of the NPDDF could be subject to an alternative use in which people occupied or used the land. In practice, it is likely to be much longer than this and future communities may choose to limit use of the land for a greater period The value of 100 y has been chosen to be a deliberately cautious minimum that could be mandated by the relevant authorities.		
References:	Appendix A (assessment context section).		
Author:	James Penfold	**Date:**	29 September 2016
Checker (basis):	Kate Thatcher	**Date:**	26 October 2016
Checker (implementation):	Renato Zagorscak	**Date:**	26 January 2023

E 3.5 Geosphere

E 3.5.1 Geometry

Name:	Geometry for Geosphere Paths		
Version:	Version 4		
Parameter Name:	Various		
Units:	m		
Description:	Width, height and total pathway length for geosphere pathways		
Value(s):	See below and Figure E-16. The shallow geosphere pathway compartments are all 19.25 m long and vary in thickness (with the final compartment pinching out to 1 m thick as the groundwater upwells in springs). The deep geosphere pathway, in the bedrock, also has varying thickness, which is greatest in line with the end of the NPD, below the Turbine Room wall, where it is 42.85 m thick. All geosphere compartments are 15.4 m wider than the total width of the NPDDF, i.e., 46.4 m. The geometry is shown in Figure E-13. In addition to these compartments, overburden either side of the NPDDF is included in the model, into which any contaminants leaking from the sides of the facility can be released. Pipe trench pathway compartments are narrower (4.4 m) and sit in the middle of the geosphere compartments, thickness of between 0.6 m and 4.8 m. Tile drain pathway compartments are further east, outside of the geosphere pathway. They are taken to be 2 m wide and have a thickness of between 0.5 m and 3.6 m.		
Justification:	The geometry of the geosphere is approximated based on the contaminant transport simulations by Arcadis & Geofirma (2023b).		
Uncertainty:	For the tile drains, the diameter of the drain is known, but once the drain has collapsed, the cross-sectional area of the collapse zone is unknown so has been assumed to be the same as the drain. The width of any contaminant plume in the overburden between the Facility and the river is based on Arcadis & Geofirma (2023b) which shows that there is uncertainty in the plume dimensions due to factors such as the dispersity. Under the Normal Evolution scenario, where there is no point leakage from the Facility, contaminants diffusing from the Facility into the surrounding fill are likely to be evenly distributed across the Facility width and therefore the contaminant plume will have a similar width to the Facility.		
Source of uncertainty:	Uncertainty about the size of the contaminant plume in the overburden is due to uncertainty in the dimensions of the source of the plume in the fill, in turn related to characteristics of the rock and groundwater flow patterns.		
References:	Arcadis Canada Inc. & Geofirma Ltd. (2023b). 2023 Near-Field Groundwater Model at the Site of the Proposed Decommissioned Rolphton Nuclear Power Demonstration (NPD) Reactor. CNL No. 64-508760-REPT-013 Rev 1. June. Taylor (2014) NPDWMF – Inactive, surface and sub-surface drainage. AECL report 64-71710-PRO-001 Revision 3.		
Author:	Louise Bruffell	**Date:**	7 December 2022
Checker (basis):	Kate Thatcher	**Date:**	10 December 2022
Checker (implementation):	Kate Thatcher	**Date:**	10 December 2022

Figure E-16 Representation of the Geosphere Pathways in the NPDDF Model



E 3.5.2 Porosity of Geological Media

Name:	Porosity of Geological Media		
Version:	Version 3		
Parameter Name:	$theta_{stage}$		
Units:	-		
Description:	Proportion of material volume that is void space.		
Value(s):	Cap infill 0.3 (Arcadis & Geofirma, 2023a, Table 3-1) Overburden 0.3 (fill – Arcadis & Geofirma, 2023a, Table 3-1) Bedrock 0.005 (Arcadis & Geofirma, 2023a, Table 3-1)		
Justification:	Porosity of the tile drains is unity while they are open, assuming no sedimentation. Once collapsed, drain will be filled with fill material from above, so the porosity is given the same value as the fill. Values for fill, overburden, and bedrock are obtained from Arcadis & Geofirma (2023a).		
Uncertainty:	A few tens of percent.		
Source of uncertainty:	Heterogeneity in the materials.		
References:	Arcadis Canada Inc. & Geofirma Ltd. (2023a). 2023 Groundwater Modelling at the Site of the Proposed Decommissioned Rolphton Nuclear Power Demonstration (NPD) Reactor. CNL No. 64-508760-REPT-012 Rev 1. June.		
Author:	Ryan Kovacs	**Date:**	4 April 2019
Checker (basis):	Louise Bruffell	**Date:**	17 March 2022
Checker (implementation):	Renato Zagorscak	**Date:**	24 March 2022

E 3.5.3 Density of Geological Media

Name:	Density of Geological Media		
Version:	Version 4		
Parameter Name:	rho_{Stage}		
Units:	kg m^{-3}		
Description:	Dry bulk density of the media.		
Value(s):	Cap infill 1855 kg m^{-3} Overburden 1855 kg m^{-3} Bedrock 2780 kg m^{-3}		
Justification:	Fill and overburden density has been estimated from the density of quartz grains and the porosity (0.3, see Section E 3.5.2). The density of quartz is 2650 kg/m^3 (DHZ, 1992). Bedrock density is estimated based on Arcadis & Geofirma (2022)		
Uncertainty:	A few tens of percent at most.		
Source of uncertainty:	Heterogeneity of the materials		
References:	DHZ (1992). Rock Forming Minerals, 2nd Edition. ISBN 0-470-21809-6 Arcadis Canada Inc. & Geofirma Ltd. (2022). Updated Geosynthesis – Nuclear Power Demonstration Closure Project – Rolphton, Ontario. CNL No. 64-509410-REPT-010 Rev 1, October		
Author:	James Penfold	**Date:**	17 April 2019
Checker (basis):	Renato Zagorscak	**Date:**	15 November 2022
Checker (implementation):	Renato Zagorscak	**Date:**	15 November 2022

E 3.5.4 Distribution Coefficients for Geological Media

Name:	Distribution Coefficients for Geological Media		
Version:	Version 4		
Parameter Name:	Kd_m		
Units:	$m^3\ kg^{-1}$		
Description:	Distribution coefficients for geological media		
Value(s):	Table E-28		
Justification:	The fill and overburden all have the same Kd values because the excavated overburden was used to backfill the trench so they have the same composition. Measurements have been made of sorption at Chalk River and provide information representative of overburden characteristics (Killey *et al*., 1995). Due to the relatively low mobility of many of the elements, only results for Sr are sufficiently conclusive to use here. The overburden values for other contaminants are taken from a coarse sand (or "drift") deposit at LLWR (Randall, 2008) and IAEA recommended values for sandy or mineral soil (IAEA, 2010). The bedrock values are adopted from a range of sources deemed to be applicable to NPD (NWMO, 2016; Crawford *et al*., 2006; Crawford, 2010; Hakanen *et al*., 2014). Analogues are chosen based on similar chemical properties of elements. Overburden values for silver and lead are obtained from Manolopoulos (2020a).		
Uncertainty:	There is significant uncertainty over orders of magnitude for Kd values, and the values from different sources are not consistent with each other.		
Source of uncertainty:	Sorption values are well accepted to be significantly dependent on local conditions and an important source of uncertainty.		
References:	Crawford J, Neretnieks I and Malmstrom M (2006). Data and uncertainty assessment for radionuclide Kd partitioning coefficients in granitic rock for use in SR_Can calculations. SKB Report R-06-75. Manolopoulos H (2020a). Arcadis Memo to CNL. Silver and Lead Site-Specific Distribution Coefficients for Soils Collected from the NPD Site. April. Crawford J (2010). Bedrock Kd data and uncertainty assessment for application in SR-Site geosphere transport calculations. SKB Report R-10-48. Hakanen M, Ervanne H and Puukko E (2014). Safety Case for the Disposal of Spent Nuclear Fuel at Olkiluoto: Radionuclide Migration Parameters for the Geosphere. Posiva Report POSIVA 2012-41. Posiva, Olkiluoto, Eurajoki, Finland. NWMO (Nuclear Waste Management Organization) (2016). Sixth Case Study: Reference Data and Codes. NWMO-TR-2016-10. Randall M (2008). Sorption Parameters for the LLWR Geosphere. Nexia Solutions report for LLWR (08) 9451. Garisto F, Gobien M, Kremer E and Medri C (2012). Fourth Case Study: Reference Data and Codes. NWMO report TR-2012-08. Fetter (1994). Applied Hydrogeology, Third Version. ISBN 0-02-336490-4. IAEA (2010). Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Terrestrial and Freshwater Environments, Technical Reports Series No 472, January 2010. Kaplan DI (2016). Geochemical data package for performance assessment calculations related to the Savannah River Site, SRNL-STI-2009-00473 Rev. 1, Savannah River National Laboratory, Aiken, SC. Killey RWD, Klukas M, Sakamoto Y, Munch JH, Young JL, Welch SJ, Risto BA, Eyvindson S and Moltyaner GL (1995). The CRL Glass Block Experiment: Radionuclide Release and Transport during the Past Thirty Years, AECL report RC-1513, November 1995. SKB (2014). Data report for the safety assessment SR-PSU. Report number SKB TR-14-10.		
Author:	Louise Bruffell	**Date:**	15 September 2021
Checker (basis):	Renato Zagorscak	**Date:**	21 September 2021
Checker (implementation):	Renato Zagorscak	**Date:**	21 September 2021

Table E-28 Distribution Coefficients for Geological Media

Element	Overburden and Infill (m^3/kg)	Bedrock (m^3/kg)
H	0	0 [b]
C	5.0E-04	0.001
Cl	0	0
Ca	0.0070~	0.013
Fe	0.04	0.12 [a]
Co	0.14	0.1 [a]
Ni	0.040	0.12 [a]
Se	0.056~	0.001
Sr	0.0072#	0.013
Zr	0.88	0.0213 [b]
Nb	0.88	0.0198 [b]
Tc	1.0E-04	0
Ag	0.025*	0.5
Cd	0.11~	0.1
Sn	0.28~	0.71
Sb	0.017~	0
Cs	0.30	0.18
Sm	0.63~	0.0148 [b]
Eu	0.63^	0.0148 [b]
Ho	0.63~	0.0148 [b]
Hf	1.5~	0.0213 [c]
Ta	0.56~	0.0198 [d]
Pb	0.040*	1.26
Po	0.19~	0.1
Ra	0.086	0.175
Ac	0.14	3
Th	0.88	1
Pa	0.10	1
U	0.015	0.0063
Np	0.014	0.018
Pu	0.10	5
Am	0.14	13
Cm	0.14	0.0148
Hg	6.3~	0

Note:

Distribution Coefficients for Overburden and Infill: Values from Randall (2008) unless noted. ~ Value from IAEA (2010). # based on laboratory measurements reported by Killey *et al*. (1995). * based on soil values from Manolopoulos (2020a). ^ Assumed to be the same as Sm. @ Value for sandy/clay sediment at pH 5.5 at Savannah River estimated by Kaplan (2016) based on measured values, likely to under-estimate actual values at more alkaline pH in the NPD, but reported Kd values for Al vary widely and it is appropriate to specify a conservatively low value.

Distribution Coefficients for Bedrock: Values for granite are from NWMO (2016), except as noted. [a] values are from Crawford *et al*. (2006). [b] values are from Crawford (2010). [c] Zr as analogue. [d] Nb as analogue.

E 3.5.5 Infiltration/Recharge to Shallow Groundwater

Name:	Recharge to Shallow Groundwater		
Version:	Version 4		
Parameter Name:	$q_{Recharge}$		
Units:	m y^{-1}		
Description:	Infiltration rate		
Value(s):	0.4 m y^{-1}		
Justification:	Assumed value from groundwater flow modelling report.		
Uncertainty:	This value depends on the other inputs and outputs of water in the groundwater flow model and is therefore sensitive to the parameters of the model (Arcadis & Geofirma, 2023c).		
Source of uncertainty:	Interannual variability and future climate change.		
References:	Arcadis Canada Inc. & Geofirma Ltd. (2023c). 2023 Resaturation Modelling for the Proposed Decommissioned Rolphton Nuclear Power Demonstration (NPD) Reactor. CNL No. 64-508760-REPT-015 Rev 3. June.		
Author:	Ryan Kovacs	**Date:**	4 April 2019
Checker (basis):	Louise Bruffell	**Date:**	13 April 2023
Checker (implementation):	Louise Bruffell	**Date:**	13 April 2023

E 3.5.6 Flows through the Geosphere

Name:	Flows through the Geosphere		
Version:	Version 4		
Parameter Name:	$q_{upstream}$, q_{c_vol}		
Units:	m/y, m^3/y		
Description:	The flow in the bedrock at the southern boundary (upstream) of the NPD and the flow in the geosphere pathways downstream of the NPD.		
Value(s):	Table E-29		
Justification:	Based on the groundwater flow modelling in Arcadis & Geofirma (2023b); A time-dependent switch is used to switch between the specified flow rates in the calculation of the advective transfer rates.		
Uncertainty:	The variation in flows between the different groundwater flow modelling cases give an indication of the uncertainty, which can range up to several orders of magnitude depending on the condition of the engineered materials and external factors.		
Source of uncertainty:	The results are derived from groundwater modelling (Arcadis & Geofirma, 2023b) and are therefore uncertain as a result of the uncertainties in the modelling.		
References:	Arcadis Canada Inc. & Geofirma Ltd. (2023b). 2023 Near-Field Groundwater Model at the Site of the Proposed Decommissioned Rolphton Nuclear Power Demonstration (NPD) Reactor. CNL No. 64-508760-REPT-013 Rev 1. June.		
Author:	Louise Bruffell	**Date:**	3 July 2023
Checker (basis):	Kate Thatcher	**Date:**	4 July 2023
Checker (implementation):	Kate Thatcher	**Date:**	4 July 2023

Table E-29 Flow Rates in the geosphere surrounding the NPD

	Units	Flow Case (1)	Flow Case (2)	Flow Case (4)	Flow Case (5)
$q_{upstream}$	m y^{-1}	6.13E-2	4.48E-2	4.46E-2	4.46E-2
Dgeo_0	m^3 y^{-1}	958.5534	976.3264	976.3264	1146.709
Dgeo_1	m^3 y^{-1}	2076.539	2336.767	2336.767	2439.801
Dgeo_2	m^3 y^{-1}	3194.525	3697.207	3697.207	3732.893
Dgeo_3	m^3 y^{-1}	3494.176	4203.867	4203.867	4203.867
Dgeo_4	m^3 y^{-1}	2871.505	3748.254	3748.254	3748.254
Dgeo_5	m^3 y^{-1}	2871.505	3748.254	3748.254	3748.254
PT_1	m^3 y^{-1}	719.1848	36573.23	36573.23	36573.23
PT_2	m^3 y^{-1}	1569.258	68361.74	68361.74	68361.74
PT_3	m^3 y^{-1}	2112.505	72496.49	72496.49	72496.49
PT_4	m^3 y^{-1}	2309.937	45463.46	45463.46	45463.46
PT_5	m^3 y^{-1}	2309.937	45463.46	45463.46	45463.46
Sgeo_1	m^3 y^{-1}	11038.16	117669.3	117669.3	117669.3
Sgeo_2	m^3 y^{-1}	7536.039	145955.6	145955.6	145955.6
Sgeo_3	m^3 y^{-1}	10821.1	203069.2	203069.2	203069.2
Sgeo_4	m^3 y^{-1}	21755.81	292673.1	292673.1	292673.1
Sgeo_5	m^3 y^{-1}	21755.81	292673.1	292673.1	292673.1
TD_1	m^3 y^{-1}	1699.142	20101.35	20101.35	20416.93
TD_2	m^3 y^{-1}	2857.537	26970.9	26970.9	27286.48
TD_3	m^3 y^{-1}	2835.884	24898.95	24898.95	25143.12
TD_4	m^3 y^{-1}	1484.233	12749.27	12749.27	12841.58
TD_5	m^3 y^{-1}	1484.233	12749.27	12749.27	12841.58

E 3.6 Biosphere

E 3.6.1 River Characteristics

Name:	River Characteristics		
Version:	Version 4		
Symbol:	See Table E-30		
Units:	See Table E-30		
Description:	Characteristics of the Ottawa River at the NPDDF site, used to determine the flow in the river.		
Value(s):	See Table E-30. Values used to derive a river flow rate (q_{River}) of 0.0709 m s^{-1} at the NPDDF location. River flows are also required at Deep River and Ottawa/Gatineau. The dilution factor applied at Deep River ($Dil_{DeepRiver}$) is taken from the ratio of the cross sectional area of the initial compartment into which discharge occurs (5 m x 1 m) and the Ottawa river (525 m x 11.5 m). The dilution factor (Dil_{Ottawa}) of 0.658 applied at Ottawa/Gatineau is taken from the ratio of reported flow rates measured at Des Joachims Generating Station (immediately upstream of NPDDF) and at the Britannia hydrometric gauge just downstream of Gatineau. This is applied to the concentrations at Deep River to calculate the concentration at Ottawa. See Table E-31. Data are available from the National Hydrometric service of the Government of Canada.		
Justification:	Based on parameter values used in support of previous assessments relating to the NPDDF. The implied average water velocity is 7 cm/s which is considered to be reasonable and compares well with the assumed value of 5 cm/s in CSA (2022).		
Uncertainty:	A factor of a few. Considered in a sensitivity case where the dilution factor of 0.35 is applied.		
Source of uncertainty:	River characteristics vary throughout the year, with seasonal patterns defined by periods of snow melt (Chouhan, 2016), and will vary as the climate changes. Recent measurements indicate flows over a nearly 70-y period range between 336 m^3/s and 1560 m^3/s, with a mean flow rate of 807 m^3/s. The volumetric flow rate used here of 428 m^3/s (Chouhan, 2016), that is used to calculate the stream velocity, is at the low end of the expected range. This is conservative because higher flow in the river will give higher dilution. By contrast, it is reasonable to use a dilution factor based on the whole historical record of river flow rates at both Des Joachims and at the Britannia hydrometric station near Gatineau. Daily flow data are available for Des Joachims from 1950 – 2016, and for the Britannia hydrometric gauge data are available from 1960 to 2021.		
References:	National Hydrometric service of the Government of Canada https://wateroffice.ec.gc.ca/search/historical_e.html Chouhan SL (2016). River Dilution Factors used for NPD's DRLs, File 64-96000-021-000-0004, July 2016.		
Author:	James Penfold	**Date:**	28 November 2022
Checker (basis):	Renato Zagorscak	**Date:**	28 November 2022
Checker (implementation):	Renato Zagorscak	**Date:**	26 January 2023

Table E-30 River Characteristics at NPDDF

Parameter	Value	Notes
River flow rate	4.28×10^5 L s^{-1}	1
River width	525 m	2
River depth	11.5 m	3

Notes:
1 Table 1 of Chouhan (2016).
2 Canadian Hydrographic Service (2006).
3 Average of the two depths provided in Table 1 of Chouhan (2016).

Table E-31 River Characteristics and Dilution Factors for Downstream Receptors*

Parameter	River flow rate (m^3 s^{-1})	Dilution Factor
NPD (Des Joachims)	807	1
Deep River^	807	0.000828
Ottawa (Britannia hydrometric gauge)	1227	0.658#

Notes:
* Data from https://wateroffice.ec.gc.ca/search/historical_e.html are the mean of the available record set (see parameter table for details).
^ Flow rate assumed to be the same as at NPD.
# Additional dilution compared to the river water concentration at Deep River.

E 3.6.2 River Sediment Characteristics

Name:	River Sediment Characteristics		
Version:	Version 4		
Symbol:	See Table E-32		
Units:	See Table E-32		
Description:	Characteristics of the Ottawa River at the NPDDF site.		
Value(s):	See Table E-32		
Justification:	Based on descriptions of sediment characteristics for the Ottawa River in the region of the NPDDF.		
Uncertainty:	Uncertainty concerning river sediment characteristics is estimated to cover a factor of about two.		
Source of uncertainty:	There is natural variability in sediment characteristics. They would also change if the river characteristics evolved with time.		
References:	AECL (2014). Chalk River Laboratories Ottawa River Sediment Remediation Assessment – Refined Conceptual Site Model. AECL General Report 175-121250-REPT-002, Revision 1. Canadian Standards Association (CSA). (2022). Guidelines for modelling radionuclide environmental transport, fate, and exposure associated with normal operation of nuclear facilities, N288.1:20, 2022 Errata, June. Smith JG and Simmonds JG (2009). The Methodology for Assessing the Radiological Consequences of Routine Releases of Radionuclides to the Environment Used in PC-CREAM 08, Health Protection Agency report HPA-RPD-058, October 2009.		
Author:	Russell Walke	**Date:**	25 August 2016
Checker (basis):	Louise Bruffell	**Date:**	26 October 2022
Checker (implementation):	Renato Zagorscak	**Date:**	26 January 2023

Table E-32 River Sediment Characteristics

Parameter	Symbol	Value	Notes
Suspended sediment concentration	ρ_{Sed}	0.013 kg m^{-3}	1
Depth of river bed sediment	L_{Sed}	0.1 m	2
Sedimentation rate	α_{Sed}	0.0005 m y^{-1}	3
Depth of shore sediments	Z_{Shore}	0.1 m	4

Notes:

1 Based on sediment data sampling at Britannia, west of Ottawa, on the Ottawa River, over a period of five years (1971-1976), from Environment Canada (https://wateroffice.ec.gc.ca).

2 Based on the sediment model described by Smith & Simmonds (2009) and shown in Diagram 2 of Part 2 of that report.

3 Section 3.3.1 of AECL (2014) notes that sedimentation rates, which vary with river depth, range from 0.5 to 1.5 mm y^{-1} at the Chalk River site. The river adjacent to the NPDDF is shallower and narrower than that at Chalk River and will therefore be flowing faster. A sedimentation rate at the bottom of the range observed at Chalk River would therefore be expected (i.e. 0.5 mm y^{-1}).

4 Used in the calculation of volatilisation of C-14, and taken to be the same as river bed sediments.

E 3.6.3 Distribution Coefficients for Freshwater Sediment

Name:	Freshwater Sediment Sorption		
Version:	Version 4		
Symbol:	Kd_m		
Units:	m^3 kg^{-1}		
Description:	Equilibrium solid-liquid partition coefficient for freshwater sediment.		
Value(s):	See Table E-33.		
Justification:	Reference values are adopted from the CSA (2022). Values for Ag and Pb are site-specific, taken from Manolopoulos (2020a,b)		
Uncertainty:	The biosphere modelling is based on the deterministic biosphere models recommended in CSA (2022).		
Source of uncertainty:	There is significant natural variability and heterogeneity in sediment properties. However, a deterministic 'reference' approach is adopted to the biosphere modelling, consistent with CSA (2022).		
References:	Canadian Standards Association (CSA). (2022). Guidelines for modelling radionuclide environmental transport, fate, and exposure associated with normal operation of nuclear facilities, N288.1:20, 2022 Errata, June. Manolopoulos H (2020a). Arcadis Memo to CNL. Silver and Lead Site-Specific Distribution Coefficients for Soils Collected from the NPD Site. April. Manolopoulos H (2020b). Arcadis Memo to CNL. Silver and Lead Site-Specific Distribution Coefficients for Ottawa River, Sediments Collected in the Vicinity of the NPD Site. September. Gobien M, Garisto F and Kremer E (2013). Fifth Case Study: Reference Data and Codes. NWMO report TR-2013-05, Revision 000. IAEA (2010). Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Terrestrial and Freshwater Environments, Technical Reports Series No 472, January 2010.		
Author:	Louise Bruffell	**Date:**	26 October 2022
Checker (basis):	Kate Thatcher	**Date:**	30 November 2022
Checker (implementation):	Kate Thatcher	**Date:**	30 November 2022

Table E-33 Freshwater Sediment Sorption

Element	Sediment (m^3 kg^{-1})	Notes
H	0	1
C	0.05	1
Cl	0.02	1
Ca	0.07	2
Fe	5	1
Co	43	1
Ni	1.4	1
Se	0.56	1
Sr	0.19	1
Zr	1	1
Nb	1.7	1
Tc	0.005	1
Ag	6	4
Cd	1.4	2
Sn	1.3	1
Sb	5.0	1
Cs	9.5	1
Sm	0.5	3
Eu	0.5	1
Ho	6.3	2
Hf	4.5	1
Ta	5.6	2
Pb	0.9	4
Po	1.5	2
Ra	7.4	1
Ac	4.5	2
Th	190	1
Pa	5.4	1
U	0.05	1
Np	0.01	1
Pu	240	1
Am	210	1
Cm	5	1

Notes:

1 Table A.26 of CSA (2022) and converted from L kg^{-1} to m^3 kg^{-1}.

2 Taken to be ten times the sand Kd (see Table E-36), based on discussion in Clause 7.8.2 of CSA (2022).

3 Eu value used for Sm, by chemical analogy.

4 Manolopoulos (2020a,b).

E 3.6.4 Water Balance

Name:	Water Balance Parameters		
Version:	Version 4		
Symbol:	See Table E-34		
Units:	See Table E-34		
Description:	Parameters that provide an input to the water balance for the domain that is modelled for the contaminant transport calculations.		
Value(s):	See Table E-34		
Justification:	Values are adopted based on description of the site and for consistency with previous assessments for the NPDDF site, where appropriate. Where site-specific information is not available, then values are based on national recommendations, as reflected in CSA (2022). The present-day climate conditions are assumed to persist in the future; climate related uncertainties cannot readily be resolved within the scope of this study and are likely to be of less significance than other uncertainties (e.g., in sorption coefficients). In the scenario in which well water is used, this is considered to be local perturbation on the system.		
Uncertainty:	The biosphere modelling is based on the deterministic biosphere models recommended in CSA (2022).		
Source of uncertainty:	There is variability in climatic conditions. However, a deterministic 'reference' approach is adopted to the biosphere modelling, consistent with CSA (2022).		
References:	AECL (2011). Derived Release Limits for AECL's Nuclear Power Demonstration (NPD) Site, Rolphton. AECL Nuclear Safety Note 64-96000-NSN-002, Revision 2. Canadian Standards Association (CSA). (2022). Guidelines for modelling radionuclide environmental transport, fate, and exposure associated with normal operation of nuclear facilities, N288.1:20, 2022 Errata, June		
Author:	James Penfold	**Date:**	17 April 2019
Checker (basis):	Louise Bruffell	**Date:**	26 October 2022
Checker (implementation):	Renato Zagorscak	**Date:**	26 January 2023

Table E-34 Water Balance Parameters for Present-day Climate

Parameter	Symbol	Value	Notes
Infiltration rate	$q_{Recharge}$	0.400 m y^{-1}	1
Irrigation area	A_{Irrig}	Area of "garden"	2
Irrigation rate	D_{Irrig}	0.350 m y^{-1}	3
Proportion of irrigation water from river	F_{Irrig}	1	4
Fraction of recharge that flows upwards e.g. by capillary action	f_{Up}	0.1	5

Natural Environment 634 Lily Lake Road:

1 Consistent with the assumed recharge (see Section E 3.5.5).

2 Area sufficient to sustain a small household of two adults, a child and an infant with the local crop ingestion rates described in Section E 3.7.3 plus feed for two pigs and 25 chickens. Note that in the model this is set to equal the "top area" of the spatial garden compartment, which is approximately 10,000 m^2.

3 Based on a rate of 1.1 x 10^{-5} L m^{-2} s^{-1} from Table 8-4 of AECL (2011).

4 Assumed value.

5 Nominal value, only used in modelling the cap where contaminated water from the NPD is assumed to be able to migrate directly into the cap by processes such as fluctuation of the water table and capillary action.

E 3.6.5 Soil and Sediment Properties

Name:	Soil and Sediment Properties		
Version:	Version 4		
Symbol:	See Table E-35		
Units:	See Table E-35		
Description:	The soil of the irrigated/gardened area is taken to be improved and is represented as being loam in texture, whilst the soil of the grazing area and the shore region are taken to be sandy.		
Value(s):	See Table E-35		
Justification:	Reference values are adopted from the CSA (2022).		
Uncertainty:	The biosphere modelling is based on the deterministic biosphere models recommended in CSA (2022).		
Source of uncertainty:	There is significant natural variability and heterogeneity in soil properties. However, a deterministic 'reference' approach is adopted to the biosphere modelling, consistent with CSA (2022).		
References:	Canadian Standards Association (CSA). (2022). Guidelines for modelling radionuclide environmental transport, fate, and exposure associated with normal operation of nuclear facilities, N288.1:20, 2022 Errata, June		
Author:	Russell Walke	**Date:**	23 August 2016
Checker (basis):	Louise Bruffell	**Date:**	26 October 2022
Checker (implementation):	Renato Zagorscak	**Date:**	26 January 2023

Table E-35 Soil Properties

Parameter	Symbol	Description	Value		Source
Bulk density	ρ_M	Dry bulk density	Loam	1300 kg m^{-3}	Clause 6.3.2.2
			Sand	1500 kg m^{-3}	Clause 6.3.2.2
			Sediment (river)	400 kg m^{-3}	Clause 6.6.2.2
Water-filled porosity	θ	Volumetric water content of the soil	Loam	0.2	Clause 6.3.4.3^
			Sand	0.1	Clause 6.3.4.3^
			Sediment (river)	0.85	*
Soil depth	Z_{soil}	Depth of soil	0.2 m		Clause 6.3.1.1
Erosion rate	ER	Soil erosion rate	Loam	5 x 10^{-8} kg dw m^{-2} s^{-1}	Clause 6.3.4.2
			Sand	1.5 x 10^{-8} kg dw m^{-2} s^{-1}	Clause 6.3.4.2

Note: * Derived from the bulk density, assuming a grain density of 2650 kg m^{-3}. ^ In the model this is calculated from the total porosity (assumed to be 0.3 for both soil textures) and saturation (ε, taken to be 0.66 for loam and 0.33 for sand).

E 3.6.6 Distribution Coefficient for Soils

Name:	Soil Sorption		
Version:	Version 4		
Symbol:	Kd_m		
Units:	m^3 kg^{-1}		
Description:	Equilibrium solid-liquid partition coefficient.		
Value(s):	See Table E-36		
Justification:	Reference values are adopted from the CSA (2022).		
Uncertainty:	The biosphere modelling is based on the deterministic biosphere models recommended in CSA (2022).		
Source of uncertainty:	There is significant natural variability and heterogeneity in soil properties. However, a deterministic 'reference' approach is adopted to the biosphere modelling, consistent with CSA (2022).		
References:	Canadian Standards Association (CSA). (2022). Guidelines for modelling radionuclide environmental transport, fate, and exposure associated with normal operation of nuclear facilities, N288.1:20, 2022 Errata, June Gobien M, Garisto F and Kremer E (2013). Fifth Case Study: Reference Data and Codes. NWMO report TR-2013-05, Revision 000. IAEA (2010). Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Terrestrial and Freshwater Environments, Technical Reports Series No 472, January 2010. Kaplan DI (2016). Geochemical data package for performance assessment calculations related to the Savannah River Site, SRNL-STI-2009-00473 Rev. 1, Savannah River National Laboratory, Aiken, SC.		
Author:	Russell Walke, James Penfold	**Date:**	8 July 2019
Checker (basis):	Louise Bruffell	**Date:**	26 October 2022
Checker (implementation):	Renato Zagorscak	**Date:**	26 January 2023

Table E-36 Soil Sorption

Element	Sand (m^3 kg^{-1})	Loam (m^3 kg^{-1})	Notes
H	0	0	1
C	0.005	0.02	1
Cl	0.002	0.006	1
Ca	0.007	0.007	2
Fe	0.32	0.89	1
Co	0.64	0.64	1
Ni	0.14	0.14	1
Se	0.056	0.22	1
Sr	0.022	0.069	1
Zr	0.032	5.0	1
Nb	0.17	2.5	1
Tc	4E-5	7E-5	1
Ag	0.09	0.12	1
Cd	0.14	0.14	5
Sn	0.13	0.45	1
Sb	0.045	0.15	1
Cs	0.53	0.37	1
Sm	0.123	0.429	3
Eu	0.123	0.429	1
Ho	0.63	3	2
Hf	0.45	1.5	1
Ta	0.56	3	2
Pb	0.27	16	4
Po	0.15	0.4	4
Ra	1.9	1.9	1
Ac	0.45	1.5	4
Th	0.7	18	1
Pa	0.54	1.8	1
U	0.11	0.31	1
Np	0.004	0.025	1
Pu	0.4	1.1	1
Am	1	4.3	1
Cm	4	18	1

Notes:

1 Table G.2 of CSA (2022).

2 Mean value for mineral (sand) or organic (loam) soils from Table 14 of IAEA (2010) and converted from L kg^{-1} to m^3 kg^{-1}.

3 Value for Eu adopted by chemical analogy.

4 Table 8-5 of Gobien *et al*. (2013).

5 Value for Ni used by chemical analogy.

E 3.6.7 Volatilisation from Soils and Surface Water

Name:	**Volatilization Rate from Soils and Surface Water**			
Version:	Version 4			
Symbol:	λ_{voln}			
Units:	s^{-1}			
Description:	Volatilization rate from soils and surface water.			
Value:		Soils ($Voln_{Soil}$)	Surface Water ($Voln_{Water}$)	
	C	4.3×10^{-7} s^{-1}	6.7×10^{-8} s^{-1}	
	Others	0 s^{-1}	0 s^{-1}	
Justification:	Reference values are adopted from the CSA (2022). For soils, the value for carbon is taken from Clause 6.3.5.1 of CSA (2022). For other elements, including Hg, a value of zero is used, consistent with clause 6.3.5.2 of CSA (2022). For surface water, the value for carbon is taken from Clause 6.6.2.5 of CSA (2022). For Hg, a value of zero is used, consistent with the approach for soils. Note CSA (2022) states that it is not necessary to model volatilisation for H-3.			
Uncertainty:	The biosphere modelling is based on the deterministic biosphere models recommended in CSA (2022).			
Source of uncertainty:	The volatilization rate will vary depending on geochemistry and atmospheric properties. There is uncertainty associated with the volatilization rate, however, a deterministic 'reference' approach is adopted to the biosphere modelling, consistent with CSA (2022).			
References:	Canadian Standards Association (CSA). (2022). Guidelines for modelling radionuclide environmental transport, fate, and exposure associated with normal operation of nuclear facilities, N288.1:20, 2022 Errata, June			
Author:	Russell Walke		**Date:**	24 August 2016
Checker (basis):	Louise Bruffell		**Date:**	26 October 2022
Checker (implementation):	Renato Zagorscak		**Date:**	26 January 2023

E 3.6.8 Crop-specific Parameters

Name:	Crop-specific Parameters		
Version:	Version 4		
Symbol:	See Table E-37 and Table E-38		
Units:	See Table E-37 and Table E-38		
Description:	Crop-specific parameters, including foliar interception fraction, consumable yield, harvest index, dry/fresh weight ratio and leaf area index, nutrient cycling fraction, canopy height.		
Value(s):	See Table E-37 and Table E-38		
Justification:	Reference values are principally adopted from the CSA (2022).		
Uncertainty:	The biosphere modelling is based on the deterministic biosphere models recommended in CSA (2022).		
Source of uncertainty:	There is uncertainty associated with all of these parameters, however, a deterministic 'reference' approach is adopted to the biosphere modelling, consistent with CSA (2022).		
References:	Canadian Standards Association (CSA). (2022). Guidelines for modelling radionuclide environmental transport, fate, and exposure associated with normal operation of nuclear facilities, N288.1:20, 2022 Errata, June		
Author:	Russell Walke	**Date:**	29 September 2016
Checker (basis):	Louise Bruffell	**Date:**	26 October 2022
Checker (implementation):	Renato Zagorscak	**Date:**	26 January 2023

Table E-37 Crop-independent Parameters

Parameter	Value	Justification
Cropping frequency, cf	1 y^{-1}	Clause 6.3.7.1 of CSA (2022)
Nutrient cycling fraction, NL	0.05	Clause 6.3.7.1 of CSA (2022)
Volume of irrigation water retained per unit leaf area, I_{wt}	0.1 L m^{-2}	Clause 7.3.1.2 of CSA (2022)
Frequency of irrigation events using contaminated water, η_I	3.34 x 10^{-6} s^{-1}	Clause 7.3.1.2 of CSA (2022)
Effective removal constant due to physical processes such as wind and rain, λ_p	2.87 x 10^{-7} s^{-1}	Clause 6.4.4 of CSA (2022)
Leaf area index, LAI	3.0	Table G.5 of CSA (2022)
Fraction of annual input of C-14 leaving the soil surface as CO2 per annum, f_{CO2}	1	Clause 7.3.4.3 of CSA (2022)
The ratio of the total plant yield to the above ground yield (total below ground for root crops), TS	2	Clause 7.3.4.3 of CSA (2022)
Mass of stable carbon per mass of plant, X_{4C}	500 gC kg-1 dw	Clause 6.4.9.3 of CSA (2022)
Concentration of stable carbon in air, X_{1C}	0.21 g m^{-3}	Clause 6.4.9.3 of CSA (2022)
Windspeed in plant canopy, u_{canopy}	0.25 m s^{-1}	Assumed.
Isotopic discrimination for plant metabolism, used in calculating H-3 uptake to plants, ID_p	0.7	Value for all plants, see Clause 6.4.8.4 of CSA (2022)
Water equivalent of the plant dry matter, used to calculate H-3 update to plants, WE_p	0.56	Value for all plants, see Clause 6.4.8.4 of CSA (2022)

Table E-38 Crop-specific Parameters

Crop	Foliar interception fraction, f_{int} (unitless)	Consumable yield, Y_c (kg fw m^{-2})	Harvest index, hi (unitless)	Dry/fresh weight ratio, DW_p (unitless)	Canopy height, Z_c, (m)	Effective deposition duration, t_e (days)	Fraction of carbon from air, f_{c_air} (unitless)
Forage	1	0.48	1	0.2	0.1	30	1
Generic feed crops	1	0.6	1	0.87	0.3	60	0.7
Generic fruit and vegetables	0.5	1	0.8	0.1	0.3	60	0.7
Potatoes	0.5	2.1	0.8	0.21	0.3	60	0.7
Berries	0.3	0.53	0.8	0.1	0.3	60	0.7
Mushrooms*	0.3	0.53	1	0.1	0.1	60	0.7

Note: Principally, from Table G.5 of CSA (2022). The canopy height is based on consideration of pasture for forage and a range of garden crops for other plants. The effective deposition duration is from Clause 6.4.5 of CSA (2022). The Fraction of plant carbon derived from air is taken from Clause 6.4.9.3 of CSA (2022) for forage, which is not irrigated, and from Clause 7.3.4.3 of CSA (2022) for other crops, which are irrigated. * Mushrooms assumed to be as berries except as follows. The harvest index for mushrooms is assumed to be 1 (all edible) and mushrooms are assumed to have a canopy height of only 0.1 m (as they may occur in fields).

E 3.6.9 Element-dependent Plant Parameters

Name:	Element-dependent Plant Parameters		
Version:	Version 4		
Symbol:	See Table E-39		
Units:	See Table E-39		
Description:	Equilibrium soil to plant concentration ratios and translocation factors.		
Value(s):	See Table E-39		
Justification:	Reference values are adopted from the CSA (2022).		
Uncertainty:	The biosphere modelling is based on the deterministic biosphere models recommended in CSA (2022).		
Source of uncertainty:	There is significant natural uncertainty in the soil-to-plant concentration ratios and further uncertainty in the translocation factor. However, a deterministic 'reference' approach is adopted to the biosphere modelling, consistent with CSA (2022).		
References:	Canadian Standards Association (CSA). (2022). Guidelines for modelling radionuclide environmental transport, fate, and exposure associated with normal operation of nuclear facilities, N288.1:20, 2022 Errata, June. Gobien M, Garisto F and Kremer E (2013). Fifth Case Study: Reference Data and Codes. NWMO report TR-2013-05, Revision 000. IAEA (2010). Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Terrestrial and Freshwater Environments, Technical Reports Series No 472, January 2010.		
Author:	Russell Walke, James Penfold	**Date:**	8 July 2019
Checker (basis):	Louise Bruffell	**Date:**	27 October 2022
Checker (implementation):	Renato Zagorscak	**Date:**	26 January 2023

Table E-39 Soil-Plant Concentration Ratios and Translocation Factors

Element	Soil-Plant Concentration Ratio, CR (Bq kg^{-1} dw plant per Bq kg^{-1} dw soil)	Translocation Factor (unitless), tf		Notes	Transfer from Soil to Berries and Mushrooms (unitless) CR_fruit	Notes
		Foliage[1]	Other Crops			
H	-	-	-	2	-	2
C	-	-	-	2	-	2
Cl	89	1	1	3	8.9	9
Ca	20	1	1	4	20	4
Fe	0.005	1	0.1	3	0.0005	9
Co	0.047	1	0.1	3	0.0047	9
Ni	0.47	1	1	3	0.047	9
Se	0.45	1	1	3	0.045	9
Sr	0.87	1	1	3	0.087	9
Zr	0.0032	1	0.1	3	3.2E-4	9
Nb	0.029	1	0.1	3	0.0029	9
Tc	3.7	1	1	3	0.37	9
Ag	0.0017	1	1	3	1.7E-4	9
Cd	0.27	1	1	4	0.27	4
Sn	0.41	1	1	3	0.041	9
Sb	0.0015	1	0.01	3	1.5E-4	9
Cs	0.053	1	1	3	0.0053	9
Sm	0.018	1	0.1	5	0.0018	5
Eu	0.018	1	0.1	3	0.0018	9
Ho	0.018	1	0.1	7	0.0018	7
Hf	0.016	1	0.1	3	0.0016	9
Ta	0.029	1	0.1	8	0.0029	8
Pb	0.006	1	1	6	0.0006	6
Po	0.0065	1	1	6	0.00065	6
Ra	0.11	1	1	3	0.011	9
Ac	0.0095	1	0.01	6	0.00095	6
Th	0.0033	1	0.01	3	3.3E-4	9
Pa	0.038	1	0.1	3	0.0038	9
U	0.01	1	0.1	3	0.001	9
Np	0.0084	1	0.1	3	8.4E-4	9
Pu	0.00014	1	0.01	3	1.4E-5	9

Element	Soil-Plant Concentration Ratio, CR (Bq kg^{-1} dw plant per Bq kg^{-1} dw soil)	Translocation Factor (unitless), tf		Notes	Transfer from Soil to Berries and Mushrooms (unitless) CR_fruit	Notes
		Foliage[1]	Other Crops			
Am	0.00063	1	0.01	3	6.3E-5	9
Cm	0.00021	1	0.01	3	2.1E-5	9

Notes: Values not needed for non-radiological contaminants.

1 Consistent with the footnote to Table G.3 in CSA (2022), a value of unit (1) is used for crops where foliage is consumed, assumed to be fruit and vegetables and forage.

2 Not required for modelling H-3 and C-14.

3 Table G.3 in CSA (2022).

4 Soil-to-plant concentration ratio represents the mean value for leguminous vegetables for 'all soils' from Table 17 of IAEA (2010). Calcium is actively transported around plants (as evidenced by its relatively high soil-to-plant concentration ratio), therefore it is assigned a translocation factor of 1.

5 Value for Eu adopted for Sm, by chemical analogy.

6 Soil-to-plant concentration ratio is the higher of the geometric mean for forage and garden crops from Table 8-4 Gobien *et al*. (2013) and converted to a dry-weight basis using a dry:fresh weight ratio of 0.2. For the translocation factor, Pb, Po and Ac are taken to be chemically analogous to Sn, Se and Th, respectively, in Table G.3 of CSA (2022).

7 Ho is a rare earth element (REE) with similarities to Eu. Neither Ho nor Eu have a biological role, so it seems reasonable to treat Ho similarly to Eu.

8 Ta is chemically similar to Nb. Neither Ta nor Nb have a biological role, so it seems reasonable to treat Ta similarly to Nb.

9 Table A.9 in CSA (2022); generic fruits and vegetables.

E 3.6.10 Terrestrial Animal Parameters

Name:	Animal Feed, Water, Air and Soil Intakes		
Version:	Version 4		
Symbol:	See Table E-40, Table E-41, Table E-42 and Table E-43		
Units:	See Table E-40, Table E-41, Table E-42 and Table E-43		
Description:	Animal feed, water, air and soil intakes.		
Value(s):	See Table E-40, Table E-41, Table E-42 and Table E-43		
Justification:	Reference values are adopted from Table G.7 of CSA (2022) and associated clauses (see Tables).		
Uncertainty:	The biosphere modelling is based on the deterministic biosphere models recommended in CSA (2022).		
Source of uncertainty:	There is natural variability in the animal feed, water, air and soil intakes. However, a deterministic 'reference' approach is adopted to the biosphere modelling, consistent with CSA (2022).		
References:	Canadian Standards Association (CSA). (2022). Guidelines for modelling radionuclide environmental transport, fate, and exposure associated with normal operation of nuclear facilities, N288.1:20, 2022 Errata, June		
Author:	Louise Bruffell	**Date:**	1 November 2022
Checker (basis):	Kate Thatcher	**Date:**	30 November 2022
Checker (implementation):	Kate Thatcher	**Date:**	30 November 2022

Table E-40 Animal-independent Parameters

Parameter	Symbol	Value	Justification
Fraction of the animal's drinking water from the contaminated source	$F_{RiverAnm}$	1	Conservative default value adopted from Clause 6.9.1.2 of CSA (2022)
The hold-up time between plant exposure to contamination and feeding	t_h	1 day	Conservative default value taken from Clause 6.10.1.3 of CSA (2022)

Table E-41 Animal Feed, Water, Air and Soil Intakes

Animal	Feed intake, Q_f (kg dw d^{-1})	Water intake, Q_w, (L d^{-1})	Soil load on feed, f_{sl} (kg dw kg^{-1} dw)	Soil from other contaminated sources, Q_s (kg dw d^{-1})	Fraction of feed from contaminated source, k_{af} (-)**
Dairy cow	19.8	115*	0.1	0.2	1
Dairy goat	2.6	8*	0.1	0.02	1
Beef cow	13.2	52*	0.1	0.1	1
Pig	3.3	9	0.001	0.03	1
Sheep	1.7	5*	0.1	0.02	1
Poultry	0.1	0.25	0.001	0.005	1
Deer	2.5	5.7	0.01	0.01	0.002
Moose	8	20	0.1	0.01	0.0002
Rabbit	0.11	0.36	0.1	0.006	1
Goose	0.14	0.14	0.082	-	0.75
Duck	0.06	0.06	0.02	-	0.75
Grouse	0.0331	0.03864	0.082	-	0.03

Notes: Data from Table G.7 of CSA (2022). * Values for dry diet conservatively adopted, given that some part of the animal's diet is taken to be from stored food during colder months. ** Conservative values adopted for the fraction of feed from contaminated sources, with the exception of deer, moose and grouse, which are based on the ratio of the home range (Table G.6 of CSA (2022)) to the total modelled area of "garden", "grazing" and "cap" soil, a total of 3.1 ha. The geese and ducks are taken to obtain feed from elsewhere during the winter. All animals are assumed to obtain all their water from contaminated sources (parameter k_{aw}).

Table E-42 Fraction of Animal Water Intakes from different sources

Animal	Fraction of water intake from direct ingestion, f_{w_w} (-)	Fraction of water intake from plant feed, f_{w_pw} (-)	Fraction of water intake from metabolic decomposition of organic matter in feed, f_{w_dw} (-)
Dairy cow	0.495	0.44	0.062
Dairy goat	0.332	0.582	0.082
Beef cow	0.413	0.510	0.071
Pig	0.329	0.583	0.082
Sheep	0.329	0.583	0.082
Poultry	0.22	0.650	0.121
Deer	0.33	0.582	0.081
Moose	0.413	0.510	0.071
Rabbit	0.413	0.509	0.071
Goose	0.22	0.650	0.121
Duck	0.22	0.650	0.121
Grouse	0.22	0.650	0.121

Note: Data from Table 16 of CSA (2022). Pig values assumed same as sheep, and poultry values the same as duck/goose.

Table E-43 Animal Product Parameters

Foodstuff	Fraction of H3 in the animal product in the form of OBT from HTO ingestion (f_{OBT})^	OBT/HTO ratio after water ingestion (f'_{OBT})^	Dry/Fresh Weight Ratio (DW_a)*	Stable carbon concentration, X_{5_C} (g C kg^{-1} fw)**	Water equivalent of the animal product dry matter, WE_a (l kg^{-1} dw) ***
Cow milk	0.04	0.042	0.1	65	0.67
Goat milk	0.07	0.075	0.1	65	0.67
Beef Meat	0.11	0.12	0.3	201	0.8
Beef Liver	0.11	0.12	0.3	201	0.8
Pork	0.13	0.15	0.5	304	0.9
Lamb	0.08	0.087	0.3	275	0.8
Chicken Meat	0.1	0.11	0.3	244	0.8
Chicken Eggs	0.08	0.087	0.3	157	0.84
Venison	0.11	0.12	0.3	201	0.8
Moose	0.11	0.12	0.3	201	0.8
Rabbit	0.11	0.12	0.3	201	0.8
Goose Meat	0.1	0.11	0.3	244	0.8
Duck Meat	0.1	0.11	0.3	244	0.8
Grouse meat	0.1	0.11	0.3	244	0.8

Note: ^ Data from Tables 17 and footnotes of Table A.11b of CSA (2022). * Data from Section 6.9.2.4 of CSA (2022), rabbits and wildfowl assumed to be as poultry. ** Data from Table 18 and footnotes of Table A.11b of CSA (2022), assume liver values same as meat, poultry value used for goose, duck and grouse meat, and use beef values for other animals for which data are not available. *** Clause 6.10.3.2 of CSA (2022), assuming beef and poultry value for missing data.

E 3.6.11 Feed-to-Animal Transfer Factors

Name:	Feed-to-Animal Transfer Factors		
Version:	Version 4		
Symbol:	F_{ing}		
Units:	Bq kg^{-1} fw animal product per Bq d^{-1} intake		
Description:	Equilibrium feed-to-animal transfer factors.		
Value(s):	See Table E-44		
Justification:	Reference values are adopted from the CSA (2022).		
Uncertainty:	The biosphere modelling is based on the deterministic biosphere models recommended in CSA (2022).		
Source of uncertainty:	There is significant natural uncertainty in the feed-to-animal transfer factors. However, a deterministic 'reference' approach is adopted to the biosphere modelling, consistent with CSA (2022).		
References:	Canadian Standards Association (CSA). (2022). Guidelines for modelling radionuclide environmental transport, fate, and exposure associated with normal operation of nuclear facilities, N288.1:20, 2022 Errata, June. Gobien M, Garisto F and Kremer E (2013). Fifth Case Study: Reference Data and Codes. NWMO report TR-2013-05, Revision 000. IAEA (2010). Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Terrestrial and Freshwater Environments, Technical Reports Series No 472, January 2010.		
Author:	Russell Walke, James Penfold	**Date:**	8 July 2019
Checker (basis):	Louise Bruffell	**Date:**	27 October 2022
Checker (implementation):	Renato Zagorscak	**Date:**	26 January 2023

Table E-44 Feed-to-Animal Transfer Factors (Bq kg^{-1} fw animal product per Bq d^{-1} intake)

Element	Cow milk	Goat milk	Beef meat	Beef liver	Pork	Lamb	Poultry*	Eggs	Deer	Moose^	Rabbit	Notes
H	-	-	-	-	-	-	-	-	-	-	-	1
C	-	-	-	-	-	-	-	-	-	-	-	1
Cl	1.84E-2	1.84E-2	1.7E-2	2.83E-2	6.51E-2	2.57E-1	1.75E+0	2.1E+0	1.37E-1	2.3E-02	1.96E+0	2
Ca	9.7E-3	7.1E-2	1.3E-2	1.3E-2	2.0E-3	2.0E-3	4.4E-2	4.4E-1	1.3E-2	1.8E-02	2.0E-3	3
Fe	3.5E-5	5.2E-2	1.4E-2	4	3E-3	2.7E-2	1.4	1.8	0.027	0.019	0.39	2
Co	1.1E-4	5.0E-3	4.3E-4	1.0E-1	4.1E-2	1.2E-2	9.7E-1	3.3E-2	1.2E-2	5.8E-04	1.8E-1	2
Ni	9.5E-4	8.3E-2	5.0E-3	5.0E-3	1.15E-2	4.55E-2	3.1E-1	3.72E-1	2.43E-2	6.8E-03	3.46E-1	2
Se	4.0E-3	6.9E-2	1.0E-1	1.0E-1	3.2E-1	9.1E-1	9.7E+0	1.6E+1	4.86E-1	1.4E-01	6.92E+0	2
Sr	1.3E-3	3.0E-2	1.3E-3	3.0E-4	2.5E-3	1.5E-3	2.0E-2	3.5E-1	4.0E-2	1.8E-03	1.9E-1	2
Zr	3.6E-6	5.5E-6	1.2E-6	1.0E-5	3.5E-3	4.5E-5	6.0E-5	2.0E-4	5.0E-5	1.6E-06	7.1E-4	2
Nb	4.1E-7	6.4E-6	2.6E-7	1.0E-5	2.0E-4	1.7E-4	3.0E-4	1.0E-3	3.0E-4	3.5E-07	4.2E-3	2
Tc	6.9E-4	1.1E-3	9.6E-4	4.0E-2	2.1E-3	4.7E-3	4.1E-1	1.9E+0	3.4E-3	1.3E-03	4.9E-2	2
Ag	3.3E-3	6.0E-2	2.1E-3	4.0E-1	2.7E-2	4.8E-4	4.0E-1	7.9E-2	3.0E-3	2.8E-03	4.2E-2	2
Cd	1.90E-04	1.60E-02	5.80E-03	5.80E-03	1.20E-03	1.20E-03	1.70E+00	1.70E+00	5.80E-03	7.9E-03	1.20E-03	3
Sn	1.1E-3	3.5E-3	1.1E-2	2.2E-2	4.4E-3	1.3E-2	1.2E+0	1.2E+0	2.0E-2	1.5E-02	2.8E-1	2
Sb	3.8E-5	2.4E-4	1.2E-3	1.0E-1	1.0E-3	1.0E-2	1.0E-1	1.0E-1	3.4E-3	1.6E-03	4.8E-2	2
Cs	4.6E-3	1.1E-1	2.2E-2	3.0E-2	2.0E-1	1.9E-1	2.7E+0	4.0E-1	1.5E-1	3.0E-02	1.1E+2	2
Sm	2.9E-5	9.5E-5	2.2E-3	4.0E-2	9.8E-5	5.0E-2	3.8E-3	3.8E-3	1.7E-2	3.0E-03	2.4E-1	4
Eu	2.9E-5	9.5E-5	2.2E-3	4.0E-2	9.8E-5	5.0E-2	3.8E-3	3.8E-3	1.7E-2	3.0E-03	2.4E-1	2
Ho	2.9E-5	9.5E-5	2.2E-3	4.0E-2	9.8E-5	5.0E-2	3.8E-3	3.8E-3	1.7E-2	3.0E-03	2.4E-1	8
Hf	1.00E-05	3.30E-05	6.30E-04	5.20E-03	1.50E-03	5.80E-03	1.00E-01	1.00E-01	2.30E-03	8.5E-04	3.20E-02	2
Ta	4.1E-7	6.4E-6	2.6E-7	1.0E-5	2.0E-4	1.7E-4	3.0E-4	1.0E-3	3.0E-4	3.5E-07	4.2E-3	9
Pb	2.5E-4	5.8E-3	4.0E-4	4.0E-4	7.1E-3	7.1E-3	4.0E-2	3.1E+0	4.0E-4	5.4E-04	7.1E-3	5
Po	3.3E-4	2.2E-3	4.5E-3	4.5E-3	4.5E-3	4.5E-3	4.5E-1	3.1E+0	4.5E-3	6.1E-03	4.5E-3	6
Ra	3.8E-4	1.1E-3	1.7E-3	9.5E-4	2.2E-3	8.6E-3	3.0E-2	3.1E-1	4.6E-3	2.3E-03	6.6E-2	2

Element	Cow milk	Goat milk	Beef meat	Beef liver	Pork	Lamb	Poultry*	Eggs	Deer	Moose^	Rabbit	Notes
Ac	2.0E-5	1.9E-5	2.5E-5	2.5E-5	2.5E-5	2.5E-5	2.5E-3	1.0E-2	2.5E-5	3.4E-05	2.5E-5	7
Th	2.3E-5	7.7E-5	2.3E-4	6.3E-2	4.6E-3	1.3E-2	1.0E-2	1.0E-2	2.0E-3	3.1E-04	2.8E-2	2
Pa	5.0E-6	1.7E-5	1.1E-5	1.1E-3	1.1E-4	3.4E-4	2.0E-3	2.0E-3	9.8E-5	1.5E-05	1.4E-3	2
U	1.8E-3	1.4E-3	3.9E-4	6.9E-4	4.4E-2	7.4E-3	7.5E-1	1.1E+0	7.3E-1	5.3E-04	4.1E-2	2
Np	4.0E-6	5.3E-5	3.8E-4	2.0E-2	4.5E-5	4.0E-4	3.1E-3	9.7E-3	6.2E-4	5.2E-04	8.9E-3	2
Pu	1.0E-5	9.4E-6	1.1E-6	2.0E-2	2.8E-5	5.3E-5	9.2E-4	1.2E-3	2.5E-4	1.5E-06	3.5E-3	2
Am	4.2E-7	6.9E-6	5.0E-4	2.0E-2	7.4E-5	1.1E-4	1.2E-3	3.0E-3	2.3E-4	6.8E-04	3.3E-3	2
Cm	9.4E-7	3.1E-6	1.9E-5	2.0E-2	3.4E-5	4.0E-4	8.5E-4	1.8E-2	1.4E-4	2.6E-05	2.0E-3	2

Notes: Values not needed for non-radiological contaminants. *Also used for geese, duck and grouse. ^ Moose transfer factors allometrically scaled from beef transfer factors using body weight of cows as 600 kg (CSA, 2022), and the body weight of moose as 400 kg (SENES, 2014), and using the following equation: $TF_m = TF_{fb} \times \left(\frac{BW_m}{BW_{cow}}\right)^{-0.75}$

1 Not required for modelling H-3 and C-14.

2 Table G.3 of CSA (2022).

3 Values for cows' milk, goat's milk, beef, pork, poultry meat and eggs from Tables 26, 27, 30, 33, 34 and 35 of IAEA (2010), respectively. The milk values are converted from d L^{-1} to d kg^{-1} using a milk density of 1.03 kg L^{-1}, consistent with footnote h to Table G.9a of CSA (2022). Values for beef liver and deer are taken to be the same as for beef meat; values for lamb and rabbit are taken to be the same as for pork.

4 Eu values adopted by chemical analogy.

5 Values for cows' milk, beef meat and poultry meat from Gobien *et al*. (2013). Milk values from Table 27 of IAEA (2010) and converted from d L^{-1} to d kg^{-1} using a milk density of 1.03 kg L^{-1}, consistent with footnote h to Table G.9a of CSA (2022). Pb value for lamb from Table 31 of IAEA (2010). Values for beef liver and deer are taken to be the same as for beef meat; values for pork and rabbit are taken to be the same as for lamb. Value for eggs is for Po from Table 35 of IAEA (2010).

6 Values for cows' milk, beef meat and poultry meat from Table 9-10 Gobien *et al.* (2013). Goat's milk values from Table 27 of IAEA (2010) and converted from d L^{-1} to d kg^{-1} using a milk density of 1.03 kg L^{-1}, consistent with footnote h to Table G.9a of CSA (2022). Po value for eggs from Table 35 of IAEA (2010).

7 Values for cows' milk, beef meat and poultry meat from Gobien *et al*. (2013). Transfer factor for goat milk is taken to be the same as for cows' milk. Values for beef liver, pork, lamb, deer and rabbit are taken to be the same as for beef meat. Value for eggs is for Th.

8 Ho is a REE with similarities to Eu. Neither Ho nor Eu have a biological role, so it seems reasonable to treat Ho similarly to Eu.

9 Ta is chemically similar to Nb. Neither Ta nor Nb have a biological role, so it seems reasonable to treat Ta similarly to Nb.

E 3.6.12 Plant-to-Honey Concentration Factors

Name:	Plant-to-Honey Concentration Ratios			
Version:	Version 1			
Symbol:	CR_h			
Units:	Bq kg^{-1} fw honey per Bq kg^{-1} dw plant			
Description:	Equilibrium plant-to-honey concentration ratios.			
Value(s)	H, C	1		
	Cs	0.057		
	U	0.41		
	Other elements	0.1 (see Clause 6.10.5.2 in CSA (2022))		
Justification:	Reference values are adopted from Table G.4 of CSA (2022).			
Uncertainty:	The biosphere modelling is based on the deterministic biosphere models recommended in CSA (2022).			
Source of uncertainty:	There is natural uncertainty in the plant-to-honey concentration ratios. However, a deterministic 'reference' approach is adopted to the biosphere modelling, consistent with CSA (2022).			
References:	Canadian Standards Association (CSA). (2022). Guidelines for modelling radionuclide environmental transport, fate, and exposure associated with normal operation of nuclear facilities, N288.1:20, 2022 Errata, June.			
Author:	Russell Walke		**Date:**	23 August 2016
Checker (basis):	Louise Bruffell		**Date:**	27 October 2022
Checker (implementation):	Renato Zagorscak		**Date:**	26 January 2023

E 3.6.13 Bioaccumulation in Freshwater Biota

Name:	Bioaccumulation in Freshwater Fish and Shellfish		
Version:	Version 4		
Symbol:	BAF, DW_{ap}, M_{aa}, M_w, DW_{aa}, ID_{aa}, WE_{aa}		
Units:	See Table E-45, Table E-46 and Table E-47.		
Description:	Equilibrium bioaccumulation factor (concentration ratio) for freshwater organisms.		
Value(s):	See Table E-45, Table E-46 and Table E-47 Also, the dry/fresh weight ratio for aquatic plants (DW_{ap}) is taken as 0.1 (7.7.4.2 of CSA (2022)).		
Justification:	Reference values are adopted from the CSA (2022). A specific activity model is used for carbon (see Table E-45).		
Uncertainty:	The biosphere modelling is based on the deterministic biosphere models recommended in CSA (2022).		
Source of uncertainty:	There is significant uncertainty in the bioaccumulation factor for freshwater fish. However, a deterministic 'reference' approach is adopted to the biosphere modelling, consistent with CSA (2022).		
References:	Canadian Standards Association (CSA). (2022). Guidelines for modelling radionuclide environmental transport, fate, and exposure associated with normal operation of nuclear facilities, N288.1:20, 2022 Errata, June. Gobien M, Garisto F and Kremer E (2013). Fifth Case Study: Reference Data and Codes. NWMO report TR-2013-05, Revision 000. IAEA (2010). Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Terrestrial and Freshwater Environments, Technical Reports Series No 472, January 2010.		
Author:	Russell Walke, James Penfold	**Date:**	8 July 2019
Checker (basis):	Louise Bruffell	**Date:**	27 October 2022
Checker (implementation):	Kate Thatcher	**Date:**	30 November 2022

Table E-45 Carbon Masses for C-14 Uptake Model to Aquatic Organisms

Parameter	Symbol	Fish	Shellfish	Plants	Notes
The mass of stable carbon in aquatic organisms (gC/kg fresh weight)	M_{aa}	121.75	120	125	1
The mass of stable carbon in the dissolved inorganic phase in water (gC/L)	M_w	0.0213			2

Notes:

1 Table 23 and Clause 7.7.5.4 and for fish and shellfish (invertebrates). For aquatic plants, the value of 500 gC/kg *dry* weight is converted to 125 gC/kg *fresh* weight using a dry:fresh weight ratio of 0.25, which is appropriate for aquatic plants in waterfowl diets, as discussed in Clause 7.7.5.6 of CSA (2022).

2 Representative value adopted from Clause 7.7.5.3 of CSA (2022).

Table E-46 Bioaccumulation Factor for Freshwater Fish and Plants

Element	Fish (L kg^{-1} fw)	Shellfish (L kg^{-1} fw)	Plants (L kg^{-1} fw)	Notes
H	-	-	-	-
C	-	-	-	-
Cl	47	140	50	1
Ca	12	34	370	2
Fe	240	2800	3100	1
Co	54	110	790	1
Ni	21	100	52	1
Se	6000	240	110	1
Sr	2	240	370	1
Zr	7	3000	3200	1
Nb	300	100	1200	1
Tc	20	9.5	7.6	1
Ag	110	800	34	1
Cd	21	100	52	7
Sn	3000	590	100	1
Sb	37	81	32	1
Cs	3500	99	220	1
Sm	130	600	5000	3
Eu	130	600	5000	1
Ho	130	600	5000	5
Hf	1100	97	1000	1
Ta	300	100	1200	6
Pb	300	22	1900	4
Po	500	22	1900	4
Ra	4	110	2200	1
Ac	25	110	2200	4
Th	6	900	1200	1
Pa	10	110	1100	1
U	0.96	99	300	1
Np	30	820	1900	1
Pu	78	720	4000	1
Am	240	1200	3100	1
Cm	30	2100	6700	1

Notes: Values not needed for non-radiological contaminants. C-14 and H-3 use a specific activity model.

1 Tables A.25a (freshwater fish muscle), A.25e (freshwater invertebrates, used for freshwater shellfish) and A25f (freshwater plants) of CSA (2022).

2 Tables 56 (freshwater invertebrates, used for freshwater shellfish) and 57 (freshwater fish tissues) of IAEA (2010). For freshwater plants, Sr used by chemical analogy.

3 Eu value used by chemical analogy.

4 Table 9-10 of Gobien *et al.* (2013) used for fish. For shellfish, Pb value for invertebrates from Table 56 of IAEA (2010), also adopted for Po. Value for Th used for Ac, by chemical analogy. For plants, values for Pb from IAEA (2010) are used for Pb and Po. The value for Ac is based on Th.

5 Ho is a REE with similarities to Eu. Neither Ho nor Eu have a biological role, so it seems reasonable to treat Ho similarly to Eu.

6 Ta is chemically similar to Nb. Neither Ta nor Nb have a biological role, so it seems reasonable to treat Ta similarly to Nb.

7 Ni used as an analogue for Cd on the basis of chemical analogy.

Table E-47 Parameters for H-3 Uptake Model to Aquatic Organisms

Parameter	Symbol	Fish	Shellfish	Plants	Notes
Dry weight of aquatic animal produce or plants per total fresh weight (kg dry weight per kg fresh weight)	DW_{aa}	0.25	0.2	0.25	1
The isotopic discrimination factor for aquatic animal metabolism (-)	ID_{aa}	0.8			2
The water equivalent of the aquatic animal dry matter (l kg^{-1} dry weight)	WE_{aa}	0.7	0.6	0.56	3

Notes:

1 Clause 7.7.4.2 of CSA (2022)

2 Clause 7.7.4.4 of CSA (2022).

3 Clause 7.7.4.5 of CSA (2022).

E 3.7 Potential Exposure Groups and Human Exposure

E 3.7.1 Farmed Area

Name:	Farmed Area			
Version:	Version 4			
Symbol:	A_{Crop}			
Units:	m^2			
Description:	The area of land required for the site resident to be self-sufficient in foods.			
Value(s):	Fruit and veg.	235		
	Potatoes	22		
	Forage	$2.08x10^5$		
	Feed	6720		
	Berries	10		
	Mushrooms	10		
Justification:	The land requirements values have been calculated based on a family farming. Intake rates, plant yields and other factors are taken from CSA (2022) and used to determine the area requirements. The area required for berries and mushrooms is assigned a nominal value of 10 m^2 as these are assumed to be interspersed with other land uses.			
Uncertainty:	The biosphere modelling is based on the deterministic biosphere models recommended in CSA (2022).			
Source of uncertainty:	There is variability in intake rates, however, a deterministic 'reference' approach is adopted to the biosphere modelling, consistent with CSA (2022).			
References:	Canadian Standards Association (CSA). (2022). Guidelines for modelling radionuclide environmental transport, fate, and exposure associated with normal operation of nuclear facilities, N288.1:20, 2022 Errata, June.			
Author:	Russell Walke		**Date:**	25 August 2016
Checker (basis):	Louise Bruffell		**Date:**	27 October 2022
Checker (implementation):	Renato Zagorscak		**Date:**	26 January 2023

E 3.7.2 Number of Farm Animals

Name:	Number of farm animals			
Version:	Version 4			
Symbol:	N_{Anm}			
Units:	unitless			
Description:	The number of farm animals assumed to be kept by the site resident. Used to calculate the water use.			
Value(s):	Dairy Cow	1		
	Dairy Goat	2		
	Beef Cow	2		
	Pig	2		
	Sheep	2		
	Poultry	30		
Justification:	The animal requirements have been calculated based on the human intake rates taken from CSA (2022).			
Uncertainty:	The biosphere modelling is based on the deterministic biosphere models recommended in CSA (2022).			
Source of uncertainty:	There is variability in intake rates, however, a deterministic 'reference' approach is adopted to the biosphere modelling, consistent with CSA (2022).			
References:	Canadian Standards Association (CSA). (2022). Guidelines for modelling radionuclide environmental transport, fate, and exposure associated with normal operation of nuclear facilities, N288.1:20, 2022 Errata, June.			
Author:	Russell Walke		**Date:**	25 August 2016
Checker (basis):	Louise Bruffell		**Date:**	27 October 2022
Checker (implementation):	Renato Zagorscak		**Date:**	26 January 2023

E 3.7.3 Intakes for the Site Resident Group

Name:	Dietary Intakes for the Site Resident Group		
Version:	Version 4		
Symbol:	I_f (intake rate) and gf (local fraction)		
Units:	See Table E-48		
Description:	Dietary intakes for the site resident group		
Value(s):	See Table E-48		
Justification:	Default values are adopted from the CSA (2022). Values from present-day site-specific surveys are less relevant to very long-term assessments, so the default values from CSA (2022) are adopted, which are conservatively based on 95th percentile energy intakes. Conservatively it is assumed that all foods except grain are obtained entirely locally by the site resident.		
Uncertainty:	The biosphere modelling is based on the deterministic biosphere models recommended in CSA (2022).		
Source of uncertainty:	There is variability in intake rates, however, a deterministic 'reference' approach is adopted to the biosphere modelling, consistent with CSA (2022).		
References:	Canadian Standards Association (CSA). (2022). Guidelines for modelling radionuclide environmental transport, fate, and exposure associated with normal operation of nuclear facilities, N288.1:20, 2022 Errata, June.		
Author:	Russell Walke	**Date:**	25 August 2016
Checker (basis):	Louise Bruffell	**Date:**	27 October 2022
Checker (implementation):	Kate Thatcher	**Date:**	1 December 2022

Table E-48 Dietary Intakes for the Site Resident Group

Category	Local Fraction	Infant	Child	Adult	Notes
Fish (g/d)	1	6.4	18.5	28.1	1
Shellfish (g/d)	1	0.6	2.1	5.7	1
Cows' milk (g/d)	1	837.5	787.6	464.5	2
Goat's milk (g/d)	1	93.1	87.5	51.6	2
Beef (g/d)	1	18	53.2	194.9	3
Beef liver (g/d)	1	1.9	5.5	8.5	1
Pork (g/d)	1	13.4	40.1	81.4	1
Lamb (g/d)	1	0.1	3.9	2.4	1
Poultry (g/d)	1	31.6	83.8	159.8	1
Eggs (g/d)	1	8.2	30.9	79	1
Grain (g/d)	0	211.7	539.7	671.8	4
Fruit & vegetables (g/d)	1	308.5	607.9	935	5
Potatoes (g/d)	1	33.1	118.4	196.7	1
Honey (g/d)	1	1.8	5.2	6.7	1

Notes:

1 Table G.9c of CSA (2022).

2 Total milk from Table G.9c of CSA (2022) split assuming that 90% comes from cows' milk and the remaining 10% comes from goat's milk.

3 Combines beef and veal from Table G.9c of CSA (2022).

4 The climate and small self-sufficient lifestyle are not amenable to providing grain.

5 Combines fruit and berries plus vegetables Table G.9c of CSA (2022).

E 3.7.4 Intakes for the Recreational/Hunter Group

Name:	Dietary Intakes for the Recreational/Hunter Group		
Version:	Version 4		
Symbol:	I_f (intake rate) and gf (local fraction)		
Units:	See Table E-49		
Description:	Dietary intakes for the recreational/hunter group		
Value(s):	See Table E-49		
Justification:	Values are based on default values from CSA (2022). Values from present-day site-specific surveys are less relevant to very long-term assessments, so values from CSA (2022) are used as a basis for deriving numbers for a group with recreational/hunting habits. The recreational/hunter group gets most of their meat from conventional sources. They are assumed to visit the contaminated NPDDF site sporadically, and so the fraction of their intake of hunted meat that may be contaminated is taken to be 10%.		
Uncertainty:	The biosphere modelling is based on the deterministic biosphere models recommended in CSA (2022).		
Source of uncertainty:	There is variability in intake rates, however, a deterministic 'reference' approach is adopted to the biosphere modelling, consistent with CSA (2022).		
References:	Canadian Standards Association (CSA). (2022). Guidelines for modelling radionuclide environmental transport, fate, and exposure associated with normal operation of nuclear facilities, N288.1:20, 2022 Errata, June.		
Author:	Russell Walke	**Date:**	25 August 2016
Checker (basis):	Louise Bruffell	**Date:**	14 November 2022
Checker (implementation):	Kate Thatcher	**Date:**	1 December 2022

Table E-49 Dietary Intakes for the Recreational/Hunter Group

Category	Local Fraction [1]	Infant	Child	Adult	Notes
Fish (g/d)	0.1	6.4	18.5	28.1	2
Shellfish (g/d)	0.1	0.6	2.1	5.7	2
Deer (g/d)	0.1	0.09	0.3	1.14	3
Rabbit (g/d)	0.1	0.24	0.75	2.82	3
Goose (g/d)	0.1	15.8	41.9	79.9	4
Duck (g/d)	0.1	15.8	41.9	79.9	4

Notes:

1 The recreational/hunter group is taken to spend 10% of their recreational/hunting time in the potentially contaminated area.

2 Based on the default dietary intakes in Table G.9c of CSA (2022).

3 High intake rates of deer and rabbit are assumed. These are taken to be three times the default dietary intakes in Table G.9c of CSA (2022).

4 The default poultry intake in Table G.9c of CSA (2022) is taken to be equally distributed between goose and duck meat.

E 3.7.5 Intakes for the Indigenous (AOPFN) Receptor Group

Name:	Dietary Intakes for the Indigenous Receptor Group		
Version:	Version 4		
Symbol:	I_f (intake rate) and gf (local fraction)		
Units:	See Table E-50		
Description:	Dietary intakes for the Indigenous receptor group		
Value(s):	See Table E-50		
Justification:	The intake rates selected represent a lifestyle in which Algonquin foods are the principal component of the receptor's diet. It is acknowledged that the Algonquin diet today also includes products purchased in shops, and it is assumed that any purchased groceries are not produced on the land surrounding the NPDDF. The diet considered here consists of the wild foods that form the Algonquin diet. The dietary survey carried out by AOPFN (Fediuk *et al*., 2021) lists four potential intake levels. Level 1 represents an AOPFN member eating Algonquin food at both the average days per year and the average serving size (166 grams). Level 4 data have been used, which represents an AOPFN member eating extremely large portions (227 grams – 454 grams) frequently. In the model, the total daily intake is 649.2 grams/day every day of the year. Data for children have not been reported in Fediuk *et al*. (2021) so are not considered here. The same intake rates as the Site Resident are used for inhalation and water (see sections E 3.7.7 and E 3.7.8). Inadvertent soil ingestion rates are given in section E 3.7.9.		
Uncertainty:	The biosphere modelling is based on the deterministic biosphere models recommended in CSA (2022).		
Source of uncertainty:	There is variability in intake rates, however, a deterministic 'reference' approach is adopted to the biosphere modelling, consistent with CSA (2022).		
References:	Fediuk, K., Gibson, G., and Firelight Research Inc. (2021). Diet and Harvest Study. Confidential Report Specific to Canadian Nuclear Laboratories Nuclear Power Demonstration Decommissioning Project. Submitted to the Algonquins of Pikwakanagan First Nation. August. Canadian Standards Association (CSA). (2022). Guidelines for modelling radionuclide environmental transport, fate, and exposure associated with normal operation of nuclear facilities, N288.1:20, 2022 Errata, June.		
Author:	Louise Bruffell	**Date:**	15 September 2021
Checker (basis):	Renato Zagorscak	**Date:**	23 September 2021
Checker (implementation):	Renato Zagorscak	**Date:**	23 September 2021

Table E-50 Dietary Intakes for the Indigenous (AOPFN) Receptor Group

Category		Local Fraction	Ingestion Rate		
			Adult	Unit	Notes/ref
Food					
	Fish	1 [1]	181.6	g d^{-1}	Fediuk *et al.*, 2021
	Moose	1 [1]	115.7	g d^{-1}	Fediuk *et al.*, 2021
	Deer	1[1]	72.2[3]	g d^{-1}	Fediuk *et al.*, 2021
	Rabbit	1 [1]	8.7[4]	g d^{-1}	Fediuk *et al.*, 2021
	Grouse	1 [1]	27.4[5]	g d^{-1}	Fediuk *et al.*, 2021
	Duck	1 [1]	12.4	g d^{-1}	Fediuk *et al.*, 2021
	Goose	1 [1]	12.4	g d^{-1}	Fediuk *et al.*, 2021
	Berries	1	67.8	g d^{-1}	Fediuk *et al.*, 2021
	Plants	1[2]	125.6	g d^{-1}	Fediuk *et al.*, 2021
	Mushrooms	1	18.7	g d^{-1}	Fediuk *et al.*, 2021
	Honey	1	6.7	g d^{-1}	CSA, 2022

Notes:

1 Assume that all these animals spend at least part of their time on the contaminated area.

2 Plants are assumed to be wild plants and therefore not cultivated or watered. They are more similar to the plants that animals would eat than to crops grown in a garden. Therefore the plants are modelled in the same way as forage for animals, rather than the cultivated plants in a garden.

3 Taken as the sum of Deer and Elk consumption.

4 Taken as the sum of rabbit and beaver consumption.

5 Taken as the sum of grouse and turkey consumption.

E 3.7.6 Parameters for Indigenous Receptor Group Medicinal Use

Name:	Parameters for Indigenous Receptor Group Medicinal Use		
Version:	Version 4		
Symbol:	$AOPFN_{ExpSmoke}$, C_{Smoke}, rho_{skin}, T_{skin}, w_t, F_{uv}		
Units:	See Table E-51		
Description:	See Table E-51		
Value(s):	See Table E-51		
Justification:	The room used for smoking medicinal plants and herbs is assumed to represent a small room in e.g. a house, rather than a large communal room. This will give higher concentrations of smoke and therefore be conservative. The resulting concentration of smoke in the room is calculated in AMBER. The same intake rates as the Site Resident are used for inhalation (see section E 3.7.7). For exposure of skin to medicines, a conservative approach is used, assuming that all UV exposed skin is contaminated by the medicine and that the medicine is on the skin all of the time.		
Uncertainty:	The biosphere modelling is based on the deterministic biosphere models recommended in CSA (2022).		
Source of uncertainty:	There is variability in intake rates, however, a deterministic 'reference' approach is adopted to the biosphere modelling, consistent with CSA (2022).		
References:	Fediuk, K., Gibson, G., and Firelight Research Inc. (2021). Diet and Harvest Study. Confidential Report Specific to Canadian Nuclear Laboratories Nuclear Power Demonstration Decommissioning Project. Submitted to the Algonquins of Pikwakanagan First Nation. August. Oatway and Mobbs, (2003). Methodology for estimating the doses to members of the public from the future use of land previously contaminated with radioactivity. National Radiation Protection Board report NRPB-W36. ISBN 0 85951 508 7 Canadian Standards Association (CSA). (2022). Guidelines for modelling radionuclide environmental transport, fate, and exposure associated with normal operation of nuclear facilities, N288.1:20, 2022 Errata, June.		
Author:	Louise Bruffell	**Date:**	15 September 2021
Checker (basis):	Renato Zagorscak	**Date:**	21 September 2021
Checker (implementation):	Renato Zagorscak	**Date:**	21 September 2021

Table E-51 Medicinal Intakes for the Indigenous Receptor Group

Category		Value	Unit	Notes/ref
Smoking				
$AOPFN_{ExpSmoke}$	Exposure to smoke	2.8[1]	Min day^{-1}	Assumed
C_{smoke}	Concentration in room	4.8E-4[2]	Kg m^{-3}	Calculated in AMBER
Rubbing				
ρ_{skin}	Density of medicine application	0.01[3]	g cm^{-2}	Assumed
T_{skin}	Fractional exposure time	1[4]	-	Assumed
w_t	Tissue weighting factor	0.01	-	Oatway & Mobbs, 2013
F_{UV}	Fraction of UV exposed skin contaminated by medicine	1[5]	-	Assumed

Notes:

1 Have assumed someone smokes the equivalent of 1 cigar worth of herbs, which takes 10 minutes, on 102 days per year. Fediuk *et al*. (2021) states that the 95th percentile usage of medicines for inhalation is 102 days per year.

2 A calculation is performed in a separate AMBER model to calculate the balance between burning of the herbs and the ventilation of the room. This is done in a separate model because the timescale to reach a steady concentration is a few hours, so is much shorter than the timescale of calculations in the PostSA model.

3 Assume 0.1 g of medicine is applied to each 10 cm^2 of skin.

4 Fediuk *et al.* (2021) states that the 95th percentile usage on medicines on the skin is almost daily. So assume that the skin is constantly exposed.

5 Assume that all UV exposed skin is contaminated with medicine.

E 3.7.7 Inhalation Rates

Name:	Inhalation Rates			
Version:	Version 4			
Symbol:	I_h			
Units:	$m^3\ y^{-1}$			
Description:	Inhalation rates			
Value(s):	**Age group**	**Average Rate**	**High Rate**	
	Infant	1830	2740	
	Child	5660	7850	
	Adult	5950	8400	
Justification:	Based on Clause 6.13.3 of CSA (2022). Note that CSA (2022) recommends that the high rate is conservatively used for all exposure groups.			
Uncertainty:	The biosphere modelling is based on the deterministic biosphere models recommended in CSA (2022).			
Source of uncertainty:	There is variability in inhalation rates, however, a deterministic 'reference' approach is adopted to the biosphere modelling, consistent with CSA (2022).			
References:	Canadian Standards Association (CSA). (2022). Guidelines for modelling radionuclide environmental transport, fate, and exposure associated with normal operation of nuclear facilities, N288.1:20, 2022 Errata, June.			
Author:	Russell Walke		**Date:**	25 August 2016
Checker (basis):	Louise Bruffell		**Date:**	27 October 2022
Checker (implementation):	Renato Zagorscak		**Date:**	26 January 2023

E 3.7.8 Water Intake Rates

Name:	Drinking Water Intake Rates			
Version:	Version 4			
Symbol:	I_w, rf_w			
Units:	L d^{-1}			
Description:	Drinking water intake rates.			
Value(s):	Age group	Average Rate	High Rate	
	Infant (I_w, L d^{-1})	0.271	0.837	
	Child (I_w, L d^{-1})	0.414	1.32	
	Adult (I_w, L d^{-1})	1.04	2.96	
	Removal factor (rf_w)	1	1	
Justification:	Based on Clause 6.15.3.2 of CSA (2022). The PostSA study cautiously uses the high rate for all ages. Hunters are assumed to get 10% of their water needs from the river (gf_w). The same values are used for site residents, hunters and self-sufficient Indigenous receptors. With the exception of hunters, all receptors are assumed to obtain 100% of their water from the Ottawa River except the Site Resident for the "Well" Disruptive Event scenarios, in which the water is assumed to be extracted either from an overburden or bedrock well downstream of the NPDDF.			
Uncertainty:	The biosphere modelling is based on the deterministic biosphere models recommended in CSA (2022).			
Source of uncertainty:	There is variability in inhalation rates, however, a deterministic 'reference' approach is adopted to the biosphere modelling, consistent with CSA (2022).			
References:	Canadian Standards Association (CSA). (2022). Guidelines for modelling radionuclide environmental transport, fate, and exposure associated with normal operation of nuclear facilities, N288.1:20, 2022 Errata, June.			
Author:	Russell Walke		**Date:**	25 August 2016
Checker (basis):	Louise Bruffell		**Date:**	27 October 2022
Checker (implementation):	Renato Zagorscak		**Date:**	26 January 2023

E 3.7.9 Inadvertent Soil Ingestion Rates

Name:	**Incidental Soil Ingestion Rates**			
Version:	Version 4			
Symbol:	I_s			
Units:	g dw d^{-1}			
Description:	Incidental soil ingestion rates			
Value(s):	**Age group**	**Site Residents and Hunters**		**Self Sufficient and AOPFN Indigenous**
		Average Rate	**High Rate**	
	Infant	0.061	0.204	0.2
	Child	0.055	0.185	0.2
	Adult	0.004	0.02	0.2
Justification:	Based on Clause 6.15.2 of CSA (2022). Note that CSA (2022) recommends that the high rate is conservatively used, and this is the case in the PostSA study. The same values are used for site residents and hunters. The value used for the self-sufficient (all age groups) and AOPFN Indigenous receptors is taken from US EPA (2014), as requested following Indigenous feedback.			
Uncertainty:	The biosphere modelling is based on the deterministic biosphere models recommended in CSA (2022).			
Source of uncertainty:	There is variability in inhalation rates, however, a deterministic 'reference' approach is adopted to the biosphere modelling, consistent with CSA (2022).			
References:	Canadian Standards Association (CSA). (2022). Guidelines for modelling radionuclide environmental transport, fate, and exposure associated with normal operation of nuclear facilities, N288.1:20, 2022 Errata, June. United States Environmental Protection Agency (US EPA). 2014. Region 4 Human Health Risk Assessment Supplemental Guidance. Technical Services Section, Superfund Division.			
Author:	Russell Walke		**Date:**	25 August 2016
Checker (basis):	Louise Bruffell		**Date:**	27 October 2022
Checker (implementation):	Kate Thatcher		**Date:**	1 December 2022

E 3.7.10 Site Resident Occupancy Rates

Name:	Occupancy Factors for the Site Resident Group			
Version:	Version 4			
Symbol:	OF, c_{res}			
Units:	Hours per day			
Description:	Occupancy factors for the site resident group. The parameter c_{res} is also used in relation to inhalation exposures, but has conservatively been set to unity.			
Value(s): Spring, Summer, Autumn		**Infant**	**Child**	**Adult**
	House*	21.15	20.4	17.9
	Bathing	0.25	0.25	0.25
	Garden	2	2	3
	Grazing area	0.25	0.5	1
	Springs	0.25	0.5	1
	Shore	0.25	0.5	1
	Swimming	0.1	0.1	0.1
Winter	House*	23.9	23.5	21.5
	Bathing	0.25	0.25	0.25
	Garden	0.1	0.2	1
	Grazing area	0	0.1	0.5
	Springs	0	0.1	0.5
	Shore	0	0.1	0.5
	Swimming	0	0	0
Justification:	Considered to be reasonable assumptions as a basis for the assessment. The site resident group is conservatively taken to spend 100% of its time within the modelled region. Outdoor occupancies are assumed and the indoor occupancy is calculated as the remaining time. The indoor (house) occupancy (*) includes the time spent bathing. The house is assumed to be located on the NPD cap.			
Uncertainty:	The values may be uncertain by a factor of two or three, although they are constrained by a 24-hour day. The primary interest is to ensure that a wide range of potential exposure pathways is covered.			
Source of uncertainty:	Inherent uncertainty about future behaviour. Conservative assumptions are adopted with regards to habits to help ensure that potential exposures are not underestimated.			
References:	None			
Author:	Russell Walke, James Penfold	**Date:**	3 September 2019	
Checker (basis):	Emma Cairns	**Date:**	14 October 2019	
Checker (implementation):	Renato Zagorscak	**Date:**	26 January 2023	

E 3.7.11 Recreational/Hunter Occupancy Rates

Name:	**Occupancy Factors for the Recreational/Hunter Group**			
Version:	Version 4			
Symbol:	OF			
Units:	Hours per week			
Description:	Occupancy factors for the site resident group			
Value(s):		**Infant**	**Child**	**Adult**
Spring, summer, fall	Shore	0	8	16
	Swimming	0	1	1
Winter	Shore	0	0	16
	Swimming	0	0	0
Justification:	This parameter reflects the occupancy of the shoreline down-stream of the NPDDF area. The adult recreational/hunter group is taken to spend two eight-hour days on the shoreline per week on average over the year. The child is taken to accompany them for one of those eight-hour days. It is assumed that hunting occurs throughout the year. Swimming is only taken to occur during spring, summer and autumn. Infants are not assumed to accompany the adults and children for hunting/recreation.			
Uncertainty:	The values may be uncertain by a factor of about two.			
Source of uncertainty:	Inherent uncertainty about future behaviour. Conservative assumptions are adopted with regards to habits to help ensure that potential exposures are not underestimated.			
References:	None			
Author:	Russell Walke		**Date:**	16 September 2016
Checker (basis):	James Penfold		**Date:**	25 October 2016
Checker (implementation):	Renato Zagorscak		**Date:**	26 January 2023

E 3.7.12 Self-Sufficient/Indigenous (AOPFN) Receptor Groups Occupancy Rates

Table E-52 Occupancies for the Self-Sufficient/Indigenous (AOPFN) Receptor Groups

Name	Occupancy Factors for the Self-Sufficient/Indigenous Receptor					
Version:	Version 4					
Symbol:	OF					
Units:	Hours per day					
Description:	Occupancy factors for the self-sufficient Indigenous receptor group					
Value(s):	**Location**	**Infant**	**Child**	**Adult**	**Reference**	
Spring, summer, fall	Dwelling (Off-site)	24	14.4	14.4	Based on an average of the lower bound of indoor occupancy for males and females from Table 2-5 of SENES (2014)	
	NPD Area (Hunting)	0	4.8*	4.8*	Assumed	
	Shore (Fishing)	0	4.8	4.8	Assumed	
Winter	Dwelling (Off-site)	24	16.8	16.8	Based on an average of the upper bound of indoor occupancy for males and females from Table 2-5 of SENES (2014)	
	NPD Area (Hunting)	0	3.6*	3.6*	Assumed	
	Shore (Fishing)	0	3.6	3.6	Assumed	
Justification:	It is assumed that time not spent indoors is evenly split between shore (fishing) and NPD area (hunting). *For the NPD area, in spring, summer and fall it is assumed that 2 h is spent on each of the larger areas (garden and grazing land) and 0.4 h in the smaller areas (the cap and springs area). In winter the equivalent times are assumed to be 1.5 h and 0.3 h. Children and adults are assumed to have the same occupancy, and it is assumed that infants do not go hunting or fishing.					
Uncertainty:	The values may be uncertain by less than a factor of about two.					
Source of uncertainty:	Inherent uncertainty about future behaviour. Conservative assumptions are adopted with regards to habits to help ensure that potential exposures are not underestimated.					
References:	None					
Author:	Louise Bruffell			**Date:**	14 November 2022	
Checker (basis):	Kate Thatcher			**Date:**	1 December 2022	
Checker (implementation):	Kate Thatcher			**Date:**	1 December 2022	

E 3.7.13 Offsite Resident Receptor Group Occupancy Rates

The offsite resident receptor groups are located in Deep River (approximately 13 km downstream from NPD) and Ottawa-Gatineau (approximately 170 km downstream from NPD).

Name:	**Occupancy Factors for the Offsite Resident Group**			
Version:	Version 4			
Symbol:	OF, c_{res}			
Units:	Hours per day			
Description:	Occupancy factors for the offsite resident groups at Deep River and Ottawa-Gatineau. The groups are only exposed by the use of river water for bathing and as drinking water, for which the occupancy values are the same as the Site Resident.			
Value(s):		**Infant**	**Child**	**Adult**
Spring, Summer, Autumn	Bathing	0.5	0.5	0.5
	Swimming	0.2	0.2	0.2
Winter	Bathing	0.5	0.5	0.5
	Swimming	0	0	0
Justification:	The occupancy values are based on those used for the Site Resident, with the exception that in this case the only exposure pathway is drinking and bathing in river water. As these are the only exposure pathways for this group the occupancy has been increased by a factor of two to reflect the variability in human habits and maximise exposures via these pathways.			
Uncertainty:	The values may be uncertain by a factor of two or three depending on an individual's habits.			
Source of uncertainty:	Inherent uncertainty about future behaviour. Reasonably conservative assumptions are adopted in relation to the bathing and water ingestion pathways.			
References:	None			
Author:	James Penfold		**Date:**	18 April 2019
Checker (basis):	Emma Cairns		**Date:**	14 October 2019
Checker (implementation):	Renato Zagorscak		**Date:**	26 January 2023

E 3.7.14 Shielding Factor (indoors)

Name:	Indoor Shielding Factor		
Version:	Version 4		
Symbol:	SF		
Units:	unitless		
Description:	Attenuation of external dose rates from contaminated soil whilst in a building		
Value(s):	0.2		
Justification:	A generic screening factor for buildings, described in HPA (2009).		
Uncertainty:	A factor of two.		
Source of uncertainty:	Building materials will vary in effectiveness, as well as the dependency on emissions energy. The factor will be dependent on energy but has been chosen to be a suitable value for more penetrating radiation, and cautious for lower energy emissions.		
References:	Smith JG and Simmonds JR (2009). The Methodology for Assessing the Radiological Consequences of Routine Release s of Radionuclides to the Environment used in PC-CREAM 08, Health Protection Agency HPR-RPD05, October 2009.		
Author:	James Penfold	**Date:**	3 September 2019
Checker (basis):	Emma Cairns	**Date:**	14 October 2019
Checker (implementation):	Renato Zagorscak	**Date:**	26 January 2023

E 3.7.15 Dilution Factor for River

Name:	Dilution Factor for River		
Version:	Version 4		
Symbol:	Dil_DeepRiver, Dil_Ottawa		
Units:	unitless		
Description:	Dilution factor for river water downstream of the NPDDF, at both Deep River and Ottawa		
Value(s):	Deep River: 0.000828 Ottawa: 0.658		
Justification:	Data based on flow rates reported at Ottawa River Regulation Planning Board, http://ottawariver.ca/river-levels-flows.php (retrieved 25 April 2019). The dilution factor applied at Deep River ($Dil_{DeepRiver}$) is taken from the ratio of the cross sectional area of the initial compartment into which discharge occurs (5 m x 1 m) and the Ottawa river (525 m x 11.5 m). The dilution factor for Ottawa is the ratio of the averaged reported flow rate at Des Joachims station (immediately upstream of NPDDF) and the reported flow rate measured at the Britannia hydrometric gauge just downstream of Gatineau. A nominal week in March 2019 was selected and the average ratio was used.		
Uncertainty:	Less than a factor of two. Considered in a sensitivity case where the dilution factor of 0.35 is applied for the Ottawa residents.		
Source of uncertainty:	The factor will vary with the total river flow rate and pattern of precipitation, but can be assumed to take a long term average value.		
References:	http://ottawariver.ca/river-levels-flows.php		
Author:	James Penfold	**Date:**	2 December 2022
Checker (basis):	Renato Zagorscak	**Date:**	9 December 2022
Checker (implementation):	Renato Zagorscak	**Date:**	26 January 2023

E 3.8 Scenario Timings

A general parameter, used in a number of scenarios and calculation cases, is the time that the scenario occurs, $t_{Scenario}$ (y). This is presented below. Other parameters are presented according the scenario or case they refer to, in the following subsections.

Name:	Timing of Scenario		
Version:	Version 4		
Symbol:	$t_{Scenario}$		
Units:	y		
Description:	The time that each scenario or calculation case occurs.		
Value(s):	See Table E-53		
Justification:	Generally, the timing of future events is set cautiously, at a time equal to the assumed period of institutional control, $t_{Control}$ = 100 y		
Uncertainty:	The value is a cautious assumption intended to explore the consequences of the scenario or case.		
Source of uncertainty:	Scenarios and calculation cases are in themselves uncertain in terms of timing and occurrence.		
References:	Lamontagne M, Halckuk S, Cassidy JF and Rogers GC (2007). Significant Canadian Earthquakes 1600 – 2006, Geological Survey of Canada, Open File 5539.		
Author:	James Penfold	**Date:**	25 April 2019
Checker (basis):	Emma Cairns	**Date:**	14 October 2019
Checker (implementation):	Renato Zagorscak	**Date:**	26 January 2023

Table E-53 Time after Closure at which each Scenario or Calculation Case Occurs

Scenario/Calculation Case	Time of Occurrence (y)
Sensitivity Cases	
Measured Inventory	0 y^
Increased Inventory	0 y^
Reduced Near-field Sorption (Concrete & Grout)	0 y^
Reduced Far-field Sorption (Overburden & Bedrock)	0 y^
Reduced Sorption in Near-field and Far-field	0 y^
Rapid Degradation	0 y^
Geosphere Bedrock Hydraulic Conductivity	0 y^
Geosphere Overburden Hydraulic Conductivity	0 y^
River Dilution Factor	0 y^
Self-Sufficient Indigenous Receptor	0 y^
Disruptive Event Scenarios	
Site Investigation (Inadvertent Human intrusion)	100 y*
Surface Erosion	100 y*
Extreme Degradation of Engineered Structures	100 y*
Fault Zone Activation	100 y*
Excavation of Above-bedrock Facility	100 y*
Overburden Well	100 y*
Bedrock Well	100 y*
Defence-in-Depth Cases	
Role of Structure	0 y^
Role of Grout	0 y^
“What If” Cases	
Facility Mass Excavation	100 y*
River Level Fall	100 y*
Undetected Fracture Zone	0 y^

Note: * assumed to occur the end of the period of institutional control (parameter $t_{Control}$, equal to 100y). ^Scenario assumptions apply from closure.

E 3.9 Data for Normal Evolution Sensitivity Cases

E 3.9.1 Case NES(a) – Measured Radionuclide Inventory

Name:	Measured Inventory
Version:	Version 4
Parameter Name:	i_{ActMat}, i_{RV}, i_{BR}, i_{FR}, i_{TR}
Units:	Bq and Bq/g
Description:	The radionuclide inventory for the PostSA based on measurement data: i_{ActMat} = inventory of activated materials in the reactor vault i_{BR} = inventory of the Boiler Room i_{FR} = inventory of the Fuelling Room i_{TR} = inventory of the Turbine Room ic_{Struct} = average radionuclide concentrations in the whole concrete structure
Value(s):	See Table E-54 (Reactor Vault) and Table E-55 (other rooms).
Justification:	These data are used to define the inventory for the assessment as follows: • Reactor vault – data from NMNTI (2017) and Edwards (2017), as presented in Porter (2022); • Reactor vault contamination –values from Porter (2022); • Boiler Room – values are the sum of activity in the moderator system, primary heat transport system and other minor systems (with the exception of the fuel handling system) as given in Porter (2022); • Fuelling Machine Room – values are the activity associated with the fuel handling system; • Turbine Room – values are the inventory associated with the non-nuclear area, above grade structure concrete, with the addition of the tritium associated with asbestos; • General contamination – activity values associated with the below-grade facility structure are divided by the total mass of the NPDDF structure. The resulting activity concentrations are then applied to all concrete in the model. The measured inventory is based on information presented by NMNTI (2017) for the aluminum, concrete, carbon steel and Zircaloy components in the Reactor Vault. The measured inventory for the stainless steel component of the Reactor Vault is based on information presented in Edwards (2017). The summary of the Reactor Vault inventory is presented in Porter (2022). This inventory uses only measurement data where possible, although the PHT fingerprint is still used to estimate the amounts of some difficult-to-measure radionuclides.
Uncertainty:	The uncertainties are several orders of magnitude for some locations and radionuclides, and the Modelled Inventory, which has been used as a Reference Inventory, has been chosen to be deliberately conservative. The Modelled Inventory is anticipated to represent an upper bound, although it is noted that the tritium inventory for the Turbine Room is greater than the modelled inventory as an earlier estimate of the tritium concentration (ORAU, 2016) is higher than that recommended for the modelled inventory (Porter, 2022).

Name:	Measured Inventory		
Source of uncertainty:	The measurements made have been extrapolated to a total activity inventory using a number of assumptions concerning the amount of material that is contaminated. There are also conventional measurement uncertainties arising from measurement statistics.		
References:	Edwards, G. (2017). C-14 in the NPD Channel End Fittings, 64-505100-400-000-0001, May 2017. NMNTI (2017). NPD Reactor Characterization Report, 64-509410-REPT-004, May 2017. ORAU (2016). Historical Site Assessment for the Nuclear Power Demonstration Waste Management Facility, 64-509410-ASD-001, July 2016. Porter, G. (2022). Nuclear Power Demonstration Waste Facility (NPDWF) Waste Inventory Report. CNL No. 64-508600-REPT-001. Revision 1.		
Author:	Renato Zagorscak	**Date:**	21 December 2022
Checker (basis):	Kate Thatcher	**Date:**	18 November 2022
Checker (implementation):	Kate Thatcher	**Date:**	21 December 2022

Table E-54 Radionuclides in the Measurement Inventory for the Reactor Vault (i_{ActMat}, Bq)

Radionuclide	Aluminum	Concrete	Carbon Steel	Stainless Steel	Zircaloy	Contam-ination
H-3	9.13E+09	1.41E+12	2.35E+08	-	2.11E+11	7.62E+08
C-14	2.97E+08	2.40E+10	8.13E+07	5.55E+09	5.30E+10	2.97E+09
Cl-36	1.21E+07	1.74E+08	1.09E+07	-	3.43E+07	2.79E+07
Ca-41	-	7.62E+09	-	-	-	-
Fe-60	-	-	-	-	-	-
Co-60	4.16E+10	3.18E+11	1.17E+10	3.04E+11	2.79E+11	2.52E+08
Ni-59	8.49E+08	-	-	2.09E+09	-	-
Ni-63	1.55E+11	6.83E+10	4.39E+09	1.94E+11	6.93E+12	1.05E+09
Se-79	-	-	-	-	-	-
Sr-90	3.11E+09	-	2.91E+06	-	2.32E+10	2.68E+10
Zr-93	-	-	-	-	2.90E+10	-
Nb-93m	-	-	-	-	-	-
Nb-94	-	-	-	-	1.85E+08	-
Tc-99	-	-	-	-	-	1.76E+07
Ag-108m	-	-	-	-	-	-
Cd-113m	-	-	-	-	-	-
Sn-121m	-	-	-	-	-	-
Sb-125	-	-	-	-	2.69E+10	-
Cs-137	6.91E+09	-	-	-	6.08E+10	4.11E+10
Sm-151	-	-	-	-	-	-
Eu-152	2.76E+08	1.23E+11	5.92E+07	-	3.48E+09	-
Eu-154	-	-	-	-	-	1.60E+08
Ho-116m	-	-	-	-	-	-
Hf-182	-	-	-	-	-	-
Th-229	-	-	-	-	-	-
Th-230	-	-	-	-	-	-
Th-232	-	-	-	-	-	-
U-232	-	-	-	-	-	-
U-233	-	-	-	-	-	-
U-234	-	-	-	-	-	-
U-235	-	-	-	-	-	-
U-238	1.21E+05	-	-	-	7.74E+04	-
Np-237	-	-	-	-	-	-
Pu-238	8.96E+07	8.30E+08	-	-	6.27E+08	1.48E+08
Pu-239	6.44E+07	2.06E+07	-	-	4.22E+08	9.98E+08
Pu-240	-	-	-	-	-	-
Pu-241	-	-	-	-	8.05E+09	-
Pu-242	-	-	-	-	-	-
Am-241	-	-	-	-	1.28E+09	1.49E+09
Am-242m	-	-	-	-	-	-
Am-243	-	-	-	-	-	-
Cm-243	-	-	-	-	-	-
Cm-244	-	-	-	-	-	-
Cm-245	-	-	-	-	-	-
Cm-246	-	-	-	-	-	-

Table E-55 Radionuclides in Other Rooms

Radionuclide	Boiler Room, i_{BR} (Bq)	Fuelling Room, i_{FR} (Bq)	Turbine Room, i_{TR} (Bq)	Generic Contamination, ic_{Struct} (Bq)*
H-3	5.88E+10	9.34E+07	1.88E+12	1.75E+12
C-14	3.33E+07	3.07E+05	2.72E+08	7.82E+10
Cl-36	3.67E+05	-	2.49E+07	1.69E+07
Ca-41	-	-	-	-
Co-60	5.03E+09	2.82E+07	3.64E+05	3.23E+06
Ni-59	-	-	-	-
Ni-63	3.87E+09	1.00E+08	1.18E+07	7.12E+06
Se-79	-	-	-	-
Sr-90	6.27E+09	1.17E+09	4.80E+06	1.21E+07
Zr-93	-	-	-	-
Nb-93m	-	-	-	-
Nb-94	-	-	-	-
Tc-99	-	1.45E+06	1.52E+06	3.39E+06
Ag-108m	-	-	-	-
Cd-113m	-	-	-	-
Sn-121m	-	-	-	-
Sb-125	-	-	-	-
Cs-137	3.76E+08	2.06E+09	1.39E+06	4.60E+07
Sm-151	-	-	-	-
Eu-152	-	-	-	-
Eu-154	7.97E+07	4.35E+06	-	-
Ho-116m	-	-	-	-
Hf-182	-	-	-	-
Th-229	-	-	-	-
Th-230	-	-	-	-
Th-232	-	-	-	-
U-232	-	-	-	-
U-233	-	-	-	-
U-234	-	-	-	-
U-235	-	-	1.78E+06	1.93E+06
U-238	-	-	2.55E+07	3.12E+07
Np-237	-	-	-	-
Pu-238	8.67E+07	2.69E+07	2.79E+06	9.70E+06
Pu-239	9.00E+08	1.07E+08	9.96E+05	2.15E+06
Pu-240	-	-	-	-
Pu-241	6.99E+09	1.27E+09	-	-
Pu-242	-	-	-	-
Am-241	9.52E+08	1.49E+08	1.44E+06	7.62E+05
Am-242m	-	-	-	-
Am-243	-	-	-	-
Cm-243	-	-	-	-
Cm-244	-	-	-	-
Cm-245	-	-	-	-
Cm-246	-	-	-	-

Note: * Will be averaged over the total mass of the NPDDF structure as represented in the model: 9,769,100 kg

E 3.9.2 Case NES(b) – Increased Modelled Radionuclide Inventory

Name:	Increased Modelled Radionuclide Inventory		
Version:	Version 4		
Parameter Name:	i_{ActMat}, i_{BR}, i_{FR}, i_{TR}, $i_{cStruct}$		
Units:	Bq and Bq g^{-1}		
Description:	The modelled radionuclide inventory for the PostSA. • i_{ActMat} = inventory of activated metals in reactor vault • i_{BR} = inventory of boiler room • i_{FR} = inventory of fuelling room • i_{TR}, = inventory of turbine room • $i_{cStruct}$ = inventory of structure (concrete walls etc)		
Value(s):	Values are taken to be those listed in Table E-17 (Reactor Vault) and Table E-18 (other rooms), increased by a factor of two.		
Justification:	The modelled inventory is primarily based on the data sources and assumptions presented in Porter (2022), and is discussed in detail in Appendix B. This scenario assumes the NES reference inventory multiplied by a factor of two. Similar to NES, only those radionuclides not screened out are considered (see Section E 3.1.1).		
Uncertainty:	Uncertainties in the inventory are discussed in Appendix B. For example, it is noted that the total activation product inventory estimated using Edwards & Adams (2019) is conservative by more than a factor of three in comparison to the total activation product inventory estimated by sample results alone (NMNTI, 2017). It is also noted that the most recent estimate of the Boiler Room inventory is around 2.5 times greater than the previous iteration estimate.		
Source of uncertainty:	The activation product inventory is calculated using neutron activation models that might not fully represent the geometry, material composition impurities and irradiation history of the facility, leading to some discrepancies. The inventory of other radionuclides is based on measurements and other estimates. Generally the key source of uncertainty relates to the assumptions made in scaling up the measured radionuclide concentration from a sample to the whole room.		
References:	Edwards and Adams (2019). Calculations of the Current NPD Reactor Vault Activation Source Term. CNL Ref #64-505100-ANL-001. February 2019. NMNTI (2017). NPD Reactor Characterization Report, 64-509410-REPT-004, May 2017. Porter, G. (2022). Nuclear Power Demonstration Waste Facility (NPDWF) Waste Inventory Report. CNL No. 64-508600-REPT-001. Revision 1.		
Author:	Renato Zagorscak	**Date:**	21 December 2022
Checker (basis):	Kate Thatcher	**Date:**	21 December 2022
Checker (implementation):	Kate Thatcher	**Date:**	21 December 2022

E 3.9.3 Case NES(c), NES(d) and NES (e) – Reduced Near-field Sorption, Reduced Far-field Sorption, and Reduced Sorption in Near-field and Far-field

Name:	Reduced Sorption		
Version:	Version 4.0		
Symbol:	Kd_{cem}, $Kd_{cem_stage_Sens}$, Kd_c,		
Units:	$m^3\ kg^{-1}$		
Description:	NES(c) – Lower values of sorption coefficients for cement and grout, $Kd_{cem_stage_sens}$, applied in Kd_{cem} NES(d) – Factor of 10 decrease applied to the sorption coefficients for overburden and bedrock NES(e) – the combination of cases NES(b) and NES(c)		
Value(s):	NES(c) – see Table E-56 NES(d) – the sorption values (Kd_m) are divided by 10 in the parameter Kd_c. NES(e) – the combination of cases NES(b) and NES(c)		
Justification:	NES(c) – Sorption coefficients for the near field (grout and concrete) are reduced. Lower limit values from Ochs *et al*. (2016) are used, where possible. Where no lower limit data are available, the best estimate values are reduced by a nominal factor of 10. NES(d) - Sorption coefficients for the far field (geosphere – overburden and bedrock) are reduced by a nominal factor of 10 to investigate the effect on calculated doses and thus sensitivity to this parameter. NES(e) – the combination of cases NES(b) and NES(c)		
Uncertainty:	Sorption coefficients are well established to be very variable and are often uncertain by an order of magnitude or more.		
Source of uncertainty:	Chemical and mineralogical properties of substrates.		
References:	Ochs M, Mallants D and Wang L (2016). Radionuclide and Metal Sorption on Cement and Concrete. Topics in Safety, Risk, Reliability and Quality, Volume 29. Savage D and Stenhouse M (2002). SFR 1 Vault Database, SKI Report 02:53, April 2002 Skagius K, Pettersson M and Wiborgh M (1999). Compilation of data for the analysis of radionuclide migration from SFL 3-5. SKB Report: R-99-13.		
Author:	James Penfold	**Date:**	17 February 2022
Checker (basis):	Renato Zagorscak	**Date:**	18 February 2022
Checker (implementation):	Renato Zagorscak	**Date:**	18 February 2022

Table E-56 Distribution Coefficients for Concrete and Grout (Sensitivity case)

Element	Stage I	Stage II	Stage III	Stage IV#	Degraded~	Notes
H	0	0	0	0	Table E-27, Stage IV	
C	0.7	2	0.2	0.0001	Table E-27, Stage IV	Stage III value taken as Best Estimate value / 10
Cl	0.005	0.01	0.002	0	Table E-27, Stage IV	
Ca	0.002	0.0003	0.003	0.013	Table E-27, Stage IV	
Fe	0.03	0.16	0.16	0.0005	Table E-27, Stage IV	Assumed as Ni (as per Savage & Stenhouse, 2002)
Co	0.03	0.16	0.16	0.0005	Table E-27, Stage IV	Assumed as Ni
Ni	0.03	0.16	0.16	0.0005	Table E-27, Stage IV	Stage IV value taken as Best Estimate value / 10
Se	0.001	0.001	0.00001	0.00001	Table E-27, Stage IV	Se(VI) assumed, cautiously
Sr	0.03	0.005	0.01	0.0001	Table E-27, Stage IV	
Zr	1	0.1	1	0.05	Table E-27, Stage IV	Stage I, IV from analogy with Nb
Nb	1	1	1	0.05	Table E-27, Stage IV	
Tc	0.0001	0.0001	0.0001	0.0001	Table E-27, Stage IV	Tc(VII) assumed, cautiously. Values taken as Best Estimate value / 10
Ag	0	0	0	0	Table E-27, Stage IV	
Cd	0.03	0.16	0.16	0.02	Table E-27, Stage IV	Assumed as Ni for Stage I, II, III, Stage IV as for “sandy sediment” estimated by Kaplan (2016) / 10
Sn	10	10	0.05	0.028	Table E-27, Stage IV	Stage III from Skagius (1999) / 10. Stage IV value based on overburden / 10.
Sb	2	2	0.05	0.028	Table E-27, Stage IV	Stage III from analogy with Sn. All other best estimate values divided by 10
Cs	0.0001	0.0001	0.001	0	Table E-27, Stage IV	No data for Stage IV. Kept it 0.
Sm	0.5	0.5	0.1	0.014	Table E-27, Stage IV	Assumed as Ac

Element	Stage I	Stage II	Stage III	Stage IV[#]	Degraded[~]	Notes
Eu	0.5	0.5	0.1	0.014	Table E-27, Stage IV	Assumed as Ac
Ho	0.5	0.5	0.1	0.014	Table E-27, Stage IV	Assumed as Eu
Hf	1	0.1	1	0.05	Table E-27, Stage IV	Assumed as Zr
Ta	1	1	1	0.05	Table E-27, Stage IV	Assumed as Nb
Pb	0.1	1	1	0.2	Table E-27, Stage IV	
Po	0.1	1	1	0.2	Table E-27, Stage IV	Assumed as Pb
Ra	0.1	0.001	0.08	0.0001	Table E-27, Stage IV	
Ac	0.5	0.5	0.1	0.014	Table E-27, Stage IV	Savage & Stenhouse (2002) values divided by 10
Pa	1	1	1	0.03	Table E-27, Stage IV	Assumes Pa(V), cautiously. Best estimate values divided by 10
Th	1	1	1	3	Table E-27, Stage IV	
U	0.4	3	10	0.005	Table E-27, Stage IV	
Np	1	1	1	0.01	Table E-27, Stage IV	
Pu	0.2	3	3	0.005	Table E-27, Stage IV	Assumes Pu (VI). Best estimate values divided by 10
Am	0.1	1	3	3	Table E-27, Stage IV	
Cm	0.5	0.5	0.1	0.014	Table E-27, Stage IV	Savage & Stenhouse (2002) values divided by 10

Note: Data from Ochs *et al*. (2016) except where indicated. [#] Values only used for BFS-PC grout. [~] Same values as Stage IV for NES, see Table E-27.

E 3.9.4 Case NES(f) - Rapid Degradation

Name:	Rapid Degradation of Engineered Barriers		
Version:	Version 4		
Parameter Name:	t_{NPD_Flow}		
Units:	y		
Description:	The condition of engineered barriers is represented through the timing at which different flow regimes through the facility (Arcadis & Geofirma, 2023b) are applied. In this sensitivity case, all engineering is assumed to be fully degraded after only 100 y.		
Value(s):	Flow regime 1 (undegraded facility with tile drains) operates from 0 y. Flow regime 4 (degraded facility with tile drain failure) operates from 100 y onwards.		
Justification:	It is very conservatively assumed that the engineering has fully degraded (in terms of hydraulic performance) after only 100 y after decommissioning is complete. This is not expected to occur, but represents a very conservative lower bound on the engineering lifetime.		
Uncertainty:	Jackson *et al*. (2011) provide details of the anticipated uncertainties in engineering performance.		
Source of uncertainty:	The main source of uncertainty is in the timescales for degradation as represented by the variation of hydraulic conductivity with time.		
References:	Arcadis Canada Inc. & Geofirma Ltd. (2023b). 2023 Near-Field Groundwater Model at the Site of the Proposed Decommissioned Rolphton Nuclear Power Demonstration (NPD) Reactor. CNL No. 64-508760-REPT-013 Rev 1. June. Jackson CP, Couch M, Yates H, Smith V, Kelly M and James M (2011). Elicitation of Uncertainties for LLWR, LLWR Environmental Safety Case report SERCO/TAS/E003796/010, Issue 2, April 2011. LLWR (2011). The 2011 Environmental Safety Case: Engineering Design, LLWR/ESC/R(11)10020, May 2011.		
Author:	James Penfold	**Date:**	28 August 2019
Checker (basis):	Emma Cairns	**Date:**	14 October 2019
Checker (implementation):	Renato Zagorscak	**Date:**	28 March 2023

Table E-57 Flow Rates within the NPD for case NES(g) – increased bedrock hydraulic conductivity (m^3 y^{-1})

Room, Face and Direction*	BRK Flow Case (1)	BRK Flow Case (2)	BRK Flow Case (4)
BRD_B_in	0.002997972	0.00224059	0.473364
BRD_B_out	3.79E-05	0.000100984	0.07258248
BRD_E_in	0	0	0
BRD_E_out	0.005680368	0.004418064	0.8204976
BRD_N_in	0	0	0
BRD_N_out	0.011676312	0.011991888	2.3352624
BRD_S_in	0.010098432	0.009782856	1.9881288
BRD_S_out	0	0	0
BRD_T_in	0	2.49E-05	0
BRD_T_out	0.002682396	0.000883613	0.30295296
BRD_W_in	0.00631152	0.005049216	0.9782856
BRD_W_out	0	0	0
BRS_B_in	0.006942672	0.002177474	0.8520552
BRS_B_out	0.000198813	0.001767226	0.1104516
BRS_E_in	0	0	0.01104516
BRS_E_out	0.010414008	0.005995944	0.8204976
BRS_N_in	0	0	0
BRS_N_out	0.022721472	0.02997972	4.73364
BRS_S_in	0.020196864	0.020196864	3.786912
BRS_S_out	0	0	0
BRS_T_in	0.000119919	0.008836128	0.03471336
BRS_T_out	0.00091517	0	0.014832072
BRS_W_in	0.0078894	0.00473364	1.2307464
BRS_W_out	0	0.000145165	0
BRU_B_in	0	0	0
BRU_B_out	0	0	0
BRU_E_in	0	0	0
BRU_E_out	0	0	0
BRU_N_in[1]	0	0	0
BRU_N_out[1]	0	0	0
BRU_S_in	0	0	0
BRU_S_out	0	0	0
BRU_T_in	0	0	0
BRU_T_out	0	0	0
BRU_W_in	0	0	0
BRU_W_out	0	0	0
DPR_B_in	0.001767226	0.001009843	0.29032992
DPR_B_out	5.68E-05	0.000157788	0.05049216

Room, Face and Direction*	BRK Flow Case (1)	BRK Flow Case (2)	BRK Flow Case (4)
DPR_E_in	0	0	0
DPR_E_out	0.001420092	0.001199189	0.23352624
DPR_N_in	0	0	0
DPR_N_out	0.002335262	0.002209032	0.4418064
DPR_S_in	0.002114359	0.001893456	0.3786912
DPR_S_out	0	0	0
DPR_T_in[2]	**0.000119919**	**0.001483207**	**0.16409952**
DPR_T_out[2]	**0.001136074**	0.000239838	0.0946728
DPR_W_in	0.000757382	0.000536479	0.10729584
DPR_W_out	0	0	0
ERV_B_in	0.000631152	7.89E-06	0.015147648
ERV_B_out	2.68E-06	0.000302953	0.0473364
ERV_E_in	0.00010414	1.01E-05	0.0078894
ERV_E_out	0.000568037	0.000757382	0.11676312
ERV_N_in	0	0	0
ERV_N_out	0.005680368	0.003471336	0.6942672
ERV_S_in	0.004418064	0.00315576	0.6627096
ERV_S_out	0	0	0
ERV_T_in	0.00066271	0.000820498	0.05364792
ERV_T_out	0.00091517	0.000694267	0.06942672
ERV_W_in	0.001640995	0.001420092	0.2209032
ERV_W_out	0	0	0
FR_B_in	0	0	0
FR_B_out	0	0	0
FR_E_in	0	0	0
FR_E_out	0	0	0
FR_N_in	0	0	0
FR_N_out	0	0	0
FR_S_in	0	0	0
FR_S_out	0	0	0
FR_T_in	0	0	0
FR_T_out	0	0	0
FR_W_in	0	0	0
FR_W_out	0	0	0
FSRS_B_in	0.000284018	5.68E-05	0.05364792
FSRS_B_out	0.008520552	0.009782856	1.3885344
FSRS_E_in	0	0	0
FSRS_E_out	0.012307464	0.01262304	1.7672256
FSRS_N_in	0	0	0
FSRS_N_out	0.010729584	0.008520552	1.8618984
FSRS_S_in	0.012938616	0.011676312	2.5561656

Room, Face and Direction*	BRK Flow Case (1)	BRK Flow Case (2)	BRK Flow Case (4)
FSRS_S_out	3.79E-05	0.000129386	0
FSRS_T_in	0.007573824	0.010729584	0.16409952
FSRS_T_out	1.36E-06	0	0
FSRS_W_in	0.010729584	0.008204976	2.0828016
FSRS_W_out	5.05E-05	0.000154632	0.000536479
FSRU_B_in	0	0	0
FSRU_B_out	0	0	0
FSRU_E_in	0	0	0
FSRU_E_out	0	0	0
FSRU_N_in	0	0	0
FSRU_N_out	0	0	0
FSRU_S_in	0	0	0
FSRU_S_out	0	0	0
FSRU_T_in	0	0	0
FSRU_T_out	0	0	0
FSRU_W_in	0	0	0
FSRU_W_out	0	0	0
NoFlowData	0	0	0
RV_B_in [2]	0.001136074	**0.000239838**	**0.0946728**
RV_B_out [2]	0.000119919	0.001483207	0.16409952
RV_E_in	0	0	0
RV_E_out	0.005049216	0.003471336	0.5364792
RV_N_in	0	0	0
RV_N_out	0.015147648	0.013885344	2.5561656
RV_S_in	0.016409952	0.013885344	2.8086264
RV_S_out	0	0	0
RV_T_in	0.001230746	0.004418064	0.16725528
RV_T_out	0.00026824	0	0
RV_W_in	0.001388534	0.000568037	0.16409952
RV_W_out	0	0.000148321	0
TR_B_in	0	0	0
TR_B_out	0	0	0
TR_E_in	0	0	0
TR_E_out	0	0	0
TR_N_in	0	0	0
TR_N_out	0	0	0
TR_S_in [1]	0	0	0
TR_S_out [1]	0	0	0
TR_T_in	0	0	0
TR_T_out	0	0	0
TR_W_in	0	0	0

Room, Face and Direction*	BRK Flow Case (1)	BRK Flow Case (2)	BRK Flow Case (4)
TR_W_out	0	0	0
WRV_B_in	0	0	0
WRV_B_out	0.000568037	0.000725825	0.12307464
WRV_E_in	8.20E-06	0.000100984	0.000631152
WRV_E_out	0.000631152	0.000154632	0.07258248
WRV_N_in	0.000284018	0.000280863	0.0473364
WRV_N_out	0.004102488	0.004102488	0.8204976
WRV_S_in	0.00473364	0.004418064	0.8836128
WRV_S_out	0	0	0
WRV_T_in	0.000410249	0.001072958	0.09151704
WRV_T_out	0.00066271	0.001009843	0.10729584
WRV_W_in	0.000599594	0.000242994	0.10414008
WRV_W_out	1.23E-05	6.00E-06	0.006942672

Note: * The location of the flows are specified as follows.

Rooms are: BRD = Boiler Room (Deep), BRS = Boiler Room (Saturated), BRU = Boiler Room (Upper), DPR = Dump Pipe Room, FR = Fuelling Room, FSRS = Fuel Storage Room (Saturated), FSRU = Fuel Storage Room (Upper), ERV = East Room of the Reactor Vault, WRV = West Room of the Reactor Vault, RV = Reactor Vault, TR = Turbine Room

Face is: N = site north (direction of groundwater flow towards the river, all other directions relative to this), S = south, E = east, W = west, T = top, B = bottom

Direction is: in = flow into the relevant compartment through the relevant face, out = flow outwards through the face.

[1] For consistency, flows taken are maximum of flow in/out north of BRU and out/in south of TR (both zero in this case).

[2] For consistency, flows taken are maximum of flow in/out bottom of RV and out/in top of DPR (bold values those changed).

Table E-58 Flow Rates in the geosphere surrounding the NPD for case NES(g) – increased bedrock hydraulic conductivity.

	Units	BRK Flow Case (1)	BRK Flow Case (2)	BRK Flow Case (4)
$q_{upstream}$	m y^{-1}	10.4	10.4	10.4
DGeo_0	m^3 y^{-1}	49869.4	53277.07	53277.07
DGeo_1	m^3 y^{-1}	70073.97	72134.66	72134.66
DGeo_2	m^3 y^{-1}	90278.53	90992.25	90992.25
DGeo_3	m^3 y^{-1}	97414.37	97414.37	97414.37
DGeo_4	m^3 y^{-1}	89820.82	89820.82	89820.82
DGeo_5	m^3 y^{-1}	89820.82	89820.82	89820.82
PT_1	m^3 y^{-1}	2957.059	3066.566	3066.195
PT_2	m^3 y^{-1}	6593.638	6837.842	6837.713
PT_3	m^3 y^{-1}	8020.759	8193.536	8193.536
PT_4	m^3 y^{-1}	6957.662	6826.698	6826.698
PT_5	m^3 y^{-1}	6957.662	6826.698	6826.698
SGeo_1	m^3 y^{-1}	65.61885	65.63946	65.63946
SGeo_2	m^3 y^{-1}	144.4301	144.4372	144.4372
SGeo_3	m^3 y^{-1}	28703.69	28703.69	28703.69
SGeo_4	m^3 y^{-1}	89362.47	89362.47	89362.47
SGeo_5	m^3 y^{-1}	89362.47	89362.47	89362.47
TD_1	m^3 y^{-1}	7067.363	7368.805	7368.805
TD_2	m^3 y^{-1}	13586.7	14103.66	14103.66
TD_3	m^3 y^{-1}	13899.54	14530.7	14530.7
TD_4	m^3 y^{-1}	7217.223	7848.375	7848.375
TD_5	m^3 y^{-1}	7217.223	7848.375	7848.375

Table E-59 Flow Rates within the NPD for case NES(h) – increased overburden hydraulic conductivity (m^3 y^{-1})

Room, Face and Direction*	OBK Flow Case (1)	OBK Flow Case (2)	OBK Flow Case (4)
BRD_B_in	0.002398378	0.002524608	0.236682
BRD_B_out	0.000347134	0.000441806	0.16725528
BRD_E_in	0	0	0
BRD_E_out	0.011676312	0.013885344	2.2721472
BRD_N_in	0	0	0
BRD_N_out	0.01420092	0.015147648	2.3037048
BRD_S_in	0.012307464	0.012938616	2.2405896
BRD_S_out	0	0	0
BRD_T_in	2.68E-05	0.000170411	0.05680368
BRD_T_out	0.001483207	0.000978286	0.04418064
BRD_W_in	0.01262304	0.014516496	2.2405896
BRD_W_out	0	0	0

Room, Face and Direction*	OBK Flow Case (1)	OBK Flow Case (2)	OBK Flow Case (4)
BRS_B_in	0.005364792	0.004418064	0.5995944
BRS_B_out	0.004102488	0.00473364	1.1991888
BRS_E_in	0	0	0
BRS_E_out	0.0315576	0.03786912	6.31152
BRS_N_in	0.00145165	0.000978286	0.23352624
BRS_N_out	0.0315576	0.04102488	4.73364
BRS_S_in	0.0315576	0.03786912	6.31152
BRS_S_out	0	0	0
BRS_T_in	0.007258248	0.015147648	0.8836128
BRS_T_out	0	0	0.001293862
BRS_W_in	0.021774744	0.023352624	4.102488
BRS_W_out	0	0	0
BRU_B_in	0	0	0
BRU_B_out	0	0.004418064	0.5049216
BRU_E_in	0	0	0
BRU_E_out	0	0.007573824	0.16725528
BRU_N_in[1]	**2.56E-05**	0.000946728	0.11676312
BRU_N_out[1]	**0.000725825**	**0.001230746**	**0.1262304**
BRU_S_in	0	0.001009843	0.0315576
BRU_S_out	0	0	0
BRU_T_in	0	0.004418064	0.17987832
BRU_T_out	0	0	0
BRU_W_in	0	0.003786912	0.3471336
BRU_W_out	0	0	0
DPR_B_in	0.001388534	0.001167631	0.11991888
DPR_B_out	0.000227215	0.000410249	0.1262304
DPR_E_in	0	0	0
DPR_E_out	0.001956571	0.00236682	0.3786912
DPR_N_in	0	0	0
DPR_N_out	0.002777069	0.002966414	0.5049216
DPR_S_in	0.00236682	0.002524608	0.473364
DPR_S_out	0	0	0
DPR_T_in[2]	**0.001041401**	**0.00249305**	**0.4418064**
DPR_T_out[2]	0.000504922	0.000280863	**0.08520552**
DPR_W_in	0.001262304	0.001514765	0.27455112
DPR_W_out	0	0	0
ERV_B_in	0.000183034	7.89E-05	0.03786912
ERV_B_out	0.001104516	0.001546322	0.2524608
ERV_E_in	0.003786912	0.003471336	0.5049216
ERV_E_out	0	1.26E-05	0
ERV_N_in	0	0	0
ERV_N_out	0.018303408	0.020196864	3.471336
ERV_S_in	0.011360736	0.011991888	2.0196864
ERV_S_out	0	0	0
ERV_T_in	0.010729584	0.014832072	2.1774744
ERV_T_out	0.0078894	0.010414008	1.2938616

Room, Face and Direction*	OBK Flow Case (1)	OBK Flow Case (2)	OBK Flow Case (4)
ERV_W_in	0.001672553	0.002303705	0.4102488
ERV_W_out	1.74E-05	0	0.03786912
FR_B_in	0	0	0
FR_B_out	0.01735668	0.030295296	4.102488
FR_E_in	0.00302953	0.007258248	1.6409952
FR_E_out	0.000820498	0.001420092	0.4102488
FR_N_in	0	0	0
FR_N_out	0.0078894	0.017041104	2.4614928
FR_S_in	0.01104516	0.019250136	3.471336
FR_S_out	0.002082802	0.001767226	0.4418064
FR_T_in	0.01262304	0.020828016	1.735668
FR_T_out	0	2.52E-05	0.000347134
FR_W_in	0.002177474	0.003786912	0.7573824
FR_W_out	0.000410249	0.002335262	0.09782856
FSRS_B_in	4.73E-05	1.55E-05	0.000261928
FSRS_B_out	0.016094376	0.020828016	2.997972
FSRS_E_in	0.008520552	0.007258248	1.6094376
FSRS_E_out	0.001956571	0.00315576	0.3786912
FSRS_N_in	0	0	0
FSRS_N_out	0.017672256	0.019881288	3.786912
FSRS_S_in	0.012938616	0.015147648	2.5877232
FSRS_S_out	0	0	0
FSRS_T_in	0.009151704	0.015147648	1.4516496
FSRS_T_out	0	6.00E-05	0
FSRS_W_in	0.005364792	0.007573824	1.4516496
FSRS_W_out	0.000504922	5.36E-05	0.005049216
FSRU_B_in	0	7.57E-05	0
FSRU_B_out	0.001861898	0.021459168	1.8618984
FSRU_E_in	0.000214592	0.00315576	0.4418064
FSRU_E_out	0	0	0.06627096
FSRU_N_in	0	0	0
FSRU_N_out	0.002997972	0.006627096	0.1893456
FSRU_S_in	0.002145917	0.008836128	0.7573824
FSRU_S_out	0.00026824	0.00315576	0.12938616
FSRU_T_in	0.00224059	0.018303408	0.7573824
FSRU_T_out	0	7.26E-05	0.000154632
FSRU_W_in	6.94E-05	0.001388534	0.17672256
FSRU_W_out	6.31E-05	0.00078894	0.04102488
NoFlowData	0	0	0
RV_B_in [2]	**0.000504922**	**0.000280863**	0.08520552
RV_B_out [2]	0.001041401	0.00249305	0.4418064
RV_E_in	0.00012623	8.20E-05	0.001041401
RV_E_out	0.008204976	0.00946728	1.420092
RV_N_in	0	0	0
RV_N_out	0.020196864	0.02209032	3.786912
RV_S_in	0.019565712	0.021143592	3.786912

Room, Face and Direction*	OBK Flow Case (1)	OBK Flow Case (2)	OBK Flow Case (4)
RV_S_out	0	0	0
RV_T_in	0.005995944	0.008836128	1.0729584
RV_T_out	0	0	0
RV_W_in	0.003124202	0.003471336	0.7258248
RV_W_out	0	0	0
TR_B_in	0	0	0
TR_B_out	0.015463224	0.01735668	3.15576
TR_E_in	0	0	0
TR_E_out	0.022721472	0.03471336	6.942672
TR_N_in	0	0	0.002682396
TR_N_out	0.00078894	0.001861898	0.13885344
TR_S_in [1]	0.000725825	0.001230746	0.1262304
TR_S_out [1]	2.56E-05	**0.000946728**	**0.11676312**
TR_T_in	0.01104516	0.01420092	1.6725528
TR_T_out	0	0	0
TR_W_in	0.029348568	0.04418064	9.46728
TR_W_out	0.002556166	0.002745511	0.78894
WRV_B_in	0	0	0
WRV_B_out	0.001262304	0.001514765	0.236682
WRV_E_in	0	0	0
WRV_E_out	0.001767226	0.001798783	0.473364
WRV_N_in	0.000378691	0.000441806	0.06942672
WRV_N_out	0.002745511	0.00315576	0.5364792
WRV_S_in	0.002808626	0.003471336	0.5364792
WRV_S_out	0	0	0
WRV_T_in	0.00157788	0.001830341	0.3471336
WRV_T_out	0.001041401	0.001230746	0.16725528
WRV_W_in	0.002177474	0.002303705	0.5049216
WRV_W_out	9.15E-05	8.52E-05	0.020828016

Note: * The location of the flows are specified as follows.

Rooms are: BRD = Boiler Room (Deep), BRS = Boiler Room (Saturated), BRU = Boiler Room (Upper), DPR = Dump Pipe Room, FR = Fuelling Room, FSRS = Fuel Storage Room (Saturated), FSRU = Fuel Storage Room (Upper), ERV = East Room of the Reactor Vault, WRV = West Room of the Reactor Vault, RV = Reactor Vault, TR = Turbine Room.

Face is: N = site north (direction of groundwater flow towards the river, all other directions relative to this), S = south, E = east, W = west, T = top, B = bottom.

Direction is: in = flow into the relevant compartment through the relevant face, out = flow outwards through the face.

[1] For consistency, flows taken are maximum of flow in/out north of BRU and out/in south of TR (bold values those changed).

[2] For consistency, flows taken are maximum of flow in/out bottom of RV and out/in top of DPR (bold values those changed).

Table E-60 Flow Rates in the geosphere surrounding the NPD for case NES(h) – increased overburden hydraulic conductivity.

	Units	OBK Flow Case (1)	OBK Flow Case (2)	OBK Flow Case (4)
$q_{upstream}$	m y^{-1}	0.0623	0.0551	0.0551
DGeo_0	m^3 y^{-1}	958.5534	992.63	1026.707
DGeo_1	m^3 y^{-1}	2076.539	2097.146	2117.753
DGeo_2	m^3 y^{-1}	3194.525	3201.662	3208.799
DGeo_3	m^3 y^{-1}	3465.616	3551.295	3551.295
DGeo_4	m^3 y^{-1}	2782.197	3050.121	3050.121
DGeo_5	m^3 y^{-1}	2782.197	3050.121	3050.121
PT_1	m^3 y^{-1}	1017.12	52793.21	52793.21
PT_2	m^3 y^{-1}	2229.394	104921	104921
PT_3	m^3 y^{-1}	3792.79	118262.1	118262.1
PT_4	m^3 y^{-1}	5751.925	87887.92	87887.92
PT_5	m^3 y^{-1}	5751.925	87887.92	87887.92
SGeo_1	m^3 y^{-1}	17523.91	178982.7	178982.7
SGeo_2	m^3 y^{-1}	16176.94	216697.9	216697.9
SGeo_3	m^3 y^{-1}	21960.54	311651	311651
SGeo_4	m^3 y^{-1}	35780.8	471115.5	471115.5
SGeo_5	m^3 y^{-1}	35780.8	471115.5	471115.5
TD_1	m^3 y^{-1}	4016.492	11503.13	11818.71
TD_2	m^3 y^{-1}	5929.19	15948.13	16263.71
TD_3	m^3 y^{-1}	6064.463	17089.62	17333.8
TD_4	m^3 y^{-1}	4196.451	14507.82	14600.12
TD_5	m^3 y^{-1}	4196.451	14507.82	14600.12

Table E-61 The fraction of total water flow out of a room which goes to the tile drains for case NES(h) – increased overburden hydraulic conductivity.

Room	$f_{TileDrain}$, Fraction of outflow going to tile drains
BR_Sat	0.008
FR_Unsat	0.036
FSR_Sat	0.028
FSR_Unsat	0.066
TR_Unsat	0.032

E 3.9.5 Case NES(g), NES(h) – Geosphere Bedrock Hydraulic Conductivity, Geosphere Overburden Hydraulic Conductivity

Name:	Increased Hydraulic Conductivity		
Version:	Version 4		
Parameter Name:	Q_{NPD}, $q_{upstream}$, q_{c_vol}, $f_{TileDrain}$		
Units:	$M^3\ y^{-1}$, m/y, $m^3\ y^{-1}$, -		
Description:	Alternative flows through the facility and surrounding geosphere. NES(g) – examines increased hydraulic conductivity (and thus flow) in bedrock compared to NES NES(h) – examines increased hydraulic conductivity (and thus flow) in the overburden fill material between the facility and the river, compared to NES		
Value(s):	NES(g) Table E-57and Table E-58. The fraction of flow to the tile drain is zero for all rooms. NES(h) Table E-59, Table E-60 and Table E-61.		
Justification:	The potential for fractures or faults in the vicinity of the NPD site is addressed to provide a stronger link between the site characteristics (as outlined in the recent update to the Geosynthesis report (Arcadis & Geofirma, 2022)) and the selection of the scenarios. Data from the recent groundwater modelling report are used (Arcadis & Geofirma, 2023a)		
Uncertainty:	The regional and site hydrogeological framework for the NPDWF site is described based on historical and 2019 local investigation and site characterization work completed at and in the vicinity of the NPD site and at the CRL site, review of MECP water well records, and review of the scientific literature (Arcadis & Geofirma, 2022). The presence and hydrogeological properties of the permeable fluvial sand and gravel layer that subparallels the Ottawa River and extends tile drain capture of overburden groundwater northwest of the NPDWF is identified as an uncertainty in modeling of groundwater flow at the NPDWF site (Arcadis & Geofirma, 2022). However, uncertainty in the extent and hydrogeological properties of the fluvial sand and gravel layer located northwest of the NPDWF will have a negligible effect on the rate and location of overburden groundwater discharge from the NPDWF to the Ottawa River and hence the NPD closure and post-closure phases. Two alternative calculation cases have therefore been considered to account for the uncertainty in the hydraulic properties of the geosphere.		
Source of uncertainty:	Resolving the uncertainty on the location and hydrogeological properties of this fluvial sand and gravel layer would enhance the confidence in the 3-D groundwater flow model and the volumes of tile drain water, but that uncertainty primarily concerns the completeness of the site characterization work and not the fate of overburden groundwater discharge from the NPDWF to the Ottawa River (Arcadis & Geofirma, 2022).		
References:	Arcadis Canada Inc. & Geofirma Ltd. 2022. 2021 Update to Geosynthesis – Nuclear Power Demonstration Closure Project – Rolphton, Ontario. CNL No. 64-509410-REPT-010 Rev 2, January. Arcadis Canada Inc. & Geofirma Ltd. (2023a). 2023 Groundwater Modelling at the Site of the Proposed Decommissioned Rolphton Nuclear Power Demonstration (NPD) Reactor. CNL No. 64-508760-REPT-012 Rev 1. June		
Author:	Louise Bruffell	**Date:**	09 February 2023
Checker (basis):	Kate Thatcher	**Date:**	10 February 2023
Checker (implementation):	Kate Thatcher	**Date:**	10 February 2023

Table E-62 Flow Rates within the NPD for case NES(g) – increased bedrock hydraulic conductivity (m^3 y^{-1})

Room, Face and Direction*	BRK Flow Case (1)	BRK Flow Case (2)	BRK Flow Case (4)
BRD_B_in	0.002997972	0.00224059	0.473364
BRD_B_out	3.79E-05	0.000100984	0.07258248
BRD_E_in	0	0	0
BRD_E_out	0.005680368	0.004418064	0.8204976
BRD_N_in	0	0	0
BRD_N_out	0.011676312	0.011991888	2.3352624
BRD_S_in	0.010098432	0.009782856	1.9881288
BRD_S_out	0	0	0
BRD_T_in	0	2.49E-05	0
BRD_T_out	0.002682396	0.000883613	0.30295296
BRD_W_in	0.00631152	0.005049216	0.9782856
BRD_W_out	0	0	0
BRS_B_in	0.006942672	0.002177474	0.8520552
BRS_B_out	0.000198813	0.001767226	0.1104516
BRS_E_in	0	0	0.01104516
BRS_E_out	0.010414008	0.005995944	0.8204976
BRS_N_in	0	0	0
BRS_N_out	0.022721472	0.02997972	4.73364
BRS_S_in	0.020196864	0.020196864	3.786912
BRS_S_out	0	0	0
BRS_T_in	0.000119919	0.008836128	0.03471336
BRS_T_out	0.00091517	0	0.014832072
BRS_W_in	0.0078894	0.00473364	1.2307464
BRS_W_out	0	0.000145165	0
BRU_B_in	0	0	0
BRU_B_out	0	0	0
BRU_E_in	0	0	0
BRU_E_out	0	0	0
BRU_N_in[1]	0	0	0
BRU_N_out[1]	0	0	0
BRU_S_in	0	0	0
BRU_S_out	0	0	0
BRU_T_in	0	0	0
BRU_T_out	0	0	0
BRU_W_in	0	0	0
BRU_W_out	0	0	0
DPR_B_in	0.001767226	0.001009843	0.29032992
DPR_B_out	5.68E-05	0.000157788	0.05049216

Room, Face and Direction*	BRK Flow Case (1)	BRK Flow Case (2)	BRK Flow Case (4)
DPR_E_in	0	0	0
DPR_E_out	0.001420092	0.001199189	0.23352624
DPR_N_in	0	0	0
DPR_N_out	0.002335262	0.002209032	0.4418064
DPR_S_in	0.002114359	0.001893456	0.3786912
DPR_S_out	0	0	0
DPR_T_in[2]	**0.000119919**	**0.001483207**	**0.16409952**
DPR_T_out[2]	**0.001136074**	0.000239838	0.0946728
DPR_W_in	0.000757382	0.000536479	0.10729584
DPR_W_out	0	0	0
ERV_B_in	0.000631152	7.89E-06	0.015147648
ERV_B_out	2.68E-06	0.000302953	0.0473364
ERV_E_in	0.00010414	1.01E-05	0.0078894
ERV_E_out	0.000568037	0.000757382	0.11676312
ERV_N_in	0	0	0
ERV_N_out	0.005680368	0.003471336	0.6942672
ERV_S_in	0.004418064	0.00315576	0.6627096
ERV_S_out	0	0	0
ERV_T_in	0.00066271	0.000820498	0.05364792
ERV_T_out	0.00091517	0.000694267	0.06942672
ERV_W_in	0.001640995	0.001420092	0.2209032
ERV_W_out	0	0	0
FR_B_in	0	0	0
FR_B_out	0	0	0
FR_E_in	0	0	0
FR_E_out	0	0	0
FR_N_in	0	0	0
FR_N_out	0	0	0
FR_S_in	0	0	0
FR_S_out	0	0	0
FR_T_in	0	0	0
FR_T_out	0	0	0
FR_W_in	0	0	0
FR_W_out	0	0	0
FSRS_B_in	0.000284018	5.68E-05	0.05364792
FSRS_B_out	0.008520552	0.009782856	1.3885344
FSRS_E_in	0	0	0
FSRS_E_out	0.012307464	0.01262304	1.7672256
FSRS_N_in	0	0	0
FSRS_N_out	0.010729584	0.008520552	1.8618984
FSRS_S_in	0.012938616	0.011676312	2.5561656

Room, Face and Direction*	BRK Flow Case (1)	BRK Flow Case (2)	BRK Flow Case (4)
FSRS_S_out	3.79E-05	0.000129386	0
FSRS_T_in	0.007573824	0.010729584	0.16409952
FSRS_T_out	1.36E-06	0	0
FSRS_W_in	0.010729584	0.008204976	2.0828016
FSRS_W_out	5.05E-05	0.000154632	0.000536479
FSRU_B_in	0	0	0
FSRU_B_out	0	0	0
FSRU_E_in	0	0	0
FSRU_E_out	0	0	0
FSRU_N_in	0	0	0
FSRU_N_out	0	0	0
FSRU_S_in	0	0	0
FSRU_S_out	0	0	0
FSRU_T_in	0	0	0
FSRU_T_out	0	0	0
FSRU_W_in	0	0	0
FSRU_W_out	0	0	0
NoFlowData	0	0	0
RV_B_in [2]	0.001136074	**0.000239838**	**0.0946728**
RV_B_out [2]	0.000119919	0.001483207	0.16409952
RV_E_in	0	0	0
RV_E_out	0.005049216	0.003471336	0.5364792
RV_N_in	0	0	0
RV_N_out	0.015147648	0.013885344	2.5561656
RV_S_in	0.016409952	0.013885344	2.8086264
RV_S_out	0	0	0
RV_T_in	0.001230746	0.004418064	0.16725528
RV_T_out	0.00026824	0	0
RV_W_in	0.001388534	0.000568037	0.16409952
RV_W_out	0	0.000148321	0
TR_B_in	0	0	0
TR_B_out	0	0	0
TR_E_in	0	0	0
TR_E_out	0	0	0
TR_N_in	0	0	0
TR_N_out	0	0	0
TR_S_in [1]	0	0	0
TR_S_out [1]	0	0	0
TR_T_in	0	0	0
TR_T_out	0	0	0
TR_W_in	0	0	0

Room, Face and Direction*	BRK Flow Case (1)	BRK Flow Case (2)	BRK Flow Case (4)
TR_W_out	0	0	0
WRV_B_in	0	0	0
WRV_B_out	0.000568037	0.000725825	0.12307464
WRV_E_in	8.20E-06	0.000100984	0.000631152
WRV_E_out	0.000631152	0.000154632	0.07258248
WRV_N_in	0.000284018	0.000280863	0.0473364
WRV_N_out	0.004102488	0.004102488	0.8204976
WRV_S_in	0.00473364	0.004418064	0.8836128
WRV_S_out	0	0	0
WRV_T_in	0.000410249	0.001072958	0.09151704
WRV_T_out	0.00066271	0.001009843	0.10729584
WRV_W_in	0.000599594	0.000242994	0.10414008
WRV_W_out	1.23E-05	6.00E-06	0.006942672

Note: * The location of the flows are specified as follows.

Rooms are: BRD = Boiler Room (Deep), BRS = Boiler Room (Saturated), BRU = Boiler Room (Upper), DPR = Dump Pipe Room, FR = Fuelling Room, FSRS = Fuel Storage Room (Saturated), FSRU = Fuel Storage Room (Upper), ERV = East room of the Reactor Vault, WRV = West room of the Reactor Vault, RV = Reactor Vault, TR = Turbine Room

Face is: N = site north (direction of groundwater flow towards the river, all other directions relative to this), S = south, E = east, W = west, T = top, B = bottom

Direction is: in = flow into the relevant compartment through the relevant face, out = flow outwards through the face.

[1] For consistency, flows taken are maximum of flow in/out north of BRU and out/in south of TR (both zero in this case).

[2] For consistency, flows taken are maximum of flow in/out bottom of RV and out/in top of DPR (bold values those changed).

Table E-63 Flow Rates in the geosphere surrounding the NPD for case NES(g) – increased bedrock hydraulic conductivity.

	Units	BRK Flow Case (1)	BRK Flow Case (2)	BRK Flow Case (4)
$q_{upstream}$	m y^{-1}	10.4	10.4	10.4
DGeo_0	m^3 y^{-1}	49869.4	53277.07	53277.07
DGeo_1	m^3 y^{-1}	70073.97	72134.66	72134.66
DGeo_2	m^3 y^{-1}	90278.53	90992.25	90992.25
DGeo_3	m^3 y^{-1}	97414.37	97414.37	97414.37
DGeo_4	m^3 y^{-1}	89820.82	89820.82	89820.82
DGeo_5	m^3 y^{-1}	89820.82	89820.82	89820.82
PT_1	m^3 y^{-1}	2957.059	3066.566	3066.195
PT_2	m^3 y^{-1}	6593.638	6837.842	6837.713
PT_3	m^3 y^{-1}	8020.759	8193.536	8193.536
PT_4	m^3 y^{-1}	6957.662	6826.698	6826.698
PT_5	m^3 y^{-1}	6957.662	6826.698	6826.698

	Units	BRK Flow Case (1)	BRK Flow Case (2)	BRK Flow Case (4)
SGeo_1	$m^3 y^{-1}$	65.61885	65.63946	65.63946
SGeo_2	$m^3 y^{-1}$	144.4301	144.4372	144.4372
SGeo_3	$m^3 y^{-1}$	28703.69	28703.69	28703.69
SGeo_4	$m^3 y^{-1}$	89362.47	89362.47	89362.47
SGeo_5	$m^3 y^{-1}$	89362.47	89362.47	89362.47
TD_1	$m^3 y^{-1}$	7067.363	7368.805	7368.805
TD_2	$m^3 y^{-1}$	13586.7	14103.66	14103.66
TD_3	$m^3 y^{-1}$	13899.54	14530.7	14530.7
TD_4	$m^3 y^{-1}$	7217.223	7848.375	7848.375
TD_5	$m^3 y^{-1}$	7217.223	7848.375	7848.375

Table E-64 Flow Rates within the NPD for case NES(h) – increased overburden hydraulic conductivity ($m^3 y^{-1}$)

Room, Face and Direction*	OBK Flow Case (1)	OBK Flow Case (2)	OBK Flow Case (4)
BRD_B_in	0.002398378	0.002524608	0.236682
BRD_B_out	0.000347134	0.000441806	0.16725528
BRD_E_in	0	0	0
BRD_E_out	0.011676312	0.013885344	2.2721472
BRD_N_in	0	0	0
BRD_N_out	0.01420092	0.015147648	2.3037048
BRD_S_in	0.012307464	0.012938616	2.2405896
BRD_S_out	0	0	0
BRD_T_in	2.68E-05	0.000170411	0.05680368
BRD_T_out	0.001483207	0.000978286	0.04418064
BRD_W_in	0.01262304	0.014516496	2.2405896
BRD_W_out	0	0	0
BRS_B_in	0.005364792	0.004418064	0.5995944
BRS_B_out	0.004102488	0.00473364	1.1991888
BRS_E_in	0	0	0
BRS_E_out	0.0315576	0.03786912	6.31152
BRS_N_in	0.00145165	0.000978286	0.23352624
BRS_N_out	0.0315576	0.04102488	4.73364
BRS_S_in	0.0315576	0.03786912	6.31152
BRS_S_out	0	0	0
BRS_T_in	0.007258248	0.015147648	0.8836128
BRS_T_out	0	0	0.001293862
BRS_W_in	0.021774744	0.023352624	4.102488
BRS_W_out	0	0	0
BRU_B_in	0	0	0

Room, Face and Direction*	OBK Flow Case (1)	OBK Flow Case (2)	OBK Flow Case (4)
BRU_B_out	0	0.004418064	0.5049216
BRU_E_in	0	0	0
BRU_E_out	0	0.007573824	0.16725528
BRU_N_in[1]	**2.56E-05**	0.000946728	0.11676312
BRU_N_out[1]	**0.000725825**	**0.001230746**	**0.1262304**
BRU_S_in	0	0.001009843	0.0315576
BRU_S_out	0	0	0
BRU_T_in	0	0.004418064	0.17987832
BRU_T_out	0	0	0
BRU_W_in	0	0.003786912	0.3471336
BRU_W_out	0	0	0
DPR_B_in	0.001388534	0.001167631	0.11991888
DPR_B_out	0.000227215	0.000410249	0.1262304
DPR_E_in	0	0	0
DPR_E_out	0.001956571	0.00236682	0.3786912
DPR_N_in	0	0	0
DPR_N_out	0.002777069	0.002966414	0.5049216
DPR_S_in	0.00236682	0.002524608	0.473364
DPR_S_out	0	0	0
DPR_T_in[2]	**0.001041401**	**0.00249305**	**0.4418064**
DPR_T_out[2]	0.000504922	0.000280863	**0.08520552**
DPR_W_in	0.001262304	0.001514765	0.27455112
DPR_W_out	0	0	0
ERV_B_in	0.000183034	7.89E-05	0.03786912
ERV_B_out	0.001104516	0.001546322	0.2524608
ERV_E_in	0.003786912	0.003471336	0.5049216
ERV_E_out	0	1.26E-05	0
ERV_N_in	0	0	0
ERV_N_out	0.018303408	0.020196864	3.471336
ERV_S_in	0.011360736	0.011991888	2.0196864
ERV_S_out	0	0	0
ERV_T_in	0.010729584	0.014832072	2.1774744
ERV_T_out	0.0078894	0.010414008	1.2938616
ERV_W_in	0.001672553	0.002303705	0.4102488
ERV_W_out	1.74E-05	0	0.03786912
FR_B_in	0	0	0
FR_B_out	0.01735668	0.030295296	4.102488
FR_E_in	0.00302953	0.007258248	1.6409952
FR_E_out	0.000820498	0.001420092	0.4102488
FR_N_in	0	0	0
FR_N_out	0.0078894	0.017041104	2.4614928

Room, Face and Direction*	OBK Flow Case (1)	OBK Flow Case (2)	OBK Flow Case (4)
FR_S_in	0.01104516	0.019250136	3.471336
FR_S_out	0.002082802	0.001767226	0.4418064
FR_T_in	0.01262304	0.020828016	1.735668
FR_T_out	0	2.52E-05	0.000347134
FR_W_in	0.002177474	0.003786912	0.7573824
FR_W_out	0.000410249	0.002335262	0.09782856
FSRS_B_in	4.73E-05	1.55E-05	0.000261928
FSRS_B_out	0.016094376	0.020828016	2.997972
FSRS_E_in	0.008520552	0.007258248	1.6094376
FSRS_E_out	0.001956571	0.00315576	0.3786912
FSRS_N_in	0	0	0
FSRS_N_out	0.017672256	0.019881288	3.786912
FSRS_S_in	0.012938616	0.015147648	2.5877232
FSRS_S_out	0	0	0
FSRS_T_in	0.009151704	0.015147648	1.4516496
FSRS_T_out	0	6.00E-05	0
FSRS_W_in	0.005364792	0.007573824	1.4516496
FSRS_W_out	0.000504922	5.36E-05	0.005049216
FSRU_B_in	0	7.57E-05	0
FSRU_B_out	0.001861898	0.021459168	1.8618984
FSRU_E_in	0.000214592	0.00315576	0.4418064
FSRU_E_out	0	0	0.06627096
FSRU_N_in	0	0	0
FSRU_N_out	0.002997972	0.006627096	0.1893456
FSRU_S_in	0.002145917	0.008836128	0.7573824
FSRU_S_out	0.00026824	0.00315576	0.12938616
FSRU_T_in	0.00224059	0.018303408	0.7573824
FSRU_T_out	0	7.26E-05	0.000154632
FSRU_W_in	6.94E-05	0.001388534	0.17672256
FSRU_W_out	6.31E-05	0.00078894	0.04102488
NoFlowData	0	0	0
RV_B_in [2]	**0.000504922**	**0.000280863**	0.08520552
RV_B_out [2]	0.001041401	0.00249305	0.4418064
RV_E_in	0.00012623	8.20E-05	0.001041401
RV_E_out	0.008204976	0.00946728	1.420092
RV_N_in	0	0	0
RV_N_out	0.020196864	0.02209032	3.786912
RV_S_in	0.019565712	0.021143592	3.786912
RV_S_out	0	0	0
RV_T_in	0.005995944	0.008836128	1.0729584
RV_T_out	0	0	0

Room, Face and Direction*	OBK Flow Case (1)	OBK Flow Case (2)	OBK Flow Case (4)
RV_W_in	0.003124202	0.003471336	0.7258248
RV_W_out	0	0	0
TR_B_in	0	0	0
TR_B_out	0.015463224	0.01735668	3.15576
TR_E_in	0	0	0
TR_E_out	0.022721472	0.03471336	6.942672
TR_N_in	0	0	0.002682396
TR_N_out	0.00078894	0.001861898	0.13885344
TR_S_in [1]	0.000725825	0.001230746	0.1262304
TR_S_out [1]	2.56E-05	**0.000946728**	**0.11676312**
TR_T_in	0.01104516	0.01420092	1.6725528
TR_T_out	0	0	0
TR_W_in	0.029348568	0.04418064	9.46728
TR_W_out	0.002556166	0.002745511	0.78894
WRV_B_in	0	0	0
WRV_B_out	0.001262304	0.001514765	0.236682
WRV_E_in	0	0	0
WRV_E_out	0.001767226	0.001798783	0.473364
WRV_N_in	0.000378691	0.000441806	0.06942672
WRV_N_out	0.002745511	0.00315576	0.5364792
WRV_S_in	0.002808626	0.003471336	0.5364792
WRV_S_out	0	0	0
WRV_T_in	0.00157788	0.001830341	0.3471336
WRV_T_out	0.001041401	0.001230746	0.16725528
WRV_W_in	0.002177474	0.002303705	0.5049216
WRV_W_out	9.15E-05	8.52E-05	0.020828016

Note: * The location of the flows are specified as follows.

Rooms are: BRD = Boiler Room (Deep), BRS = Boiler Room (Saturated), BRU = Boiler Room (Upper), DPR = Dump Pipe Room, FR = Fuelling Room, FSRS = Fuel Storage Room (Saturated), FSRU = Fuel Storage Room (Upper), ERV = East room of the Reactor Vault, WRV = West room of the Reactor Vault, RV = Reactor Vault, TR = Turbine Room

Face is: N = site north (direction of groundwater flow towards the river, all other directions relative to this), S = south, E = east, W = west, T = top, B = bottom

Direction is: in = flow into the relevant compartment through the relevant face, out = flow outwards through the face.

[1] For consistency, flows taken are maximum of flow in/out north of BRU and out/in south of TR (bold values those changed).

[2] For consistency, flows taken are maximum of flow in/out bottom of RV and out/in top of DPR (bold values those changed).

Table E-65 Flow Rates in the geosphere surrounding the NPD for case NES(h) – increased overburden hydraulic conductivity.

	Units	OBK Flow Case (1)	OBK Flow Case (2)	OBK Flow Case (4)
$q_{upstream}$	m y^{-1}	0.0623	0.0551	0.0551
DGeo_0	m^3 y^{-1}	958.5534	992.63	1026.707
DGeo_1	m^3 y^{-1}	2076.539	2097.146	2117.753
DGeo_2	m^3 y^{-1}	3194.525	3201.662	3208.799
DGeo_3	m^3 y^{-1}	3465.616	3551.295	3551.295
DGeo_4	m^3 y^{-1}	2782.197	3050.121	3050.121
DGeo_5	m^3 y^{-1}	2782.197	3050.121	3050.121
PT_1	m^3 y^{-1}	1017.12	52793.21	52793.21
PT_2	m^3 y^{-1}	2229.394	104921	104921
PT_3	m^3 y^{-1}	3792.79	118262.1	118262.1
PT_4	m^3 y^{-1}	5751.925	87887.92	87887.92
PT_5	m^3 y^{-1}	5751.925	87887.92	87887.92
SGeo_1	m^3 y^{-1}	17523.91	178982.7	178982.7
SGeo_2	m^3 y^{-1}	16176.94	216697.9	216697.9
SGeo_3	m^3 y^{-1}	21960.54	311651	311651
SGeo_4	m^3 y^{-1}	35780.8	471115.5	471115.5
SGeo_5	m^3 y^{-1}	35780.8	471115.5	471115.5
TD_1	m^3 y^{-1}	4016.492	11503.13	11818.71
TD_2	m^3 y^{-1}	5929.19	15948.13	16263.71
TD_3	m^3 y^{-1}	6064.463	17089.62	17333.8
TD_4	m^3 y^{-1}	4196.451	14507.82	14600.12
TD_5	m^3 y^{-1}	4196.451	14507.82	14600.12

Table E-66 The fraction of total water flow out of a room which goes to the tile drains for case NES(h) – increased overburden hydraulic conductivity.

Room	$f_{TileDrain}$, Fraction of outflow going to tile drains
BR_Sat	0.008
FR_Unsat	0.036
FSR_Sat	0.028
FSR_Unsat	0.066
TR_Unsat	0.032

E 3.9.6 Case NES(i) – Increased Dilution in the River

Name:	Dilution Factor for River		
Version:	Version 4		
Symbol:	Dil_DeepRiver, Dil_Ottawa		
Units:	Unitless		
Description:	Dilution factor for river water downstream of the NPDDF, at both Deep River and Ottawa		
Value(s):	Deep River: 0.000828 Ottawa: 0.35		
Justification:	Data based at reported flow rates reported at Ottawa River Regulation Planning Board, http://ottawariver.ca/river-levels-flows.php (retrieved 25 April 2019). There is no additional dilution assumed at Deep River, conservatively. The dilution factor applied at Deep River ($Dil_{DeepRiver}$) is taken from the ratio of the cross sectional area of the initial compartment into which discharge occurs (5 m x 1 m) and the Ottawa river (525 m x 11.5 m). The dilution factor for Ottawa is the ratio of the averaged reported flow rate at Des Joachims station (immediately upstream of NPDDF) and the reported flow rate measured at the Britannia hydrometric gauge just downstream of Gatineau. A nominal week in March 2019 was selected and the average ratio was used for NES. This sensitivity scenario examines the impact of the river dilution factor, by applying a lesser dilution factor of 0.35 (similar to the ratio used for CNL's NSDF project) to the calculated concentration in river water at Deep River as opposed to the factor of 0.658 used in NES. This approach is adopted to reflect the uncertainty in river flows, as river characteristics may vary throughout the year due to seasonal patterns and climate changes.		
Uncertainty:	Less than a factor of two.		
Source of uncertainty:	The factor will vary with the total river flow rate and pattern of precipitation, but can be assumed to take a long term average value.		
References:	http://ottawariver.ca/river-levels-flows.php		
Author:	James Penfold	**Date:**	16 February 2022
Checker (basis):	Renato Zagorscak	**Date:**	22 March 2022
Checker (implementation):	Renato Zagorscak	**Date:**	26 January 2023

E 3.9.7 Case NES(j) – Self-Sufficient Indigenous Receptor

Name:	Dietary Intakes for the Self-Sufficient Receptor Group		
Version:	Version 4		
Symbol:	I_f (intake rate) and gf (local fraction)		
Units:	See Table E-67		
Description:	Dietary intakes for the self-sufficient receptor group		
Value(s):	See Table E-67		
Justification:	The self-sufficient receptor represents a group of peoples, including adults, children and infants, using the area surrounding the NPDDF, including the Ottawa River, for hunting and gathering, following a traditional lifestyle. Values are based on values from SENES (2014) and CSA (2022). The dietary intake rates for this receptor are based on food intake data normalized to the conservative (high) energy intakes of 4480 kcal/d for adults and 2879 kcal/d for children, as laid out in SENES (2014). No values for infants are given in SENES (2014), thus the intake rates of either the adult or child (whichever gives the most conservative value for each food type) is scaled based on the daily energy intake for an infant of 1525 kcal/d (CSA, 2022). Mushrooms and honey have been identified as important in the NPD area but are not discussed in SENES (2014); therefore, the CSA N288.1:20 (CSA, 2022) ingestion rate (95th percentile energy intake) for mushrooms has been added to the consumption rates suggested in SENES (2014). The same intake rates as the Site Resident are used for inhalation, water, and soil ingestion rates (see sections E 3.7.7, E 3.7.8 and E 3.7.9).		
Uncertainty:	The biosphere modelling is based on the deterministic biosphere models recommended in CSA (2022).		
Source of uncertainty:	There is variability in intake rates, however, a deterministic 'reference' approach is adopted to the biosphere modelling, consistent with CSA (2022).		
References:	Canadian Standards Association (CSA). (2022). Guidelines for modelling radionuclide environmental transport, fate, and exposure associated with normal operation of nuclear facilities, N288.1:20, 2022 Errata, June. SENES Consultants Limited (2014) – Aboriginal Lifestyle Characterization. Prepared for Nuclear Waste Management Organization. NWMO TR-2014-13. SENES Reference No. 350696. June.		
Author:	Louise Bruffell	**Date:**	1 November 2022
Checker (basis):	Kate Thatcher	**Date:**	1 December 2022
Checker (implementation):	Kate Thatcher	**Date:**	1 December 2022

Table E-67 Dietary Intakes for the Self-Sufficient Indigenous Receptor Group

Category	Local Fraction*	Ingestion Rate			Unit	Notes/ref
		Infant	Child	Adult		
Food						
Deer[1]	0.1 [1]	189.7 [5]	270.4	557.3	g/d	SENES, 2014
Moose[1]	0.1 [1]	189.7 [5]	270.4	557.3	g/d	SENES, 2014
Grouse	0.44 [1]	94.9 [5]	135.4	278.7	g/d	SENES, 2014
Duck	0.44 [1]	147.6 [6]	278.7	278.7	g/d	SENES, 2014
Fish [2]	1	207.03 [5]	295.1	608.2	g/d	SENES, 2014
Berries[3]	0.2 [1]	918.6 [6]	1,734.2	1,038.1	g/d	SENES, 2014
Mushrooms[4]	1	1.0	3.9	4.8	g/d	CSA, 2022
Honey	1	1.8	5.2	6.7	g/d	CSA, 2022

Notes:

* Local fractions are based on the scenario description and on the nature of the receptor.

1 The local fraction for deer and moose assumes that all hunting occurs in the contaminated area, however, is set to 0.1 to account for the likely use of less contaminated foraging sites within a large home range, as recommended in CSA, 2022. The local fraction of grouse, duck and berries are taken from CSA, 2022.

2 Fish are assumed to be taken from the Ottawa River.

3 Berries will be considered separately from other fruits and vegetables, and will be modeled as strawberries (as per CSA, 2022).

4 Modeled as Generic Fruit and Vegetables from CSA (2022).

5 Derived by scaling the adult intake value.

6 Derived by scaling the child intake value.

E 3.10 Data for Disruptive Event Scenarios

E 3.10.1 Case DE(a): Site Investigation (Inadvertent Human Intrusion)

Name:	Drill Crew Exposure Characteristics		
Version:	Version 4		
Symbol:	See 'Value(s)'		
Units:	See 'Value(s)'		
Description:	The exposure group characteristics for a drill crew that is assumed to inadvertently penetrate the NPDDF Reactor Vault after its closure.		
Value(s):	• Mass of contaminated material retrieved, M_{intrus}: 5 kg • Exposure duration, t_{HI}: 12 hours • External dose factors: Point source, DCF_P (see Table E-68).		
Justification:	The parameterization of the site investigation scenario assumes that a drill crew inadvertently core through the Reactor Vault, and retrieve a sample of the waste metals present within. The most common drill core used in North America is NQ sized as it provides good sized samples but is small enough to be economically drilled quickly in multiple hard rock types and to great depths (https://canadamines.ca/basics-of-logging-core-samples-for-mineral-exploration/). HQ and larger cores are used for shallow unconsolidated deposits. Core boxes for NQ cores normally hold 4.57 m (15 feet) – the typical length of a core barrel. It was estimated that 12 coolant tubes, which is the maximum number of coolant vertical tubes, will be captured by 2 sections of core and stored in a single core boxes holding 4.57 m of core in 3 sections. Assuming density of Zircaloy of 6560 kg/m^3 and density of grout of 2100 kg/m^3, an estimate of the mass of Zircaloy in the core sample was made, being 0.437 kg in 16.25 kg of grout, dictated by the core sample size of 4.5 m. Therefore, the 5 kg value of metal used is a factor of 10 more conservative than would be expected. The exposure conditions assume typical practice for a drill crew, based on the considerations presented by Penfold *et al*. (2011). In view of the shallow depth of the Facility, only one day's drilling was assumed. Inadvertent ingestion rates are as specified for the Site Resident.		
Uncertainty:	The scenario assumptions are defined cautiously, recognising the uncertainty of the exposure situation ever occurring. Even if the larger PQ size core was used, the mass of Zircaloy would only be around 1.4 kg		
Source of uncertainty:	The scenario is highly uncertain but has been parameterised in a cautious way so as to bound the potential exposure.		
References:	ICRP (2008). Nuclear Decay Data for Dosimetric Calculations. ICRP Publication 107, Ann. ICRP 38 (3), 2008. Penfold JSS, Little RH and Ramlakan A (2011). Postclosure Safety Assessment: Analysis of Human Intrusion and Other Disruptive Scenarios, NWMO DGR-TR-2011-27. Smith GM, Fearn HS, Smith KR, Davis JP and Klos R (1988). Assessment of the radiological impact of disposal of solid radioactive waste at Drigg. National Radiological Protection Board Memorandum NRPB-M148.		
Author:	James Penfold	**Date:**	6 July 2019
Checker (basis):	Emma Cairns	**Date:**	10 July 2019
Checker (implementation):	Renato Zagorscak	**Date:**	27 January 2023

Table E-68 External Dose Factors for the Site Investigation Scenario

Parents[A]	Mean Gamma Energy[B], MeV	External Dose Coefficient from a Point Source[C] DCFp, Sv h^{-1} Bq^{-1}
H-3	0.0E+00	0.0E+00
C-14	0.0E+00	0.0E+00
Cl-36	1.5E-04	2.0E-17
Ca-41	5.0E-04	7.0E-17
Fe-60*	6.7E-03	9.4E-16
Co-60	2.5E+00	3.5E-13
Ni-59	2.4E-03	3.3E-16
Ni-63	0.0E+00	0.0E+00
Se-79	0.0E+00	0.0E+00
Sr-90	1.2E-06	1.7E-19
Nb-93m	2.0E-03	2.8E-16
Nb-94	1.6E+00	2.2E-13
Zr-93	0.0E+00	0.0E+00
Tc-99	7.0E-07	9.8E-20
Ag-108m	1.6E+00	2.3E-13
Cd-113m	7.3E-05	1.0E-17
Sn-121m	5.1E-03	7.1E-16
Sb-125	4.5E-01	6.2E-14
Cs-137	5.6E-01	7.9E-14
Sm-151	1.6E-05	2.2E-18
Eu-152	1.2E+00	1.6E-13
Eu-154	1.3E+00	1.8E-13
Ho-166m	1.6E+00	2.3E-13
Hf-182	2.4E-01	3.4E-14
Pb-210*	5.3E-03	7.5E-16
Po-210	9.7E-06	1.4E-18
Ra-226*	1.7E+00	2.4E-13
Ra-228*	8.7E-01	1.2E-13
Ac-227*	4.5E-01	6.2E-14
Th-228*	1.5E+00	2.1E-13
Th-229*	3.3E-01	4.6E-14
Th-230	1.8E-03	2.5E-16
Th-232	1.5E-03	2.1E-16
Pa-231	4.5E-02	6.3E-15
U-232	2.0E-03	2.9E-16
U-233	1.3E-03	1.8E-16

Parents[A]	Mean Gamma Energy[B], MeV	External Dose Coefficient from a Point Source[C] DCFp, Sv h^{-1} Bq^{-1}
U-234	2.0E-03	2.8E-16
U-235	1.9E-01	2.7E-14
U-236	1.8E-03	2.5E-16
U-238	3.1E-02	4.3E-15
Np-237	2.6E-01	3.6E-14
Pu-238	2.1E-03	2.9E-16
Pu-239	1.1E-03	1.5E-16
Pu-240	1.9E-03	2.7E-16
Pu-241	5.3E-06	7.4E-19
Pu-242	1.7E-03	2.4E-16
Am-241	2.9E-02	4.1E-15
Am-242m	2.7E-02	3.8E-15
Am-243	2.4E-01	3.4E-14
Cm-242	2.0E-03	2.8E-16
Cm-243	1.4E-01	1.9E-14
Cm-244	1.7E-03	2.4E-16
Cm-245	1.1E-01	1.5E-14
Cm-246	4.8E-03	6.8E-16

Notes:

A Includes contribution from short-lived daughters (see Section E 3.2.1), indicated by "*".

B Data are taken from ICRP (2008). The mean gamma energy is the sum of contributions from gamma emissions, x-rays and annihilation. In each case, the mean energy is calculated as the sum of the products of energy and intensity of emissions.

C Dose factors for objects taken a distance of 1 m from a point source and are obtained by multiplying the mean gamma energy in MeV by 1.4×10^{-13} Sv h^{-1} per Bq MeV^{-1} (Smith *et al.*, 1988).

E 3.10.2 Case DE(b) - Surface Erosion

Name:	Concentration in Soil		
Version:	Version 4.0		
Symbol:	Not applicable		
Units:	Not applicable		
Description:	After erosion of the overburden, the exposure group can be directly exposed to the overburden material that is directly contaminated by groundwater.		
Value(s):	Concentration of the garden, used in dose calculations, $C_{V\ Garden}$ is assigned the value of the concentration in the overburden, C_V		
Justification:	Although it is highly unlikely, scoping studies have indicated that an extreme flood could reach the same elevation as the ground surface at the NPDDF. Although such an event would be most likely to result in increased flow through the facility this would not increase doses as there would be more dilution. Therefore, the most conservative case to consider is if the flood, or some other event, were to result in the removal of some of the geosphere to result in exposing the material directly contaminated with leakage from the NPDDF. This scenario uses the same human Resident Receptor as the NES, and they are assumed to have the same habits as in the NES, except that they are very conservatively assumed to spend time on the contaminated surface through which the groundwater directly flows; for this case, this area is simulated as the “garden” in which vegetables are grown, because this further increases the receptor’s exposure.		
Uncertainty:	Studies have suggested an extreme event would be needed to result in this situation occurring.		
Source of uncertainty:	Potential for climate change to affect water balance.		
References:			
Author:	James Penfold	**Date:**	12 June 2017
Checker (basis):	Renato Zagorscak	**Date:**	27 January 2023
Checker (implementation):	Renato Zagorscak	**Date:**	27 January 2023

E 3.10.3 Case DE(c): Extreme Degradation

Name:	Extreme Degradation		
Version:	Version 4		
Parameter Name:	t_{NPD_Flow}		
Units:	y		
Description:	The condition of engineered barriers is represented through the timing at which different flow regimes through the facility (Arcadis & Geofirma, 2023b) are applied. In this sensitivity case, engineering is assumed to become extremely degraded (hydraulic conductivity of 1E-06 m/s) above bedrock, and degraded (hydraulic conductivity of 1E-08 m/s) below bedrock, after 1000 y.		
Value(s):	Flow regime 1 (undegraded facility with tile drains) operates from 0 y Flow regime 2 (undegraded facility with no tile drains) operates from 100 y Flow regime 5 (extremely degraded facility with tile drain failure) operates from 1000 y onwards The flows for the different flow regimes can be found in Table E-26 and Table E-29.		
Justification:	It is very conservatively assumed that the engineered barriers have become extremely degraded (in terms of hydraulic performance) 1000 y after decommissioning is complete.		
Uncertainty:	Jackson *et al*. (2011) provide details of the anticipated uncertainties in engineering performance. Arcadis & Geofirma (2023b) provides a calculation of flows through the NPDDF in which it Is assumed to have a very high hydraulic conductivity.		
Source of uncertainty:	The main source of uncertainty is in the timescales for degradation as represented by the variation of hydraulic conductivity with time.		
References:	Arcadis Canada Inc. & Geofirma Ltd. (2023b). 2023 Near-Field Groundwater Model at the Site of the Proposed Decommissioned Rolphton Nuclear Power Demonstration (NPD) Reactor. CNL No. 64-508760-REPT-013 Rev 1. June. Jackson CP, Couch M, Yates H, Smith V, Kelly M and James M (2011). Elicitation of Uncertainties for LLWR, LLWR Environmental Safety Case report SERCO/TAS/E003796/010, Issue 2, April 2011. LLWR (2011). The 2011 Environmental Safety Case: Engineering Design, LLWR/ESC/R(11)10020, May 2011.		
Author:	Louise Bruffell	**Date:**	30 June 2023
Checker (basis):	Kate Thatcher	**Date:**	4 July 2023
Checker (implementation):	Kate Thatcher	**Date:**	4 July 2023

E 3.10.4 Case DE(d): Fault Zone Activation

Name:	Fault Zone Activation		
Version:	Version 4		
Parameter Name:	t_{NPD_Flow}, Q_{NPD}, $q_{upstream}$, q_{c_vol}		
Units:	y		
Description:	Examines the impacts of an extreme seismic event occurring, damaging the facility (in the same manner as Extreme Degradation case – Section E 3.10.3) but also creating a fracture zone, which will be represented using a higher conductivity in the bedrock between the facility and the river compared to that of the NES. Grout and concrete are extremely degraded (hydraulic conductivity of 1E-06 m/s).		
Value(s):	Flow regime 1 (undegraded facility with tile drains) operates from 0 y Flow regime 2 (undegraded facility with no tile drains) operates from 100 y Alternative Flow regime 5 (extremely degraded facility with tile drain failure and fault zone) operates from 1000 y onwards See Table E-69 and Table E-70 for alternative flow 5 values.		
Justification:	It is very conservatively assumed that the engineered barriers have become extremely degraded (in terms of hydraulic performance) 1000 y after decommissioning is complete, and a seismic event has induced a fracture zone in the bedrock.		
Uncertainty:	Jackson *et al*. (2011) provide details of the anticipated uncertainties in engineering performance. Arcadis & Geofirma (2023b) provides a calculation of flows through the NPDDF and the geosphere in which it Is assumed to have a very high hydraulic conductivity.		
Source of uncertainty:	The main source of uncertainty is in the timescales for degradation as represented by the variation of hydraulic conductivity with time.		
References:	Arcadis Canada Inc. & Geofirma Ltd. (2023b). 2023 Near-Field Groundwater Model at the Site of the Proposed Decommissioned Rolphton Nuclear Power Demonstration (NPD) Reactor. CNL No. 64-508760-REPT-013 Rev 1. June. Jackson CP, Couch M, Yates H, Smith V, Kelly M and James M (2011). Elicitation of Uncertainties for LLWR, LLWR Environmental Safety Case report SERCO/TAS/E003796/010, Issue 2, April 2011. LLWR (2011). The 2011 Environmental Safety Case: Engineering Design, LLWR/ESC/R(11)10020, May 2011.		
Author:	Louise Bruffell	**Date:**	30 June 2023
Checker (basis):	Kate Thatcher	**Date:**	4 July 2023
Checker (implementation):	Kate Thatcher	**Date:**	4 July 2023

Table E-69 Flow Rates within the NPD for case DE(d) – Fault Zone Activation (m^3 y^{-1})

Room, Face and Direction*	Fault Zone Flow Case (5)
BRD_B_in	0
BRD_B_out	69.42672
BRD_E_in	0
BRD_E_out	85.20552
BRD_N_in	0
BRD_N_out	119.9189
BRD_S_in	126.2304
BRD_S_out	0
BRD_T_in	72.58248
BRD_T_out	0
BRD_W_in	72.58248
BRD_W_out	0
BRS_B_in	0.08205
BRS_B_out	217.7474
BRS_E_in	0
BRS_E_out	246.1493
BRS_N_in	7.258248
BRS_N_out	246.1493
BRS_S_in	410.2488
BRS_S_out	0
BRS_T_in	94.6728
BRS_T_out	0.097829
BRS_W_in	208.2802
BRS_W_out	0
BRU_B_in	0
BRU_B_out	82.04976
BRU_E_in	0
BRU_E_out	7.573824
BRU_N_in[1]	10.72958
BRU_N_out[1]	3.786912
BRU_S_in	14.83207
BRU_S_out	0
BRU_T_in	23.98378
BRU_T_out	0.007574
BRU_W_in	56.80368
BRU_W_out	10.41401
DPR_B_in	0
DPR_B_out	34.71336
DPR_E_in	0

Room, Face and Direction*	Fault Zone Flow Case (5)
DPR_E_out	10.41401
DPR_N_in	0
DPR_N_out	31.5576
DPR_S_in	29.66414
DPR_S_out	0
DPR_T_in[2]	**82.04976**
DPR_T_out[2]	0
DPR_W_in	10.72958
DPR_W_out	0
ERV_B_in	0
ERV_B_out	17.98783
ERV_E_in	9.46728
ERV_E_out	3.786912
ERV_N_in	0
ERV_N_out	126.2304
ERV_S_in	75.73824
ERV_S_out	0
ERV_T_in	97.82856
ERV_T_out	37.86912
ERV_W_in	6.942672
ERV_W_out	3.15576
FR_B_in	2.019686
FR_B_out	261.9281
FR_E_in	113.6074
FR_E_out	9.151704
FR_N_in	0
FR_N_out	217.7474
FR_S_in	246.1493
FR_S_out	8.836128
FR_T_in	63.1152
FR_T_out	0.91517
FR_W_in	82.04976
FR_W_out	6.627096
FSRS_B_in	0
FSRS_B_out	179.8783
FSRS_E_in	72.58248
FSRS_E_out	9.782856
FSRS_N_in	0
FSRS_N_out	246.1493
FSRS_S_in	164.0995
FSRS_S_out	0

Room, Face and Direction*	Fault Zone Flow Case (5)
FSRS_T_in	151.4765
FSRS_T_out	0
FSRS_W_in	47.3364
FSRS_W_out	0
FSRU_B_in	10.09843
FSRU_B_out	227.2147
FSRU_E_in	47.3364
FSRU_E_out	2.903299
FSRU_N_in	0
FSRU_N_out	37.86912
FSRU_S_in	123.0746
FSRU_S_out	14.5165
FSRU_T_in	69.42672
FSRU_T_out	3.15576
FSRU_W_in	16.72553
FSRU_W_out	5.680368
NoFlowData	0
RV_B_in [2]	0
RV_B_out [2]	82.04976
RV_E_in	0.091517
RV_E_out	37.86912
RV_N_in	0
RV_N_out	220.9032
RV_S_in	195.6571
RV_S_out	0
RV_T_in	97.82856
RV_T_out	0
RV_W_in	47.3364
RV_W_out	0
TR_B_in	0
TR_B_out	170.411
TR_E_in	0
TR_E_out	504.9216
TR_N_in	0
TR_N_out	41.02488
TR_S_in [1]	**3.786912**
TR_S_out [1]	**10.72958**
TR_T_in	75.73824
TR_T_out	0.041025
TR_W_in	662.7096
TR_W_out	44.18064

Room, Face and Direction*	Fault Zone Flow Case (5)
WRV_B_in	0
WRV_B_out	17.0411
WRV_E_in	0
WRV_E_out	34.71336
WRV_N_in	4.102488
WRV_N_out	31.5576
WRV_S_in	25.56166
WRV_S_out	0
WRV_T_in	34.71336
WRV_T_out	13.56977
WRV_W_in	34.71336
WRV_W_out	1.609438

Notes: * The location of the flows are specified as follows.

Rooms are: BRD = Boiler Room (Deep), BRS = Boiler Room (Saturated), BRU = Boiler Room (Upper), DPR = Dump Pipe Room, FR = Fuelling Room, FSRS = Fuel Storage Room (Saturated), FSRU = Fuel Storage Room (Upper), ERV = East Room of the Reactor Vault, WRV = West Room of the Reactor Vault, RV = Reactor Vault, TR = Turbine Room

Face is: N = site north (direction of groundwater flow towards the river, all other directions relative to this), S = south, E = east, W = west, T = top, B = bottom

Direction is: in = flow into the relevant compartment through the relevant face, out = flow outwards through the face.

[1] For consistency, flows taken are maximum of flow in/out north of BRU and out/in south of TR (bold values those changed).

[2] For consistency, flows taken are maximum of flow in/out bottom of RV and out/in top of DPR (bold values those changed).

Table E-70 Flow Rates in the geosphere surrounding the NPD for case DE(d) – Fault Zone Activation.

	Units	Fault Zone Flow Case (5)
$q_{upstream}$	m y^{-1}	0.415
DGeo_0	m^3 y^{-1}	10607.83
DGeo_1	m^3 y^{-1}	21383.6
DGeo_2	m^3 y^{-1}	32159.36
DGeo_3	m^3 y^{-1}	36298.34
DGeo_4	m^3 y^{-1}	32957.18
DGeo_5	m^3 y^{-1}	32957.18
PT_1	m^3 y^{-1}	24992.43
PT_2	m^3 y^{-1}	49911.39
PT_3	m^3 y^{-1}	53547.72
PT_4	m^3 y^{-1}	33197.02
PT_5	m^3 y^{-1}	33197.02
SGeo_1	m^3 y^{-1}	48560.92
SGeo_2	m^3 y^{-1}	53948.8
SGeo_3	m^3 y^{-1}	101785.1
SGeo_4	m^3 y^{-1}	197463.8
SGeo_5	m^3 y^{-1}	197463.8
TD_1	m^3 y^{-1}	12804.27
TD_2	m^3 y^{-1}	18461.55
TD_3	m^3 y^{-1}	17532.22
TD_4	m^3 y^{-1}	9179.317
TD_5	m^3 y^{-1}	9179.317

E 3.10.5 Case DE(e): Excavation of Above-Bedrock Facility

Name:	Excavation of Above-Bedrock Facility		
Version:	Version 4		
Parameter Name:	V_{Exc}		
Units:	m^3		
Description:	Volume into which the disrupted NPDDF is dispersed in the "what if" Mass Excavation case. Examines the impacts of the above-bedrock portion of the facility being excavated and mixed with soil, using the following assumptions: • The facility is being excavated down to the level of bedrock; • The excavated material is dispersed into garden soil at a ratio of 1:10 (grout and concrete to soil) and the garden used to grow crops; and • No house is built inside the excavated hole. The exposure group is the site resident (adult, child, infant), whereas other aspects are represented similarly to Mass Excavation Scenario (Section E 3.12.1)		
Value(s):	V_{Exc} is calculated based on the spatial volumes of the components assumed to be excavated. These include the NPD_Cap, NPD_FSRu, NPD_FR, NPD_BRu, and NPD_TR. f_{Exc} = 0.1		
Justification:	Inadvertent mass excavation of the entire facility is unlikely in the future given that the facility is built into bedrock and the difficulty of breaking through the bedrock, and the reinforced concrete and metallic components of the reactor. This is particularly true for the deeper parts of the facility, given that the bottom of the facility is at a depth of 15.2 m into the bedrock (about 50 feet). The most likely scenario is that the overburden over the facility would be excavated. But even this would not be easy and would not be done except for a very good reason given that the depth of the overburden over the bedrock at the site of the facility is about 7.6 m (or about 25 feet). Nevertheless, this disruptive event scenario examines mass excavation to the level of bedrock assuming dispersion of the material in the garden.		
Uncertainty:	The entire Facility Excavation is considered in a "What If" scenario (Section E 3.12.1), which is very conservative.		
Source of uncertainty:	The main source of uncertainty is the depth of excavation (covered under the "What If" scenario), and the ratio of soil to facility material. 10:1 ratio of soil to facility material used is conservative, as farmers generally tend to remove rocks from their fields (so as not to damage equipment). Furthermore, the metallic components of the facility would likely not be left in the field. Any metallic materials potentially left in the field would have to degrade/corrode before radionuclides embedded in the material are released into the soil and become available for plant uptake. This aspect was conservatively neglected in the assessment of the mass excavation scenario.		
References:	Not Applicable		
Author:	Louise Bruffell	**Date:**	9 February 2023
Checker (basis):	Kate Thatcher	**Date:**	10 February 2023
Checker (implementation):	Kate Thatcher	**Date:**	10 February 2023

E 3.10.6 Case DE(f): Overburden Well

Name:	Overburden Well		
Version:	Version 4.0		
Symbol:	t_{NPD_Flow}, Q_{NPD}, $q_{upstream}$, q_{c_vol}		
Units:	-, $m^3\ y^{-1}$, m/y, $m^3\ y^{-1}$,		
Description:	Alternative flows through the facility and surrounding geosphere for the case examining the impacts of the resident receptor using an overburden well intersecting water in the shallow geosphere.		
Value(s):	Water for drinking and for irrigation is taken from the "SGeo1" compartment in the numerical model rather than the "River1" compartment. Flow regime 1 (undegraded facility with tile drains) operates from 0 y Alternate Flow regime 2 (undegraded facility with no tile drains) operates from 100 y Alternate Flow regime 4 (degraded facility with tile drain failure) operates from 1000 y onwards See Table E-71 and Table E-72 for alternative flow values taking into account the overburden well.		
Justification:	The Normal Evolution scenario models transport of contaminants in river water to the garden and grazing land, assuming that it is extracted from the river. A more conservative assumption is that it is sourced from a groundwater well. This case considers a groundwater well, intersecting water in the shallow geosphere (i.e., the tile drain trench), being used for this purpose. The same amounts of water are assumed to be drawn (Q_Irri for the irrigation of soil, and Q_AnmWat for the animal's water released onto the grazing land). The alternative flows provided by Geofirma are determined by placing a 6" diameter well in the tile drain trench, which lies at the top of the bedrock. The closest compartment we have to this feature is SGeo1. This compartment also contains the highest concentration of contaminants within the shallow geosphere.		
Uncertainty:	Although wells are relatively common in the vicinity of the site, it is unclear whether a well would be created with the river very close-by.		
Source of uncertainty:	Human habits.		
References:	Arcadis Canada Inc. & Geofirma Ltd. (2023a). 2023 Groundwater Modelling at the Site of the Proposed Decommissioned Rolphton Nuclear Power Demonstration (NPD) Reactor. CNL No. 64-508760-REPT-012 Rev 1. June. Arcadis Canada Inc. & Geofirma Ltd. (2023b). 2023 Near-Field Groundwater Model at the Site of the Proposed Decommissioned Rolphton Nuclear Power Demonstration (NPD) Reactor. CNL No. 64-508760-REPT-013 Rev 1. June. Arcadis Canada Inc. & Geofirma Ltd. (2023c). 2023 Resaturation Modelling for the Proposed Decommissioned Rolphton Nuclear Power Demonstration (NPD) Reactor. CNL No. 64-508760-REPT-015 Rev 3. June.		
Author:	Louise Bruffell	**Date:**	9 February 2023
Checker (basis):	Kate Thatcher	**Date:**	10 February 2023
Checker (implementation):	Kate Thatcher	**Date:**	10 February 2023

Table E-71 Flow Rates within the NPD for case DE(f) – overburden well (m^3 y^{-1})

Room, Face and Direction*	OB Well Flow Case (2)	OB Well Flow Case (4)
BRD_B_in	0.001388534	0.08520552
BRD_B_out	0.000946728	0.31242024
BRD_E_in	0	0
BRD_E_out	0.011991888	1.9250136
BRD_N_in	0	0
BRD_N_out	0.016094376	2.3983776
BRD_S_in	0.012307464	2.1459168
BRD_S_out	0	0
BRD_T_in	0.001672553	0.27770688
BRD_T_out	2.27E-05	0
BRD_W_in	0.013569768	2.0828016
BRD_W_out	0	0
BRS_B_in	0.000757382	0.1420092
BRS_B_out	0.008204976	1.7672256
BRS_E_in	0	0
BRS_E_out	0.0315576	4.73364
BRS_N_in	0.000568037	0.12938616
BRS_N_out	0.05680368	5.995944
BRS_S_in	0.03786912	6.31152
BRS_S_out	0	0
BRS_T_in	0.031242024	1.735668
BRS_T_out	0.000157788	0.003786912
BRS_W_in	0.022721472	4.102488
BRS_W_out	0	0
BRU_B_in	0.007573824	0.3471336
BRU_B_out	0.029348568	2.051244
BRU_E_in	0	0
BRU_E_out	0.014516496	0.4418064
BRU_N_in[1]	**0.002209032**	0.23037048
BRU_N_out[1]	0.010414008	**0.2682396**
BRU_S_in	0.01262304	0.5680368
BRU_S_out	0.000504922	0.03471336
BRU_T_in	0.024614928	0.8520552
BRU_T_out	0.002177474	0.11991888
BRU_W_in	0.013885344	0.9151704
BRU_W_out	0.006942672	0.05049216
DPR_B_in	0.000410249	0.029348568
DPR_B_out	0.001041401	0.25561656
DPR_E_in	0	0

Room, Face and Direction*	OB Well Flow Case (2)	OB Well Flow Case (4)
DPR_E_out	0.002177474	0.315576
DPR_N_in	0	0
DPR_N_out	0.002745511	0.473364
DPR_S_in	0.00224059	0.4418064
DPR_S_out	0	0
DPR_T_in[2]	**0.005680368**	**0.8520552**
DPR_T_out[2]	6.94E-06	**0.009151704**
DPR_W_in	0.001420092	0.25877232
DPR_W_out	0	0
ERV_B_in	0	0
ERV_B_out	0.00236682	0.315576
ERV_E_in	0.002272147	0.3471336
ERV_E_out	1.10E-05	0
ERV_N_in	0	0
ERV_N_out	0.014832072	2.5561656
ERV_S_in	0.008836128	1.5463224
ERV_S_out	0	0
ERV_T_in	0.012307464	1.735668
ERV_T_out	0.0078894	0.946728
ERV_W_in	0.001893456	0.29664144
ERV_W_out	0	0.026192808
FR_B_in	0.00473364	0.2524608
FR_B_out	0.0315576	4.418064
FR_E_in	0.01104516	2.051244
FR_E_out	0.000757382	0.19250136
FR_N_in	0.000138853	0
FR_N_out	0.0473364	4.102488
FR_S_in	0.03786912	4.418064
FR_S_out	0.000284018	0.26192808
FR_T_in	0.023352624	1.1676312
FR_T_out	0.002429935	0.05049216
FR_W_in	0.00946728	1.104516
FR_W_out	0.005049216	0.13569768
FSRS_B_in	0	0
FSRS_B_out	0.023983776	3.471336
FSRS_E_in	0.003061087	0.946728
FSRS_E_out	0.004102488	0.473364
FSRS_N_in	0	0
FSRS_N_out	0.017987832	3.471336
FSRS_S_in	0.015147648	2.5877232
FSRS_S_out	0	0

Room, Face and Direction*	OB Well Flow Case (2)	OB Well Flow Case (4)
FSRS_T_in	0.02051244	1.9250136
FSRS_T_out	0.000176723	0
FSRS_W_in	0.009151704	1.7672256
FSRS_W_out	3.12E-06	0
FSRU_B_in	0.003786912	0.24299352
FSRU_B_out	0.0315576	3.15576
FSRU_E_in	0.00473364	0.7573824
FSRU_E_out	0.00029033	0.04102488
FSRU_N_in	0	0
FSRU_N_out	0.020196864	0.8836128
FSRU_S_in	0.025561656	1.8618984
FSRU_S_out	0.002934857	0.14516496
FSRU_T_in	0.020196864	1.0098432
FSRU_T_out	0.002082802	0.028717416
FSRU_W_in	0.002966414	0.2524608
FSRU_W_out	0.001072958	0.0473364
NoFlowData	0	0
RV_B_in [2]	**6.94E-06**	0.009151704
RV_B_out [2]	0.005680368	0.8520552
RV_E_in	5.05E-05	0.000473364
RV_E_out	0.006942672	1.0098432
RV_N_in	0	0
RV_N_out	0.019565712	3.471336
RV_S_in	0.018303408	3.15576
RV_S_out	0	0
RV_T_in	0.01104516	1.262304
RV_T_out	0	0
RV_W_in	0.003061087	0.7258248
RV_W_out	0	0
TR_B_in	0.005049216	0.473364
TR_B_out	0.03471336	3.786912
TR_E_in	0	0
TR_E_out	0.06627096	10.414008
TR_N_in	0.000378691	0.016094376
TR_N_out	0.004418064	0.28717416
TR_S_in [1]	**0.010414008**	0.2682396
TR_S_out [1]	0.002209032	**0.23037048**
TR_T_in	0.04102488	1.5147648
TR_T_out	0.002429935	0.15147648
TR_W_in	0.06942672	13.254192
TR_W_out	0.0157788	0.9151704

Room, Face and Direction*	OB Well Flow Case (2)	OB Well Flow Case (4)
WRV_B_in	0	0
WRV_B_out	0.002019686	0.315576
WRV_E_in	0	0
WRV_E_out	0.001735668	0.473364
WRV_N_in	0.000473364	0.07573824
WRV_N_out	0.003786912	0.5995944
WRV_S_in	0.003471336	0.5680368
WRV_S_out	0	0
WRV_T_in	0.002587723	0.4418064
WRV_T_out	0.001609438	0.21459168
WRV_W_in	0.002682396	0.5680368
WRV_W_out	9.47E-05	0.022405896

Notes: * The location of the flows are specified as follows.

Rooms are: BRD = Boiler Room (Deep), BRS = Boiler Room (Saturated), BRU = Boiler Room (Upper), DPR = Dump Pipe Room, FR = Fuelling Room, FSRS = Fuel Storage Room (Saturated), FSRU = Fuel Storage Room (Upper), ERV = East Room of the Reactor Vault, WRV = West Room of the Reactor Vault, RV = Reactor Vault, TR = Turbine Room.

Face is: N = site north (direction of groundwater flow towards the river, all other directions relative to this), S = south, E = east, W = west, T = top, B = bottom.

Direction is: in = flow into the relevant compartment through the relevant face, out = flow outwards through the face.

[1] For consistency, flows taken are maximum of flow in/out north of BRU and out/in south of TR (bold values those changed).

[2] For consistency, flows taken are maximum of flow in/out bottom of RV and out/in top of DPR (bold values those changed).

Table E-72 Flow Rates in the Geosphere Surrounding the NPD for Case DE(f) – Overburden Well

	Units	OB Well Flow Case (2)	OB Well Flow Case (4)
$q_{upstream}$	m y^{-1}	0.045	0.0448
DGeo_0	m^3 y^{-1}	1001.516	1035.593
DGeo_1	m^3 y^{-1}	2227.26	2247.867
DGeo_2	m^3 y^{-1}	3453.003	3460.14
DGeo_3	m^3 y^{-1}	3959.69	3959.69
DGeo_4	m^3 y^{-1}	3655.948	3655.948
DGeo_5	m^3 y^{-1}	3655.948	3655.948
PT_1	m^3 y^{-1}	36573.23	36573.23
PT_2	m^3 y^{-1}	68361.74	68361.74
PT_3	m^3 y^{-1}	72496.49	72496.49
PT_4	m^3 y^{-1}	45463.46	45463.46
PT_5	m^3 y^{-1}	45463.46	45463.46
SGeo_1	m^3 y^{-1}	117669.3	117669.3
SGeo_2	m^3 y^{-1}	145955.6	145955.6
SGeo_3	m^3 y^{-1}	195929.3	195929.3
SGeo_4	m^3 y^{-1}	270346.1	270346.1
SGeo_5	m^3 y^{-1}	270346.1	270346.1
TD_1	m^3 y^{-1}	13725.11	13725.11
TD_2	m^3 y^{-1}	18574.2	18574.2
TD_3	m^3 y^{-1}	17359.44	17359.44
TD_4	m^3 y^{-1}	9310.281	9310.281
TD_5	m^3 y^{-1}	9310.281	9310.281

E 3.10.7 Case DE(g): Bedrock Well

Name:	Overburden Well		
Version:	Version 4.0		
Symbol:	t_{NPD_Flow}, Q_{NPD}, $q_{upstream}$, q_{c_vol}		
Units:	-, $m^3\ y^{-1}$, m/y, $m^3\ y^{-1}$,		
Description:	Alternative flows through the facility and surrounding geosphere for the case examining the impacts of the resident receptor using a well intersecting the bedrock release plume between the facility and the river.		
Value(s):	Water for drinking and for irrigation is taken from the "DGeo1" compartment in the numerical model rather than the "River1" compartment. Flow regime 1 (undegraded facility with tile drains) operates from 0 y Alternate Flow regime 2 (undegraded facility with no tile drains) operates from 100 y Alternate Flow regime 4 (degraded facility with tile drain failure) operates from 1000 y onwards. See Table E-73 and Table E-74 for alternative flow values taking into account the bedrock well.		
Justification:	The Normal Evolution scenario models transport of contaminants in river water to the garden and grazing land, assuming that it is extracted from the river. A more conservative assumption is that it is sourced from a groundwater well. This case considers a 6" diameter groundwater well, intersecting the bedrock release plume between the facility and the river, being used for this purpose. The same amounts of water are assumed to be drawn (Q_Irri for the irrigation of soil, and Q_AnmWat for the animal's water released onto the grazing land).		
Uncertainty:	Although wells are relatively common in the vicinity of the site, it is unclear whether a well would be created with the river very close-by.		
Source of uncertainty:	Human habits.		
References:	Arcadis Canada Inc. & Geofirma Ltd. (2023a). 2023 Groundwater Modelling at the Site of the Proposed Decommissioned Rolphton Nuclear Power Demonstration (NPD) Reactor. CNL No. 64-508760-REPT-012 Rev 1. June. Arcadis Canada Inc. & Geofirma Ltd. (2023b). 2023 Near-Field Groundwater Model at the Site of the Proposed Decommissioned Rolphton Nuclear Power Demonstration (NPD) Reactor. CNL No. 64-508760-REPT-013 Rev 1. June. Arcadis Canada Inc. & Geofirma Ltd. (2023c). 2023 Resaturation Modelling for the Proposed Decommissioned Rolphton Nuclear Power Demonstration (NPD) Reactor. CNL No. 64-508760-REPT-015 Rev 3. June.		
Author:	Louise Bruffell	**Date:**	9 February 2023
Checker (basis):	Kate Thatcher	**Date:**	10 February 2023
Checker (implementation):	Kate Thatcher	**Date:**	10 February 2023

Table E-73 Flow Rates within the NPD for case DE(g) – bedrock well (m^3 y^{-1})

Room, Face and Direction*	BR Well Flow Case (2)	BR Well Flow Case (4)
BRD_B_in	0.000568037	0.005364792
BRD_B_out	0.003471336	1.0098432
BRD_E_in	0	0
BRD_E_out	0.01735668	2.6508384
BRD_N_in	0	0
BRD_N_out	0.02524608	3.786912
BRD_S_in	0.018303408	3.15576
BRD_S_out	0	0
BRD_T_in	0.005995944	0.946728
BRD_T_out	0	0
BRD_W_in	0.020828016	3.15576
BRD_W_out	0	0
BRS_B_in	0.000142009	0
BRS_B_out	0.023037048	4.102488
BRS_E_in	0	0
BRS_E_out	0.0236682	3.471336
BRS_N_in	0.001230746	0.2997972
BRS_N_out	0.08204976	9.46728
BRS_S_in	0.05049216	8.520552
BRS_S_out	0	0
BRS_T_in	0.04102488	2.36682
BRS_T_out	0	0.001546322
BRS_W_in	0.0315576	5.995944
BRS_W_out	0	0
BRU_B_in	0.00946728	0.4418064
BRU_B_out	0.03471336	2.4614928
BRU_E_in	0	0.5995944
BRU_E_out	0.019881288	0.631152
BRU_N_in[1]	**0.002650838**	0.4102488
BRU_N_out[1]	0.00631152	**0.30610872**
BRU_S_in	0.009782856	0.4102488
BRU_S_out	0.000473364	0.030610872
BRU_T_in	0.029664144	0.946728
BRU_T_out	0.002682396	0.15147648
BRU_W_in	0.017987832	0.6627096
BRU_W_out	0.012307464	0.05049216
DPR_B_in	0.00012623	0
DPR_B_out	0.002587723	0.631152
DPR_E_in	0	0

Room, Face and Direction*	BR Well Flow Case (2)	BR Well Flow Case (4)
DPR_E_out	0.002808626	0.3786912
DPR_N_in	0	0
DPR_N_out	0.003786912	0.6627096
DPR_S_in	0.00302953	0.5995944
DPR_S_out	0	0
DPR_T_in[2]	**0.012307464**	**1.9565712**
DPR_T_out[2]	0	0
DPR_W_in	0.001988129	0.3471336
DPR_W_out	0	0
ERV_B_in	0	0
ERV_B_out	0.005049216	0.7258248
ERV_E_in	0.00302953	0.5049216
ERV_E_out	0	0
ERV_N_in	0	0
ERV_N_out	0.013885344	2.4299352
ERV_S_in	0.009782856	1.6725528
ERV_S_out	0	0
ERV_T_in	0.012938616	1.893456
ERV_T_out	0.007573824	0.946728
ERV_W_in	0.00091517	0.13885344
ERV_W_out	2.34E-05	0.0946728
FR_B_in	0.005680368	0.3471336
FR_B_out	0.04102488	5.364792
FR_E_in	0.012307464	2.36682
FR_E_out	0.003471336	0.315576
FR_N_in	0	0
FR_N_out	0.0473364	4.418064
FR_S_in	0.04102488	5.049216
FR_S_out	0.005364792	0.28086264
FR_T_in	0.029032992	1.57788
FR_T_out	0.001893456	0.07258248
FR_W_in	0.012307464	1.5147648
FR_W_out	0.005995944	0.23983776
FSRS_B_in	0	0
FSRS_B_out	0.03471336	5.049216
FSRS_E_in	0.005364792	1.4832072
FSRS_E_out	0.00473364	0.5049216
FSRS_N_in	0	0
FSRS_N_out	0.021774744	4.102488
FSRS_S_in	0.019565712	3.471336
FSRS_S_out	0	0

Room, Face and Direction*	BR Well Flow Case (2)	BR Well Flow Case (4)
FSRS_T_in	0.027455112	2.6192808
FSRS_T_out	0.000132542	0
FSRS_W_in	0.01104516	2.209032
FSRS_W_out	1.93E-05	0.000217747
FSRU_B_in	0.005364792	0.3471336
FSRU_B_out	0.04418064	4.418064
FSRU_E_in	0.006627096	1.0414008
FSRU_E_out	0.000315576	0.08204976
FSRU_N_in	0	0
FSRU_N_out	0.021774744	0.9151704
FSRU_S_in	0.031242024	2.3352624
FSRU_S_out	0.004102488	0.2051244
FSRU_T_in	0.02524608	1.2938616
FSRU_T_out	0.001925014	0.03786912
FSRU_W_in	0.003786912	0.3471336
FSRU_W_out	0.001830341	0.09151704
NoFlowData	0	0
RV_B_in [2]	0	0
RV_B_out [2]	0.012307464	1.9565712
RV_E_in	0.0001641	0.00946728
RV_E_out	0.005680368	0.6942672
RV_N_in	0	0
RV_N_out	0.025877232	4.418064
RV_S_in	0.022721472	4.102488
RV_S_out	0	0
RV_T_in	0.016725528	2.0196864
RV_T_out	0	0
RV_W_in	0.004102488	0.9782856
RV_W_out	0	0
TR_B_in	0.005049216	0.5680368
TR_B_out	0.04418064	5.680368
TR_E_in	0	0
TR_E_out	0.07573824	13.569768
TR_N_in	0.000473364	0.03471336
TR_N_out	0.001925014	0.11360736
TR_S_in [1]	**0.00631152**	0.30610872
TR_S_out [1]	0.002650838	**0.4102488**
TR_T_in	0.0473364	2.4614928
TR_T_out	0.002682396	0.19565712
TR_W_in	0.08204976	18.303408
TR_W_out	0.014832072	2.0828016

Room, Face and Direction*	BR Well Flow Case (2)	BR Well Flow Case (4)
WRV_B_in	0	0
WRV_B_out	0.003124202	0.473364
WRV_E_in	0	0
WRV_E_out	0.002335262	0.6627096
WRV_N_in	0.000599594	0.09151704
WRV_N_out	0.00473364	0.7573824
WRV_S_in	0.004102488	0.6942672
WRV_S_out	0	0
WRV_T_in	0.004102488	0.6627096
WRV_T_out	0.002461493	0.315576
WRV_W_in	0.003786912	0.78894
WRV_W_out	0.000129386	0.0315576

Notes: * The location of the flows are specified as follows.

Rooms are: BRD = Boiler Room (Deep), BRS = Boiler Room (Saturated), BRU = Boiler Room (Upper), DPR = Dump Pipe Room, FR = Fuelling Room, FSRS = Fuel Storage Room (Saturated), FSRU = Fuel Storage Room (Upper), ERV = East Room of the Reactor Vault, WRV = West Room of the Reactor Vault, RV = Reactor Vault, TR = Turbine Room

Face is: N = site north (direction of groundwater flow towards the river, all other directions relative to this), S = south, E = east, W = west, T = top, B = bottom

Direction is: in = flow into the relevant compartment through the relevant face, out = flow outwards through the face.

[1] For consistency, flows taken are maximum of flow in/out north of BRU and out/in south of TR (bold values those changed).

[2] For consistency, flows taken are maximum of flow in/out bottom of RV and out/in top of DPR (bold values those changed).

Table E-74 Flow Rates in the geosphere surrounding the NPD for case DE(g) – Bedrock Well

	Units	BR Well Flow Case (2)	BR Well Flow Case (4)
$q_{upstream}$	m y^{-1}	0.0605	0.0557
DGeo_0	m^3 y^{-1}	0	0
DGeo_1	m^3 y^{-1}	318.4799	318.4799
DGeo_2	m^3 y^{-1}	2379.345	2379.345
DGeo_3	m^3 y^{-1}	3399.937	3399.937
DGeo_4	m^3 y^{-1}	3248.066	3248.066
DGeo_5	m^3 y^{-1}	3248.066	3248.066
PT_1	m^3 y^{-1}	36573.23	36573.23
PT_2	m^3 y^{-1}	68361.74	68361.74
PT_3	m^3 y^{-1}	72425.09	72425.09
PT_4	m^3 y^{-1}	45240.19	45240.19
PT_5	m^3 y^{-1}	45240.19	45240.19
SGeo_1	m^3 y^{-1}	117669.3	117669.3
SGeo_2	m^3 y^{-1}	145955.6	145955.6
SGeo_3	m^3 y^{-1}	195929.3	195929.3
SGeo_4	m^3 y^{-1}	270346.1	270346.1
SGeo_5	m^3 y^{-1}	270346.1	270346.1
TD_1	m^3 y^{-1}	19238.24	19238.24
TD_2	m^3 y^{-1}	25434.31	25434.31
TD_3	m^3 y^{-1}	23362.49	23362.49
TD_4	m^3 y^{-1}	11972.16	11972.16
TD_5	m^3 y^{-1}	11972.16	11972.16

E 3.11 Data for Defence-in-Depth Cases

Most data used in Disruptive Event scenarios and other calculation cases are the same as the reference data used in the Normal Evolution scenario, and documented in Section E 3.1 to E 3.7 This section presents alternative parameter assumptions and/or additional data used in the suite of additional calculation cases described in Appendix D (Scenarios and Calculation Cases).

E 3.11.1 Case DD(a) - Role of Existing Structure

Name:	Reactor Structure material		
Version:	Version 4		
Symbol:	Q_{NPD}, $q_{upstream}$, q_{c_vol}, $f_{TileDrain}$, $f_{stage_Cem/Grout}$		
Units:	$m^3\ y^{-1}$, m/y, $m^3\ y^{-1}$, -		
Description:	Alternative flows are applied through the facility and surrounding geosphere assuming the concrete structure is fully degraded.		
Value(s):	Alternative flows given in Table E-75, Table E-76 and Table E-77. In terms of chemical properties, structural concrete is modelled as being fully degraded (i.e., Stage IV) beginning at 0 y post-closure.		
Justification:	The material properties are discussed in Sections E 3.4.2, E 3.4.5, 0, E 3.4.7.		
Uncertainty:	Uncertainties are discussed in terms of the material properties.		
Source of uncertainty:	Variability in material properties.		
References:	See Section E 3.4. Arcadis Canada Inc. & Geofirma Ltd. (2023a). 2023 Groundwater Modelling at the Site of the Proposed Decommissioned Rolphton Nuclear Power Demonstration (NPD) Reactor. CNL No. 64-508760-REPT-012 Rev 1. June. Arcadis Canada Inc. & Geofirma Ltd. (2023b). 2023 Near-Field Groundwater Model at the Site of the Proposed Decommissioned Rolphton Nuclear Power Demonstration (NPD) Reactor. CNL No. 64-508760-REPT-013 Rev 1. June. Arcadis Canada Inc. & Geofirma Ltd. (2023c). 2023 Resaturation Modelling for the Proposed Decommissioned Rolphton Nuclear Power Demonstration (NPD) Reactor. CNL No. 64-508760-REPT-015 Rev 3. June.		
Author:	Louise Bruffell	**Date:**	9 February 2023
Checker (basis):	Kate Thatcher	**Date:**	14 February 2023
Checker (implementation):	Kate Thatcher	**Date:**	14 February 2023

Table E-75 Flow Rates within the NPD for case DD(a) – Role of Existing Structure (m^3 y^{-1})

Room, Face and Direction*	Struct Flow Case (1)	Struct Flow Case (2)	Struct Flow Case (4)
BRD_B_in	0.6627096	0.16094376	0.1420092
BRD_B_out	3.786912	4.73364	5.049216
BRD_E_in	0	0	0
BRD_E_out	6.942672	5.364792	6.31152
BRD_N_in	0.1262304	0.011991888	0.010414008
BRD_N_out	4.418064	4.418064	5.364792
BRD_S_in	9.151704	8.520552	9.782856
BRD_S_out	0	0	0
BRD_T_in	0.000536479	0.00157788	0.24614928
BRD_T_out	0.000378691	4.73E-05	0.005995944
BRD_W_in	4.73364	4.418064	5.364792
BRD_W_out	0.0946728	0.14516496	0.05049216
BRS_B_in	9.782856	5.995944	5.995944
BRS_B_out	9.782856	10.414008	11.676312
BRS_E_in	0	0.010729584	0
BRS_E_out	34.71336	23.6682	29.664144
BRS_N_in	3.471336	3.0610872	2.840184
BRS_N_out	9.46728	7.258248	9.782856
BRS_S_in	22.09032	17.35668	24.299352
BRS_S_out	0.3471336	0.10729584	0.09782856
BRS_T_in	0.004102488	0.019881288	1.0098432
BRS_T_out	1.48E-06	6.63E-05	0.00315576
BRS_W_in	17.987832	14.20092	17.041104
BRS_W_out	0	0	0
BRU_B_in	0	3.15576	3.15576
BRU_B_out	0	3.0295296	4.102488
BRU_E_in	0	6.00E-05	0.001009843
BRU_E_out	0	0.1735668	0.5680368
BRU_N_in[1]	**0.4418064**	**6.627096**	**6.627096**
BRU_N_out[1]	**0.9782856**	**5.680368**	**5.680368**
BRU_S_in	0	1.893456	2.997972
BRU_S_out	0	0.08836128	0.18618984
BRU_T_in	0	0.014832072	0.3471336
BRU_T_out	0	0.010414008	0.16409952
BRU_W_in	0	4.73364	5.364792
BRU_W_out	0	0.005049216	0.04102488
DPR_B_in	0.31242024	0.06627096	0.05364792
DPR_B_out	3.0295296	3.471336	3.471336
DPR_E_in	0	0	0

Room, Face and Direction*	Struct Flow Case (1)	Struct Flow Case (2)	Struct Flow Case (4)
DPR_E_out	2.8717416	2.1774744	2.3037048
DPR_N_in	0	0	0
DPR_N_out	2.3983776	1.9881288	2.209032
DPR_S_in	5.364792	4.418064	4.73364
DPR_S_out	0	0	0
DPR_T_in[2]	**6.627096**	**6.942672**	**7.258248**
DPR_T_out[2]	**4.418064**	**1.9881288**	**2.0196864**
DPR_W_in	1.735668	1.5463224	1.6409952
DPR_W_out	0.030295296	0.019250136	0.017672256
ERV_B_in	3.471336	1.57788	1.5147648
ERV_B_out	2.2721472	1.8303408	1.893456
ERV_E_in	6.627096	6.942672	7.573824
ERV_E_out	3.15576	0.9782856	0.9782856
ERV_N_in	0	0	0
ERV_N_out	25.877232	16.409952	18.303408
ERV_S_in	14.832072	7.8894	9.151704
ERV_S_out	0	0	0
ERV_T_in	1.0414008	0.008520552	1.2307464
ERV_T_out	2.6192808	4.102488	4.73364
ERV_W_in	8.204976	4.73364	4.73364
ERV_W_out	3.786912	2.3352624	2.4614928
FR_B_in	0.03471336	2.36682	2.5561656
FR_B_out	16.725528	20.51244	23.037048
FR_E_in	4.102488	11.360736	13.254192
FR_E_out	1.3885344	0.2840184	0.315576
FR_N_in	0.13254192	0.13569768	0.1104516
FR_N_out	4.102488	7.573824	10.414008
FR_S_in	17.041104	13.885344	17.672256
FR_S_out	0.3786912	0.4418064	0.473364
FR_T_in	0.014832072	0.014516496	0.4102488
FR_T_out	3.47E-06	0.004418064	0.06627096
FR_W_in	3.0610872	7.258248	8.204976
FR_W_out	0.01262304	0.03471336	0.08520552
FSRS_B_in	0.0631152	0.013885344	0.013254192
FSRS_B_out	20.51244	18.618984	20.828016
FSRS_E_in	13.885344	6.627096	7.258248
FSRS_E_out	0.3471336	1.4832072	1.6409952
FSRS_N_in	0.11991888	0.14516496	0
FSRS_N_out	19.250136	12.62304	15.463224
FSRS_S_in	8.520552	7.8894	9.151704
FSRS_S_out	1.2938616	1.2307464	1.9250136

Room, Face and Direction*	Struct Flow Case (1)	Struct Flow Case (2)	Struct Flow Case (4)
FSRS_T_in	0.014832072	0.023352624	1.3885344
FSRS_T_out	0	0	0
FSRS_W_in	6.627096	8.204976	9.151704
FSRS_W_out	2.1774744	0.9782856	0.946728
FSRU_B_in	0	1.6409952	1.7672256
FSRU_B_out	0.006942672	17.672256	19.565712
FSRU_E_in	1.1991888	2.4930504	2.9348568
FSRU_E_out	0.003471336	0.78894	0.8204976
FSRU_N_in	0	0.03786912	0
FSRU_N_out	0.00473364	3.471336	4.418064
FSRU_S_in	0.4102488	6.942672	8.520552
FSRU_S_out	0.07573824	0.08520552	0.10729584
FSRU_T_in	0.005364792	0.02524608	0.473364
FSRU_T_out	0	0.002209032	0.03471336
FSRU_W_in	0.002209032	3.471336	3.471336
FSRU_W_out	0.23352624	0.22405896	0.24299352
NoFlowData	0	0	0
RV_B_in [2]	4.418064	1.9881288	2.0196864
RV_B_out [2]	6.627096	6.942672	7.258248
RV_E_in	0.1104516	0.0473364	0.022721472
RV_E_out	10.098432	5.995944	6.627096
RV_N_in	0.011360736	0	0
RV_N_out	15.7788	12.307464	14.832072
RV_S_in	17.672256	12.62304	14.832072
RV_S_out	0	0	0
RV_T_in	9.46728	8.204976	7.8894
RV_T_out	2.3983776	0.8836128	0.8204976
RV_W_in	4.102488	3.786912	4.102488
RV_W_out	0.021143592	0.02209032	0
TR_B_in	3.15576	11.360736	11.04516
TR_B_out	7.573824	24.299352	24.614928
TR_E_in	0.012307464	0	0
TR_E_out	9.46728	22.721472	34.71336
TR_N_in	0	0.6942672	0.631152
TR_N_out	0.4418064	9.782856	10.729584
TR_S_in [1]	0.9782856	5.680368	5.680368
TR_S_out [1]	0.4418064	6.627096	6.627096
TR_T_in	0.001640995	0.0315576	0.5995944
TR_T_out	5.05E-05	0.015463224	0.22721472
TR_W_in	12.938616	50.49216	66.27096
TR_W_out	0.000883613	0.473364	0.3471336

Room, Face and Direction*	Struct Flow Case (1)	Struct Flow Case (2)	Struct Flow Case (4)
WRV_B_in	0	0	0
WRV_B_out	1.9565712	2.0196864	2.1459168
WRV_E_in	0.013254192	0.022405896	0.002524608
WRV_E_out	2.209032	1.8303408	2.3037048
WRV_N_in	0.18303408	0.13254192	0.14516496
WRV_N_out	2.3352624	2.3352624	2.6508384
WRV_S_in	2.051244	1.9881288	2.1774744
WRV_S_out	0.23037048	0.12307464	0.11676312
WRV_T_in	0.020828016	0.002903299	0.4102488
WRV_T_out	1.7987832	1.6409952	1.8618984
WRV_W_in	4.418064	4.102488	4.418064
WRV_W_out	0.03471336	0.0473364	0.02209032

Notes: * The location of the flows are specified as follows.

Rooms are: BRD = Boiler Room (Deep), BRS = Boiler Room (Saturated), BRU = Boiler Room (Upper), DPR = Dump Pipe Room, FR = Fuelling Room, FSRS = Fuel Storage Room (Saturated), FSRU = Fuel Storage Room (Upper), ERV = East Room of the Reactor Vault, WRV = West Room of the Reactor Vault, RV = Reactor Vault, TR = Turbine Room.

Face is: N = site north (direction of groundwater flow towards the river, all other directions relative to this), S = south, E = east, W = west, T = top, B = bottom.

Direction is: in = flow into the relevant compartment through the relevant face, out = flow outwards through the face.

[1] For consistency, flows taken are maximum of flow in/out north of BRU and out/in south of TR (bold values those changed).

[2] For consistency, flows taken are maximum of flow in/out bottom of RV and out/in top of DPR (bold values those changed).

Table E-76 Flow Rates in the geosphere surrounding the NPD for case DD(a) – Role of Existing Structure.

	Units	Struct Flow Case (1)	Struct Flow Case (2)	Struct Flow Case (4)
$q_{upstream}$	m y^{-1}	0.0601	0.0415	0.0414
DGeo_0	m^3 y^{-1}	992.63	1112.633	1112.633
DGeo_1	m^3 y^{-1}	2097.146	2419.194	2419.194
DGeo_2	m^3 y^{-1}	3201.662	3725.756	3725.756
DGeo_3	m^3 y^{-1}	3494.176	4203.867	4203.867
DGeo_4	m^3 y^{-1}	2871.505	3748.254	3748.254
DGeo_5	m^3 y^{-1}	2871.505	3748.254	3748.254
PT_1	m^3 y^{-1}	877.0599	36573.23	36573.23
PT_2	m^3 y^{-1}	1788.959	68361.74	68361.74
PT_3	m^3 y^{-1}	2314.987	72496.49	72496.49
PT_4	m^3 y^{-1}	2406.109	45463.46	45463.46
PT_5	m^3 y^{-1}	2406.109	45463.46	45463.46
SGeo_1	m^3 y^{-1}	10928.66	117669.3	117669.3
SGeo_2	m^3 y^{-1}	7291.835	145955.6	145955.6
SGeo_3	m^3 y^{-1}	10648.32	203069.2	203069.2
SGeo_4	m^3 y^{-1}	21886.77	292673.1	292673.1
SGeo_5	m^3 y^{-1}	21886.77	292673.1	292673.1
TD_1	m^3 y^{-1}	1678.535	20842.01	20842.01
TD_2	m^3 y^{-1}	2850.4	27846.26	27846.26
TD_3	m^3 y^{-1}	2835.884	25631.48	25631.48
TD_4	m^3 y^{-1}	1484.233	13026.19	13026.19
TD_5	m^3 y^{-1}	1484.233	13026.19	13026.19

Table E-77 The fraction of total water flow out of a room which goes to the tile drains for case DD(a) – Role of Existing Structure.

Room	$f_{TileDrain,}$ Fraction of outflow going to tile drains
BR_Deep	0.438
BR_Sat	0.758
BR_Unsat	0.603
DTPR	0.850
FR_Unsat	0.869
FSR_Sat	0.884
FSR_Unsat	0.723
RV	0.939
TR_Unsat	0.102

E 3.11.2 Case DD(b) - Role of Grout

Name:	Grout material		
Version:	Version 4.0		
Symbol:	Q_{NPD}, $q_{upstream}$, q_{c_vol}, $f_{TileDrain}$, $f_{stage_Cem/Grout}$		
Units:	$m^3\ y^{-1}$, m/y, $m^3\ y^{-1}$, -		
Description:	Alternative flows are applied through the facility and surrounding geosphere assuming the grout in the rooms is fully degraded.		
Value(s):	Alternative flows given in Table E-78, Table E-79 and Table E-80. In terms of chemical properties, the grout is modelled as being fully degraded (i.e., Stage F) beginning at 0 y post-closure.		
Justification:	The material properties are discussed in Sections E 3.4.2, E 3.4.5, 0, E 3.4.7.		
Uncertainty:	Uncertainties are discussed in terms of the material properties.		
Source of uncertainty:	Variability in material properties.		
References:	See Section E 3.4. Arcadis Canada Inc. & Geofirma Ltd. (2023a). 2023 Groundwater Modelling at the Site of the Proposed Decommissioned Rolphton Nuclear Power Demonstration (NPD) Reactor. CNL No. 64-508760-REPT-012 Rev 1. June. Arcadis Canada Inc. & Geofirma Ltd. (2023b). 2023 Near-Field Groundwater Model at the Site of the Proposed Decommissioned Rolphton Nuclear Power Demonstration (NPD) Reactor. CNL No. 64-508760-REPT-013 Rev 1. June. Arcadis Canada Inc. & Geofirma Ltd. (2023c). 2023 Resaturation Modelling for the Proposed Decommissioned Rolphton Nuclear Power Demonstration (NPD) Reactor. CNL No. 64-508760-REPT-015 Rev 3. June.		
Author:	Louise Bruffell	**Date:**	9 February 2023
Checker (basis):	Kate Thatcher	**Date:**	14 February 2023
(Checker (implementation):	Kate Thatcher	**Date:**	14 February 2023

Table E-78 Flow Rates within the NPD for case DD(b) – Role of Grout (m^3 y^{-1})

Room, Face and Direction*	Grout Flow Case (1)	Grout Flow Case (2)	Grout Flow Case (4)
BRD_B_in	0.00066271	1.77E-05	0
BRD_B_out	0.031242024	0.05049216	10.098432
BRD_E_in	0	0	0
BRD_E_out	0.0473364	0.05364792	7.573824
BRD_N_in	0	0	0
BRD_N_out	0.05364792	0.06627096	10.729584
BRD_S_in	0.019250136	0.015463224	3.15576
BRD_S_out	0.002051244	0.003471336	0.5364792
BRD_T_in	0.10414008	0.14516496	24.299352
BRD_T_out	0.007258248	0.0001641	0
BRD_W_in	0.015147648	0.011991888	1.0098432
BRD_W_out	0.00170411	0.003471336	1.0414008
BRS_B_in	0.05364792	0.0473364	1.7672256
BRS_B_out	0.15147648	0.19565712	31.5576
BRS_E_in	0	0	0
BRS_E_out	0.3786912	0.3471336	34.71336
BRS_N_in	0.011991888	0.010098432	1.104516
BRS_N_out	0.15147648	0.19565712	21.459168
BRS_S_in	0.26508384	0.29032992	41.02488
BRS_S_out	0.004418064	0.002556166	0
BRS_T_in	0.27139536	0.315576	34.71336
BRS_T_out	0.03471336	0.04418064	0.8520552
BRS_W_in	0.12307464	0.1262304	13.569768
BRS_W_out	0	0	0.04102488
BRU_B_in	0	0.04418064	11.04516
BRU_B_out	0	0.31242024	37.86912
BRU_E_in	0	0	0
BRU_E_out	0	0.01420092	4.418064
BRU_N_in[1]	0	0.002650838	1.5463224
BRU_N_out[1]	**0.005680368**	**0.024299352**	**2.2721472**
BRU_S_in	0	0.010098432	5.049216
BRU_S_out	0	0	0
BRU_T_in	0	0.29032992	24.614928
BRU_T_out	0	0.05364792	5.364792
BRU_W_in	0	0.02997972	12.62304
BRU_W_out	0	0	14.832072
DPR_B_in	0.010098432	0.007258248	0.3786912
DPR_B_out	0.00026824	0.00078894	0.7258248
DPR_E_in	7.26E-05	0	0.026192808

Room, Face and Direction*	Grout Flow Case (1)	Grout Flow Case (2)	Grout Flow Case (4)
DPR_E_out	0.004102488	0.00473364	0.631152
DPR_N_in	0	0	0
DPR_N_out	0.00631152	0.005364792	1.5147648
DPR_S_in	0.008520552	0.008204976	1.8303408
DPR_S_out	0	0	0
DPR_T_in[2]	**0.002082802**	**0.003786912**	**1.6409952**
DPR_T_out[2]	**0.03786912**	**0.0315576**	**1.4832072**
DPR_W_in	0.004418064	0.005049216	0.5049216
DPR_W_out	0	0	0.015147648
ERV_B_in	0	0	0
ERV_B_out	0.0315576	0.03786912	3.786912
ERV_E_in	0.001230746	0.0001641	0.1420092
ERV_E_out	0.01420092	0.016409952	2.6508384
ERV_N_in	0	0	0
ERV_N_out	0.0473364	0.03786912	6.942672
ERV_S_in	0.010098432	0.003786912	1.57788
ERV_S_out	0.000277707	0.001956571	0.00473364
ERV_T_in	0.1104516	0.11676312	14.516496
ERV_T_out	0.03471336	0.030295296	4.102488
ERV_W_in	0.0078894	0.005995944	0.6942672
ERV_W_out	0.011676312	0.013569768	0.8836128
FR_B_in	0.012938616	0.00946728	6.942672
FR_B_out	0.1893456	0.22405896	30.295296
FR_E_in	0.004418064	0.009151704	3.471336
FR_E_out	0.002303705	0.003786912	0.4418064
FR_N_in	0	0	0.16409952
FR_N_out	0.04102488	0.09782856	21.459168
FR_S_in	0.03471336	0.08520552	21.143592
FR_S_out	0.000725825	0.00066271	0.10414008
FR_T_in	0.1735668	0.1420092	15.147648
FR_T_out	0.002587723	0.013254192	4.102488
FR_W_in	0.013569768	0.07258248	10.098432
FR_W_out	0	0	2.6192808
FSRS_B_in	7.26E-05	6.31E-05	0.022721472
FSRS_B_out	0.10098432	0.157788	17.041104
FSRS_E_in	0.023037048	0.00473364	1.893456
FSRS_E_out	0.019250136	0.04102488	4.73364
FSRS_N_in	0	0	0
FSRS_N_out	0.0946728	0.10098432	20.828016
FSRS_S_in	0.05364792	0.04102488	8.836128
FSRS_S_out	0.000473364	0.003786912	0.11360736

Room, Face and Direction*	Grout Flow Case (1)	Grout Flow Case (2)	Grout Flow Case (4)
FSRS_T_in	0.14832072	0.25877232	31.5576
FSRS_T_out	0.00315576	0	0
FSRS_W_in	0.012938616	0.023352624	2.9032992
FSRS_W_out	0.013254192	0.01420092	2.4614928
FSRU_B_in	0	0.07258248	7.573824
FSRU_B_out	0	0.2840184	37.86912
FSRU_E_in	0	0.005680368	4.102488
FSRU_E_out	0	0	0.5364792
FSRU_N_in	0	0	0
FSRU_N_out	0	0.03471336	9.782856
FSRU_S_in	0	0.07573824	17.041104
FSRU_S_out	0	0.015147648	0.8836128
FSRU_T_in	0	0.1262304	17.35668
FSRU_T_out	0	0.028717416	2.36682
FSRU_W_in	0	0.0631152	4.102488
FSRU_W_out	0	0.014832072	3.0926448
NoFlowData	0	0	0
RV_B_in [2]	0.03786912	0.0315576	1.4832072
RV_B_out [2]	0.002082802	0.003786912	1.6409952
RV_E_in	0.014832072	0.016409952	1.262304
RV_E_out	0.008204976	0.005364792	1.6725528
RV_N_in	0.001230746	0.001230746	0
RV_N_out	0.21459168	0.22721472	27.139536
RV_S_in	0.09782856	0.10098432	16.094376
RV_S_out	0	0	0
RV_T_in	0.05680368	0.06627096	8.520552
RV_T_out	0	0	0
RV_W_in	0.03471336	0.03786912	4.73364
RV_W_out	0	0	0
TR_B_in	0.009782856	0.018303408	4.102488
TR_B_out	0.14516496	0.5049216	18.303408
TR_E_in	0.004418064	0.017041104	0.00631152
TR_E_out	7.57E-05	0.14516496	13.569768
TR_N_in	0	0	0.315576
TR_N_out	0.4102488	2.4930504	24.299352
TR_S_in [1]	0.005680368	0.024299352	2.2721472
TR_S_out [1]	0	**0.002650838**	**1.5463224**
TR_T_in	0.5049216	2.9032992	34.71336
TR_T_out	0	0	2.0196864
TR_W_in	0.02051244	0.10098432	17.987832
TR_W_out	0	0.04102488	8.520552

Room, Face and Direction*	Grout Flow Case (1)	Grout Flow Case (2)	Grout Flow Case (4)
WRV_B_in	0.003471336	0.001988129	0.005680368
WRV_B_out	0.000309264	0.000725825	0.946728
WRV_E_in	0	0	0
WRV_E_out	0.03471336	0.030295296	4.102488
WRV_N_in	0.004418064	0.004102488	0.6627096
WRV_N_out	0.010414008	0.011991888	2.840184
WRV_S_in	0.010414008	0.011676312	1.3569768
WRV_S_out	0	0	0.025877232
WRV_T_in	0.031242024	0.024930504	5.049216
WRV_T_out	0.010098432	0.008204976	0.7573824
WRV_W_in	0.012938616	0.01420092	1.7041104
WRV_W_out	0.001672553	0.00145165	0.15463224

Notes: * The location of the flows are specified as follows.

Rooms are: BRD = Boiler Room (Deep), BRS = Boiler Room (Saturated), BRU = Boiler Room (Upper), DPR = Dump Pipe Room, FR = Fuelling Room, FSRS = Fuel Storage Room (Saturated), FSRU = Fuel Storage Room (Upper), ERV = East Room of the Reactor Vault, WRV = West Room of the Reactor Vault, RV = Reactor Vault, TR = Turbine Room.

Face is: N = site north (direction of groundwater flow towards the river, all other directions relative to this), S = south, E = east, W = west, T = top, B = bottom.

Direction is: in = flow into the relevant compartment through the relevant face, out = flow outwards through the face.

[1] For consistency, flows taken are maximum of flow in/out north of BRU and out/in south of TR (bold values those changed).

[2] For consistency, flows taken are maximum of flow in/out bottom of RV and out/in top of DPR (bold values those changed).

Table E-79 Flow Rates in the geosphere surrounding the NPD for case DD(b) – Role of Grout.

	Units	Grout Flow Case (1)	Grout Flow Case (2)	Grout Flow Case (4)
$q_{upstream}$	m y^{-1}	0.0614	0.0435	0.0435
DGeo_0	m^3 y^{-1}	958.553	976.3264	1010.403
DGeo_1	m^3 y^{-1}	2076.539	2336.767	2357.374
DGeo_2	m^3 y^{-1}	3194.525	3697.207	3704.344
DGeo_3	m^3 y^{-1}	3494.176	4203.867	4203.867
DGeo_4	m^3 y^{-1}	2871.505	3748.254	3748.254
DGeo_5	m^3 y^{-1}	2871.505	3748.254	3748.254
PT_1	m^3 y^{-1}	731.1658	36573.23	36573.23
PT_2	m^3 y^{-1}	1594.035	68361.74	68361.74
PT_3	m^3 y^{-1}	2136.923	72496.49	72496.49
PT_4	m^3 y^{-1}	2319.168	45463.46	45463.46
PT_5	m^3 y^{-1}	2319.168	45463.46	45463.46
SGeo_1	m^3 y^{-1}	11038.16	117669.3	117669.3
SGeo_2	m^3 y^{-1}	7536.039	145955.6	145955.6
SGeo_3	m^3 y^{-1}	10821.1	203069.2	203069.2
SGeo_4	m^3 y^{-1}	21755.81	292673.1	292673.1
SGeo_5	m^3 y^{-1}	21755.81	292673.1	292673.1
TD_1	m^3 y^{-1}	1699.142	20101.35	20307.42
TD_2	m^3 y^{-1}	2857.537	26970.9	27042.27
TD_3	m^3 y^{-1}	2835.884	24898.95	24898.95
TD_4	m^3 y^{-1}	1484.233	12749.27	12749.27
TD_5	m^3 y^{-1}	1484.233	12749.27	12749.27

Table E-80 The fraction of total water flow out of a room which goes to the tile drains for case DD(b) – Role of Grout.

Room	$f_{TileDrain,}$ Fraction of outflow going to tile drains
BR_Deep	0.0037
BR_Sat	0.080
BR_Unsat	0.034
DTPR	0.031
FR_Unsat	0.062
FSR_Sat	0.088
FSR_Unsat	0.082
RV	0.010
TR_Unsat	0.020

E 3.12 Data for "What-if" Cases

E 3.12.1 Case WI(a) – Facility Mass Excavation

Name:	Volume Excavated		
Version:	Version 4.0		
Symbol:	V_{Exc} f_{Exc}		
Units:	m^3 (V_{Exc})		
Description:	Volume into which the disrupted NPDDF is dispersed in the "what if" Mass Excavation case.		
Value(s):	V_{Exc} is calculated based on the spatial volumes of the components assumed to be excavated. These include: NPD_Cap, NPD_FSRu, NPD_FSRs, NPD_FR, NPD_RV, NPD_ERV, NPD_WRV, NPD_DPR, NPD_BRu, NPD_BRs, NPD_BRd, NPD_TR and NPD_Fill. f_{Exc} = 0.1		
Justification:	The excavated material is assumed to be mixed with surface soil at a loading of 10% (any greater may not permit it to be used for agriculture).		
Uncertainty:	Not relevant		
Source of uncertainty:	It is extremely unlikely that an excavation would extract the NPDDF structure in the manner assumed. The volume chosen is deliberately extremely cautious.		
References:	Not applicable.		
Author:	Louise Bruffell	**Date:**	9 February 2023
Checker (basis):	Kate Thatcher	**Date:**	10 February 2023
Checker (implementation):	Kate Thatcher	**Date:**	10 February 2023

E 3.12.2 Case WI(b) - River Level Fall

Name:	Groundwater Discharge Location		
Version:	Version 4.0		
Symbol:	Not applicable		
Units:	Not applicable		
Description:	The location at which contaminated groundwater flowing from the NPDDF to the river along the top surface of the bedrock in the geosphere and trench is assumed to be released to the surface. (Note- tile drains discharge to the shore sediment in the normal evolution scenario)		
Value(s):	The releases from the geosphere compartments are redirected from “River1_Sed” to the adjacent “Shore1” compartment in the numerical model (see Figure E-16).		
Justification:	Hydrogeological modelling (Arcadis & Geofirma, 2023a) indicates that groundwater from the vicinity of the NPDDF will migrate in the overburden and the bedrock, and be released in the Ottawa River, close to the shore, with some emerging in springs. If all the contaminated groundwater released via an upwelling into the river bed were instead to occur on dry land there would be higher environmental concentrations in a location where people may be exposed, and this scenario is designed to examine this possibility. In the assessment, the only aspect that is modified is to route the release of the contaminants from the river sediment to the shoreline.		
Uncertainty:	Field observations and modelling results both fail to show a significant release of groundwater to dry land under the present-day conditions, so this scenario is of low likelihood.		
Source of uncertainty:	Potential for climate change to affect water balance.		
References:	Arcadis Canada Inc. & Geofirma Ltd. (2023a). 2023 Groundwater Modelling at the Site of the Proposed Decommissioned Rolphton Nuclear Power Demonstration (NPD) Reactor. CNL No. 64-508760-REPT-012 Rev 1. June.		
Author:	James Penfold	**Date:**	29 September 2016
Checker (basis):	Richard Little	**Date:**	20 October 2016
Checker (implementation):	Louise Bruffell	**Date:**	10 March 2023

E 3.12.3 Case WI(c) – Undetected Fracture Zone

Name:	Undetected Fracture Zone		
Version:	Version 4.0		
Symbol:	Not applicable		
Units:	Not applicable		
Description:	Examines the impact of an undetected fracture zone being present.		
Value(s):	Same as in Section E 3.9.5 NES(g) – Geosphere Bedrock Hydraulic Conductivity Section E 3.9.5 NES(g) – Geosphere Bedrock Hydraulic Conductivity. See Table E-57 and Table E-58.		
Justification:	An on-site field characterization program was developed and performed (see Arcadis & Geofirma, 2022). The results of the field program were integrated with information from a variety of previous on-site investigations, as well as information from literature and other sources, into the Geosynthesis Report (Arcadis & Geofirma, 2022). The Geosynthesis Report (Arcadis & Geofirma, 2022) interpreted the available information and also included a lineament analysis. Some notable discussions in the Geosynthesis Report (Arcadis & Geofirma, 2022) are as follows: • there is no evidence to suggest that lineaments in the surrounding area extend to within the NPD site boundary. • the 2019 geological structural data indicate the presence of metre-scale and sub-metre fracture zones, and broken zones and subhorizontal sheeting fractures. The 2019 shallow bedrock investigations show no evidence of a 90 m-wide, east-west striking, south-dipping shear zone or similar major structural features in the vicinity of the NPDWF. Based on this, it is not credible that a large *fault feature* would be present on site. However, a new What-If Case has been included in the 4th Iteration PostSA to examine the impact of an undetected *fracture zone* by using a bedrock conductivity one order of magnitude greater than that identified in the calibrated model (Arcadis & Geofirma, 2023b).		
Uncertainty:	Such an increase in hydraulic conductivity would address both uncertainty in the measured values, as well as a potential undetected fracture zone. Applying the higher bedrock conductivity to the entire bedrock downgradient of the facility would be conservative, rather than limiting it to a defined area.		
Source of uncertainty:	Site characterisation.		
References:	Arcadis Canada Inc. & Geofirma Ltd. (2023b). 2023 Near-Field Groundwater Model at the Site of the Proposed Decommissioned Rolphton Nuclear Power Demonstration (NPD) Reactor. CNL No. 64-508760-REPT-013 Rev 1. June. Arcadis Canada Inc. & Geofirma Ltd. 2022. 2021 Update to Geosynthesis – Nuclear Power Demonstration Closure Project – Rolphton, Ontario. CNL No. 64-509410-REPT-010 Rev 2 January		
Author:	Renato Zagorscak	**Date:**	27 January 2023
Checker (basis):	Louise Bruffell	**Date:**	10 March 2023
Checker (implementation):	James Penfold	**Date:**	19 June 2023

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APPENDIX F: MATHEMATICAL MODELS

APPENDIX F - MATHEMATICAL MODELS

F 1 INTRODUCTION

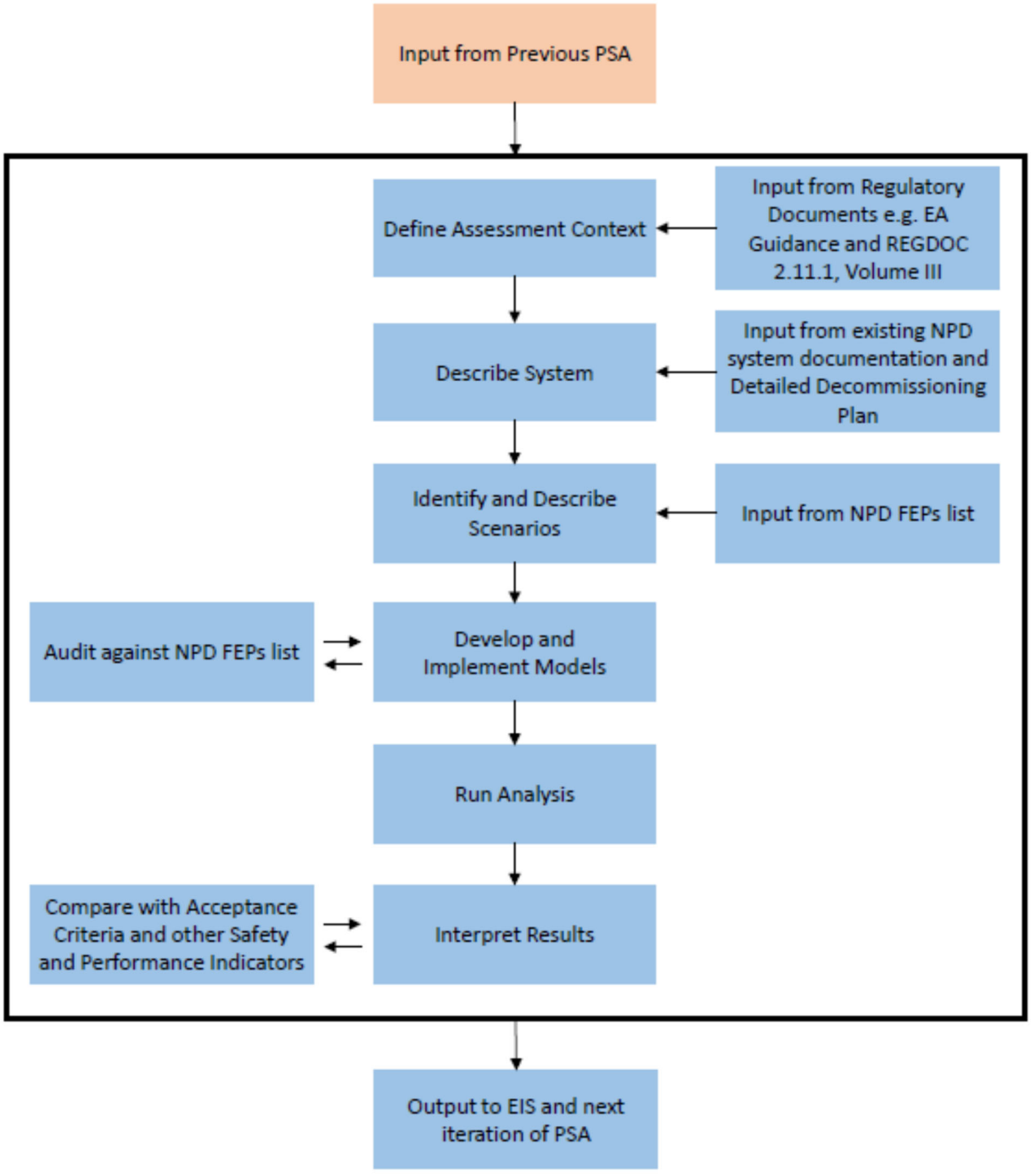
Canadian Nuclear Laboratories (CNL, acting on behalf of Atomic Energy of Canada Limited, AECL) is proposing in-situ disposal of the Nuclear Power Demonstration Waste Facility (NPDWF), thereafter referred to as the Nuclear Power Demonstration Disposal Facility (NPDDF). This 4th Iteration Postclosure Safety Assessment (PostSA) will support the final EIS submission.

This 4th Iteration PostSA has been undertaken using international best practice, specifically the International Atomic Energy Agency's (IAEA's) Improving Safety Assessment Methodologies (ISAM) guidance (IAEA, 2004). This is a systematic, stepwise approach, the main stages of which are illustrated in Figure F-1. The PostSA has been documented in a way that corresponds to the ISAM approach, with a main report describing the key elements of the assessment and its outcomes.

This appendix presents the mathematical models used to implement the scenarios described in Appendix D and the conceptual models and data presented in Appendix E. This includes information on the modelling approach in Section F 2 which explains the methods used and the computer code selected for the PostSA. The following sections then present the two main parts of the mathematical model:

- dynamic models, which deal with representing the gradual movement of contaminants through the modelled system (the wastes, NPDDF, and its surrounding environment), and its evolution in time, are presented in Section F 3, and
- equilibrium models and dose calculations, which represent processes that are quick in relation to the model calculations (typically processes that act over timeframes of less than a year, such as uptake of radionuclides into plants), are described in Section F 4.

Figure F-1: Approach to Postclosure Safety Assessment, adapted from ISAM (IAEA, 2004)



F 2 MATHEMATICAL MODELLING APPROACH

F 2.1 Methods

A variety of mathematical approaches can be used to represent the conceptual models presented in Appendix E. Many processes can be dealt with adequately using simple models because a degree of equilibrium between different media can be assumed over the timescales of relevance to post-closure safety assessment. Given that the key endpoint, radiation dose, is assessed in terms of the annual effective dose to a potentially exposed person, processes that can be reasonably averaged over a year (e.g., uptake to cropped plants) or occur much faster than this (e.g., sorption) can be treated as being in a state of equilibrium between media in the model. However, processes such as radionuclide migration in groundwater (by advection or diffusion) require dynamic modelling as they are more gradual.

There are consequently two components to the NPDDF model:

- A dynamic model, which represents the processes that gradually transport contaminants through the region of interest (e.g., dispersion in groundwater); and
- An equilibrium model, which represents materials that can be assumed to be in equilibrium with the dynamic parts of the model (e.g., fish in river water).

The equilibrium parts of the model can be represented with algebraic expressions (e.g., the dose to a person from ingestion of vegetables is the product of an assumed annual ingestion rate, the concentration of radionuclides in the vegetables at a given time, and dose conversion factors).

The dynamic model requires an approach that enables first- and second-order differential equations to be represented. In safety assessments, compartment models are typically applied to solving such problems (e.g., IAEA (2004), CSA (2022), Quintessa *et al*. (2011)). These involve representing key features as 'compartments' that are assumed to occupy a user-defined space and have particular physical properties. Contaminants are taken to be uniformly distributed within each compartment at any given time (though they may be partitioned differentially between different phases within each compartment). Contaminants can be transferred from one compartment to another to represent processes defined in the conceptual model, such as erosion and water flow. These transfers can be defined by transfer rates that quantify the associated fraction of the amount of a contaminant in a compartment that is moved to another compartment per unit time. A number of such transfers can operate between compartments, and the decay/ingrowth of contaminants within the compartments can also be represented. Thus, a general expression for the change in the amount of radionuclide *N* in compartment *i* with time is:

$$\frac{dN_i}{dt} = \left(\sum_{j \neq i} \lambda_{ji} N_j + \lambda_M M_i \right) - \left(\sum_{j \neq i} \lambda_{ij} N_i + \lambda_N N_i \right) \quad (1)$$

Where:

i, j are the two compartments;

N, M are the amounts (Bq) of radionuclides N and M in a compartment (M is the parent of N in a decay chain);

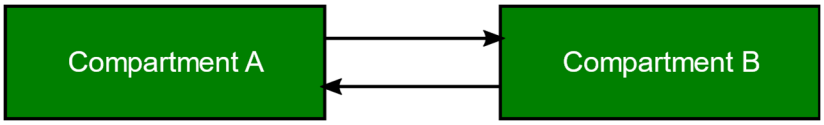
λ_M, λ_N are the decay constants for radionuclides M and N (y^{-1}); and

λji, λij are transfer coefficients (y^{-1}) representing the gain and loss of radionuclide N from compartments i by transfer from and to compartment j, respectively.

The solution provides the time-dependent inventory of each compartment. Although a conventional compartment model essentially works in terms of total amounts of contaminants in a compartment, assumptions about compartment sizes allow estimates of the associated concentrations to be made. Transfer rates themselves can be defined in terms of other values and equations, and may be time-dependent.

A key assumption in compartment modelling is that that the distribution of contaminants within a compartment can be approximated as being uniform (either because relatively rapid mixing occurs in the compartment or because an average concentration is reasonable for the assessment purposes). If this assumption does not hold, then further discretisation may be needed (e.g., into a series of soil layers or sections of an aquifer). Care is needed to ensure that the discretisation is sufficiently refined not to add excessive numerical dispersion (Robinson, 2005). Equally, there needs to be enough discretisation such that the assumption that each compartment has uniform concentrations at any given point in time is reasonable.

Contaminant transport by diffusion cannot be represented directly with the general first-order expression that underlies compartment models (Equation 1), as the rate of transport is dependent on the concentration gradient. However, it is possible to represent diffusion by using a combination of transfers between the two compartments across which diffusion occurs:



In this case, the flux of contaminants (Bq y^{-1}) in each direction can be expressed by:

$$\phi_{Diff,AB} = \frac{A\, D_{Eff} (C_A - C_B)}{L_{Diff}} \qquad (2)$$

Where

A is the area across which diffusion occurs (m^2);

D_{Eff} is the effective diffusion coefficient ($m^2\ y^{-1}$);

C_A, C_B is the concentration of the contaminant in compartments A and B respectively (Bq m^{-3}); and

L_{Diff} is the diffusion length (m) (essentially the distance between the centres of each compartment, perpendicular to the face across which diffusion is occurring).

The transfer rate (y^{-1}) for diffusion can then be readily calculated by dividing each side of the equation by the amount of the contaminant in the compartment at given time.

F 2.2 Code

A variety of mathematical tools can be used to represent the models presented in Section F 2.1. Although many processes can be dealt with adequately using simple algebraic models, processes such as radionuclide migration in groundwater (by advection or diffusion) require dynamic modelling.

The identified scenarios and conceptual models (see Appendix D and E) make it clear that the assessment-level code needs to represent a wide variety of different features together with time-dependent events and processes. A wide range of potential calculation endpoints is of interest.

These requirements are fulfilled by the AMBER compartment modelling code. Other similar applications are available, e.g., GoldSim, but in this instance AMBER was selected. AMBER offers greater efficiency in the model development and quality assurance process compared to other codes because the mathematical model is fully transparent via the user interface and text-based case files. AMBER also, uniquely for this calibre of contaminant transport codes, includes both spatial awareness and three-dimensional visualization. AMBER allows the user to define and visualize three-dimensional 'cells' linked to the model compartments. This enables the code to automatically compute key properties such as volumes, interface areas and distances between compartments. The specific three-dimensional representation of the geometry of the NPDDF needed in the assessment models mean that these capabilities represent a strong advantage for AMBER over other codes.

AMBER was originally developed for modelling contaminants from radioactive waste repositories and this remains its core area of application and development. AMBER is a very 'open' modelling tool that does not prescribe any particular ways of representing processes or geometry of the modelled system, but does provide methods for developing equations and data to describe relevant processes in a time-dependent way. AMBER has a proven track record for performance assessment of radioactive waste disposal facilities and a strong quality assurance status (e.g., see Medri (2015), Thomson *et al*. (2008), Walke *et al*. (2011), and further references in Appendix A of Quintessa (2021a)).

AMBER is a flexible software tool that allows users to build their own dynamic compartment models to represent the migration, degradation and fate of radioactive and non-radioactive contaminants in environmental systems. The AMBER model interface displays the network of models and transfers, which can be organised into nested sub-models, as well as a 3D representation of the model (if this has been defined – it is not required). Equations and data are defined as AMBER parameters which, with information on the model structure, are saved in text-based case files which allow easy checking of the model.

The code is flexible and allows any number of contaminants, compartments and transfers to be represented. The user can define complex algorithms and data sets and allows the import/export of data to facilitate its integrated use with other software tools and databases. In addition to using the graphical interface, AMBER also allows text-based editing, auditing and 'future-proof' recording of case files, with in-built parameter checking and 'units awareness'. The code has full probabilistic capabilities (Monte Carlo or Latin Hypercube sampling) and includes a wide range of available probability density functions. It has two

fast solvers that permit complex time-varying source terms, environmental properties and transfer processes, which may be linear or non-linear, to be represented.

AMBER has a wide international user base, with over 90 organisations in more than 35 countries owning licences. There are in excess of 120 publications describing assessments in which AMBER has been applied (Quintessa, 2021a), including several international code inter-comparison exercises (e.g., BIOMOVS II (1996); Limer *et al*. (2012); Olyslaegers *et al*. (2005)).

AMBER is managed and developed under Quintessa's ISO 9001:2015 registered QA system that incorporates the requirements of TickIT software quality system (www.TickIt.org). Each release is extensively tested against a broad set of verification and validation tests (Quintessa, 2021b). AMBER's capabilities are fully described in a Reference Manual (Quintessa, 2021c).

AMBER meets the requirements of CNL's Code Management Program, and has been also validated in accordance with CNL's Management System Document, *Design and Development of Analytical, Scientific and Design Computer Programs* (CNL, 2020).

The equations presented in this section, and the associated data included in Appendix E, have been implemented directly, using the same parameter names. Output of results and data can be made directly to Microsoft Excel in files stamped with the date and model filename. This ensures that the Quality Assurance of results is very efficient.

F 3 DYNAMIC MODEL

F 3.1 Materials and Physical Properties

The materials to be considered in the PostSA are identified in the conceptual model description (see Appendix E). Those associated with the facility and its geological environment are subject to groundwater flow and are therefore represented in the dynamic model. Also included in the dynamic model are key parts of the surface environment in which radionuclides are dispersed, including the Ottawa river, parts of the shore, and soils that may become contaminated.

As noted, a key aspect of such a model is the assumptions about the media through which contaminants may be transported. In AMBER, these are defined as a "nameset" (a list over which parameters can be indexed). The 'names' are:

- Aluminum;
- CSteel (carbon steel);
- SSteel (stainless steel);
- Zircaloy;
- Grout;
- Concrete (structural concrete);

- Infill (concrete);
- Water;
- Overburden;
- Bedrock;
- Soil_Loam (loamy soil);
- Soil_Sand (sandy soil); and
- Sed (sediment).

The first four items are solid metals from which radionuclides may be released as a result of corrosion. (It was determined that, on the basis of reported corrosion rates, aluminum would dissolve very rapidly so corrosion releases are only modelled for steels and Zircaloy, with aluminum being assumed to corrode so quickly that the contaminants within aluminum are effectively instantly available once the Facility is resaturated.) Prior to their release, the radionuclides in these materials are assumed not to be available for release into the NPDDF model because they are locked into the solid matrix of the metal.

The corrosion rates used have been reviewed and compared with values available in the technical literature and from anthropogenic analogue studies (CNL, 2021). The corrosion behaviour of carbon steel, stainless steel, and zirconium alloys under disposal conditions has been extensively studied in various countries and there is a large database of relevant measurements. In all three cases, results are available from long-term studies for exposure periods up to 10 y. These long-term measurements are important as it is observed that the corrosion rate decreases with time and only attains a steady-state value appropriate for long-term prediction after 1-3 y exposure. Evidence from archaeological and more-recent analogue studies are also consistent with the rates used in the safety assessments. Various factors that could lead to an enhanced rate of radionuclide release under disposal conditions have also been reviewed and none are expected to have a significant impact on the release rate.

With the exception of water, the remaining items are represented as porous materials through which water can flow. Associated with each material are physical properties that are used in modelling the processes that apply. These are:

ρ_m dry bulk density (kg m^{-3});

θ_m porosity (-), noting that the water-filled porosity depends on the location of the medium as well as its material;

$KD_{,m}$ sorption coefficient (m^3 kg^{-1}), which is the ratio of the amount of a contaminant that is sorbed to surfaces to that which is dissolved in the pore fluid in a saturated porous medium (also dependent on element *e*); and

D_{Eff} the effective diffusion coefficient of the material (which controls the rate of diffusion).

In concrete and the grout backfill these parameters have time dependent values that represent the changes in material properties due to the gradual degradation of cementitious materials.

F 3.2 Waste and Facility

F 3.2.1 Compartments and Structure

The conceptual model (Appendix E) shows that the NPDDF can be represented as the Fuel Storage room, Fuelling Room, Reactor Vault, Left of Reactor Vault Room, Right of Reactor Vault Room, Dump Pipe Room, Boiler Room and Turbine Room. A distinction is made between those regions of the NPDDF that lie below bedrock and those that lie within the overburden. This is because the flows through these two geosphere media differ and this influences the flows within the NPDDF.

Reactor Vault

The majority of the radioactivity in the NPDDF is initially present and will remain in the Reactor Vault; therefore, this is a particular focus for the model.

The Reactor Vault is surrounded by concrete walls that, initially, will permit radionuclide transport by diffusion through them. Each of the faces has to be represented separately so that contaminant transport in both advective and diffusive regimes can be represented. Diffusion through these walls is most accurately represented if they are split into layers of gradually increasing thickness. The number of layers is a pragmatic modelling choice; a balance between complexity and the required “accuracy” of the representation of the process. Robinson (2005) discusses how much discretisation is needed to represent diffusive processes within compartment models. A measure of the accuracy, when compared with an analytic solution, is that the error resulting from discretisation into a finite number of compartments is equal to the inverse of the number of compartments squared (Robinson, 2005). Discretisation into five compartments implies an absolute error of less than 4% which is an appropriate balance of complexity and accuracy for the reactor vault. Each compartment is a factor of three greater in width than the preceding compartment (Robinson, 2005).

The geometric arrangement of the system of compartments around the Reactor Vault is shown in Figure F-2. In the model, each face of the vault (“wall”) is represented as a submodel connected to the central “ReactorVault” compartment by a number of transfers (see Figure F-3). Each submodel contains compartments for each of the five layers that represent the wall, linked by transfers (Figure F-4).

Figure F-2: Geometry of the Reactor Vault Model

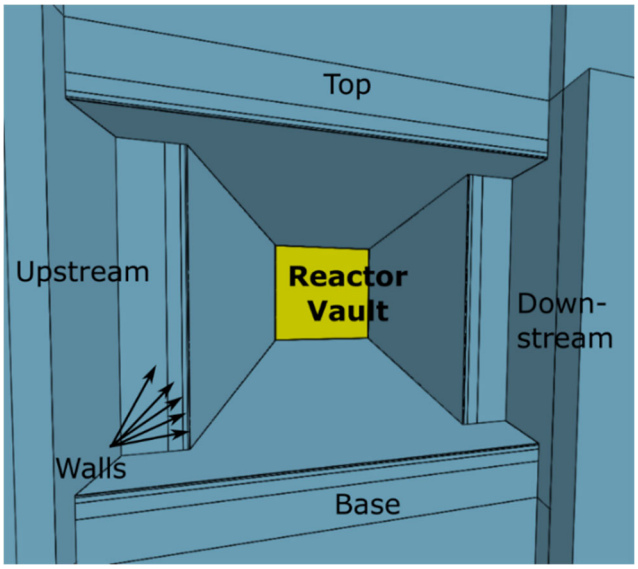


Figure F-3: Reactor Vault Compartment and Submodels (coloured blue)

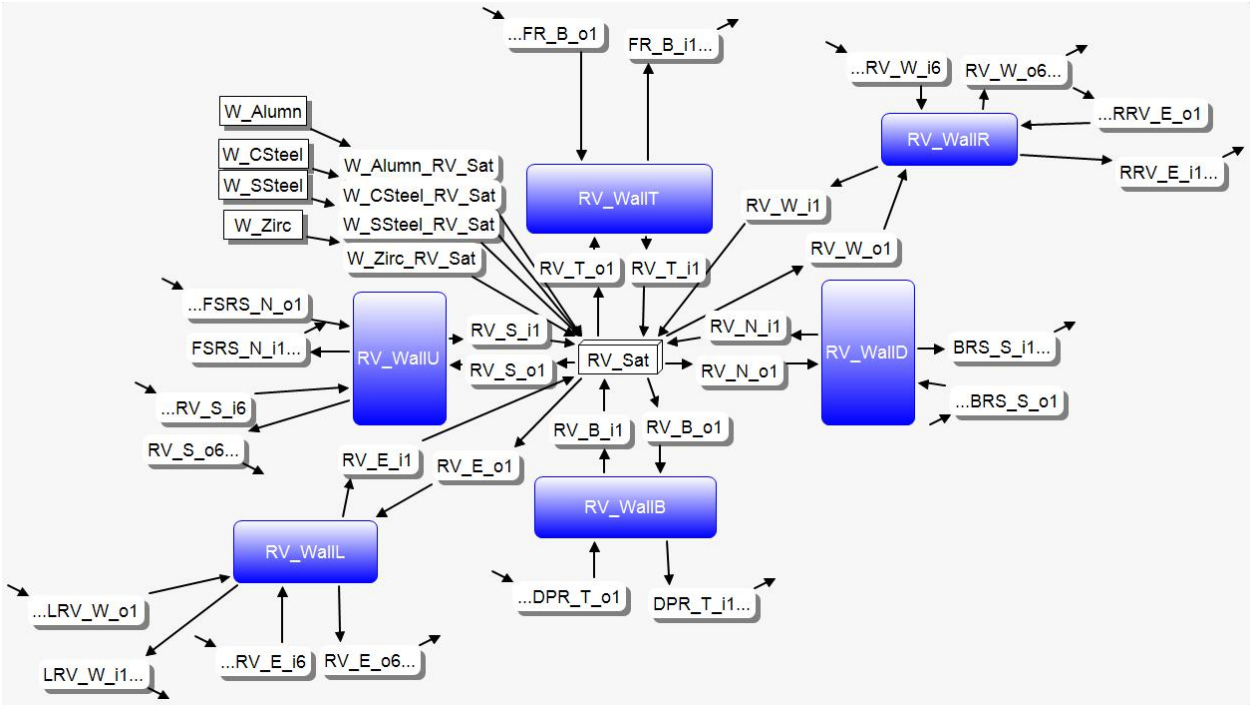


Figure F-4: Compartment Representation of "Upstream" Vault Wall

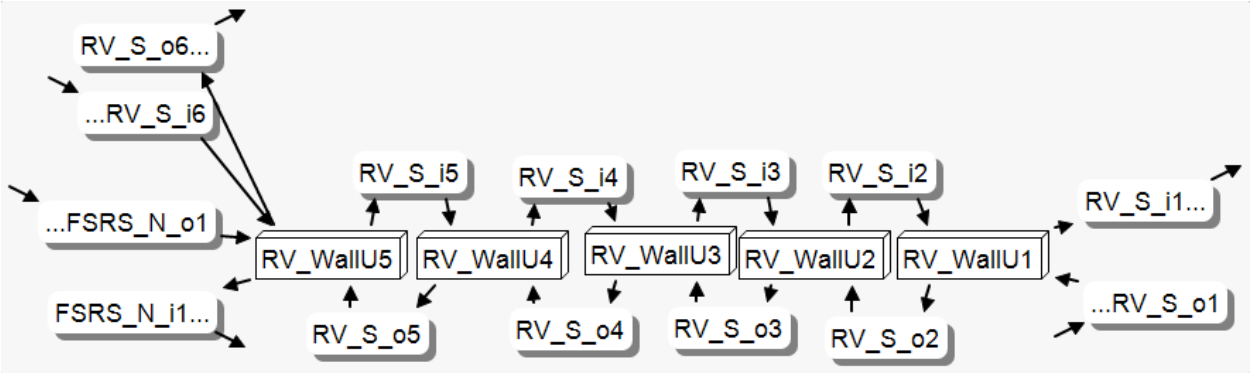


Figure F-3 shows that there are a large number of transfers from the Reactor Vault walls that are connected to other parts of the model. These represent contaminant transport beyond the Reactor Vault into the surrounding rooms.

Other Rooms in the NPDDF Structure

Each room of the NPDDF is represented as an interior (which is backfilled with grout) and the surrounding structural walls (made of concrete, and of varying thickness). Rooms are assumed to be either above bedrock (in the overburden) or below it (surrounded by fill, within the excavated bedrock). The distinction between the overburden and bedrock is necessary because the groundwater flows in these parts of the geosphere are different. They consequently induce differing flows within the NPDDF itself, as demonstrated by Arcadis & Geofirma (2023a,b). It is also necessary to distinguish the parts of the Boiler Room that lie below the level of the Reactor Vault, as these will be connected to the Dump Pipe Room beneath the Reactor Vault. The Dump Pipe Room is represented as a specific compartment as it will resaturate before the Reactor Vault. In general terms, therefore, the model for these rooms is the same as for the Reactor Vault. The difference is that, recognizing the smaller inventory present, and the need to keep the model size manageable, the wall on each face is represented with a single compartment rather than being discretized into five slices. Although this makes the representation of diffusion less accurate, when compared with an analytical solution, the approach is cautious in that it will tend to overemphasize the rate of contaminant transport. Furthermore, the estimated resaturation timescales of a few decades (see Arcadis & Geofirma (2023c)) mean than diffusion is only important for a very short period at the beginning of the assessment, after which advection dominates. Advective flows take place from each room to each adjacent room, and through the outer walls of the rooms and into the geosphere.

Cap

Above each of the uppermost rooms is a section of the cap. It is intended that a concrete cap will be constructed over only the nuclear area of the NPDDF, although the overlying mound may extend beyond this. In the model the whole cap is represented by three layers, the concrete slab, infill and topsoil. The concrete cap covers the area directly above the Reactor Vault, and parts of the fuel storage room and the boiler room which are within the bedrock (see Figure F-6). The remaining layers of the cap cover the whole footprint of the facility and the depth of the concrete cap, where it is not present, is modelled as infill. The

concrete cap is assumed to be 0.6 m thick. This is overlain by 2 m of infill, with a 0.15 m soil covering on top.

Geometry

The resulting model geometry is shown in Figure F-5 and Figure F-6. This is intentionally simplified from the actual NPDDF structure as this facilitates the representation of the model in the AMBER code, but nevertheless captures the main features of the building and the location of the contamination therein.

Figure F-5: Cross-sectional Illustration of the Geometry Used to Represent the NPDDF in the AMBER Model

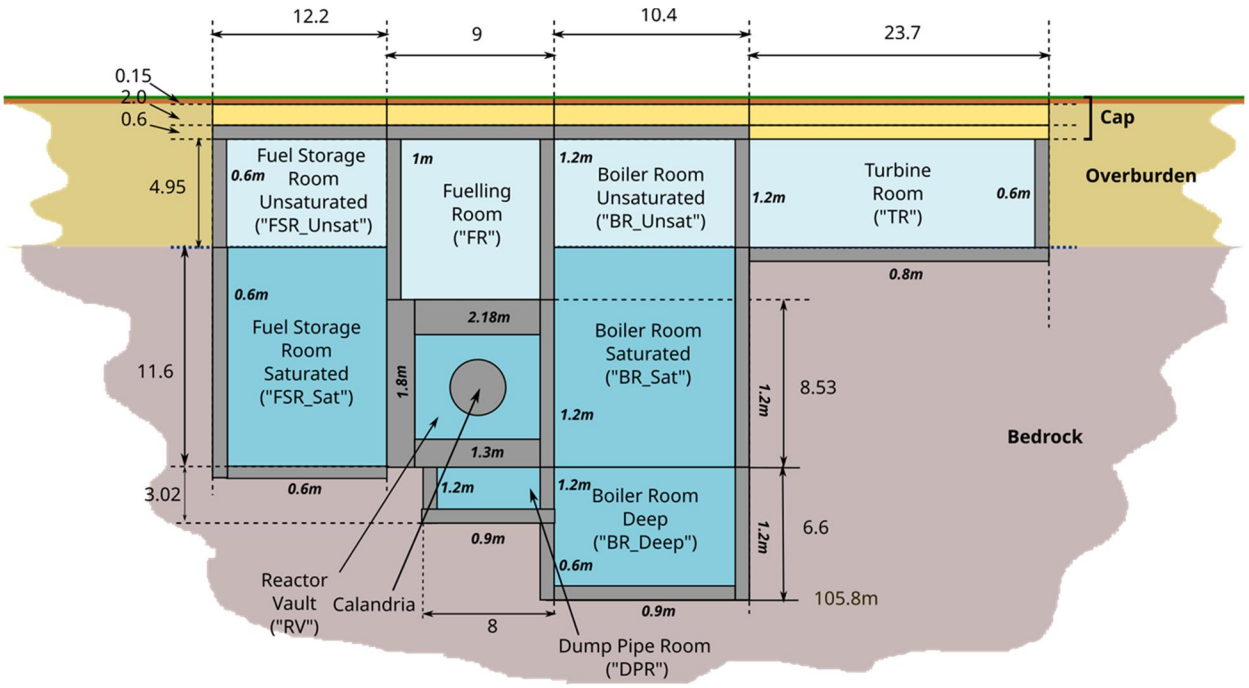
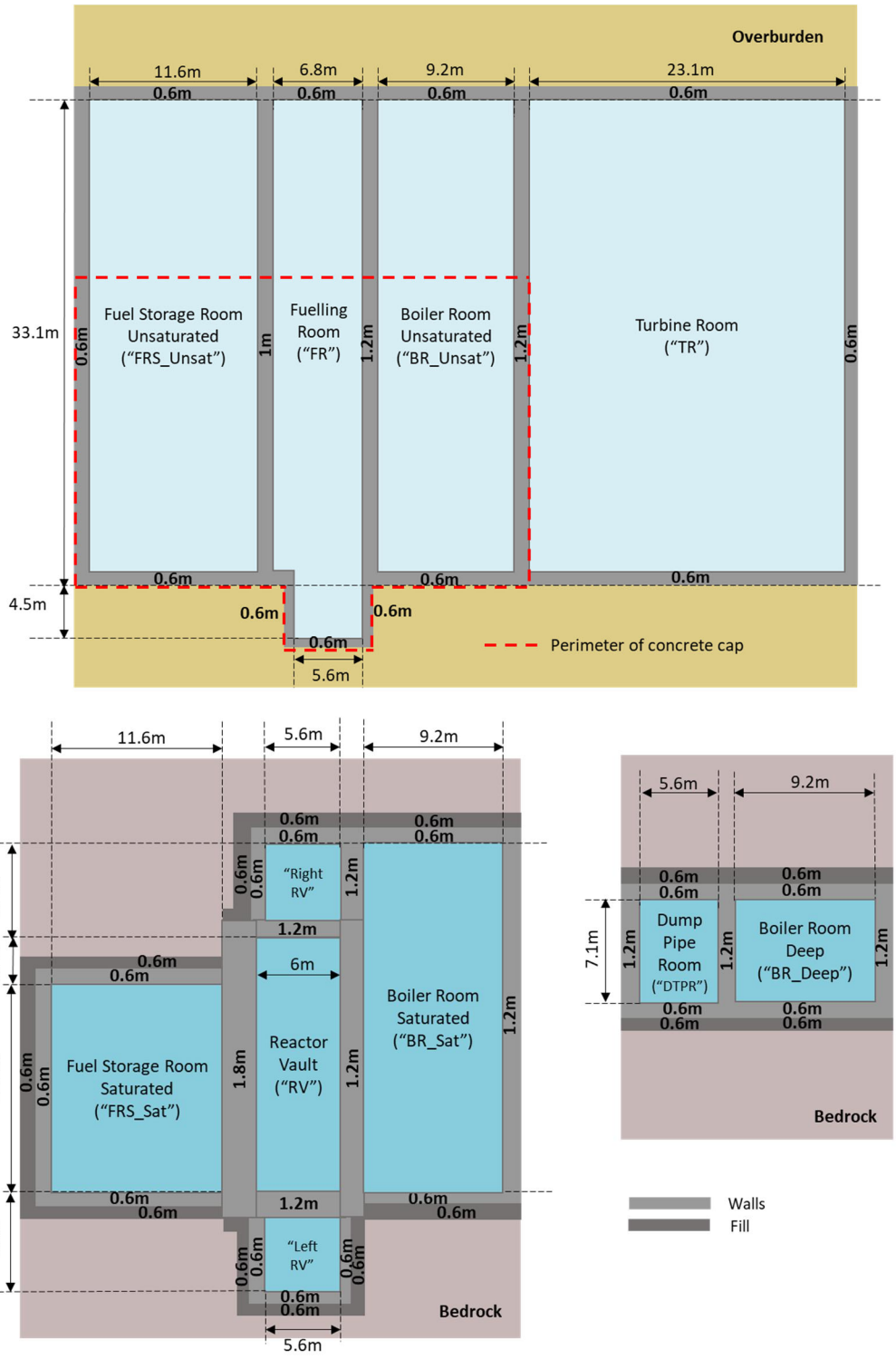


Figure F-6: Plan of the Geometry Used to Represent the NPDDF in the AMBER Model (Plan view at three different levels)



Where the NPDDF is constructed within bedrock, the gap between the Facility walls and the bedrock has been filled with concrete. This is represented in the model, with compartments adjacent to the Fuel Storage Room, Reactor Vault, Left of Reactor Vault Room, Right of Reactor Vault Room, Dump Pipe Room and Boiler Room.

The spatial representation of the NPDDF model in AMBER is shown in Figure F-7, and the associated compartments and submodels shown in Figure F-8 and defined in Table F-1. The dimensions of the compartments are summarized in Figure F-5.

Figure F-7: Spatial Representation of the NPDDF Model in AMBER, with Cut-away to Reactor Vault (Highlighted)

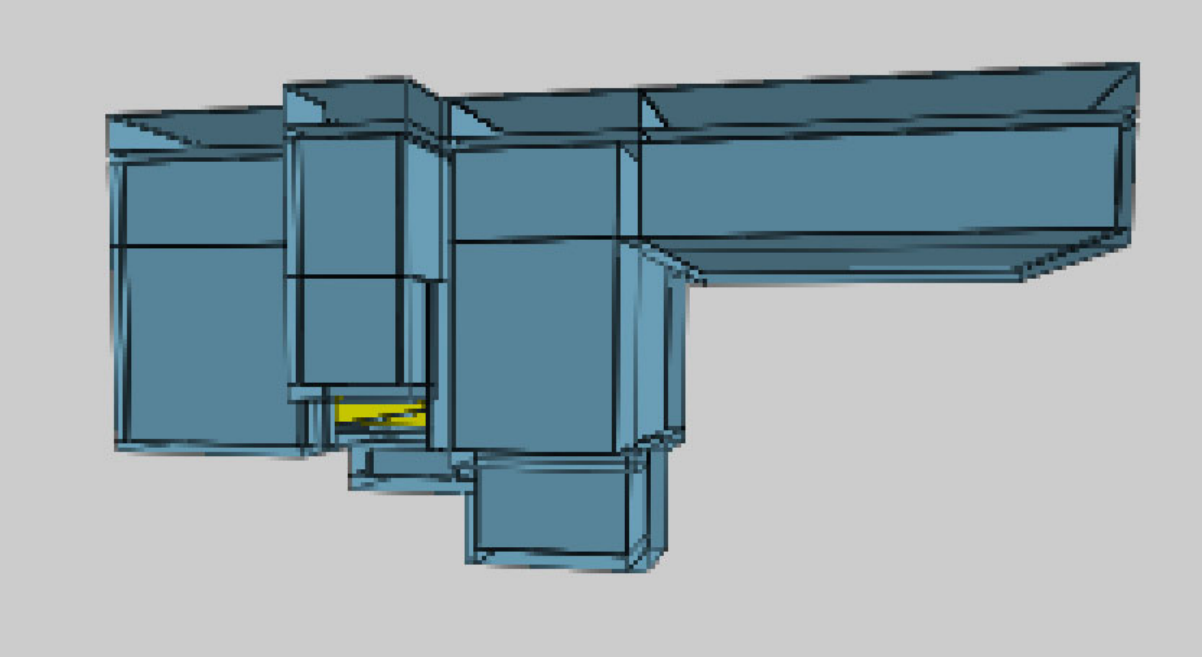


Figure F-8: Compartments and Submodels in the NPDDF Model

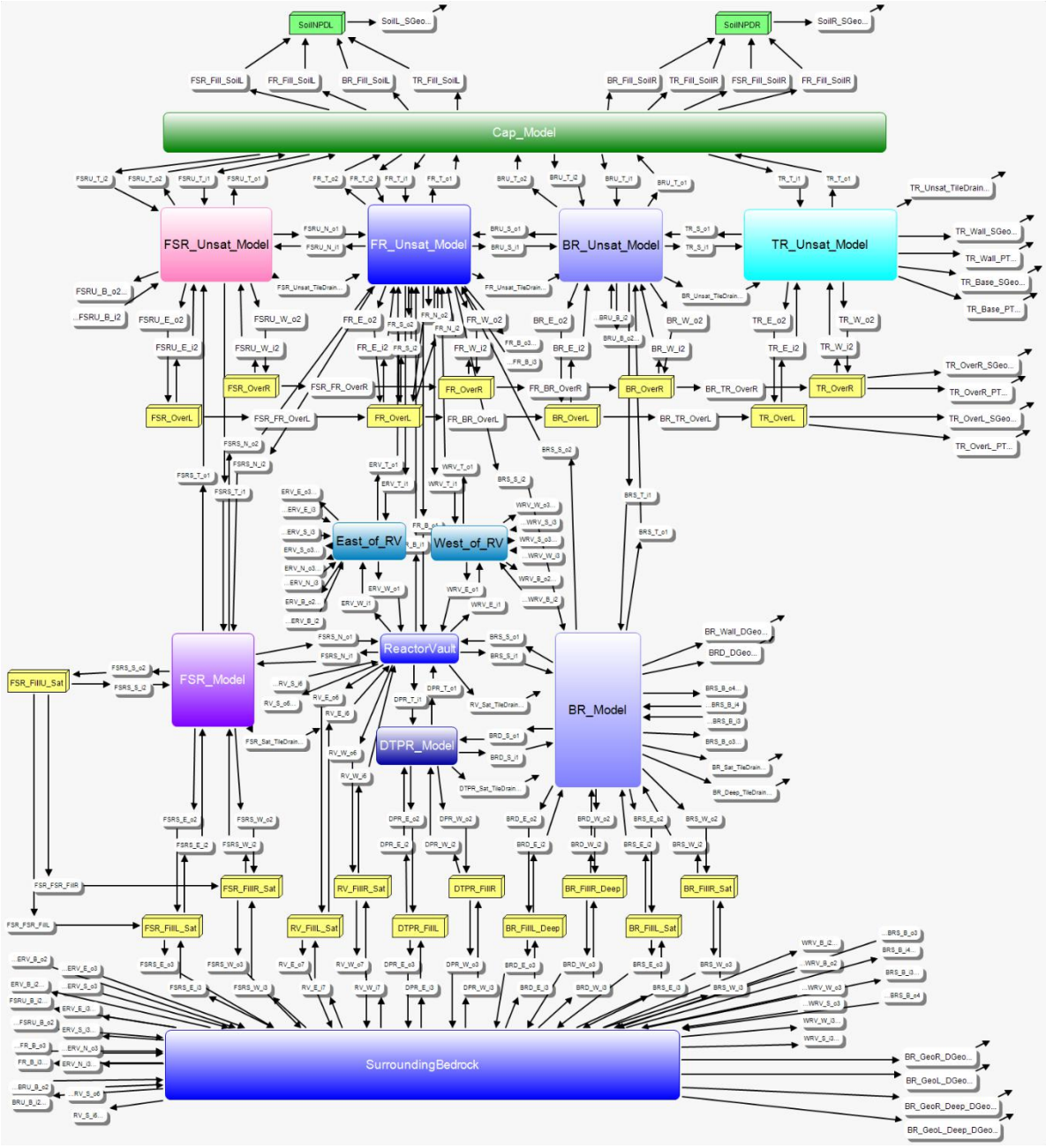


Table F-1: NPDDF Model Compartments

Component	Compartment name(s)*	Associated Materials
Wastes	W_Alumn, W_CSteel, W_SSteel, W_Zirc	Aluminum, CSteel, SSteel and Zircalloy
Spent Fuel Storage Room	FSR_Unsat, FSR_Sat	Grout
Spent Fuel Storage Room Walls	FSR_WallU_Unsat, FSR_WallL_Unsat, FSR_WallR_Unsat, FSR_WallU_Sat, FSR_WallL_Sat, FSR_WallR_Sat, FSR_Base	Structural Concrete
Fuelling Room	FR_Unsat	Grout
Fuelling Room Walls	FR_WallL_Unsat, FR_WallR_Unsat, FR_WallD_Unsat, FR_WallU_Unsat	Structural Concrete
Reactor Vault	RV_Sat	Grout
Reactor Vault Walls	RV_WallD1…5, RV_Wall_U1…5, RV_WallL1…5, RV_WallR1…5, RV_WallT1…5, RV_WallB1…5	Structural Concrete
Dump Tank Pipe Room	DTPR_Sat	Grout
Dump Tank Pipe Room Walls	DTPR_WallU, DTPR_WallL, DTPR_WallR, DTPR_Base, DTPR_WallD	Structural Concrete
Boiler Room	BR_Unsat, BR_Sat, BR_Deep	Grout
Boiler Room_Walls	BR_WallL_Unsat, BR_WallR_Unsat, BR_WallD_Unsat, BR_WallL_Sat, BR_BaseR_Sat, BR_BaseL_Sat, BR_WallR_Sat, BR_WallD_Sat, BR_WallL_Deep, BR_WallR_Deep, BR_WallD_Deep, BR_WallU_Deep, BR_Base	Structural Concrete
Turbine Room	TR_Unsat	Grout
Turbine Room Walls	TR_WallL_Unsat, TR_WallR_Unsat, TR_WallD_Unsat, TR_Base	Structural Concrete
Cap	FSR_Soil, FSR_Fill, FSR_Cap, FSR_FillT, FR_Soil, FR_Fill, FR_Cap, FR_FillT, BR_Soil, BR_Fill, BR_Cap, BR_FillT, TR_Soil, TR_Fill, TR_FillT	Soil_Loam, Infill and Concrete
Infill	FSR_FillU_Sat, FSR_FillR_Sat, FSR_FillL_Sat, RV_FillR_Sat, RV_FillL_Sat, DTPR_FillR, DTPR_FillL, BR_FillR_Sat, BR_FillL_Sat, BR_FillR_Deep, BR_FillL_Deep, LeftRV_FillU, LeftRV_FillL, LeftRV_FillD, RightRV_FillU, RightRV_FillR	Concrete

Note: *In previous iterations the rooms above bedrock were referred to as “Unsat”(urated) and those below as “Sat”(urated). Since then modelling has shown that the above bedrock portion will become saturated if tile drains fail, and this is represented in these compartments. However, the original nomenclature has been retained.

F 3.2.2 Processes

Resaturation

Before any radionuclides can be released and transported by advection from the wastes the vault must refill with water. This is modelled using the outputs from detailed modelling (Arcadis & Geofirma, 2023c) from which resaturation times are derived for use in the assessment model.

Advective flows of groundwater through and within the NPDDF are set to zero before the resaturation time t_{Resat} (y) and equal to the relevant flow rate (see F 3.2.3) subsequently.

As the majority of the radioactivity is contained in the Reactor Vault metals, a more detailed approach is taken to representing the timing at which resaturation permits the contaminants to begin to be released from the activated metals. The resaturation time is coupled with the elevation of the bottom and top of the NPDDF to determine a rate of resaturation (z_{Rate}) in m y^{-1}. This assumes that the rate of change of water level is constant. The parameter z_{Rate} is used with the value of the lowest elevation of the NPDDF ($z_{Base,NPDDF}$) and the base (z_{Base}) and top (z_{Top}) elevation of the Reactor Vault to determine the fraction that is saturated, $f_{ResatRV}$:

$f_{ResatRV} = 0$ where $t < (z_{Base} - z_{Base,NPDDF}) / z_{Rate}$ (3)

$f_{ResatRV} = 1$ where $t > (z_{Top} - z_{Base,NPDDF}) / z_{Rate}$ (4)

with linear interpolation in between these times.

Release Rate of Contaminants

Once the NPDDF has resaturated, contaminants within saturated porous media (concrete and grout) are assumed to be instantaneously released and available for transport once contacted by water. The contaminants may then diffuse, or be transported by advection, according to the mathematical models described later.

Radionuclides in activated metal are only available for transport once they have been released from the solid metal matrix due to corrosion. Corrosion of all the wastes is assumed to occur once the Reactor Vault begins to resaturate (i.e., $t > t_{Resat0}$) as the rate of corrosion in humid and saturated conditions is not greatly different (Walke *et al.*, 2011).

The rate of release by corrosion, $\lambda_{Corr,m}$ (y^{-1}) is:

$$\lambda_{Corr,m}(t) = \frac{q_{Corr,m}}{L_{Corr,m}\,(1-f_{Corr,m})} \quad (5)$$

Where

$q_{Corr,m}$ is the corrosion rate of the metal m (m y^{-1})

$L_{Corr,m}$ is the assumed initial ‘plate’ thickness of metals (m); and

$$f_{Corr,m}(t) = \frac{q_{Corr,m}(t-t_{Resat0})}{L_{Corr,m}}\,(0 \le f_{Corr} \le 1) \quad (6)$$

Note that the rate of release is time-dependent because the thickness of the metal reduces with time, the fraction remaining at any given time being (1 - $f_{Corr}(t)$). The process is represented in the model by transfers from compartments representing the bulk metal wastes into the grout within the Reactor Vault (the four such compartments at the top left of Figure F-3).

Diffusive Transport

Diffusion can occur between adjacent compartments via their common surface area, provided they are at least partly saturated. Conservatively, it has been assumed that all structures and materials in which diffusion occurs are saturated. As this process is primarily applied to the NPDDF structure, which sits within saturated rock and is resaturated after only a few decades, this simplification is considered reasonable. Diffusive transfers operate in both directions between compartments, in order that the net flow follows the concentration gradient that exists between them. The diffusion length scales and the Peclet number were considered in the spatial discretization of the NPD, but the primary driver in the discretization was the need to represent the NPD rooms and walls between them in a realistic way. This is particularly true for the Reactor Vault, where most of the inventory resides. Here, all walls were more finely discretized so that diffusion through them is modelled more realistically. In general terms the rate of diffusion from compartment *A* to *B*, $\lambda_{Diff\ A,B}$ (y^{-1}), is:

$$\lambda_{Diff\ A,B}(t) = \frac{A_{AB}}{L_{AB}V_A}\frac{p_{Diff\ A}+p_{Diff\ B}}{2} \quad (7)$$

Where

A_{AB} is the common surface area between compartments *A* and *B* (m^2);

L_{AB} is the distance between the centres of the adjacent compartments (m);

V_A is the total volume of compartment *A* (in m^3);

$p_{Diff\ A}$ is a compartment-dependent term for the rate of diffusion of a contaminant ($m^2\ y^{-1}$).

And $p_{Diff\ A}$ is calculated with

$$p_{Diff\ A} = \frac{D_{Eff\ A}}{\theta_A R_A} \quad (8)$$

where

$D_{Eff\ A}$ is the effective diffusion coefficient of material A ($m^2\ y^{-1}$);

θ_A the water filled porosity of A (-); and

R_A is the element-dependent retardation due to sorption (-), calculated with:

$$R_A = 1 + \frac{\rho_A Kd_A}{\theta_A} \quad (9)$$

Where ρ_A is the density ($kg\ m^{-3}$) and Kd_A is the sorption coefficient ($m^3\ kg^{-1}$) of material A.

Saturated Advective Transport and Groundwater Flow

Advective flows can operate between all adjacent compartments in the NPDDF model once they have resaturated, and are calculated based on detailed groundwater flow modelling (see Arcadis & Geofirma (2023a,b)). The flows from one compartment (A) to an adjacent compartment (B) are represented with:

$$\lambda_{Adv\ A,B}(t) = \frac{Q_{AB}}{V_A \theta_A R_A} \quad (10)$$

Where Q_{AB} ($m^3\ y^{-1}$) is the flow of water from compartment A to compartment B, which is calculated by Arcadis & Geofirma (2023a,b) and can vary with time as the concrete walls surrounding the NPDDF, and other engineered features, degrade. Additional details are given in Section F 3.2.3.The porosity and retardation (θ_A and R_A) also vary with time in response to the chemical evolution of the grout and other cementitious material in the NPDDF.

Flows up into the concrete cap, and downwards from the concrete cap are available from Arcadis & Geofirma (2023a,b), taking into account the effectiveness of the cap. The resaturation model (Arcadis & Geofirma, 2023c) includes details of the engineered cap and cover, and estimates infiltration rates over the building area including: infiltration through the engineered cover and concrete cap and into the building; infiltration through the engineered cover and into the building where the concrete cap is not present; and infiltration through the engineered cover and into the overburden surrounding the facility. These values vary depending on the integrity of the concrete cap.

For the AMBER model, the flow into the layers of the cover above the concrete slab is assumed to be the general recharge rate. Lesser flows infiltrate past this point and are determined as follows. The flow through the concrete slab, where present, is the minimum of the estimated infiltration rate through the concrete cap (multiplied by its' area) and the flow into the top of the room below, as given by Arcadis & Geofirma (2023b). Where the former is the minimum, the remaining flow into the top of the room is assumed to have infiltrated through the area of engineered cap above the room where the concrete slab is not present. Cautiously, it is also assumed that a fraction of the recharge (f_{Up}) also flows back up into the soil, as a result of capillary action and variable water table. Any net excess water permeating the membrane is assumed to leak from the fill layer of the cap into surrounding soil on either side of the NPDDF.

In the infill surrounding the rooms lying within the bedrock, flows are calculated similarly to the walls. The net flow in and out of the sides of the NPDDF is then added to the flow in the adjacent surrounding bedrock.

Finally, Arcadis & Geofirma (2023b) notes that water flowing through three rooms (the Fuel Storage Room, Fueling Room and Turbine Room) may leak to the tile drains. In each case, the fraction of the total water flow through the room that leaks to the tile drain is $f_{TileDrain}$ and this is used to calculate the amount of flow. This pathway is only modelled while the tile drains are operable ($t < t_{TileDrain}$).

Chemical Degradation of Concrete and Grout

As cement (in grout and concrete) degrades its properties change and this can affect the mobility of radionuclides. It is therefore necessary to model the degradation of the cements present in the facility. As discussed by Berner (1992) and Wilson (2020), the chemical degradation of cements and grout can be

represented with a simple 3 or 4-stage model with the duration of each stage being related to the number of pore flushes (n_{flush}) of the cement body.

$$n_{flush} = \frac{Q_{NPD,tot}}{V_{Comp}} t \quad (11)$$

Where V_{Comp} (m^3) is the total pore volume within a compartment (representing a room or a wall) and $Q_{NPD,tot}$ is the total net flow through it (in $m^3\ y^{-1}$). In Berner's model, for generic cements Stage 1 is complete after 100 flushes, Stage 2 after 1000 and Stage 3 after 7450 flushes. For BFS-PC grout, Wilson (2020) concludes that Stages 1 and 2 will not occur and that Stage 3 conditions will last for 1978 flushes, with a further Stage 4 concluding after 4386 flushes. These values are assigned to $n_{Stage}(N)$, allowing the Stage N that is active at any given time to be determined by comparing n_{flush} to $n_{Stage}(N)$. The values for parameters that are dependent on cement degradation are then assumed to transition to the value for each stage based on n_{flush} and $n_{Stage}(N)$.

Several model parameters vary with the cement degradation stage: θ (porosity); ρ (bulk density); Kd (sorption coefficient) and Sol, the solubility limit (only used for lead).

Overall, the number of pore flushes needed to degrade concrete and grout depends on the groundwater composition. In the NPD, some water entering a room has already passed through another room. This "conditioned" water is less effective in degrading concrete or grout than "fresh" groundwater and so more pore flushes would be needed to degrade the concrete or grout. This effect is conservatively neglected in the model calculations. Consequently:

- The duration of each Stage is underestimated in the model;
- Because pH decreases with time, the duration of high pH conditions is underestimated in the model; and
- Since high pH conditions correspond to high sorption, the sorption properties of the concrete or grout are underestimated in the model.

F 3.2.3 Representation of Water Flows within the NPDDF

Detailed groundwater flow modelling is required to determine the flows into, through, and out of the NPDDF. The geology, the external groundwater flow conditions, the structural materials, and their state of degradation all have a bearing on the flows between rooms. Figure F-9 shows a part of the detailed groundwater flow model and the computed flows through surfaces, illustrating the complexity and variability of flows through the facility.

The detailed groundwater flow and transport modelling presented in Arcadis & Geofirma (2023a,b) has been used to calculate flows for use in the AMBER model. As illustrated in Figure F-5 and Figure F-6 in Section F 3.2.1, each room is represented as a cuboid surrounded by walls, and a layer of infill for those rooms below the bedrock surface. Flows may occur through any surface of the room – "top", "bottom", "north", "east", "south" and west" – both inwards and outwards, as shown in Figure F-10. Flows out of the outermost walls

(or infill) then enter the geosphere adjacent to the NPDDF, either the overburden (for those rooms above bedrock), or the bedrock itself (for those rooms below the bedrock surface).

Arcadis & Geofirma (2023a,b) have examined the effects of the degradation of the engineered structure on the groundwater flows in, through and out of the NPDDF with a series of calculation cases, as this has a significant affect. Of the cases modelled by Arcadis & Geofirma (2023a), four of the five are used in the AMBER model:

(1) Undegraded facility with tile drains functioning.

(2) Undegraded facility with degraded cap and tile drain failure.

(4) Degraded facility with tile drain failure.

(5) Very degraded facility with tile drain failure.

For each of these cases, Arcadis & Geofirma (2023b) provides a set of calculated flows for each face of each room. These are then used to specify flow rates in the compartment model, a part of which is shown in Figure F-11.

One complication is that the representation of the NPDDF in the PostSA model is slightly simplified compared with the groundwater flow model. This means that in some cases the flows calculated by Arcadis & Geofirma (2023b) from room A to room B differ from the inflow calculated by Arcadis & Geofirma (2023b) to room B from room A. This is generally because one room overlaps another, so some of the water leaving room A (for example) flows elsewhere (to other rooms, or simply out into the geosphere).

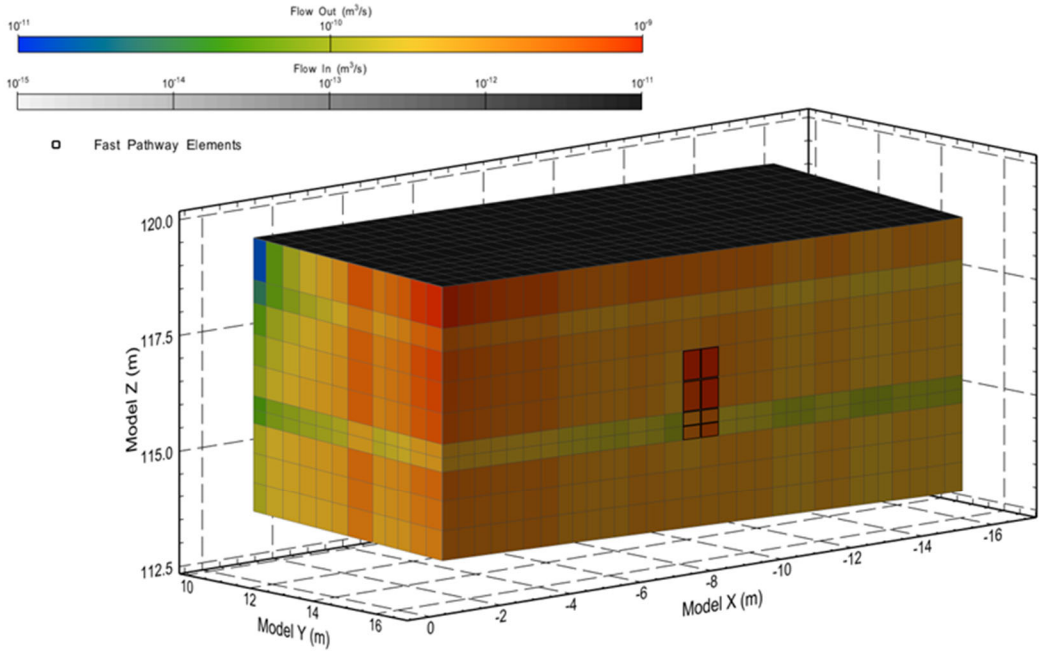
While the AMBER model represents overlapping rooms, so that flows out of one room can flow into two different rooms, for example, it also requires each room to be connected by a single flow rate. Furthermore, it is desirable that the flows themselves balance, so that the total flow in and out of each room is equal. This means some manipulation of the results provided by Arcadis & Geofirma (2023b) is required. A suitably balanced model, with consistent flows between each adjoining room, has been achieved in the following way.

- Firstly, for each side of each room, a value N is assigned to be the number of adjacent compartments along that side.
- Then $A_{out} = \sum_{i=1}^{N} \mathrm{A} \rightarrow C_i$, where A_{out} is the total flow out of that side of room A, and A → C_i is the flow from room A to the i^{th} adjacent compartment. Similarly, $A_{in} = \sum_{i=1}^{N} \mathrm{A} \leftarrow C_i$, where A_{in} is the total flow into that side of room A, and A ← C_i is the flow into room A from the i^{th} adjacent compartment. The values for A_{out} and A_{in} are those provided by Arcadis & Geofirma (2023b), whereas the values A → C_i for i=1,…,N are those needed for AMBER.
- To calculate these values for AMBER, any sides of any rooms which have N =1 are considered first. In such cases A_{out} = A → C_1 and A_{in}= A ← C_1.
- Next, sides with N=2 are considered where A_{out} = A → C_1 + A → C_2. In many cases it can be calculated, for example, that $\mathrm{A} \rightarrow C_1 = A_{out} - \mathrm{A} \rightarrow C_2$, where A → C_2 is already known from the previous step.
- We continue this way considering sides with N=3 and finally N=4 (the maximum N value assigned).

- For any flows which remain unknown at the end of this process, the total flow as given by Arcadis & Geofirma (2023b) is split based on the area of the interfaces between the compartments. This is only the case for the north side of the saturated Fuel Storage Room.
- For cases in which the sum of the calculated flows does not agree with total flow as given by Arcadis & Geofirma (2023b), the maximum of the two is taken. This is only the case for a small number of flows around the Fuelling Room (where the most complex flows and most overlaps are) and in some cases between the Reactor Vault and Dump Pipe Room, and between the Turbine Room and Upper Boiler Room.

This approach has been applied to all of the rooms within the model, and provides a model with flows balanced to within a few percent in most rooms and for most flow scenarios. The flow rates are reported in Arcadis & Geofirma (2023b) and are also presented in the relevant model parameter data in Appendix E.

Figure F-9: Modelled Groundwater Flows In and Out of the Reactor Vault, from Arcadis & Geofirma (2023b)



Note: The figure above shows groundwater inflow occurring at the top surface of the Reactor Vault and outflow towards the base and through a fast pathway (red).

Figure F-10: Conceptual Representation of Groundwater Flowing In and Out of a Room in the NPDDF

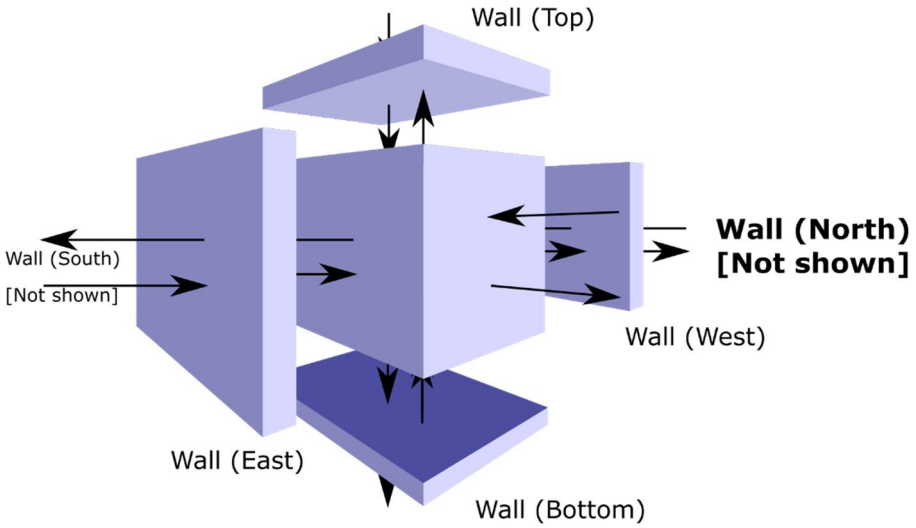
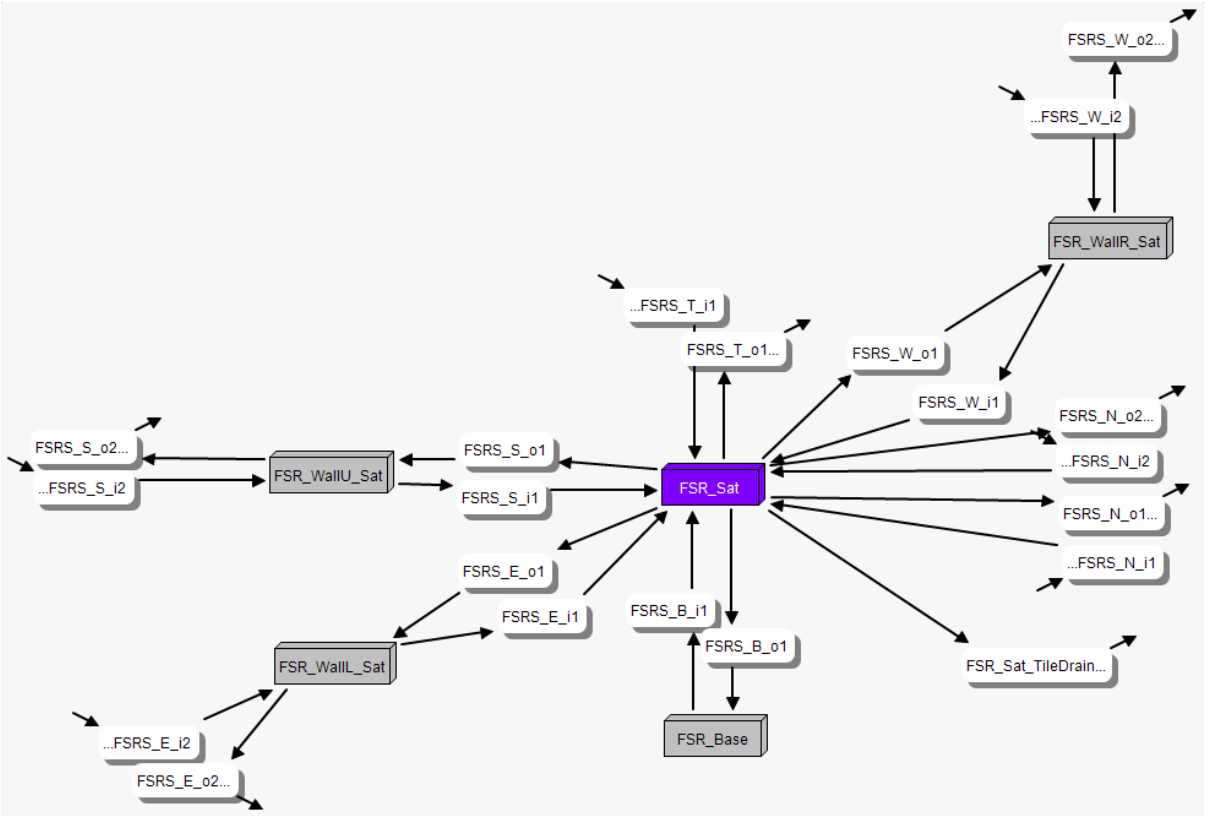


Figure F-11: Compartment Model Representation of Groundwater Flowing In and Out of a Room in the NPDDF (Top and North Compartments Not Shown)



F 3.3 Geosphere

F 3.3.1 Compartments and Structure

The overall conceptualisation of the geosphere involves four principal pathways for contaminant transport through the geosphere:

- transport in the overburden
- transport in the disturbed region of infill surrounding the cooling water pipes in the pipe trench;
- transport in the bedrock; and
- transport via the Tile Drains.

Groundwater flow modelling (Arcadis & Geofirma, 2023a) shows that the contaminant transport in these regions, as illustrated in Figure F-12 and Figure F-13, is through two distinct pathways - in the overburden (including the pipe trench and tile drain), and beneath this in a region of the bedrock. Arcadis & Geofirma (2023b) gives the flow rates in the overburden, pipe trench, tile drain and bedrock at three points between the facility and the river, depending on the integrity of the facility structure, concrete cap and tile drains. As noted in the preceding section, the model also shows that a relatively small portion of the total amount of contaminants in the NPDDF are released via the Tile Drain for the NES: 8.3% of the contaminants in the Fuel Storage Room above bedrock, 2.8% of the contaminants in the Fuel Storage Room below bedrock, 5% of the contaminants from the Fueling Room, and 2.9% of the contaminants from the Turbine Room. The main action of the Tile Drain is to capture and divert uncontaminated groundwater from upstream, which does not require explicit representation in the AMBER assessment model.

Figure F-12: Contaminant Concentrations for a Groundwater Model Simulation in which Tile Drains have Failed and the NPDDF Structure is Degraded

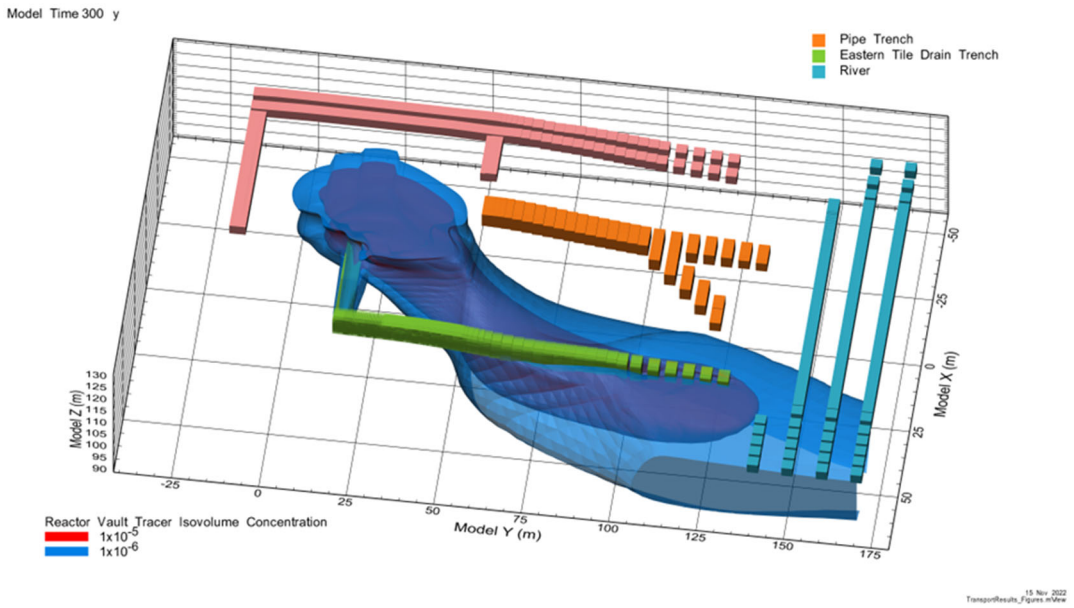
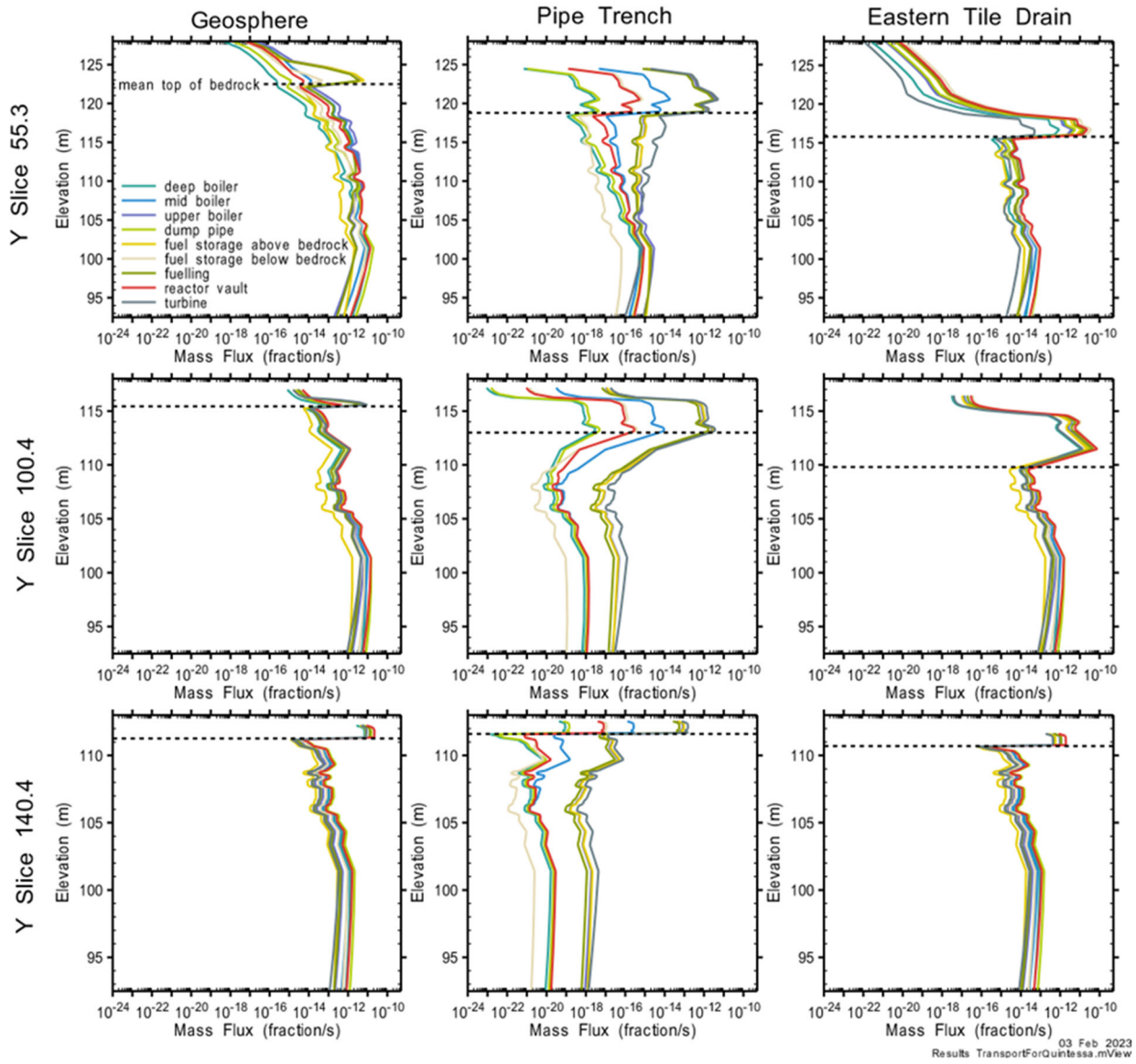


Figure F-13: Contaminant Fluxes at 100 y between the NPDDF and River, for a Groundwater Model Simulation in which Tile Drains have Failed and the Structure is Degraded



The pathway in the overburden is discretized into five compartments of equal length (see Figure F-14 and Figure F-15). This is required to ensure that the model does not introduce excessive numerical dispersion, and properly represents advective transport (Robinson, 2005). Given the short distance to the point of discharge to the biosphere at the river no transverse dispersion is represented. The pathway in the bedrock is represented in the same way, with an additional compartment representing the rock lying beneath the Turbine Room. The overburden pathway is cautiously assumed to discharge via springs to soils near the river, while the bedrock pathway discharges through the riverbed into the river.

The geometry of the geosphere is approximated based on the contaminant transport simulations by Arcadis & Geofirma (2023a). The shallow geosphere pathway compartments are all 19.25 m long and have varying thickness (with the final compartment pinching out to 1 m thick as the groundwater upwells in springs). The deep geosphere pathway, in the bedrock, also has varying thickness, which is greatest where it interfaces to the boiler room wall, at 18 m thick. All geosphere compartments are 15.4 m wider than the total width of the NPDDF, i.e., 46.4 m. The geometry is shown in Figure F-16. In addition to these compartments, overburden either side of the NPDDF is included in the model, into which any contaminants leaking from the sides of the facility can be released. Pipe trench pathway compartments are narrower (4.4 m) and sit in the middle of the geosphere compartments, with a thickness of between 0.6 m and 4.8 m. Tile drain pathway compartments are further east, outside of the geosphere pathway. They are taken to be 2 m wide and have a thickness of between 1.9 m and 3.6 m.

The Tile Drain potentially provides a very rapid pathway direct to the shore. Arcadis & Geofirma (2023a) indicates that the only rooms from which contaminants will leak to the tile drain for the NES are the Fuel Storage Room, Fueling Room and Turbine Room. The tile drain is not assumed to exhibit any significant leakage to the surrounding overburden. This is cautious, as it maximises the release of contaminants into the river shore. However, the tile drains are assumed to fail after 100 y, as a result of blockage or collapse.

Table F-2: Geosphere Model Compartments

Component	Compartment name(s)	Associated Materials
Overburden pathway	SGeo_1, SGeo_2, SGeo_3, SGeo_4, SGeo_5	Overburden
Bedrock pathway	DGeo_0, DGeo_1, DGeo_2, DGeo_3, DGeo_4, DGeo_5	Bedrock
Pipe trench	PT_1, PT_2, PT_3, PT_4, PT_5	Overburden
Tile Drain	TD_1, TD_2, TD_3, TD_4, TD_5	Overburden

Figure F-14: Spatial Structure of the Geosphere Model

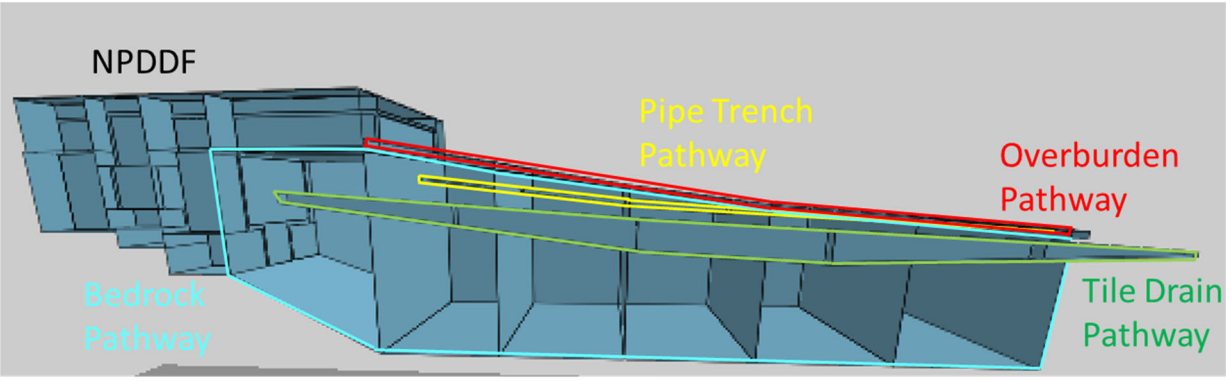


Figure F-15: Compartment Representation of the Geosphere Transport Pathways and their Interface with the River and Shore

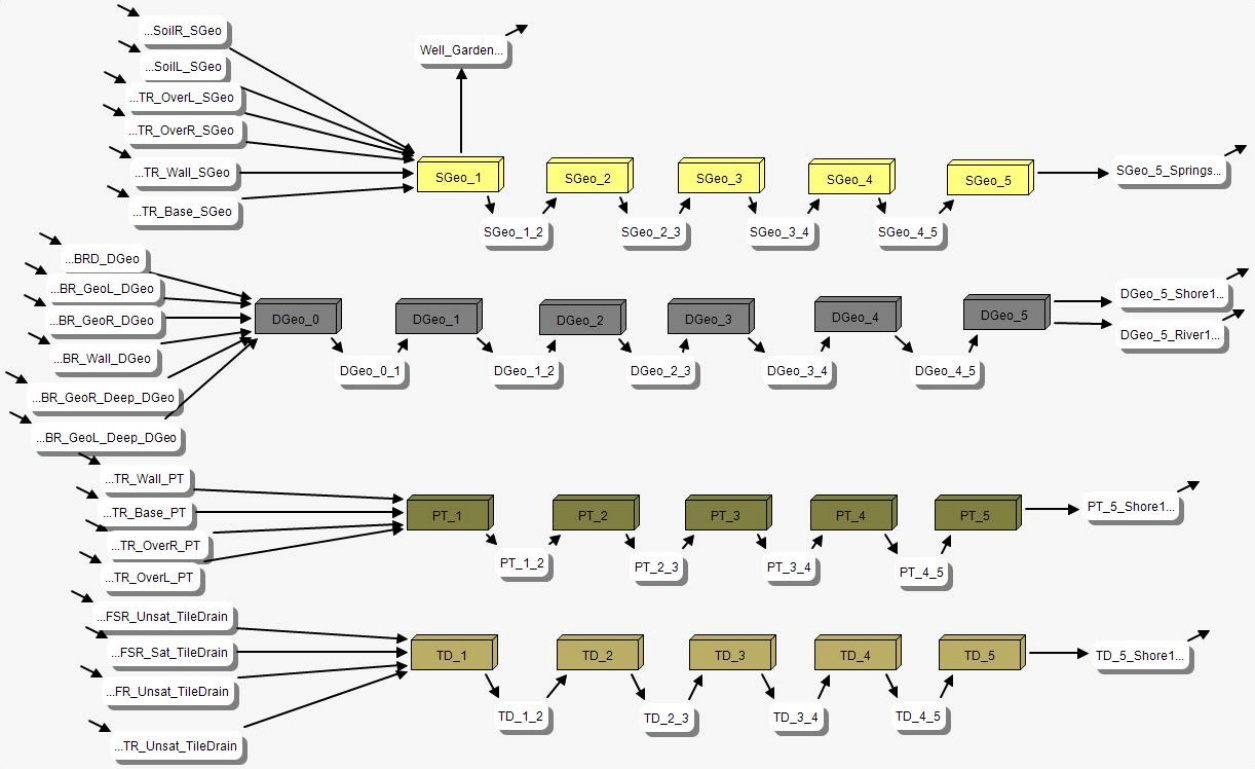
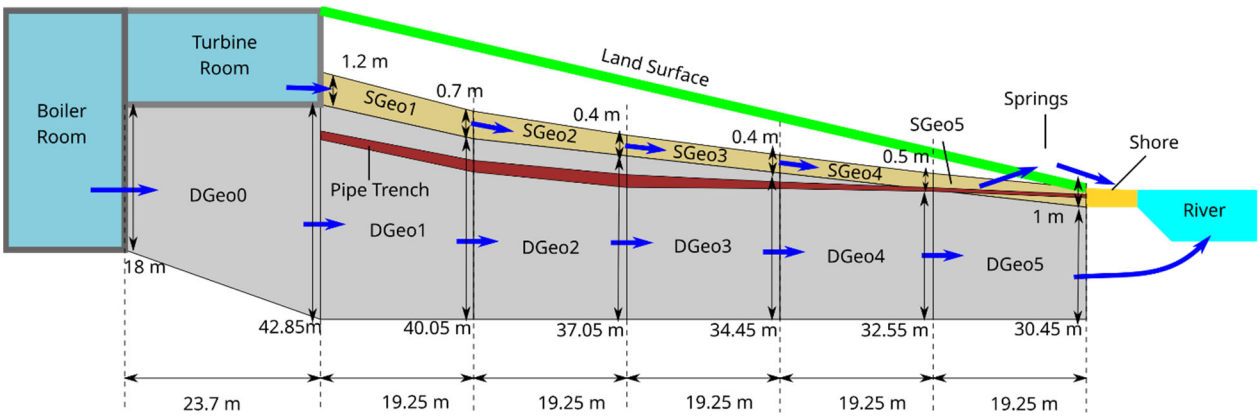


Figure F-16: Cross-Section of the Geosphere Compartments, showing Key Dimensions (not to scale)



F 3.3.2 Processes

Flow through the Tile Drain

The tile drain is assumed to capture a portion $f_{TileDrain}$ of the groundwater flowing through the Fuel Storage Room, Fuelling Room and Turbine Room of the NPDDF (Q_{Tot} m^3 y^{-1}). The flows within the NPDDF are not adjusted to allow for this portion; this would be complex as the flows through each face may be differently affected, and double-counting the flows is also conservative. The water captured by the Tile Drain flows to the *Shore* compartment. This is only assumed to flow while the drain is open (i.e., before $t_{TileDrain}$).

Transport through the Geosphere

The flow leaving the NPDDF through the side walls of the facility enters the overburden or the bedrock via the infill (depending on whether the room is above or below the bedrock).

The rate of transport through the geosphere compartment *A* to *B* is represented with:

$$\lambda_{Adv,A}(t) = \frac{Q_A}{V_A \theta_A R_A} \quad (12)$$

Where the rate of transport may be time-dependent if the value of the flow rate Q_A (m^3 y^{-1}) varies (e.g., in response to the collapse of the Tile Drain at some point in the future). For the geosphere, the flow rate Q_A is in line with those reported by Arcadis & Geofirma (2023b).

F 3.4 Dynamic Biosphere Model

F 3.4.1 Compartments and Structure

The biosphere model represented in the assessment is a part of the surface environment in which concentrations of contaminants released from the NPDDF in the long-term are expected to be highest. It is also necessary to consider an area sufficiently large to support a suitable range of potential exposure groups that are expected to be amongst the most exposed people to the contaminants. The emphasis is therefore on representing the locations in the surface environment where contaminants are first released from the geosphere, as well as media that people routinely use, such as soil for crops and water for drinking.

Geosphere modelling (Arcadis & Geofirma, 2023a) identifies the main points of release as being an area close to the shore of the Ottawa river where springs are expected to occur, fed by the shallow groundwater pathway (in the overburden), and the river bed close to the shore (fed by groundwater from the bedrock). The primary points of release are therefore soils and the river. Appendix E discusses media of interest and presents a conceptual description of the processes by which contaminants can behave in these media and ultimately expose people. These include:

- sediments: river bed/shoreline sediments;
- soils: garden soil, soil used for horticultural production, soil used for grazing;
- river water;
- atmosphere;

- plants: horticultural and garden plants, pasture; and
- animals: livestock, fish, game.

Only the first three of these media require dynamic modelling; contaminant concentrations in plants, animals and the atmosphere can be calculated using equilibrium factors such as presented by IAEA (2010).

The geometry of the biosphere is determined by the area of soil required to support a subsistence farmer, which has been estimated to be 10,000 m^3 (see Appendix E). This can be achieved with a strip of land the same width as the NPDDF and 200 m in length. This geometry has been chosen with regard to the topography of the area, and is orientated “downstream” of the facility so that the associated river and river bank will contain contaminants released from the NPDDF. The geometry is shown in Figure F-17.

The land between this strip of soil and the river itself is assumed to be of less quality, but could be cleared and used to graze animals. For the same length as the garden, and a maximum width of 100 m, an area of approximately 20,000 m^3 is represented, sufficient to support animals for a subsistence farmer. With the geometry of these components specified, sufficient to support a key potential exposure group, the remainder of the media of interest can be defined.

The garden is assumed to be irrigated with contaminated water, whilst the soil of grazing land may receive contamination as a result of animals drinking contaminated river water. In addition to the main garden and grazing soil compartments. Two other areas of soil are represented explicitly, to capture processes that may transport contaminants to them directly:

- The geosphere section closest to the river is assumed to be overlain by soil into which springs form; this section is 19.25 m in length and the full width of the geosphere pathway (approximately 4 m); and
- A strip of soil (approximately 5 m wide) either side of the NPDDF cap is represented separately, as the soil may receive potentially contaminated water deflected by the engineered cap. These strips are considered part of the garden.

The river adjacent to the grazing land is split into three sections, each of which has a river water and river sediment compartment. This is necessary so as to approximate the dilution and dispersion of contaminants in the river. An initial river compartment, the length (in the direction of river flow) of the contamination plume in the geosphere, receives the contaminated groundwater released from the geosphere. This is assigned a nominal length of approximately 46 m (width of the plume with no dispersion) and is cautiously only 5 m wide (perpendicular to the shoreline). Subsequent downstream river compartments increase to a width of 50 m (ten times the initial width of the plume), 200 m downstream (Figure F-17).

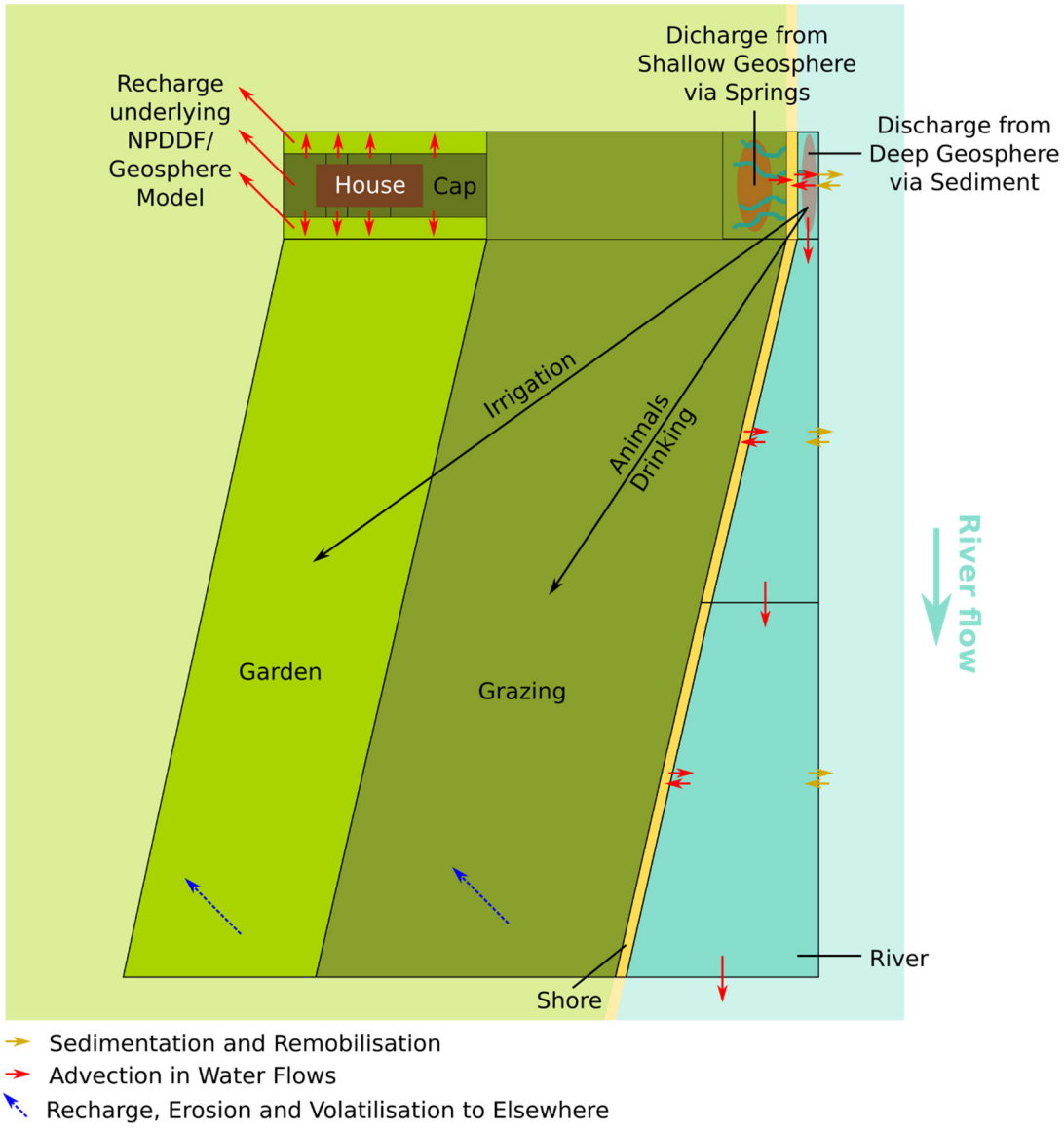
Between the river and the grazing soil is a 2 m wide strip of “shore” sediments, on which a person may reside when fishing, for example.

The overall arrangement of these compartments is shown in Figure F-17. The compartments represented in the model are listed in Table F-3.

Table F-3: Biosphere Model Compartments

Component	Compartment name(s)	Associated Materials
Springs	Springs	Soil_Sand
Garden	Garden, SoilNPDL, SoilNPDR	Soil_Loam
Grazing land	Grazing	Soil_Sand
Shoreline	Shore1, Shore2, Shore3	Sediment
River Water	River1, River2, River3	Water
River Sediment	River1_Sed, River2_Sed, River3_Sed	Sediment

Figure F-17: Representation of the Biosphere in the PostSA Model



F 3.4.2 Processes

Irrigation and Animal Watering

Irrigation and animal watering can be represented with an advective transfer from an appropriate point within the river.

The volume of water pumped from the river, Q_{Abs} ($m^3\ y^{-1}$), is a key input parameter and, depending on the scenario, will be comprised of that which is applied to the soil as irrigation water, Q_{Irrig} ($m^3\ y^{-1}$), and that which is used to water animals, Q_{AnmWat} ($m^3\ y^{-1}$). Water used for domestic purposes is taken to be returned to the river as waste water and the contaminant concentration is conservatively taken to be non-depleted.

The water needed for irrigation is given by:

$$Q_{Irrig} = F_{Irrig}\ A_{Crop}\ D_{Irrig} \quad (13)$$

where:

F_{Irrig} is the proportion of irrigation water provided by the river (unitless);
A_{Crop} is the area of farmland used for irrigated crops, m^2; and
D_{Irrig} is the depth of irrigation water required for each crop, m y^{-1}.

The water needed as drinking water for animals is given by:

$$Q_{AnmWat} = \sum_{Animals}(F_{RiverAnm}\ N_{Anm}\ I_{WatAnm}) \quad (14)$$

where:

$F_{RiverAnm}$ is the proportion of the animals' drinking water that is provided by the river (unitless);
N_{Anm} is the number of animals that require watering (unitless); and
I_{WatAnm} is the ingestion rate of water by animals, l day^{-1} converted to $m^3\ y^{-1}$.

Infiltration/recharge and Interflow

The volume of water leaving the garden soil by infiltration and interflow, Q_{Soil} ($m^3\ y^{-1}$) is given by:

$$Q_{Soil} = A_{Soil} q_{Recharge} + Q_{Irrig} \quad (15)$$

where:

A_{Soil} is the area of the soil, m^2; and
$q_{Recharge}$ is the annual rate of recharge, m y^{-1}, based on groundwater flow modelling.

For the grazing soil the volume of water is

$$Q_{Soil} = A_{Soil} q_{Recharge} + Q_{AnmWat} \quad (16)$$

Not all components of the preceding equation will be relevant to all locations. For example, irrigation is only applied to soil used for crops, and animal watering is only relevant to grazing land. However, all of the water

infiltrating through the soil compartment is taken to act as recharge at all locations. The rate of infiltration through soil is thus:

$$\lambda_{Adv} = \frac{Q_{Soil}}{V\ \theta\ R} \quad (17)$$

where:

V	is the volume of the soil, m^3;
θ	is the total porosity of the soil (unitless); and
R	is the retardation of the soil (unitless).

Surface Water Transport

Surface water flows can be represented by advective transfers, with the water velocity (q_{Rivew}, m y^{-1}) and water body area and volume (A, m^2 and V, m^3) being provided as inputs. The rate of transport of contaminants in the river (λ_{River} y^{-1}) is:

$$\lambda_{River} = \frac{A\ q_{River}}{V}$$

Sedimentation and resuspension are modelled using a simple sedimentation rate (α_{Sed}, in m y^{-1}). The rate of transfer of contaminants from river water to the bed sediment (λ_{Sed} y^{-1}) takes account of the sorption of contaminants to the suspended sediment, as follows:

$$\lambda_{Sed} = \frac{\alpha_{Sed}\ \rho_{Sed} A\ K_d}{V\ (1+\rho_{Sed} K_d)} \quad (18)$$

where ρ_{Sed} is the suspended sediment concentration in the river, in kg m^{-3}. Sediment can also be remobilized from the bed sediments at a rate of λ_{Remo} y^{-1}:

$$\lambda_{Remo} = \frac{\alpha_{Sed}\rho_{Sed}}{\rho_c L_{Sed}} \quad (19)$$

where ρ_c is the density of sediment, in kg m^{-3}. The depth of sediment that actively exchanges with the water column is given by L_{Sed} in m. No downstream bed-sediment transport is represented, but this is a conservative assumption.

River water is also assumed to exchange with the shore of the river. This is modelled as a narrow strip of sediment of 0.3 m depth. River water exchanges freely with this at a rate governed by the vertical interface area with the riverbank sediments (A_{Sed}) and the hydraulic conductivity of the riverbank sediments (K_{Sed}, noting that, conservatively, the hydraulic gradient has been assumed to be 1). This is modelled as an advective transfer in the same form as previously, i.e.

$$\lambda_{Adv,A}(t) = \frac{K_{Sed}\ A_{Sed}}{V_A \theta_A R_A} \quad (20)$$

Here, the properties of the denominator relate to the donor compartment. Where this is river water (for the transfer into the sediments) θ_A (the porosity of river water) and R_A (the retardation) are both equal to 1. For river sediments, they are derived from the sediment porosity and distribution coefficients.

Erosion

Erosion of the surface soil is characterized by an erosion rate, *ER* (kg dry weight m^{-2} y^{-1}), and the associated erosive transfer rate, λ_{Eros} (y^{-1}), of contaminants out of the soil layer is characterized by[1]:

$$l_{Eros} = \frac{ER(1-f_{wat})}{\rho_c Z_{soil}} \quad (21)$$

where:

Z_{Soil} is the depth of the donor soil compartment, m;
ρ_c is the density of the donor soil compartment, kg m^{-3}; and
f_{wat} is the fraction of radionuclide in soil in the water phase (i.e., not sorbed), which is given by:

$$f_{wat} = \frac{\theta_W}{\theta_W + Kd\ \rho_c}. \quad (22)$$

where:

θ_W is the water filled porosity (unitless).

Losses due to Crop Removal

The transfer rate due to crop removal, λ_c (y^{-1}), is given by[2]:

$$l_{crop} = \sum_{crops}\left(\frac{A_{crop} CR\ DW_p\ Y_c\ NL\ cf}{hi\ V_{soil}\rho_c}\right) \quad (23)$$

where:

A_{crop} is the area used for each crop (m^2);
CR is the plant/soil concentration ratio (Bq kg^{-1} dry weight plant per Bq kg^{-1} dry soil);
DW_p is the dry/fresh weight ratio for plant products (kg dry plant kg^{-1} fresh or stored plant);
Y_c is the consumable plant yield (kg fresh weight plant m^{-2} soil);
NL is the nutrient loss rate (or fraction of crop harvested for food) (unitless);
cf is the cropping frequency (y^{-1});
hi is the harvest index (mass of consumable product divided by the mass of total above ground plant; total below ground plant for root crops) (unitless); and
V_{soil} is the volume of the soil compartment (m^3).

Volatilization

Consistent with Clause 6.3.5.1 of CSA (2022), volatilization from the soil is applicable for C-14. Volatilization rates for C-14 are defined directly in CSA (2022) (see Appendix E).

[1] Clause 6.3.4.1 of CSA (2022).

[2] Based on Clause 6.3.7.1 of CSA (2022).

F 4 EQUILIBRIUM BIOSPHERE PROCESSES

Mathematical expressions representing equilibrium relationships are described in the subsections below. The expressions are principally based on those given in CSA (2022).

F 4.1.1 General Calculation of Concentrations in Biosphere Media

The dynamic model provides amounts of contaminants in compartments as an output, *Amount* (Bq). The amounts can be converted to volumetric or mass concentrations, depending on the compartment properties.

Volumetric concentrations, C_V (Bq m^{-3}), are given by:

$$C_V = \frac{Amount}{V} \quad (24)$$

where:

V is the compartment volume (m^3).

The concentration of contaminants in the liquid phase, C_L (Bq l^{-1}), is calculated with:

$$C_L = \frac{C_V}{\theta_w + \rho_c K_d}. \quad (25)$$

The wet weight concentration, C_W (Bq kg^{-1}), is given by:

$$C_W = \frac{C_V}{\theta_w \rho_w + \rho_c}. \quad (26)$$

where:

ρ_w is the density of water, kg m^{-3}.

The total concentration (i.e., in solid and liquid phase) by dry mass, C_T (Bq kg^{-1}) is given by:

$$C_T = \frac{Amount}{M} \quad (27)$$

Where the mass M (kg) is $V\ \rho_c$.

F 4.1.2 Concentration in Air due to Volatilization from Soil and Shore

Volatilization of C-14 from soil and shore leads to an equilibrium air concentration, $C_{air[i]}$ (Bq m^{-3}), downwind of each compartment (i), which is given by[3]:

$$C_{air[i]} = Z_{soil}\ \rho_b\ l_{vol}\ D_{res}\ C_{res}\ C_{T[i]} \quad (28)$$

[3] Based on Clause 7.2.5.1 of CSA (2022).

where:

Z_{soil} is the depth of the top mixed soil layer (m);
ρ_b is the dry bulk density of the soil (kg dry soil m^{-3});
λ_{vol} is the volatilization rate (s^{-1});
D_{res} is the air dilution factor (s m^{-1}); and
C_{res} is a correction factor that accounts for the location of the receptor relative to the irrigated field (unitless). This is cautiously assumed to be 1.

The air dilution factor accounts for dispersion in air from source to receptor, and is the air concentration at the receptor divided by the source strength, as given by[4]:

$$D_{res} = 4.87\ A_f^{\frac{1}{8}} - 3.56 \quad (29)$$

where the receptor is downwind at the end of the field (C_{res} = *1*) and
A_f is the area of the soil or shore compartment (m^2).

The C-14 concentration in air within the plant canopy, C_{canopy}, Bq m^{-3}, is used to provide a C-14 concentration in plants and is calculated according to:

$$C_{canopy} = \frac{f_{CO2}\ F_{Voln}}{u_{canopy}\ Z_c\ W_{soil}} \quad (30)$$

where:

f_{CO2} is the fraction of annual input of C-14 leaving the soil surface as CO_2 per annum (unitless);
F_{Voln} is the transfer flux of C-14 from the soil to the atmosphere (Bq y^{-1});
u_{canopy} is the windspeed within the plant canopy (m y^{-1});
Z_c is the height of the plant canopy (m); and
W_{soil} is the width of the soil compartment perpendicular to the direction of the air flow within the canopy (m).

F 4.1.3 Concentration in Air due to Volatilization from Water

Volatilization of C-14 from water results in an air concentration, $C_{air[i]}$ (Bq m^{-3}), above water compartments (*i*), which is given by:

$$C_{air[i]} = Z_{wat}\ l_{vol}\ D_{wat}\ C_{V[i]} \quad (31)$$

where:

Z_{wat} is the depth of the water (m);
λ_{vol} is the volatilization rate (s^{-1}); and
D_{wat} is the air dilution factor (s m^{-1}).

[4] Clause 7.2.5.2 of CSA (2022).

The air dilution factor accounts for the dispersion in air from source to receptor, and is the air concentration at receptor divided by the source strength, as given by[5]:

$$D_{wat} = e^{[5\ ln(ln(A_{wat}))-9]} \quad (32)$$

where:

A_{wat} is the area of the water compartment (m^2).

F 4.1.4 Contamination of Vegetation

The concentration in crops, $C_{Plant[Crop]}$ (Bq kg^{-1} fresh weight), for radionuclides other than C-14 arises through interception of irrigation water and root uptake and is given by:

$$C_{Plant[\mathrm{Crop}]} = P_{PlantIrrig}\ C_{V,Wat} + P_{PlantSoil[\mathrm{Crop}]}\ C_{T[i]} \quad (33)$$

where:

$C_{V,Wat}$ is the concentration in irrigation water used in the scenario (Bq m^{-3});

$P_{PlantIrrig}$ represents interception of irrigation water (l kg^{-1} fresh weight); and

$P_{PlantSoil}$ represents plant uptake from soil (Bq kg^{-1} fresh weight)/(Bq kg^{-1} dry weight soil).

$P_{PlantIrrig}$ for radionuclides other than H-3 and C-14 is given by[6]:

$$P_{PlantIrrig} = P_{24} = \frac{LAI\ I_{wt}\ h_i\ tf\ hi\left[1-e^{(-l_p\ t_e)}\right]}{l_p\ Y_c} \quad (34)$$

where:

LAI is the leaf area index - leaf area per unit ground surface area (unitless);

I_{Wt} is the volume of water retained per unit leaf area (l m^{-2});

η_I is the frequency of irrigation events using contaminated water (s^{-1});

tf is the translocation factor from foliage to consumable product;

λ_p is the effective removal constant due to physical processes such as wind and rain (s^{-1}); and

t_e is the effective duration of deposition(s).

$P_{PlantIrrig}$ for H-3 is given by[7]:

$$P_{PlantIrrig}[H3] = P_{PlantIrrig-HTO} + P_{PlantIrrig-OBT} \quad (35)$$

where:

$P_{PlantIrrig-HTO}$ is the HTO transfer from irrigation water to plants (l kg^{-1} fresh weight); and

[5] Based on Equation 7.5 and Chapter 7.3.4 of Davis *et al*. (1993).

[6] Clause 7.3.1.1 of CSA (2022).

[7] Clauses 7.3.2 and 7.3.3 of CSA (2022).

$P_{PlantIrrig-OBT}$ is the transfer parameter from irrigation water HTO to OBT in the plant (l kg^{-1} fresh weight).

$$P_{PlantIrrig-HTO} = 1 - DW_p \quad (36)$$

where:

DW_p is the dry/fresh weight ratio for plant products (kg dry weight kg^{-1} fresh weight).

$$P_{PlantIrrig-OBT} = DW_p \, ID_p WE_p \quad (37)$$

where:

ID_p is the isotopic discrimination factor for plant metabolism (unitless); and

WE_p is the water equivalent of the plant dry matter (l water kg^{-1} dry weight).

For most plants, $P_{PlantSoil[Crop]}$ is given by[8]:

$$P_{PlantSoil} = P_{34} = CR \, DW_p \quad (38)$$

where:

CR is the concentration ratio (Bq kg^{-1} dry weight plant)/(Bq kg^{-1} dry weight soil); and

DW_p is the dry/fresh weight ratio for plant products (kg dry weight plant kg^{-1} fresh weight plant).

For berries and mushrooms the value is simply set to CR_{Fruit}, which is given in terms of wet weight.

The C-14 concentration in crops, $C_{Plant[Crop,C14]}$ (Bq kg^{-1} fresh weight), is the highest of that provided by the CSA (2022) models for uptake from irrigation water and uptake from air:

$$C_{Plant[Crop,C14]} = max\left(P_{PlantIrrig} \, C_{River} \, , P_{PlantAir} \, C_{canopy}\right) \quad (39)$$

where

$P_{PlantIrrig}$ represents C-14 uptake from irrigation water (l kg^{-1} fresh weight); and

$P_{PlantAir}$ represents C-14 uptake from the atmosphere (m^3 kg^{-1} fresh weight).

The $P_{PlantIrrig}$ term for C-14 is given by[9]:

$$P_{PlantIrrig[C-14]} = P_{24_C14} = \frac{\left(1-f_{c_air}\right)L' \, f_{CO2}}{Y_c\left(\frac{TS}{hi}-1\right)cf} \quad (40)$$

[8] Clause 6.8.1 of CSA (2022).

[9] Clause 7.3.4.2 of CSA (2022).

where[10]:

f_{c_air}	is the fraction of plant stable carbon derived from air (unitless);
L'	is annual average irrigation rate (l m^{-2} s^{-1});
f_{CO2}	is the fraction of annual input of C-14 leaving the soil surface as CO_2 per annum (unitless);
TS	is the ratio of the total plant yield to the above ground yield (total below ground for root crops) (unitless*);*
hi	is the harvest index (unitless); and
cf	is the cropping frequency (y^{-1}).

The $P_{PlantAir}$ term for C-14 is given by[11]:

$$P_{PlantAir[\mathrm{C14}]} = \frac{f_{c_air}\, X_{4C}\, DW_p}{X_{1C}} \quad (41)$$

where:

$f_{c,air}$	is the fraction of plant stable carbon derived from air (unitless);
X_{4C}	is the mass of stable carbon per mass of plant (gC kg^{-1} dry weight);
DW_p	is the dry/fresh weight ratio for plant products (kg dry plant kg^{-1} fresh or stored plant); and
X_{1C}	is the concentration of stable carbon in air (gC m^{-3}).

F 4.1.5 Concentration in Honey

The radionuclides concentration in honey, C_{honey} (Bq kg^{-1} fresh weight), is given by[12]:

$$C_{honey} = \frac{CR_h}{DW_p}\, C_{Plant[Fruit\ and\ Vegetables]} \quad (42)$$

where:

CR_h	is concentration ratio for honey (Bq kg^{-1} fresh weight honey per Bq kg^{-1} dry plant); and
DW_p	is dry/fresh weight ratio for plant products (kg dry plant kg^{-1} fresh or stored plant).

F 4.1.6 Contamination of Animal Produce

Contamination of animal produce may arise due to ingestion of soil, ingestion of water or ingestion of animal feed. The concentration in animal produce, C_{Anm} (Bq kg^{-1} fresh weight), is calculated by:

$$\mathrm{C_{Anm}} = \mathrm{P_{AnmSoil}}\, \mathrm{C_{T[i]}} + \mathrm{P_{AnmWat}}\, \mathrm{C_{V,Wat}} + \mathrm{P_{AnmPlant}}\, \mathrm{C_{Plant[Crop]}} \quad (43)$$

[10] Note that AMBER will convert between time units of years and seconds.

[11] Clause 6.4.9.2 of CSA (2022).

[12] Based on Clause 6.10.5.1 of CSA (2022).

where

$P_{AnmSoil}$ represents the transfer from soil to animal produce due to ingestion of soil (kg^{-1} fresh weight produce kg^{-1} dry weight soil);

P_{AnmWat} represents the transfer from water to animal produce due to ingestion of river water (l kg^{-1} fresh weight); and

$P_{AnmPlant}$ represents the transfer from animal feed to animal produce (kg fresh weight animal kg^{-1} dry weight feed).

$P_{AnmSoil}$ for radionuclides other than H-3 and C-14 is given by[13].

$$P_{AnmSoil} = \left(k_{af}\ Q_f\ f_{sl} + Q_s\right)F_{ing} \quad (44)$$

where:

k_{af} is the fraction of feed from contaminated sources (unitless);

Q_f is the feed consumption rate by the animal (kg day^{-1} dry weight);

f_{sl} is the soil load on feed as consumed (kg dry soil per kg dry feed);

Q_s is the soil consumption rate of the animal from sources other than feed (kg day^{-1} dry weight); and

F_{ing} is the fraction of animal's daily intake by ingestion that appears in each kg of produce (kg^{-1} fresh weight).

Note that wild animals drink from the river while domesticated animals take water from the same source as used for irrigation (which might be a well).

Consistent with CSA (2022), the soil ingestion pathway for contamination of animal produce is expected to be negligible for H-3 and C-14.

P_{AnmWat} for radionuclides other than H-3 is given by[14]:

$$P_{AnmWat} = k_{aw}\ Q_w\ F_{ing} \quad (45)$$

where:

k_{aw} is the fraction of the animal's drinking water from the contaminated source;

Q_w is the water consumption of the animal (l d^{-1}); and

F_{ing} is the fraction of the animal's daily intake by ingestion that appears in each kg of produce (d kg^{-1} fresh weight).

P_{AnmWat} for tritium is given by[15]:

[13] Clause 6.11.1.1 of CSA (2022).

[14] Clause 6.9.1.1 of CSA (2022).

[15] Clauses 6.9.2.1 and 6.9.3.1 of CSA (2022)

$$P_{AnmWat}[H3] = P_{AnmWat-HTO} + P_{AnmWat-OBT} \quad (46)$$

where:

$P_{AnmWat-HTO}$ is the transfer of tritiated water (HTO) to animals through water ingestion (l kg^{-1} fresh weight); and

$P_{AnmWat-OBT}$ is the transfer of tritiated water to organically bound tritium in animals through water ingestion (l kg^{-1} fresh weight).

$$P_{AnmWat-HTO} = k_{aw}\, f_{w,w}(1 - DW_a) \quad (47)$$

where:

f_{w_w} is the fraction of the animal water intake derived from direct ingestion of water; and

DW_a is the dry to fresh weight ratio for animal products (kg dry weight per kg fresh weight).

$$P_{AnmWat-OBT} = P_{AnmWat-HTO}\, f'_{OBT} \quad (48)$$

where:

f'_{OBT} is the OBT/HTO ratio in the animal as a result of HTO ingestion and metabolic processes.

$P_{AnmPlant}$ for radionuclides other than C-14 an H-3 is given by[16]:

$$P_{AnmPlant} = \frac{k_{af}\, Q_f\, F_{ing}\, e^{(-l_r\, t_h)}}{DW_p} \quad (49)$$

where:

k_{af} is the fraction of feed from contaminated sources (unitless);

Q_f is the feed consumption by the animal (kg day^{-1} dry weight);

F_{ing} is the fraction of animal's daily intake by ingestion which appears in each kg of produce (d kg^{-1} fresh weight);

λ_r is the radioactive decay constant (s^{-1});

t_h is the hold-up time between plant exposure to contamination and feeding (s); and

DW_p is the dry/fresh weight ratio for plant products (kg dry plant kg^{-1} fresh or stored plant).

$P_{AnmPlant}$ for tritium is given by[17]:

$$P_{AnmPlant}[H3] = P_{AnmPlant-HTO} + P_{AnmPlant-OBT} \quad (50)$$

where:

$P_{AnmPlant-HTO}$ is the transfer of HTO from feed to animals; and

$P_{AnmPlant-OBT}$ is the transfer of OBT from feed to animals.

[16] Clause 6.10.1.1 of CSA (2022).

[17] Clauses 6.10.2.1 and 6.10.3.1 of CSA (2022)

$$P_{AnmPlant-HTO} = k_{af}\left((1-f_{OBT})f_{w,pw} + 0.5\,f_{w,dw}\right)\frac{1-DW_a}{1-DW_p} \quad (51)$$

where:

k_{af}	is the fraction of feed from contaminated sources;
f_{w_pw}	is the fraction of the animal water intake derived from water in the plant feed;
f_{OBT}	is the fraction of total tritium in the animal product in the form of OBT as a result of HTO ingestion;
f_{w_dw}	is the fraction of the animal water intake that results from the metabolic decomposition of the organic matter in the feed;
$1\text{-}DW_a$	is the water content of the animal product (l water kg^{-1} fresh weight); and
$1\text{-}DW_p$	is the water content of the plant (l water kg^{-1} fresh weight).

$$P_{AnmPlant-OBT} = k_{af}\left(f_{OBT}f_{w,pw} + 0.5\,f_{w,dw}\right)\frac{DW_a WE_a}{DW_p WE_p} \quad (52)$$

where:

DW_a	is the dry to fresh weight ratio for animal products (kg dry weight kg^{-1} fresh weight);
WE_a	is the water equivalent of the animal product dry matter (l water kg^{-1} dry weight);
DW_p	is the dry to fresh weight ratio for plant products (kg dry weight kg^{-1} fresh weight); and
WE_p	is the water equivalent of the plant dry matter (l water kg^{-1} dry weight).

$$P_{AnmPlant}[C14] = \frac{k_{af}X_{5C}}{X_{4C}DW_p} \quad (53)$$

where:

X_{5_C}	is the stable carbon concentration in the animal (g C kg^{-1} fresh weight); and
X_{4_C}	is the stable carbon concentration in feed (g C kg^{-1} dry weight).

F 4.1.7 Concentration in Aquatic Animals

The radionuclide concentration in aquatic animals, C_{Aq} (Bq kg^{-1} fresh weight), for radionuclides except H-3 and C-14 is provided by the bioaccumulation factor (BAF), which relates the concentration in the edible portion (Bq kg^{-1} fresh weight) to the total concentration (dissolved plus particulate) in the water (Bq l^{-1}):

$$C_{Aq} = BAF\ C_{River}. \quad (54)$$

The model for H-3 is the transfer from HTO concentration in surface water to HTO and OBT in aquatic animals, $C_{Aq[H3]}$ (Bq kg^{-1} fresh weight), provided by[18]:

$$C_{Aq[H3]} = \left((1-DW_{aa}) + (DW_{aa}ID_{aa}WE_{aa})\right)C_{River} \quad (55)$$

[18] Based on Clause 7.7.4 of CSA (2022).

where:

DW_{aa} is the dry weight of aquatic animal product per total fresh weight (kg dry weight kg^{-1} fresh weight);
ID_{aa} is the isotopic discrimination factor for aquatic animal metabolism (unitless); and
WE_{aa} is the water equivalent of the aquatic animal dry matter (l kg^{-1} dry weight).

The model for C-14 transfer from surface water to aquatic animals, $C_{Aq[C14]}$ (Bq kg^{-1} fresh weight), is provided by[19]:

$$C_{Aq[C14]} = \frac{M_{aa}}{M_w} C_{River} \quad (56)$$

where:

M_{aa} is the mass of stable carbon in aquatic animals (gC kg^{-1} fresh weight); and
M_w is the mass of stable carbon in the dissolved inorganic phase in water (gC l^{-1}).

F 4.2 Biosphere Exposure Pathways

F 4.2.1 Dose Due to Ingestion

The dose due to ingestion of contaminated plant produce, $E_{IngPlant}$ (Sv y^{-1}) is given by[20]:

$$E_{IngPlant} = \sum_{\text{Crops}} \left(g_f \, I_f \, DCF_f \, C_{Plant} \right) \quad (57)$$

where:

g_f is the fraction of plant or animal produce from contaminated source (unitless);
I_f is the intake of plant or animal produce (kg fresh weight y^{-1}); and
DCF_f is dose coefficient for intake by ingestion (Sv Bq^{-1}).

The dose due to ingestion of honey, $E_{IngHoney}$ (Sv y^{-1}), is given by:

$$E_{IngHoney} = g_f \, I_f \, DCF_f \, C_{honey}. \quad (58)$$

The dose due to ingestion of animal produce, E_{IngAnm} (Sv y^{-1}), is given by:

$$E_{IngAnm} = \sum_{\text{AnmProduce}} \left(g_f \, I_f \, DCF_f \, C_{Anm} \right). \quad (59)$$

The dose from ingestion of fish and shellfish from the river, E_{IngAq} (Sv y^{-1}) is given by:

$$E_{IngAq} = \sum_{\text{Aquatics}} \left(g_f \, I_f \, DCF_f \, C_{Aq} \right). \quad (60)$$

[19] Based on Clause 7.7.5.1 of CSA (2022).

[20] Based on Clause 6.15.4.1 of CSA (2022).

The dose from incidental ingestion of soil, $E_{IngSoil}$ (Sv y^{-1}), is given by[21]:

$$E_{IngSoil} = \sum_i \left(I_s \; EF_{s[i]} \; DCF_f \; C_{T[i]} \right) \quad (61)$$

where:

I_s is the incidental intake of soil/sediment (kg day^{-1} dry weight); and

$EF_{s[i]}$ is the number of days per year in which incidental soil ingestion may occur from compartment *i*.

The dose due to incidental ingestion of river bed sediment, E_{IngSed} (Sv y^{-1}), includes a dilution factor based on CSA (2022), which allows for non-equilibrium between suspended sediments and riverbank deposits, and is given by[22]:

$$\mathrm{E_{IngSed}} = \sum_i \left(\mathrm{I_s \; EF_{s[i]} \; DCF_f \; DF_s \; C_{T[i]}} \right) \quad (62)$$

where:

DF_s is the dilution factor for shoreline deposits.

F 4.2.2 Dose from Water Immersion

The effective dose from external irradiation from surface water immersion when swimming, $E_{ImmSwim}$ (Sv y^{-1}), is given by[23]:

$$\mathrm{E_{ImmSwim}} = \mathrm{DCF_w \; OF_w \; C_{River}} \quad (63)$$

where:

DCF_w is the dose coefficient for immersion in an infinite, uniformly contaminated water medium (Sv y^{-1} per Bq l^{-1}) and

OF_w is the fraction of the year spent swimming in the surface water body (unitless).

The effective dose from external irradiation from immersion while taking a bath, $E_{ImmBath}$ (Sv y^{-1}), is given by[24]:

$$E_{ImmBath} = DCF_w \; D_c \; r_{f,w} \; OF'_w \; C_{v,wat} \quad (64)$$

where:

D_c is a correction factor to account for the finite size of a bathtub;

rf_w is the removal factor to account for processes such as sedimentation and removal of radionuclides by water treatment plants (unitless); and

[21] Based on Clause 6.15.4.1 of CSA (2022).

[22] Based on Clause 7.11.1 of CSA (2022).

[23] Based on Clause 7.6.1.1 of CSA (2022).

[24] Based on Clause 7.6.1.1 of CSA (2022).

OF_w' is the fraction of the year spent taking baths (unitless).

F 4.2.3 Dose due to External Irradiation from Soil

The effective dose due to external irradiation from contaminated soil, $E_{ExtSoil}$ (Sv y^{-1}), is provided by[25]:

$$E_{ExtSoil} = \sum_i \left(f_{o[i]} DCF_e \, C_{V[i]} \right) \quad (65)$$

where:

f_o is the fraction of total time spent by the individual at the exposure location (unitless);

DCF_e is the effective dose coefficient for ground contamination to an infinite depth (Sv y^{-1} per Bq m^{-3}).

F 4.2.4 External Dose from Contaminated Shore and River Bed Sediment

The effective dose due to external irradiation from contaminated river bed sediment, E_{ExtSed} (Sv y^{-1}), is given by[26]:

$$E_{ExtSed} = OF_s \, W_s \, DCF_s \, DF_s \, C_{V[\mathrm{BedSediment}]} \quad (66)$$

where:

OF_s is the shoreline occupancy factor, or fraction of time an individual spends over contaminated shoreline (unitless);

W_s is the shore-width factor that describes the shoreline exposure geometry (unitless);

DCF_s is the dose coefficient for sediment uniformly contaminated to a depth of 5 cm (Sv y^{-1} per Bq m^{-3});

DF_s is the dilution factor for shoreline deposits; and

$C_{V[\mathrm{BedSediment}]}$ refers to the volumetric concentration in the associated river bed sediment compartment (Bq m^{-3}).

F 4.2.5 Internal Dose from Drinking Water

The internal dose from drinking contaminated water, E_{IngWat} (Sv y^{-1}), is provided by[27]:

$$E_{IngWat} = rf_w \, k''_w \, I_w \, DCF_f \, C_{River} \quad (67)$$

[25] Based on Clause 7.10.1 of CSA (2022) which is for a shoreline. Here the shoreline width factor and dilution for shoreline deposits are both equal to 1.There is no irradiation from soil while in the house, as the soil underneath is not contaminated as a result of irrigation or any other process.

[26] Based on Clause 7.10.1 of CSA (2022).

[27] Based on Clause 7.5.1 of CSA (2022).

where:

rf_w	is the removal factor to account for processes such as sedimentation and removal of radionuclides by water treatment plants (unitless);
$k"_w$	is the fraction of drinking water intake from the contaminated source (unitless);
I_w	is the drinking water intake rate (l y^{-1}); and
DCF_f	is the dose coefficient for intake by ingestion (Sv Bq^{-1}).

F 4.2.6 Internal Dose from Inhalation of C-14 as CO2

The internal dose from inhalation of C-14 as CO_2, E_{InhAir} (Sv y^{-1}), is provided by:

$$E_{InhAir} = I_h \, DCF_g \, \Sigma_i \left(OF_i C_{air_{[i]}} \right) \quad (68)$$

Where:

I_h	is the inhalation rate (m^3 y^{-1});
DCF_g	is the dose coefficient for inhalation of C14 as CO2 (Sv Bq^{-1});
OF_i	is the occupancy factor (unitless) in each location; and
$C_{air[i]}$	is the equilibrium air concentration downwind of each location (Bq m^{-3}).

F 4.2.7 Internal Dose from Inhalation of Smoke

The internal dose from inhalation of smoke, $E_{InhSmoke}$ (Sv y^{-1}), is provided by:

$$\boldsymbol{E_{InhSmoke} = I_h T_{Inh} \sum_i \left(DCF_i \, C_{a[i]} \right)} \quad (69)$$

Where,

I_h	is the inhalation rate (m^3 h^{-1});
T_{Inh}	is the number of hours per year exposure (h y^{-1});
$DCFi$	is dose coefficient for intake by inhalation (Sv Bq^{-1}); and
$C_{a[i]}$	is the radionuclide concentration in air (attached to smoke particles) (Bq m^{-3}).

$$\boldsymbol{C_{a[i]} = C_{Forage[i]} \cdot C_{smoke} / DW} \quad (70)$$

Where,

$C_{Forage[i]}$	is the radionuclide concentration in forage plants (Bq kg^{-1});
DW	is the dry weight to wet weight ratio of forage plants (kg kg^{-1}); and
C_{smoke}	is the concentration of smoke particles in the air of the room (kg m^{-3}).

It is assumed that the medicinal herbs are foraged from the grazing area.

To calculate the concentration of smoke particles in the room, it was assumed that medicinal herbs are burned at a constant rate and that the room is ventilated. The ventilation rate of 1 air change per hour is assumed, representing a house without a basement, which is a cautious value for Canadian houses (Parekh

et al., 2007). The adopted value also fits within the range of 0.12 to 1.2 air change rates per hour during the heating months for modern airtight Canadian houses, as recently reported by Purdy & Parekh (2018).

The total mass of herbs and all the radionuclides contained therein are assumed to end up suspended in the air as smoke particles, which is a cautious assumption given some ash residue is likely. A calculation is performed in a separate AMBER model to calculate the balance between the burning of the herbs and the ventilation of the room, leading to the concentration of smoke particles in the air in the room of 4.8E-4 kg/m^3. This is done in a separate model because the timescale to reach a steady concentration is a few hours, which is much shorter than the timescale of calculations in the PostSA model.

The conversion of volatile radionuclides (e.g., C-14) into a gas, during the burning process, has not been accounted for. Instead, they are assumed to be inhaled as smoke particles and the dose coefficients for inhalation for particulates are used in Equation 69. For C-14 this is a cautious approach because the dose coefficients for dust inhalation are 2 orders of magnitude larger than for exposure to gas.

The input of smoke particles is treated as a source in AMBER and is equivalent to the mass of herbs burned per hour. It is assumed that this burning takes place continually so that a constant concentration of smoke particles is reached in the room. In reality, the herbs would be burned for a specific time period, so the concentration in the room is likely to be lower than that calculated when assuming constant burning.

F 4.2.8 Dose due to Application of Contaminated Plant Material to Skin

The individual annual effective dose for irradiation of the skin, E_{Skin} (Sv y^{-1}), is provided by (Oatway & Mobbs, 2003):

$$\boldsymbol{E_{Skin} = \sum_i \left(DCF_{skin[i]}\, C_{Forage[i]} \right) \rho_{skin} T_{skin} w_t F_{UV}} \quad (71)$$

Where,

$DCF_{skin[i]}$	is the sum of the equivalent dose rate to the basal layer of the skin for beta and gamma irradiation for radionuclide *i* (Sv y^{-1} per Bq cm^{-2}) .
$C_{Forage[i]}$	is the radionuclide concentration in foraged plants for radionuclide *i* (Bq g^{-1}).
ρ_{skin}	is the density of the medicine on the skin (g cm^{-2}).
T_{skin}	is the fractional time that the skin is exposed (-).
w_t	tissue weighting factor for UV exposed skin (-).
F_{UV}	fraction of UV exposed skin contaminated with medicine (-).

It is assumed that the medicinal herbs are foraged from the grazing area. It is also assumed that there is no dilution/concentration of contaminants between the plant matter that is collected and the medicine that is applied to the skin.

A conservative approach is used, assuming that 17% of the skin is UV-exposed (which has a higher radiosensitivity than the non-UV exposed skin (RCLEA, 2011)), that all of the UV-exposed skin is contaminated by the medicine, and that the medicine is on that UV-exposed skin all the time.

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APPENDIX G: DETAILED RESULTS

APPENDIX G – DETAILED RESULTS

G 1 INTRODUCTION

Canadian Nuclear Laboratories (CNL, acting on behalf of Atomic Energy of Canada Limited, AECL) is proposing the in-situ disposal of the Nuclear Power Demonstration Waste Facility (NPDWF), thereafter referred to as the Nuclear Power Demonstration Disposal Facility (NPDDF). This 4th Iteration Postclosure Safety Assessment (PostSA) will support the final EIS submission.

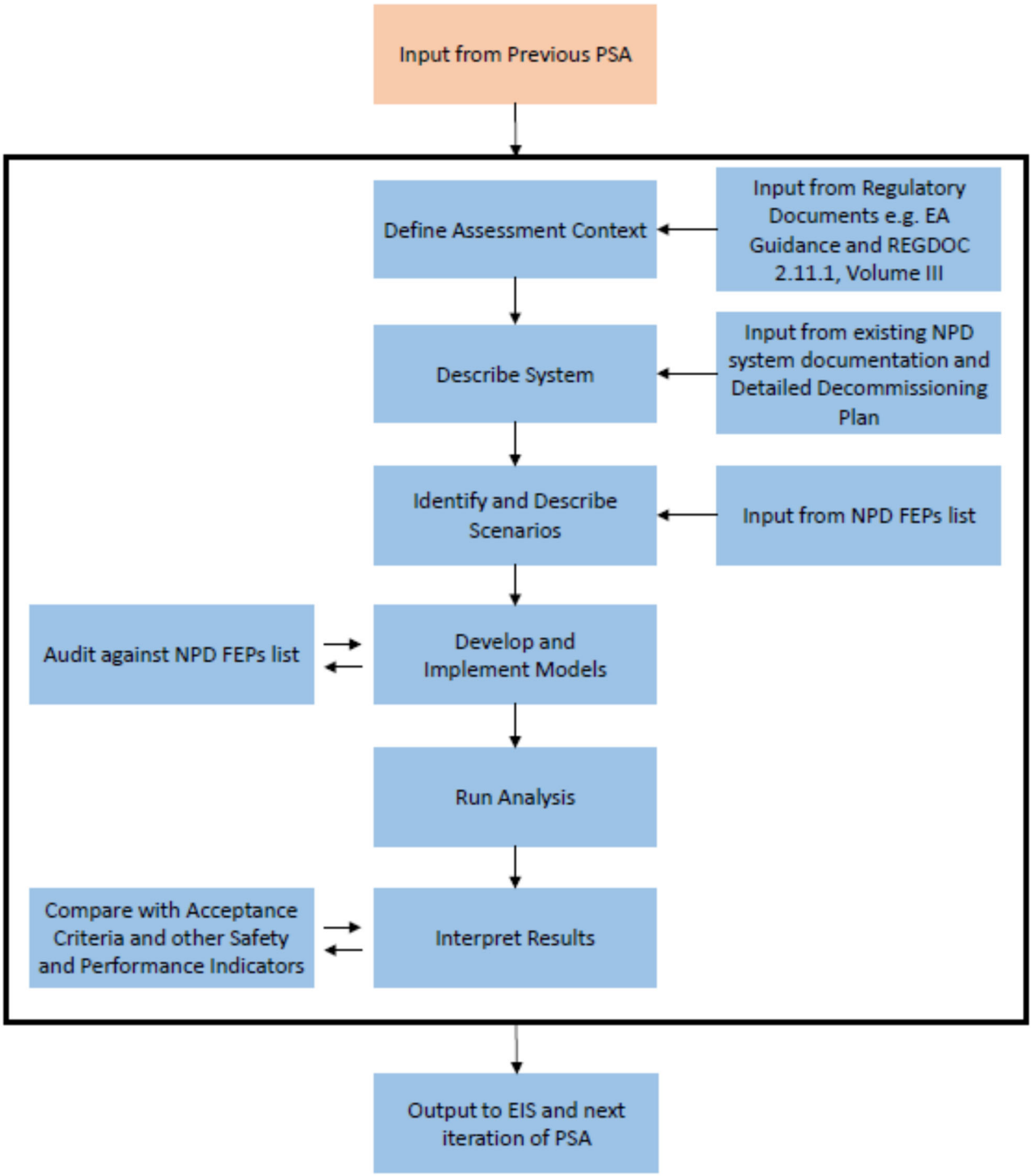
This 4th iteration of the PostSA has been undertaken using international best practice, specifically the International Atomic Energy Agency's (IAEA's) Improving Safety Assessment Methodologies (ISAM) guidance (IAEA, 2004). This is a systematic, stepwise approach, the main stages of which are illustrated in Figure G-1. This PostSA has been documented in a way that corresponds to the ISAM approach, with a main report describing the key elements of the assessment and its outcomes.

This appendix presents the detailed results from the study. It is organized according to the scenarios and calculation cases that have been assessed and which are described in Appendix D.

The focus is on the assessment timeframe of 10,000 y for the reasons outlined in the assessment context (presented in Appendix A). During the first 100 y after closure, it is assumed that Institutional Controls will remain over the NPDDF. During this period, the NPDDF and its surroundings will be monitored to ensure that the closure engineering is functioning as anticipated, and access to the site will be controlled. In graphs, this period is shaded yellow to indicate that the controls could mitigate any adverse consequences. During this period, the only receptors for releases of radioactivity from the Facility are offsite – Institutional Controls will prevent any public use of the land immediately in and around the NPDDF. Conservatively, alternative uses of the site are assumed to occur immediately after this period and can include unrestricted use of the location for activities including farming and use of local resources. Although the highest impacts on people and the environment are anticipated to occur in the next 10,000 y, some graphs and tables give results out to 100,000 y to illustrate the potential consequences beyond the assessment timeframe[1]. To emphasize that these results are illustrative, and are subject to greater uncertainty, this region is shaded grey in the graphs.

[1] The main assessment timeframe of 10,000 y was defined based on modelling results from previous iterations of assessment. In practice, some of the improvements made for this iteration of the PostSA, most notably the groundwater flow modelling, have resulted in peak doses occurring at and slightly beyond this point. This was not anticipated but because calculations were made out to 100,000 y for all scenarios the peak doses have been captured.

Figure G-1 Approach to Postclosure Safety Assessment, Adapted from ISAM (IAEA, 2004)



G 2 NORMAL EVOLUTION SCENARIO

The Normal Evolution Scenario is a reference description of the most plausible expected future evolution of the disposal system, with conservative bias built into the assumptions. Appendix D provides a description of the Normal Evolution scenario and what it entails. Appendix E presents important information on how the scenario is represented in the model and the data used to characterize it. The reader is referred to Appendix D and Appendix E for details of this scenario; however, a brief high-level overview of key interactions is presented in Table G-1. The main assumptions for the scenario are outlined below:

- Radioactivity is initially present:
  - as generic contamination in the NPDDF structure,
  - in the Calandria and associated materials in the Reactor Vault,
  - in the fuel handling system in the Fuelling Room,
  - in redundant pipework in the Boiler Room, and
  - in wastes in the Turbine Room.
- The radionuclide inventories are based, where possible, on a combination of neutron activation modelling calculations and measurement data obtained from the NPDDF or suitably analogous materials.
- Non-radioactive hazardous substances are also present, with the principal contaminant of interest being lead, the majority of which is present as shielding in the Fuelling Room and Reactor Vault.
- Radionuclides in the activated metals of the Calandria are released gradually as they corrode at a rate of 0.1 μm y (steels) and 0.01 μm y^{-1} (Zircaloy). Aluminum dissolution is rapid (within 1 y). Radionuclides in all other materials are assumed to be in the form of contamination and are assumed to be instantaneously available for release. In recognition of the very large amount of lead present in some rooms, its releases are constrained by pH-dependent solubility limits.
- The NPDDF resaturates in 85 y. Once the Facility is resaturated, contaminated groundwater can move between the rooms. Contamination can also diffuse through the walls of any room into the surrounding infill, and thence to the surrounding geology.
- Institutional control is maintained for 100 y. Tile drains are assumed to fail after 100 y as the system is assumed not to be maintained after closure.
- Chemical degradation of the cement in the facility (the concrete walls and grout) is dependent on the amount of water flow through each room. As cement degrades, the properties of the cement-based materials can change, including porosity, sorption characteristics, and elemental solubility.
- Water flow through the rooms changes after 100 y (when tile drains are assumed to fail) and again after 1000 y (when the engineered barriers are assumed to have degraded and permit greater flows of water through the structure). This is represented by the model switching between alternative sets of flow rates for these different flow regimes. The flows themselves are calculated separately, by the detailed groundwater flow model in Arcadis & Geofirma (2023a).

- The facility is overlain by a concrete cap covered by fill material, a liner and soil. It is assumed to degrade over time. For the period 0 to 100 y post-closure, the concrete cap is assigned a hydraulic conductivity of 10^{-10} m/s. Conservatively, from 100 y on, the concrete cap is assigned a higher hydraulic conductivity of 10^{-8} m/s, reflecting its degradation.
- Groundwater migrates to the surface environment via: 1) the overburden and cooling pipe trench, 2) the path of Tile Drains, and 3) through the bedrock. For the portion of the NPDDF that lies in the overburden, contaminants will be released and travel through the overburden pathway. For the portion of the NPDDF that lies within the bedrock, contaminants will be released and travel through the bedrock. Contaminated groundwater from the overburden is released in springs close to the riverbank. Contaminated groundwater from the bedrock is released into the Ottawa river, via the riverbed.
- For the Normal Evolution scenario, it is assumed that contaminated river water is used to irrigate crops and as drinking water by people and animals. A site resident receptor lives on the NPDDF site, farms adjacent soil and raises livestock, as well as fishing in the river. Receptors downstream of the NPDDF are also considered, using river water for drinking, bathing and swimming.

Table G-1 Interactions Assessed in the Normal Evolution Scenario

Environmental Component	Consideration
Air	Inhalation of C-14 volatilised from surface media.
Surface Water	Springs close to the river are not suitable for drinking or other uses but can contaminate soil. River water is used for drinking, crop irrigation, bathing and swimming. Fish, shellfish, aquatic plants and wildfowl live in the river. Livestock and wild animals drink from the river.
Soil	“Garden” soil used for growing crops (vegetables, potatoes, fruit) and animal feed. “Grazing” soil used as forage for livestock. Residence in a house built on the Facility cap.
Groundwater	Groundwater transports contaminants from the Facility to the river and groundwater springs, but is not used by people directly.
Sediment	Contaminated groundwater is released in seepages and springs, and through the riverbed sediment to the river. People fishing the river are exposed to the shoreline sediments.

In the Normal Evolution scenario, the NPDDF is closed as planned with no unforeseen events. There is no human intrusion into the facility (human intrusion is assessed separately, in disruptive event scenarios). The engineered barriers are assumed to physically degrade after 1000 y, which could come as a result of earthquakes in the vicinity, given the local tectonic profile (see Appendix D and Appendix E for more detailed discussion on how seismicity is incorporated into the Normal Evolution scenario and other scenarios).

Global warming of several degrees centigrade persists for a period of more than 100,000 y from the present. The environment is assumed to remain broadly the same as the present day.

Contaminants migrate through the backfill and walls of the Facility. Initially, this is dominated by diffusive transport due to the low hydraulic conductivity of the Facility structure and grout. Degradation of the Facility structure and grout increases the hydraulic conductivity and consequently groundwater flows through the facility will increase. This in turn will increase the rate of leaching and subsequent degradation of the cement-based materials. The porewater in the majority of the grouted Facility is initially highly alkaline due to the conditioning effect of the grout and concrete. Contaminants sorb to the concrete and grout consistent with these conditions. Concrete and grout within the Facility are gradually degraded by groundwater as the cement constituents are slowly leached. As they degrade, their porewater pH falls and their porosity increases.

Groundwater flows through the base of the overburden and within the bedrock. Groundwater in the overburden emerges close to the shore in springs and seepages. Groundwater flowing in the bedrock downgradient of the facility will flow towards the river and discharge under the riverbed, close to the shore. In the aquatic environment, the contaminants may sorb to sediments or be taken up by aquatic flora and fauna. The dominant process will, however, be advection, dispersion and subsequent dilution in the very large volume of water.

River water is extracted from the river by people for domestic use. Conservatively, it is assumed that the water is used by people for drinking and to irrigate soil for crops that are subsequently consumed. Members of the community fish the river and are exposed to contaminants sorbed onto bank sediments. They swim in the river and use it for washing. Wild animals also live in and drink the river water. Other people, such as Indigenous peoples and recreational users of the land (including those fishing the river) may therefore be exposed to contaminants in the river water by different activities.

G 2.1 Containment within the Facility

G 2.1.1 Inventory in the NPDDF

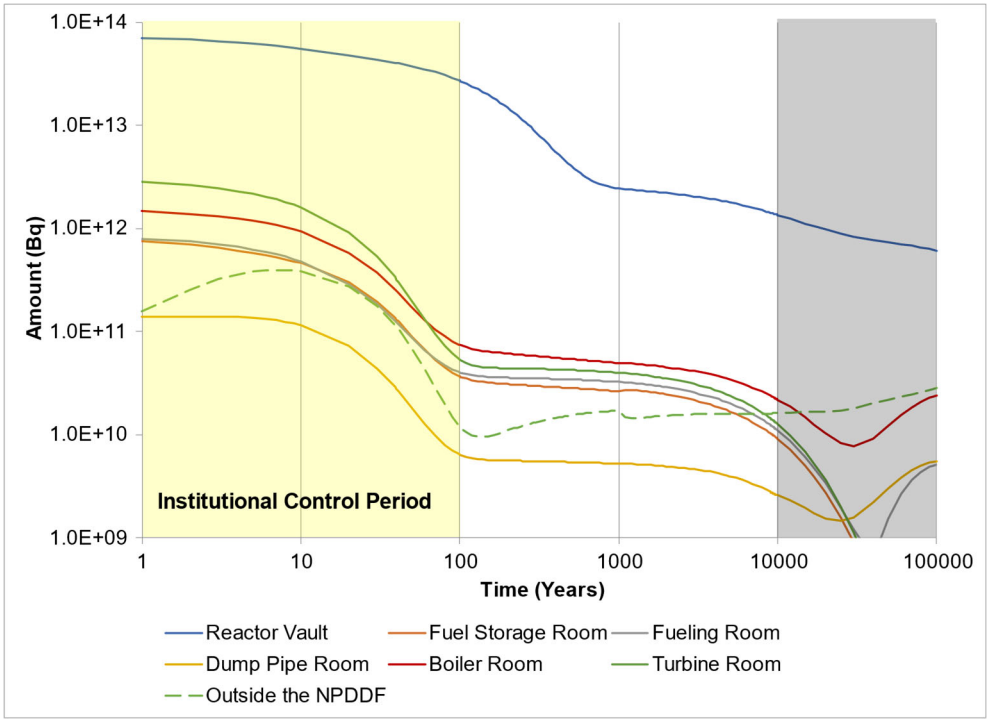
It is assumed that all radioactivity and other non-radiological contaminants are initially contained within the Reactor Vault, Dump Pipe Room, Fuel Storage, Boiler Room, Fueling Room and Turbine Room. There is also some low-level radionuclide contamination which is assumed to be spread throughout the whole of the Facility structure. The largest radionuclide inventory is in the Reactor Vault, mainly associated with neutron activation of the Calandria and the concrete walls. Radionuclides in the Reactor Vault are distributed between four types of metal and the concrete walls. In other locations, radionuclides are assumed initially to be present on the surfaces of the materials present, including redundant pipework and machinery.

A key objective of the NPDDF is to confine radionuclides within the structure for a sufficient period of time to allow for radioactive decay to reduce the hazard to levels that meet safety criteria. The change in amount of radioactivity within the NPDDF over time indicates how effectively the materials within the Facility retard transport and contribute to the containment safety function. The PostSA model shows that the total amount

of radioactivity *within* the Reactor Vault is always higher than the radioactivity beyond the Facility (i.e., the rest of the facility plus the geosphere and the biosphere). By 10,000 y after closure, 99% of the remaining radioactivity is still contained within the Facility (Figure G-2).

The majority of the radioactivity in the Reactor Vault is associated with the Zircaloy components in the reactor vessel. The inventory within the Zircaloy is dominated by longer lived radionuclides (principally, Zr-93, Ni-59/63 and C-14) and the Zircaloy is assumed to corrode very slowly in the alkaline environment of the reactor vault. Both of these factors give rise to limited releases of radionuclides from the Zircaloy over the whole PostSA period. The inventory of carbon steel and stainless steel also decreases gradually. The corrosion rate of both forms of steel is relatively low, at 0.1 μm y^{-1} in the alkaline-conditioned environment of the Facility. By 30,000 y after closure the steel has entirely corroded and the associated radioactivity has been released into the Reactor Vault. By contrast, aluminum corrodes very rapidly in an alkaline environment, and is thus assumed to release radionuclides embedded in the material into the Reactor Vault as soon as the NPDDF is assumed to be resaturated (after 85 y). In addition, there is initially some contamination in the concrete walls of the vault.

Figure G-2 Amount of Radioactivity within, and Outside of the NPDDF



Note: for information on radioactivity outside of the NPDDF see Section 5.1.1.3 which discusses releases from the facility and Section 5.1.2 which discusses contaminants in the environment.

In Figure G-2, the decrease in activity in the NPDDF within the first 100 y is a result of short-lived radionuclides, that dominate the radioactivity, both decaying (such as for Co-60, Pu-241) and being released (principally H-3). The concentrations of longer-lived and less mobile radionuclides decrease more slowly, as radionuclides migrate from the water in the Reactor Vault into the walls, firstly by diffusion, then, once the Facility has resaturated, by advection.

Non-radioactive contaminants are modelled in the same way as radionuclides. However, because lead is present as a bulk material it is inappropriate to assume that it is instantaneously available for release once resaturation begins. The rate of release of lead from a room is limited by the solubility of lead in water. For this reason, pH-dependent solubility limits are applied to all parts of the model in which lead may be present. These act to prevent the dissolution (and subsequent groundwater transport) of lead at greater than a specified molar concentration. As a result, all of the lead remains in the NPDDF over the whole assessment period, with less than 10 kg being released after 10,000 y. As with the radionuclides, it can be seen that lead in a few key locations (the Fuelling Room, Reactor Vault and Boiler Room) dominates the inventory (see Figure G-3).

The chemical conditions in the NPDDF are determined by the properties of the concrete structure and grout backfill and are a key factor in its behaviour and indeed the effectiveness of the NPDDF in containing key radionuclides. As described by Wilson (2020), these conditions evolve over time as the cement phases in the grout are leached, and so ultimately the effectiveness of this barrier is reduced. Representing the change in chemical conditions in the NPDDF environment is therefore a key aspect of the model. The timing of the changes in chemical conditions is related to the amount of water that has flowed through each room. Once a certain number of “flushes” of the pore-space have occurred the cement chemistry will change, as described by Wilson (2020). The flow rates through each room also depend on the physical condition of the structure and grout, and are calculated by Arcadis & Geofirma (2023a) (Table G-2). The effectiveness of the concrete structure and undegraded grout in limiting flows through the rooms is clearly significant. It is not until after the structure and grout have fully degraded (> 1000 y) that there is sufficient flow through the rooms to begin to leach the cement significantly. The consequence is that the high-alkaline conditions in the NPDDF are preserved for many thousands of years.

Table G-3 gives the timescales for chemical degradation of concrete and Table G-4 provides the timescales for grout, in each case based on the degradation stages recommended by Wilson (2020):

- Stage I: 0 - 100 flushes
- Stage II: 100 - 1,000 flushes
- Stage III: 1001 - 7,450 flushes
- Stage IV: more than 7,450 flushes

In order to provide a suitable representation of the effects of pH evolution on solubility, the earlier phases of grout degradation can be subdivided, as follows:

- Stage A: 0 - 106 flushes
- Stage B: 106 – 227 flushes
- Stage C: 227 - 643 flushes
- Stage D: 643 – 1978 flushes
- Stage E: 1978 - 4386 flushes
- Stage F: more than 4386 flushes

Here, Stages A – D correspond with Stages I-III, Stage E corresponds to Stage IV, and Stage F corresponds to background conditions.

Table G-2 Total Flow Rate through Each Room in the NPDDF

Room	Modelled Volume (m^3)	Undegraded, Tile Drains Functioning, $m^3\ y^{-1}$ (0 – 100 y)	Undegraded, Cap degraded and Tile Drains Not Functioning, $m^3\ y^{-1}$ (100 – 1000 y)	Degraded, Tile Drains Not Functioning, $m^3\ y^{-1}$ (>1000 y)
Above Bedrock				
Fuel Storage Room	2239	0.013	0.058	4.3
Fueling Room	2488	0.032	0.087	8.8
Boiler Room	1838	0.0033	0.065	2.9
Turbine Room	4592	0.041	0.12	15
Below Bedrock				
Fuel Storage Room	1905	0.039	0.046	7.1
Reactor Vault	1880	0.029	0.032	5.0
East of Reactor Vault	122	0.029	0.024	3.8
West of Reactor Vault	129	0.007	0.009	1.6
Dump Tank Pipe Room	201	0.0055	0.0058	1.0
Boiler Room	2691	0.066	0.093	12
Boiler Room (deep)	642	0.028	0.028	4.5

Table G-3 Time at Which Concrete Degradation Stages Begin

Room	Stage I	Stage II	Stage III	Stage IV
Above Bedrock				
Fuel Storage Room	0	25,000	>100,000	>100,000
Fueling Room	0	15,000	>100,000	>100,000
Boiler Room	0	30,000	>100,000	>100,000
Turbine Room	0	15,000	>100,000	>100,000
Below Bedrock				
Fuel Storage Room	0	12,000	>100,000	>100,000
Reactor Vault	0	15,000	>100,000	>100,000
East of Reactor Vault	0	3,250	25,000	>100,000
West of Reactor Vault	0	7,000	60,000	>100,000
Dump Tank Pipe Room	0	8,750	80,000	>100,000
Boiler Room	0	9,900	90,000	>100,000
Boiler Room (deep)	0	7,000	60,000	>100,000

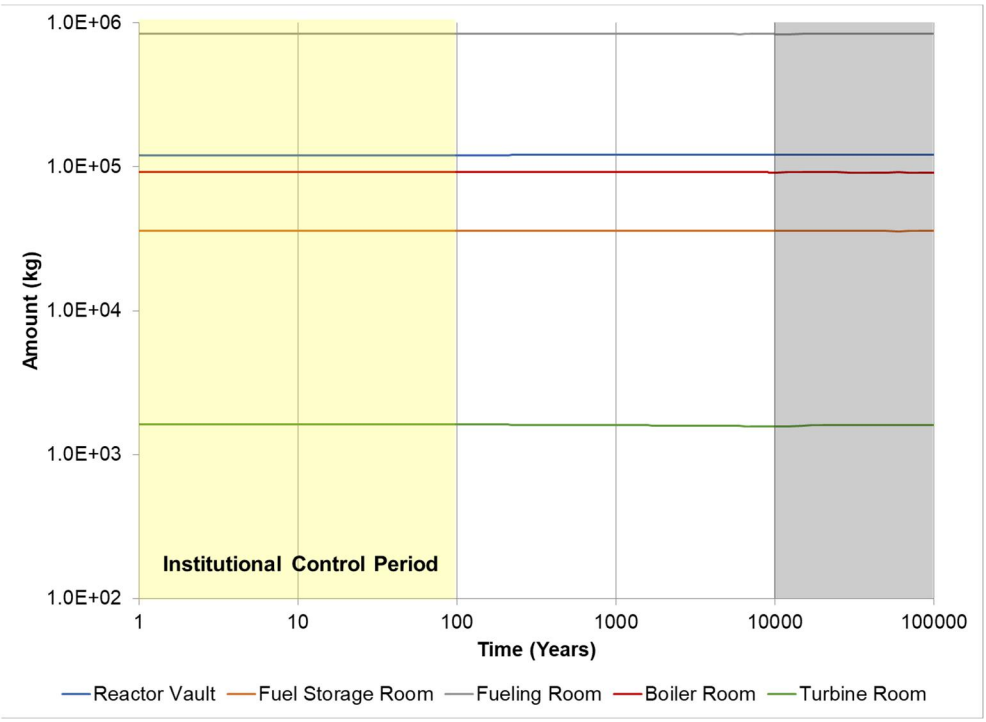
Note: Greyed-out cells are after the main assessment timeframe of 10,000 y.

Table G-4 Time at Which Grout Degradation Stages Begin

Room	Stage A	Stage B	Stage C	Stage D	Stage E	Stage F
Above Bedrock						
Fuel Storage Room	0	25,000	50,000	>100,000	>100,000	80,000
Fueling Room	0	15,000	30,000	80,000	>100,000	80,000
Boiler Room	0	30,000	60,000	>100,000	>100,000	90,000
Turbine Room	0	15,000	30,000	80,000	>100,000	100,000
Below Bedrock						
Fuel Storage Room	0	15,000	30,000	80,000	>100,000	>100,000
Reactor Vault	0	15,000	30,000	80,000	>100,000	>100,000
East of Reactor Vault	0	3,250	6,000	15,000	50,000	>100,000
West of Reactor Vault	0	8,000	15,000	40,000	>100,000	>100,000
Dump Tank Pipe Room	0	9,200	20,000	60,000	>100,000	>100,000
Boiler Room	0	12,000	25,000	60,000	>100,000	>100,000
Boiler Room (deep)	0	7,000	15,000	40,000	>100,000	>100,000

Note: Greyed-out cells are after the main assessment timeframe of 10,000 y.

Figure G-3 Amount of Non-Radioactive Contaminants (Pb) within the NPDDF

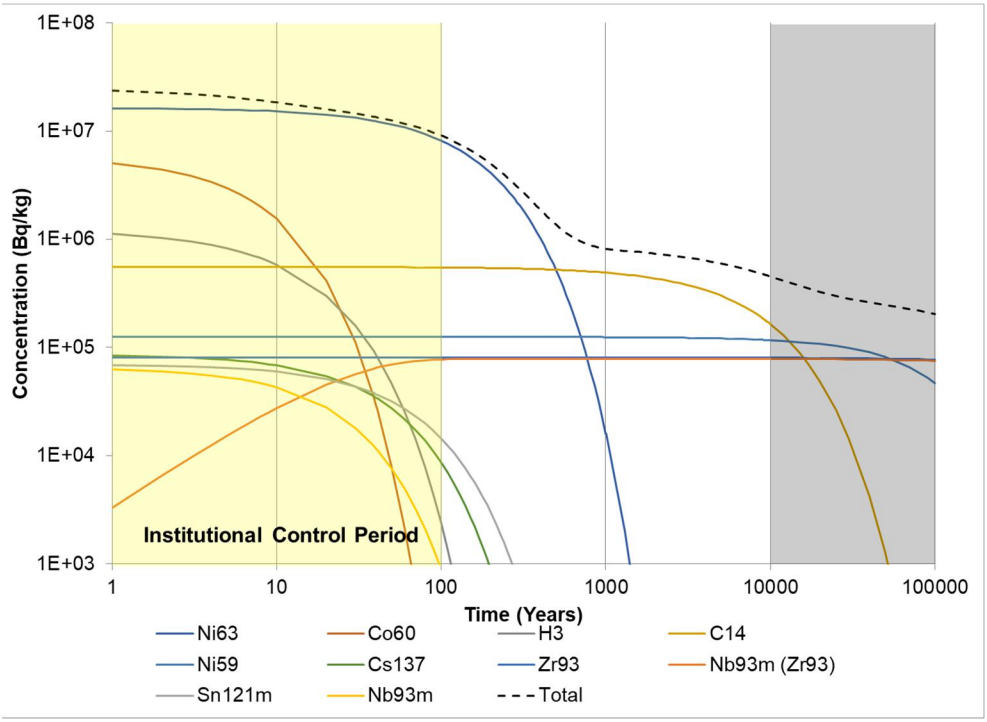


G 2.1.2 Concentrations in the NPDDF

The average concentration of key radionuclides in the Reactor Vault is shown in Figure G-4. This is calculated from the total radioactivity of all materials (grout, concrete walls, and wastes) in the vault divided by the total mass. With the exception of Nb-93m, a daughter of Zr-93, all concentrations fall with time. This is mainly due to radioactive decay, but contaminants are also gradually released in groundwater. Consistent with the observations noted above, radionuclides present in the matrix of activated metals (such as Zr-93) remain virtually unchanged until more than 10,000 y as they have long half-lives and are retained in the metal. Initially, the average total concentration is $2x10^7$ Bq kg^{-1} but this declines over the first thousand years as the dominant radionuclide (Ni-63, with half-life of 100 y) decays. C-14 (half-life of 5,700 y) is dominant from 500 – 12,000 y. Both these radionuclides are mainly from the aluminum, stainless steel and Zircaloy of the Calandria. In the longer term, Ni-59 (half-life of 101,000 y) and Zr-93 (half-life of 1.53 million y) are dominant.

Because of the prevalence of long-lived radionuclides, and their effective confinement, the average concentration in the Reactor Vault only decreases slowly. The concentration is $8x10^5$ Bq kg^{-1} after 1,000 y and $5x10^5$ Bq kg^{-1} by 10,000 y. This illustrates that the Facility is effectively containing radionuclides within the structure as they decay.

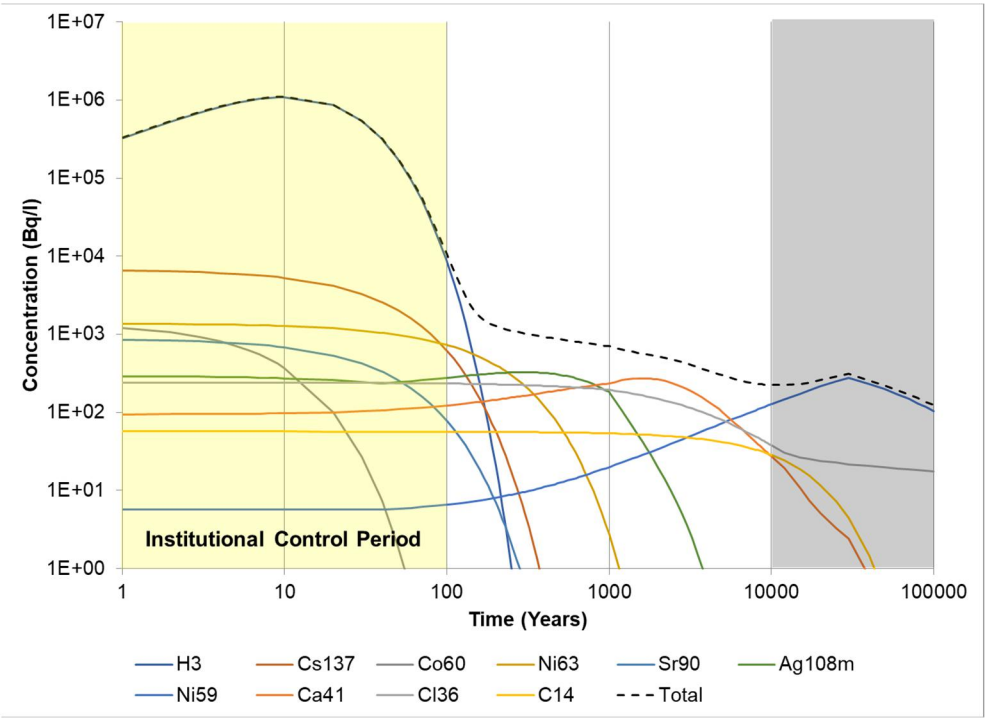
Figure G-4 Average Concentrations of Radionuclides in Reactor Vault



The concentrations in water that fills the Reactor Vault are up to $1x10^6$ Bq l^{-1} due to H-3 (Figure G-5). However, the dominant radionuclides are all short-lived and decay to 700 Bq l^{-1} after 1,000 y. Concentrations of most radionuclides monotonically decrease, but Ca-41 and Ni-59 can be seen to increase

before peaking and then decreasing. This is because these radionuclides are dominantly present in activated metals and are released by corrosion faster than they are released from the Reactor Vault in groundwater. It is only once radioactive decay dominates the rate of accumulation that the concentrations fall.

Figure G-5 Radionuclide Concentrations in Water in the Reactor Vault



The resaturation of the Reactor Vault (complete 85 y after closure) is not obvious in Figure G-5. This is because in this period the migration of contaminants is driven by diffusive processes which are assumed to occur at all times. Following resaturation, the groundwater flows through the NPDDF are very low (less than 1 $m^3 y^{-1}$ per room, see Table G-2) as the engineered structures and grout limit the flow of water (a hydraulic conductivity of $1x10^{-11}$ m s^{-1} is assumed for the concrete structure (Arcadis & Geofirma, 2023a)). After resaturation, and up to around 1,000 y, it is assumed that the concrete and grout is still intact. This limits water flows through the Reactor Vault to just 0.03 $m^3 y^{-1}$.

The average concentrations of radionuclides in other rooms are shown in Figure G-6 and Figure G-7. The highest concentrations in both solids and water are generally in the Reactor Vault, particularly after the initial release of tritium has decayed, within the first 100 y or so.

In solid material, after the 100 y institutional control period, concentrations of radionuclides in rooms other than the Reactor Vault are more than a hundred times lower than the initial concentrations in the Reactor Vault, with a maximum of $2x10^4$ Bq kg^{-1}. Concentrations in a number of rooms surrounding the Reactor Vault can be seen to increase after about 40,000 y. This corresponds to corrosion of the metals in the Reactor Vault, and the associated release of radionuclides which gradually migrate into other rooms.

Figure G-6 Concentration of Radioactivity in Various NPDDF Rooms

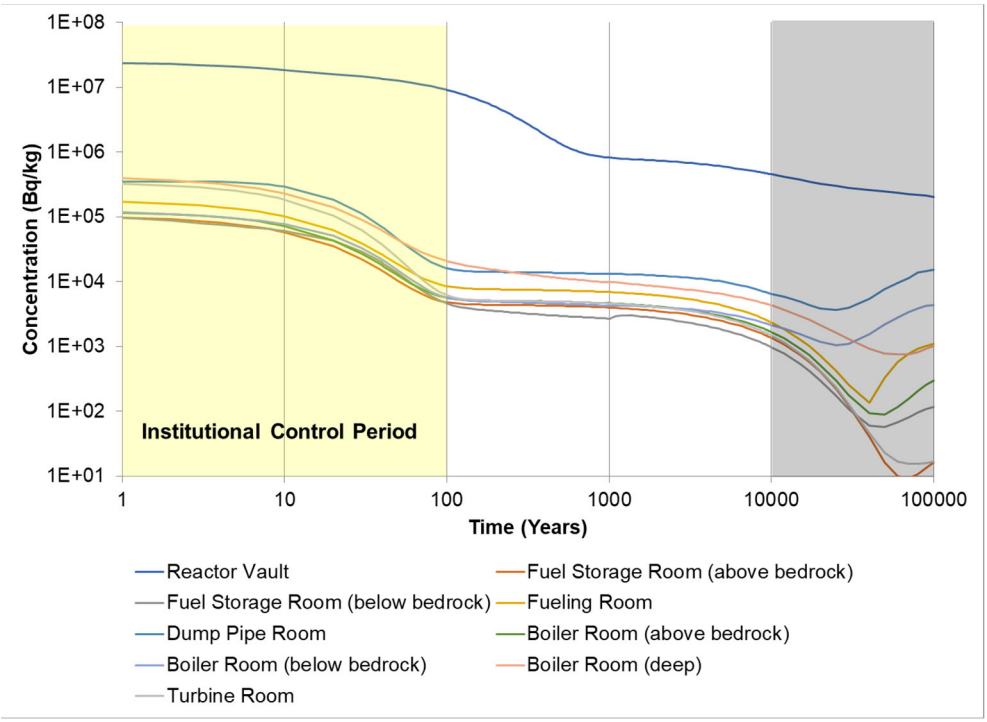
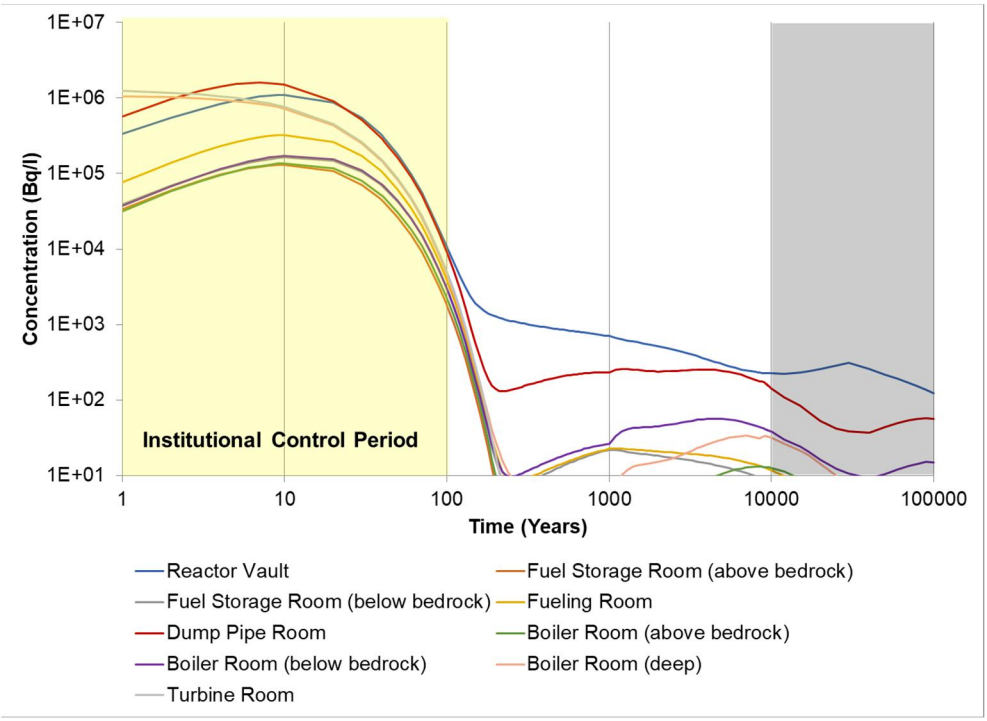


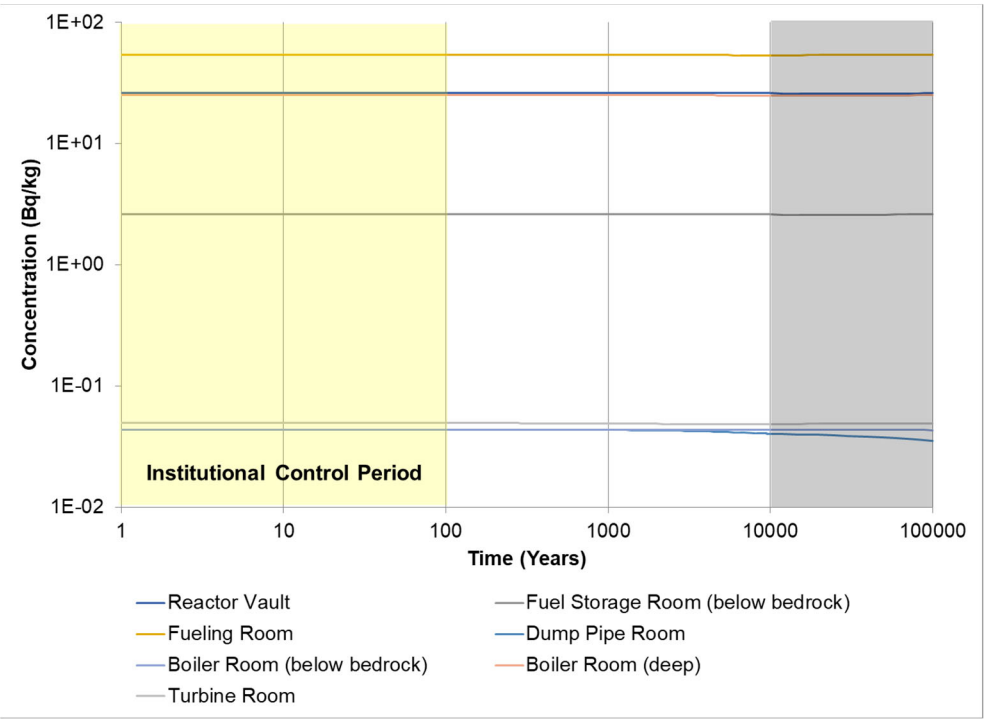
Figure G-7 Concentration of Radioactivity in Water in the NPDDF



After 300 y the radionuclide concentrations in the water in the NPDDF are about $1x10^{3}$ Bq l^{-1}, with the Reactor Vault and Dump Pipe Room having the highest concentrations of radionuclides in water (Figure G-7).

In practice, lead will be present as solid metal sheet, bricks and other items. For the purposes of the assessment, the total mass has been conservatively assumed to be dispersed within the grout filling the rooms and consequently available for dissolution, subject to solubility considerations. Even with this conservative assumption, the lead concentration changes very little over the assessment timeframe, as shown in Figure G-8. The average concentration in the Fuelling Room is 54 mg kg^{-1}, in the Reactor Vault and Boiler Room it is 26 mg kg^{-1} and 25 mg kg^{-1} respectively.

Figure G-8 Concentrations of Lead within the NPDDF Rooms



G 2.1.3 Releases from the Facility

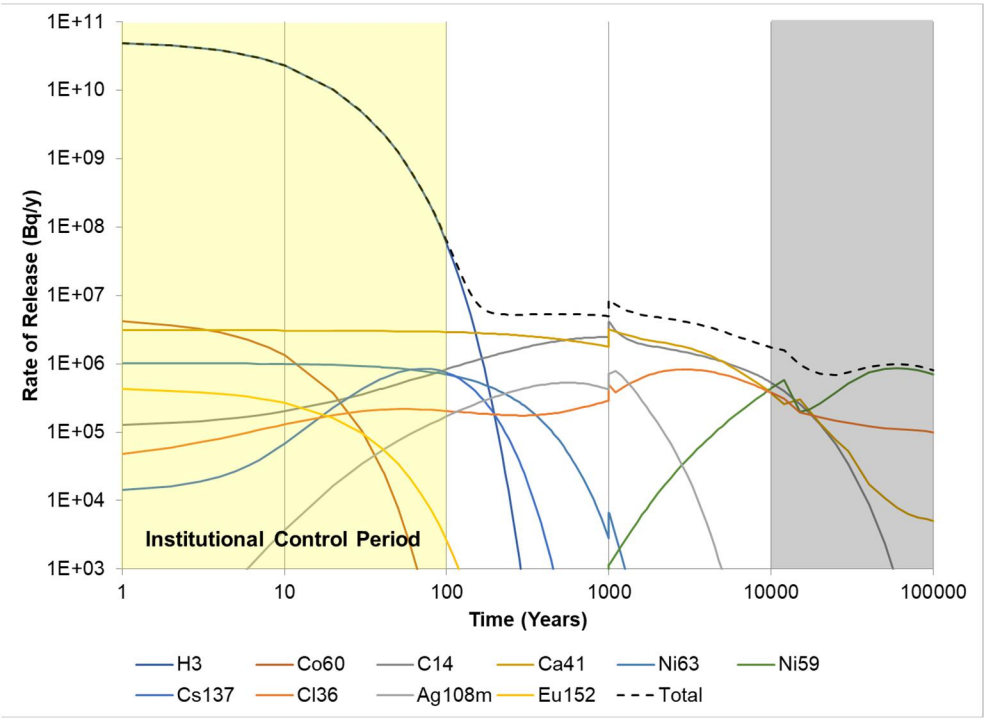
Another way of understanding the performance of the Facility in confining radionuclides and other contaminants is to examine the rate at which radionuclides are released to the surrounding environment. The rate of release of contaminants from the Reactor Vault walls is illustrated in Figure G-9. Initially, H-3 is released at $5x10^{10}$ Bq y^{-1} as it diffuses out of the Reactor Vault walls into adjacent structures. However, the release rate drops rapidly due to the short half-life and high mobility of the radionuclide.

This very noticeable release of H-3, which dominates the first 100 y, is a result of a conservative approach to representing diffusive releases in the PostSA, which are assumed to occur even before the facility has

resaturated. (No advective flows occur out of the facility during the resaturation period, the first 85 y.) The duration of resaturation was based on modelling (Arcadis & Geofirma, 2023c). Immediately following this period, the facility is assumed to have fully resaturated so the water table is at the same depth within the NPDDF as the surrounding geosphere. Groundwater is then assumed to flow through the facility thus permitting a release of contaminants by advection as well as diffusion. The approach taken is deliberately cautious and can be expected to overestimate the significance of the tritium release. A more realistic representation is not possible to implement due to the reliance upon discrete scenarios used in the flow modelling. In the whole period after 140 y, the rate of radionuclide release is less than $9x10^6$ Bq y^{-1} which is a small fraction of the current Derived Release Limits (DRLs) for NPD (CNL, 2011).

From 150 y after closure, the main radionuclide released from the Reactor Vault is Ca-41, with C-14 dominating between 575 and 1,000 y. The concrete and grout are assumed to have completely degraded, physically, at 1,000 y. At this point, flows through these structures increase and can be seen to result in an increased rate of release of radionuclides. Other changes can be seen after 10,000 y, when the rate of release of some contaminants (Ca-41 and Ni-59) increases suddenly. This corresponds to the end of the first stage of concrete and grout degradation in various rooms in the NPDDF (the timings differ for different rooms, see Table G-3 and Table G-4). This results in changes to the sorption of key radionuclides, which can lead to a sudden increase in their availability for transport in solution. For example, at 15,000 y the Ca sorption coefficient is reduced from 0.007 to 0.001 m^3 kg^{-1}.

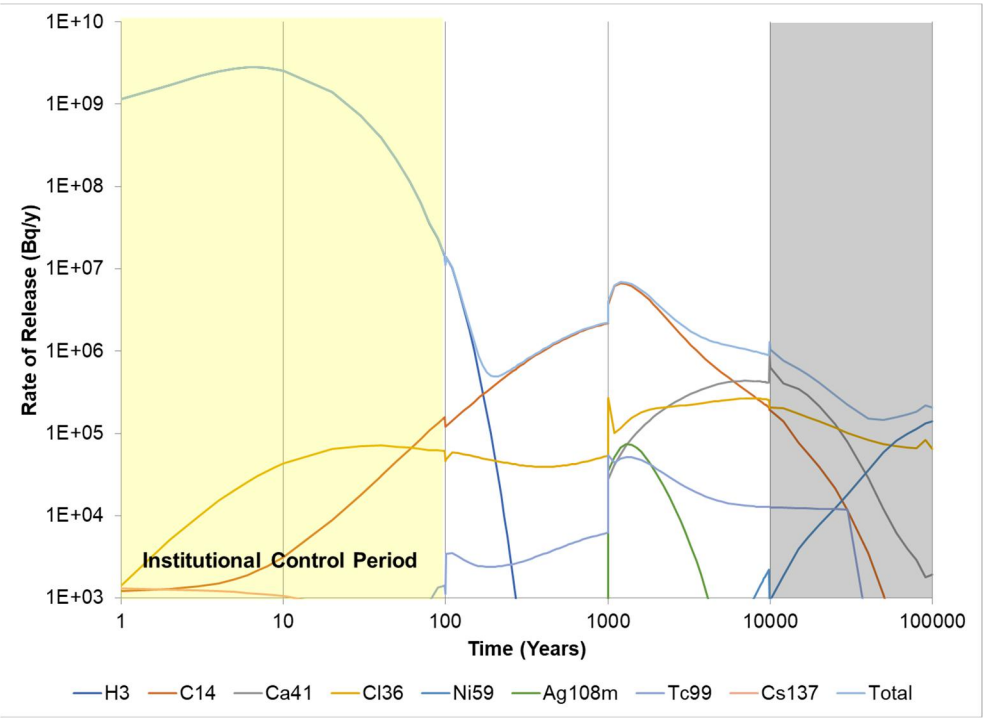
Figure G-9 Rate of Release of Radionuclides from Reactor Vault



Radionuclides are present in various rooms within the NPDDF, and thus there are several pathways to the surrounding geosphere. Radionuclides from rooms above the bedrock can be released into adjacent rooms, the below bedrock rooms, the cap and the overburden surrounding the Facility. For rooms within the bedrock, the main pathway is via the infill surrounding the NPDDF walls and the surrounding bedrock.

Figure G-10 shows that tritium dominates the total release to the geosphere for up to 170 y after closure. After this time, C-14 is the dominant radionuclide up to 6,000 y, with Ca-41 dominating subsequently until 30,000 y when Cl-36 and subsequently Ni-59 dominate in the far future. The largest release is of H-3 through the walls, by diffusion, beginning almost immediately after the closure of the NPDDF and mainly from the sides of the structure (into the overburden and bedrock), and via the cap. The peak release rate of 3×10^{9} Bq y^{-1} occurs after only 7 y. However, after 160 y this has fallen to a rate of less than 1×10^{6} Bq y^{-1}. There is an increase in the release of contaminants after the engineered barriers are assumed to become fully degraded at 1,000 y after closure. At this point there is a sharp increase in the release rate of C-14 and other contaminants, leading to a peak release rate of 7×10^{6} Bq y^{-1} after 1,200 y. Radionuclide releases into the bedrock are larger than other pathways for the whole period of the assessment although the difference is much greater after a few hundred years. The shallow geosphere (overburden) and Pipe Trench convey similar fluxes of radionuclides.

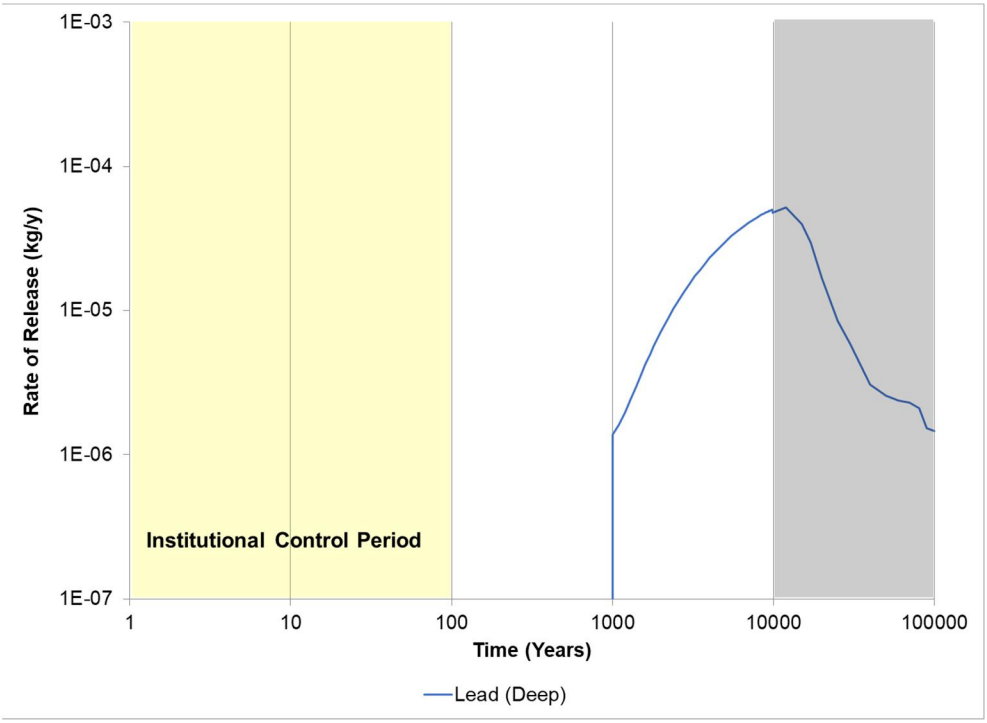
Figure G-10 Total Rate of Release of Radionuclides to the Geosphere



The rate of release of lead into the Geosphere never exceeds 1×10^{-4} kg y^{-1} (Figure G-11). Releases of lead do not commence until after the NPDDF has resaturated. Releases from rooms are limited by the solubility of lead in the porewater of the grout, and the changing solubility conditions can be seen in the pattern of

lead releases. At 1,000 y, the flows through the NPDDF significantly increase as the structure is assumed to have fully degraded, leading to a much increased release, but this declines after 12,000 y when the first stage of grout degradation is complete in the Boiler Room (and is complete in other rooms shortly thereafter at around 15,000). The solubility of lead in "Stage 1" conditions is 1,000 mol m^{-3}, but this decreases to 59 mol m^{-3} in Stage 2.

Figure G-11 Rate of Release of Lead to the Geosphere



G 2.2 Contaminants in the Environment

In the PostSA model, the geosphere downstream of the NPDDF is represented by three pathways:

- a shallow pathway at the base of the overburden, which discharges via springs and seepages to soil near the river (representing the cooling pipe trench and overburden between the facility and the river);
- a pathway to represent Tile Drains, located in the overburden and bedrock; and
- a deep pathway, in the bedrock, which discharges to the riverbed.

Downstream of the NPDDF these pathways are split into five equal sections of 20 in length, and there is an additional deep geosphere compartment lying beneath the Turbine Room.

Radionuclide concentrations in the geosphere are much lower than in the NPDDF. The highest concentration in the overburden is 0.04 Bq l^{-1} (after 90 y), as a result of the rapid release of tritium from the NPDDF. The highest concentration in the bedrock is 3,000 Bq l^{-1} after 7 y. This is higher than the overburden because, while the releases from the NPDDF are divided between the two pathways, there is a higher inventory located in the deeper parts of the NPDDF and a lower flow rate through the bedrock. The high flow in the overburden acts to dilute the radionuclides released from the NPDDF to a greater degree than the releases to the bedrock.

The profile of the concentrations in the groundwater (Figure G-12) can be seen to mirror the fluxes shown in Figure G-10. After the initial tritium dominated pulse, concentrations are dominated by C-14 (170 – 5,000 y) and in the long-term Ca-41 (5,000 – 30,000 y) in the bedrock. In the period after 1,000 y the peak concentration in the bedrock (deep geosphere pathway) is 6.5 Bq l^{-1} and 1E-3 Bq l^{-1} in the overburden (shallow geosphere pathway), as a result of the pulse of contamination released when the engineered structures are assumed to be fully degraded.

Figure G-12 Radionuclide Concentrations in the Groundwater

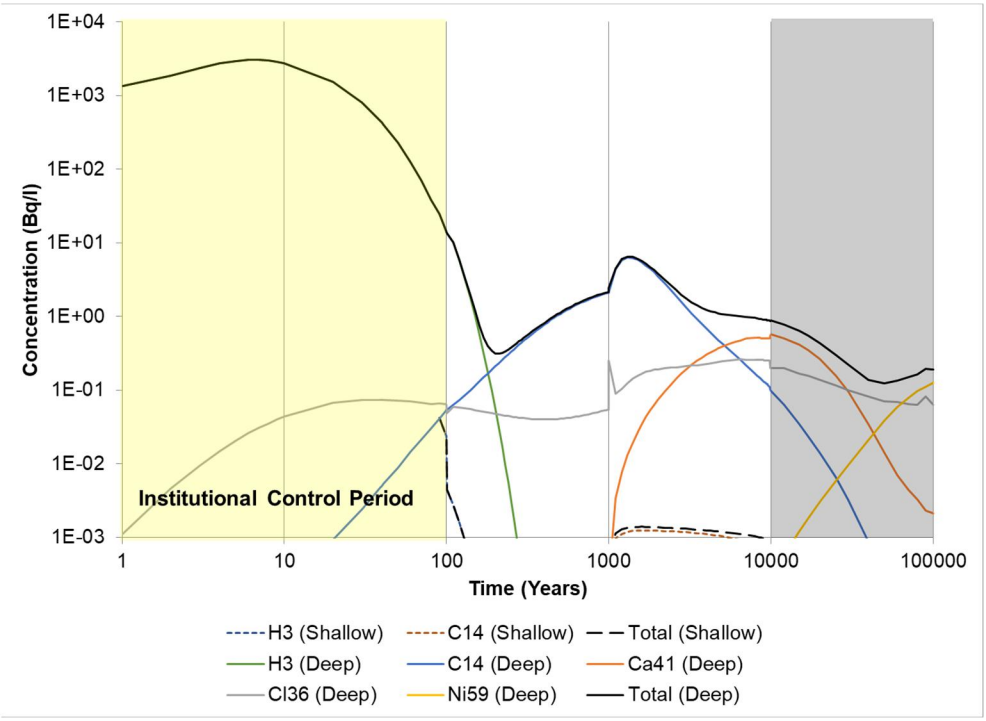
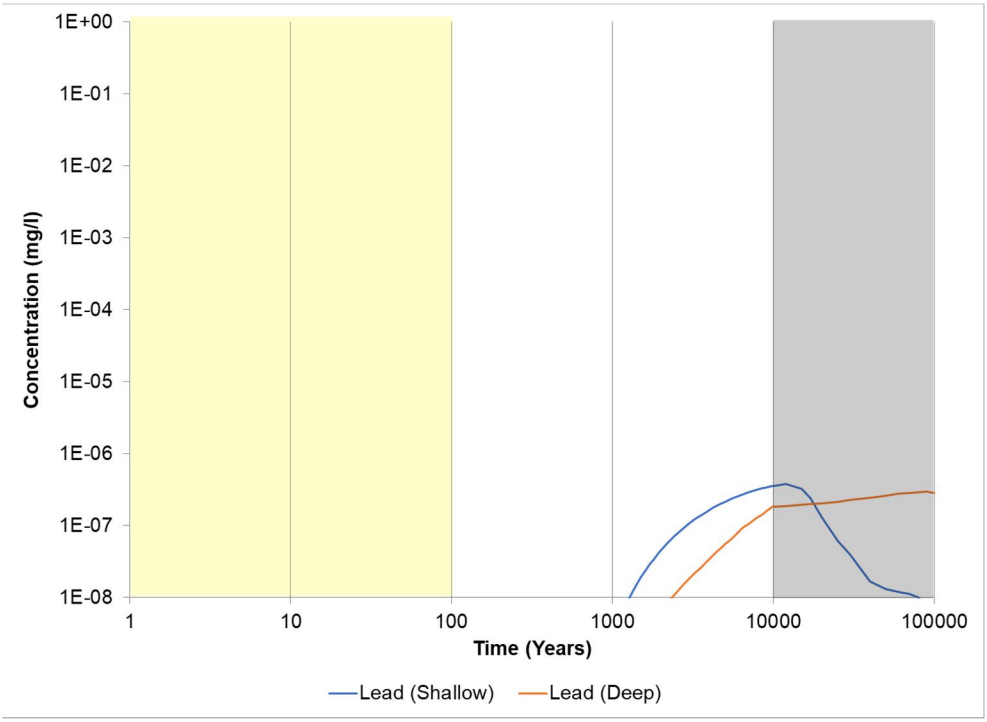


Figure G-13 shows that the highest lead concentration in overburden groundwater is $4x10^{-7}$ mg l^{-1} and occurs in the overburden at 12,000 y. The highest concentration in the bedrock is $3x10^{-7}$ mg l^{-1} after 90,000 y. The EQS for lead set out in Appendix A is the Ontario Ministry of Environment and Climate Change (MOECC) background level. The relevant MOECC's generic Site Condition Standards for groundwater, are:

- 0.1 mg l^{-1}, the generic site condition standards for shallow soils in a potable ground water condition;
- 0.02 mg l^{-1}, the generic site condition standards for shallow soils in a non- potable ground water condition;
- 0.01 mg l^{-1}, the generic site condition standards for use within 30 m of a water body in a potable groundwater condition; and
- 0.02 mg l^{-1}, the generic site condition standards for use within 30 m of a water body in a non-potable groundwater condition.

The calculated concentrations of lead are far lower than these criteria.

Figure G-13 Lead Concentrations in the Groundwater



Groundwater concentrations are tabulated in Table G-5 for the five radionuclides present with the highest peak concentration and Table G-6 for the non-radioactive contaminants of interest. As may be seen, the radioactivity is dominated by radionuclides that are not significantly sorbed in the concrete and grout, and thus may be readily released from the NPDDF. The radionuclide accounting for the highest concentrations is tritium (H-3) (peak concentration of $1x10^4$ Bq l^{-1}). Tritium is assumed to be present throughout the NPDDF. However, tritium is released rapidly and falls below 1 Bq l^{-1} after 160 y; thereafter the concentration in groundwater of all radionuclides remains below 6.5 Bq l^{-1}.

Table G-5 Radionuclides with the Five Highest Concentrations in Bedrock Groundwater (Bq l^{-1})

Time (y)	H3	C14	Ca41	Cl36	Ni59	Total
100	1E+01	5E-02	2E-07	6E-02	<1E-10	1E+01
300	2E-04	5E-01	8E-06	4E-02	<1E-10	5E-01
1000	<1E-10	2E+00	2E-04	6E-02	<1E-10	2E+00
3000	<1E-10	1E+00	2E-01	2E-01	6E-07	2E+00
10000	<1E-10	1E-01	6E-01	2E-01	4E-04	9E-01
30000	<1E-10	3E-03	1E-01	1E-01	1E-02	2E-01
50000	<1E-10	3E-04	1E-02	7E-02	4E-02	1E-01
Maximum (Bq l^{-1})	3E+03	6E+00	6E-01	3E-01	4E-02	3E+03
Time of peak (y)	7	1,300	10,000	6,500	50,000	7

Note: concentrations in overburden groundwater are significantly lower.

Table G-6 Concentrations of Non-Radioactive Contaminants in Groundwater (mg l^{-1})

Time (y)	Lead (Overburden)	Lead (Bedrock)
100	<1E-10	<1E-10
300	<1E-10	<1E-10
1000	3E-10	<1E-10
3000	1E-07	2E-08
10000	4E-07	2E-07
30000	4E-08	2E-07
50000	1E-08	3E-07
Maximum (mg l^{-1})	4E-07	3E-07
Time of peak (y)	12,000	90,000

Background levels (at NPD site) of radionuclide concentrations, as well as the applicable criteria for such radionuclides are given in Table G-7. Tritium and C-14 concentrations in the groundwater are above the background levels at NPD up to 160 y and 15,000 y respectively. However, both values are much lower than the applicable criteria, i.e., by a factor of 2.5 - 3.5 for tritium and by a factor of 16 for C-14.

Table G-7 Background levels and Applicable Criteria of Radionuclide Concentrations in Groundwater (Bq l^{-1})

Reference	H3	C14	Cl36
Groundwater quality (background levels at NPD)*	7.645	0.038	0.2
Health Canada Drinking Water Guidelines (HC, 2019)	7000	-	-
World Health Organization Drinking Water Guidelines	10,000	100	-

Note: * Arcadis (2023).

G 2.2.1 Concentrations in the Surface Environment

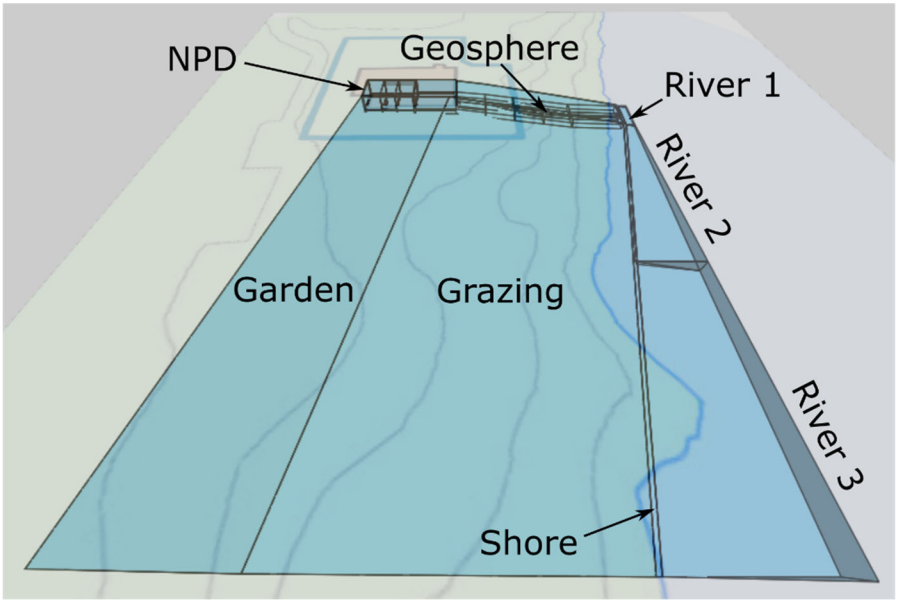
The model of the surface environment is shown in Figure G-14. The river is represented in three sections (River 1, River 2, River 3) each of which has a bed sediment compartment beneath the river water, and a "Shore" compartment which represents the accessible river shore. Contaminated groundwater from the bedrock is released into the sediments of the "River 1" compartment. The river flow rate is taken to be uniform through the three river compartments, at 0.07 m s^{-1} based on river characteristics presented in the model and data description (Appendix E). Inland from this is a 100 m wide strip of land assumed to be used for "Grazing", within which there is an area of groundwater springs where contaminated water from the overburden is released. Further inland is an area of better quality soil assumed to be used for crops ("Garden") and which is irrigated with river water. The soil in the cap overlying the NPDDF is also represented.

The rate of release of radionuclides to the environment (shown in Figure G-10) indicates that the concentrations in media like the springs, soils, river water and sediment will be very much lower than found within the Facility. The average concentrations in these media are presented in Figure G-15.

The highest concentrations are found in media closely associated with the assumed points of release of contaminated groundwater. Initially, the highest concentrations ($1x10^4$ Bq kg^{-1}) occur in the cap overlying the NPDDF, as a result of tritium diffusion into the concrete cap overlying the facility, and a conservative assumption of some upwards movement of water in the cap (see Figure G-16). This has decreased substantially to 200 Bq kg^{-1} by the end of institutional control, although the highest concentrations of radionuclides in the surface environment continue to be those in the cap. Factors that could result in the upwards migration of contaminated water into the cap include capillary action, fluctuations in the water table and the action of biota. Capillary action is a natural phenomenon whereby a liquid can flow in narrow porous spaces in opposition gravity. It occurs because of intermolecular forces between the liquid and surrounding solid surfaces, specifically the combination of surface tension and adhesive forces between the liquid and the walls of the pore. Short-term fluctuations of the water table could occur after intermittent but heavy precipitation, resulting in a local raising of the water table until the water can drain away. During this time,

contaminants in the water and media through which it is flowing will appear to be temporarily transported upwards. Finally, the transpiration stream of rooting plants can act to draw water up through the ground into the plant. In practice, all factors may act to some degree. A sufficiently thick and engineered cap could prevent these processes from occurring, but, conservatively and in order to illustrate the possible significance of the pathway, it has been assumed that upwards flow by these methods occurs at a rate of 10% of the downwards flow (which is driven by infiltration).

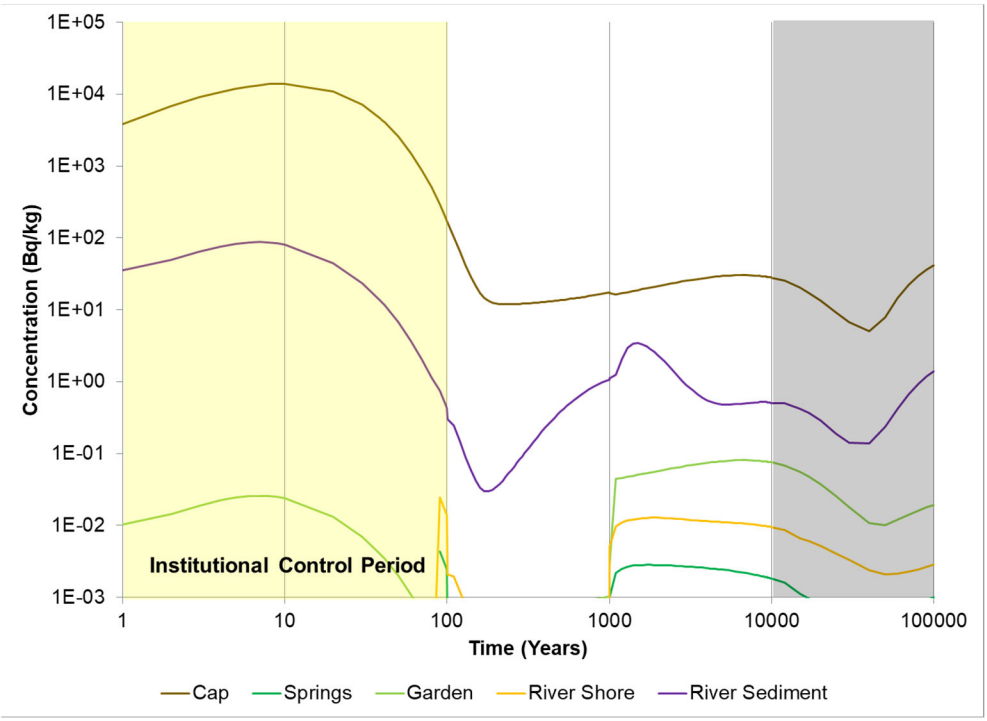
Figure G-14 Location and Size of Surface Environmental Media in the AMBER Model



The highest concentration aside from the cap, after the period of institutional control (0 to 100 y), is 3 Bq kg^{-1} in the river sediments (see Figure G-17). River sediment is the main point of discharge for radionuclides in the deep groundwater pathway. Radionuclides in the shallow pathway discharge in springs and at the shoreline, and concentrations are lower in these media. As can be seen from Figure G-16 to Figure G-18, the dominant radionuclides differ according to the pathway. While H-3 is ubiquitous, C-14 is the most significant radionuclide in shoreline and riverbed sediments, and the cap.

The highest concentration in the Garden, where food is assumed to be grown (noting that a 'garden' is only considered to be used for food after the institutional control period of 100 y), is only 0.08 Bq kg^{-1}, dominated by C-14, and occurring after 7,000 y (Figure G-19). Radionuclide concentrations in river water (i.e., radionuclides originating from the NPDDF) are also very low, owing to the large amount of dilution offered by the river (Figure G-20). Initially (after 2 y) the river water concentration is 0.006 Bq l^{-1} due to H-3, but after the institutional control period the concentrations of radionuclides peak at only $1x10^{-5}$ Bq l^{-1}.

Figure G-15 Environmental Concentrations of Radionuclides



Concentrations of radionuclides in the cap, river shore, river sediment, river water and, garden are shown in Figure G-16 to Figure G-20 respectively. Summary tables of radionuclides present with the highest concentration in each environmental medium, and lead, are presented in Table G-8 to Table G-12.

Figure G-16 Concentrations of Radionuclides in NPDDF Cap

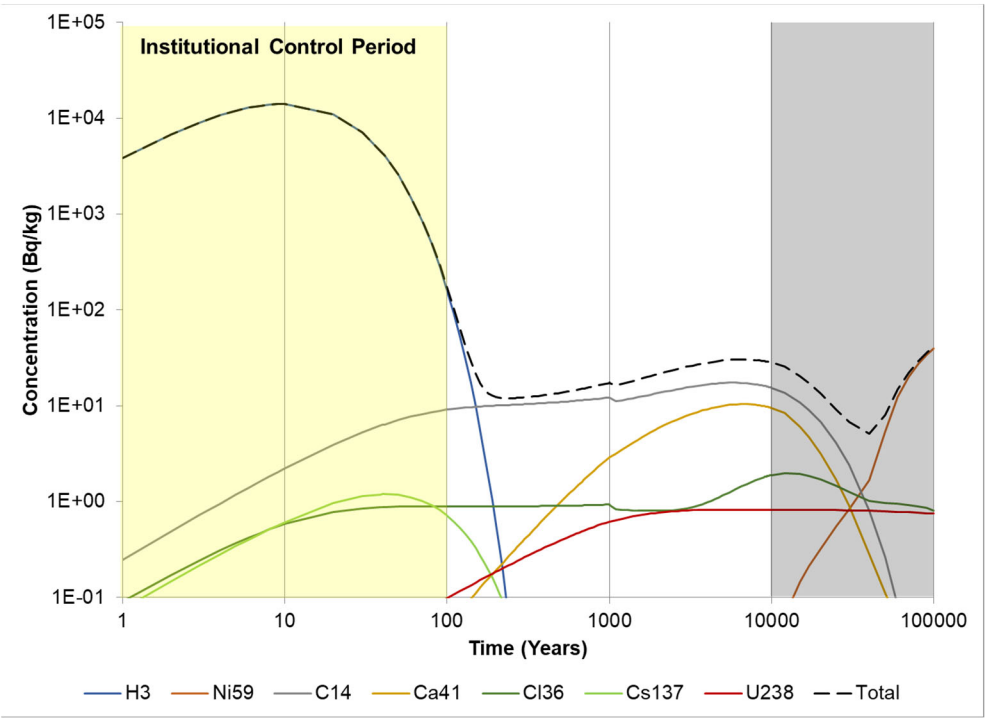


Figure G-17 Concentrations of Radionuclides in River Bed Sediment

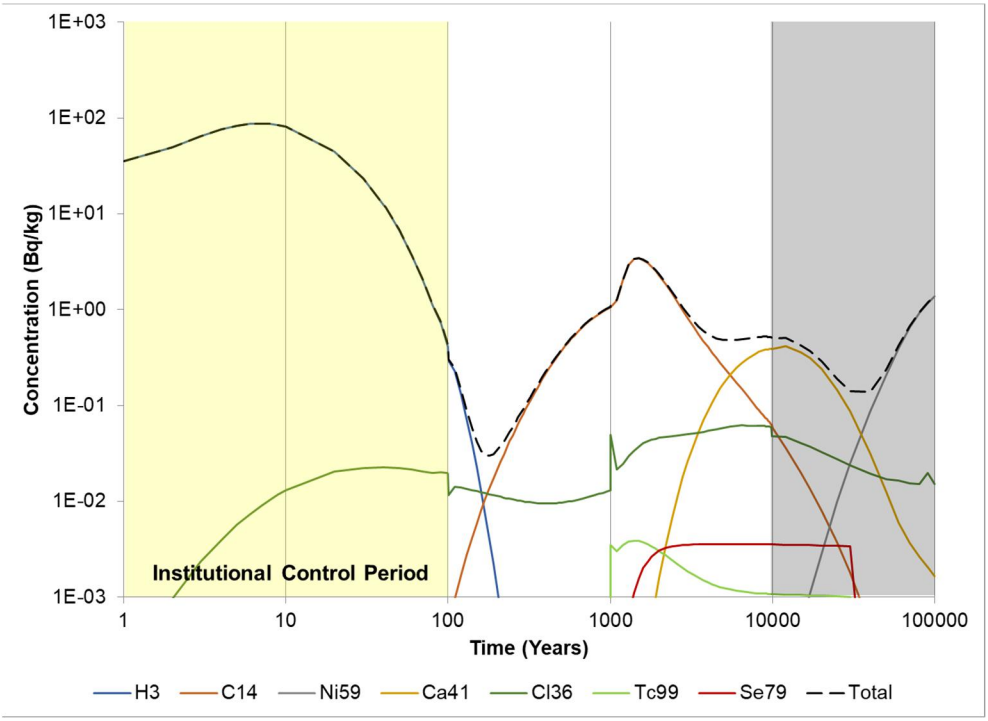


Figure G-18 Concentrations of Radionuclides in River Shore

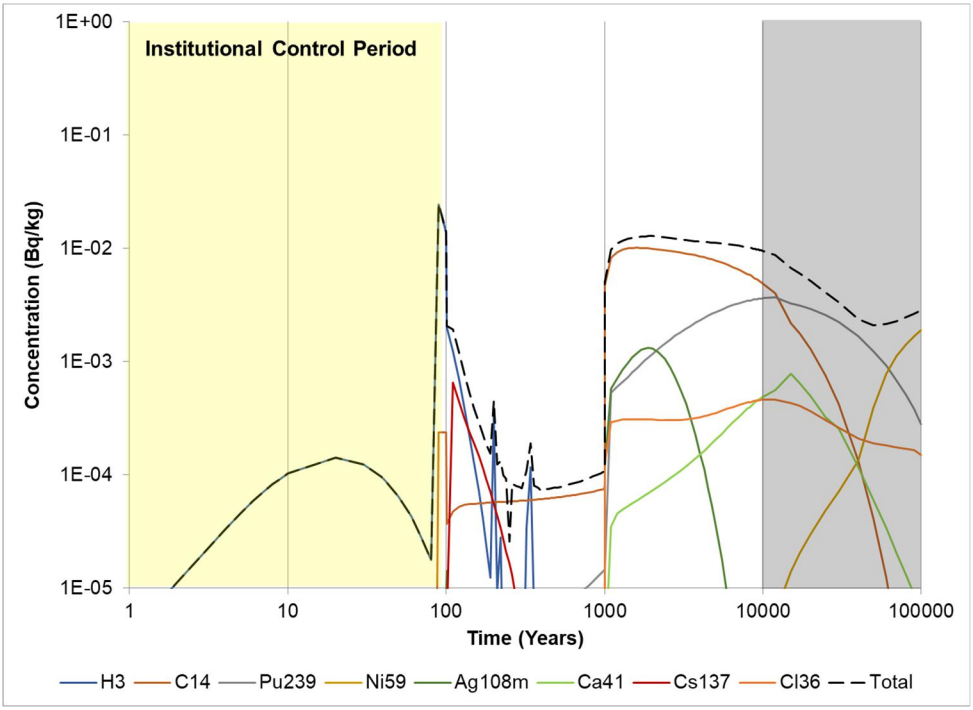
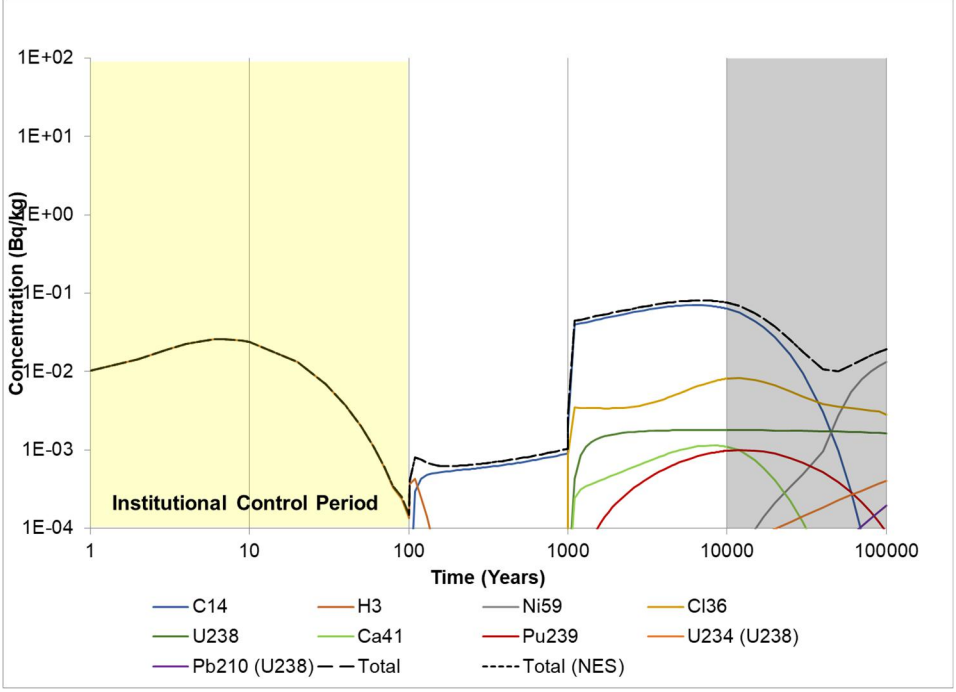


Figure G-19 Concentrations of Radionuclides in Garden



Note: Am241 (Pu-241) indicates that the dose is from Am-241 that is present as a decay product from Pu-241 that was present at the time of closure.

Figure G-20 Concentrations of Radionuclides in River Water

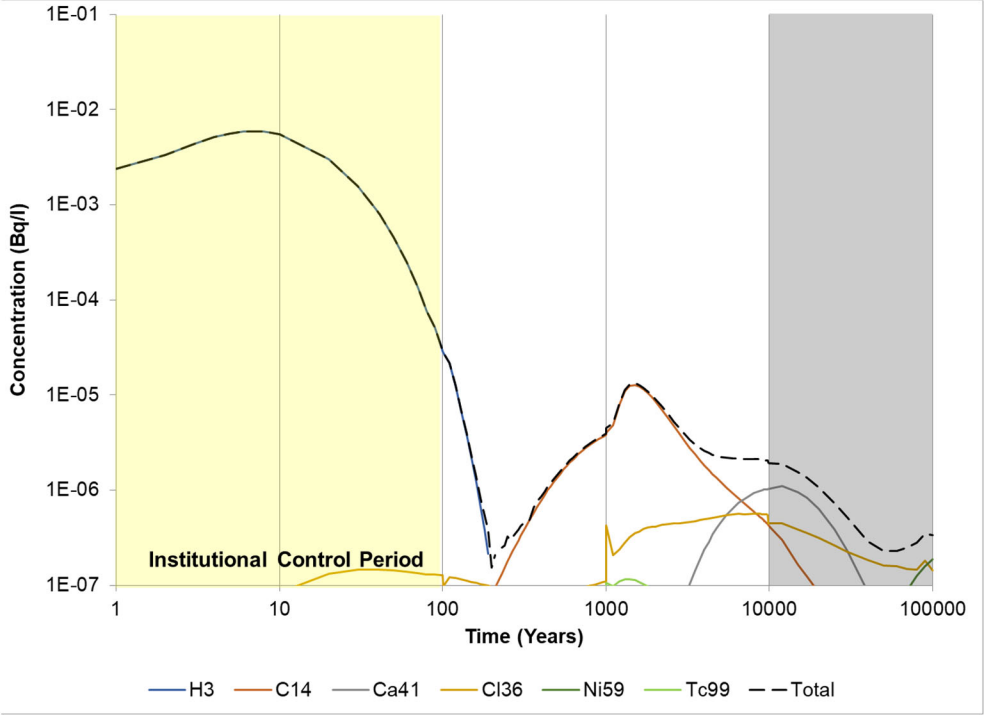


Table G-8 Radionuclides Present at the Highest Concentration in NPDDF Cap

Time (y)	Radionuclides (Bq kg^{-1})					
	H3	Ni59	C14	Ca41	Cl36	Total
100	2E+02	3E-08	9E+00	5E-02	9E-01	2E+02
300	2E-03	3E-07	1E+01	4E-01	9E-01	1E+01
1000	<1E-10	4E-06	1E+01	3E+00	9E-01	2E+01
3000	<1E-10	1E-04	2E+01	8E+00	8E-01	3E+01
10000	<1E-10	3E-02	2E+01	9E+00	2E+00	3E+01
30000	<1E-10	8E-01	2E+00	9E-01	1E+00	7E+00
50000	<1E-10	5E+00	3E-01	1E-01	1E+00	8E+00
Maximum (Bq kg^{-1})	1E+04	5E+00	2E+01	1E+01	2E+00	1E+04
Time of Peak (y)	10	50,000	6,000	6,500	12,000	10

Table G-9 Radionuclides Present at the Highest Concentration in River Shore

Time (y)	Radionuclides (Bq kg^{-1})					
	H3	C14	Pu239	Ni59	Ag108m	Total
100	1E-02	2E-04	6E-09	<1E-10	9E-06	1E-02
300	2E-07	6E-05	5E-06	<1E-10	3E-07	8E-05
1000	2E-07	8E-05	1E-05	<1E-10	1E-05	1E-04
3000	<1E-10	9E-03	2E-03	8E-09	6E-04	1E-02
10000	<1E-10	5E-03	4E-03	3E-06	2E-08	9E-03
30000	<1E-10	4E-04	2E-03	7E-05	<1E-10	3E-03
50000	<1E-10	4E-05	1E-03	4E-04	<1E-10	2E-03
Maximum (Bq kg^{-1})	2E-02	1E-02	4E-03	4E-04	1E-03	2E-02
Time of Peak (y)	90	1,600	12,000	50,000	1,900	90

Table G-10 Radionuclides Present at the Highest Concentration in River Sediment

Time (y)	Radionuclides (Bq kg^{-1})					
	H3	C14	Ni59	Ca41	Cl36	Total
100	4E-01	5E-04	<1E-10	<1E-10	2E-02	4E-01
300	4E-06	9E-02	<1E-10	3E-10	1E-02	1E-01
1000	<1E-10	1E+00	<1E-10	2E-06	1E-02	1E+00
3000	<1E-10	8E-01	<1E-10	3E-02	5E-02	9E-01
10000	<1E-10	6E-02	2E-05	4E-01	5E-02	5E-01
30000	<1E-10	2E-03	2E-02	9E-02	2E-02	1E-01
50000	<1E-10	2E-04	2E-01	1E-02	2E-02	2E-01
Maximum (Bq kg^{-1})	9E+01	3E+00	2E-01	4E-01	6E-02	9E+01
Time of Peak (y)	7	1,500	50,000	12,000	6,500	7

Table G-11 Radionuclides Present at the Highest Concentration in Garden

Time (y)	Radionuclides (Bq kg^{-1})					
	C14	H3	Ni59	Cl36	U238	Total
100	1E-08	1E-04	<1E-10	1E-05	<1E-10	1E-04
300	6E-04	9E-09	<1E-10	7E-05	4E-06	7E-04
1000	9E-04	<1E-10	<1E-10	9E-05	2E-05	1E-03
3000	6E-02	<1E-10	6E-08	4E-03	2E-03	7E-02
10000	6E-02	<1E-10	2E-05	8E-03	2E-03	8E-02
30000	1E-02	<1E-10	5E-04	5E-03	2E-03	2E-02
50000	1E-03	<1E-10	3E-03	4E-03	2E-03	1E-02
Maximum (Bq kg^{-1})	7E-02	3E-02	3E-03	8E-03	2E-03	8E-02
Time of Peak (y)	6,000	7	50,000	12,000	9,000	7,000

Table G-12 Radionuclides Present at the Highest Concentration in River Water

Time (y)	Radionuclides (Bq l^{-1})					
	H3	C14	Ca41	Cl36	Ni59	Total
100	3E-05	2E-09	<1E-10	1E-07	<1E-10	3E-05
300	2E-10	3E-07	<1E-10	8E-08	<1E-10	4E-07
1000	3E-08	4E-06	<1E-10	1E-07	<1E-10	4E-06
3000	<1E-10	3E-06	7E-08	5E-07	<1E-10	4E-06
10000	<1E-10	4E-07	1E-06	4E-07	<1E-10	2E-06
30000	<1E-10	2E-08	2E-07	2E-07	3E-09	5E-07
50000	<1E-10	2E-09	3E-08	2E-07	3E-08	2E-07
Maximum (Bq l^{-1})	6E-03	1E-05	1E-06	6E-07	3E-08	6E-03
Time of Peak (y)	7	1,500	12,000	6,500	50,000	7

Background levels of radionuclide concentrations in different environmental media at the NPD site are given in Table G-13. Tritium concentrations in the river water are much lower (several orders of magnitude) than the background levels, while tritium concentrations in the river sediment are elevated (one order of magnitude) compared to the background levels although only during the period of institutional control. However, the tritium levels in the river are much lower than the guidance levels. C-14 concentrations in the river sediment are one order of magnitude lower than the background concentrations. Both tritium and C-14 concentrations in the garden and the shore are much lower (several orders of magnitude) than the soil background levels.

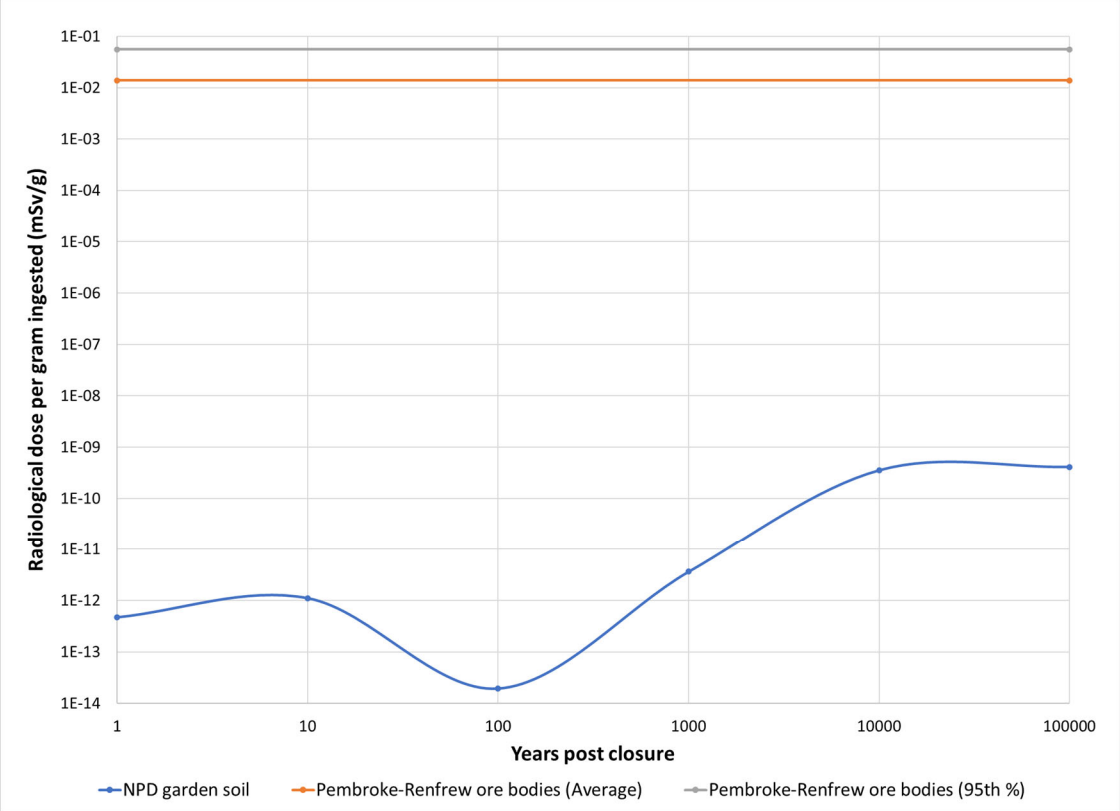
Comparison of radiotoxicity concentrations in garden soil, due to releases from the Facility, to naturally occurring surficial uranium ore deposits in the region, obtained from OGS (1981), is given in Figure G-21. The NPDDF is located within the same region as these comparison sites (approximately 60 km from Pembroke, and 100 km from Renfrew) and has similar environmental conditions. The comparison shows that concentrations in the soil are more than seven orders of magnitude lower compared to the naturally occurring deposits for the entire duration of the assessment.

Table G-13 Background Levels of Radionuclide Concentrations at NPD Site

Reference*	H3	C14
Surface Water Quality (Bq l-1)		
Surface water quality (obtained from manholes)	< 198	-
Des Joachims	1.65	-
Deep River	1.71	-
Sediment Quality (Bq g^{-1})		
Ottawa River Sediment upstream of NPD	0.0031	0.014
Ottawa River Sediment downstream of NPD	0.0024	0.0020
Soil Quality		
Background Reference Areas (BRA)	0.055	0.018

Note: * Arcadis (2023).

Figure G-21 Comparison of radiotoxicity of contaminated soil from the garden at NPD with naturally occurring surficial uranium ore bodies in the Pembroke-Renfrew area



Concentrations of lead only accumulate on a long timescale owing to the solubility limitation that restricts the release of this contaminant. The peak concentration of lead in the river is very small indeed at $1x10^{-10}$ mg l^{-1} and in the springs is $4x10^{-5}$ mg l^{-1}, compared with the EQS of $1x10^{-3}$ mg l^{-1}. During the

assessment timeframe, the highest concentration in soil is 1 mg kg^{-1} in the cap after 12,000 y. This is despite the very conservative assumption that upwards transport of contaminants in groundwater would occur through the cap, since the cap is expected to be designed in such a manner so as to avoid becoming saturated. It has been conservatively assumed that water can migrate against gravity with 10% of the rate that infiltrating water percolates downwards to the water table, e.g., 0.04 m y^{-1} compared with the infiltration rate of 0.4 m y^{-1}. These are much lower than the EQS of 45 mg kg^{-1} for soil and the EQS of 31 mg kg^{-1} for sediment (see Figure G-22 and Table G-14).

Figure G-22 Lead Concentrations in the Surface Environment

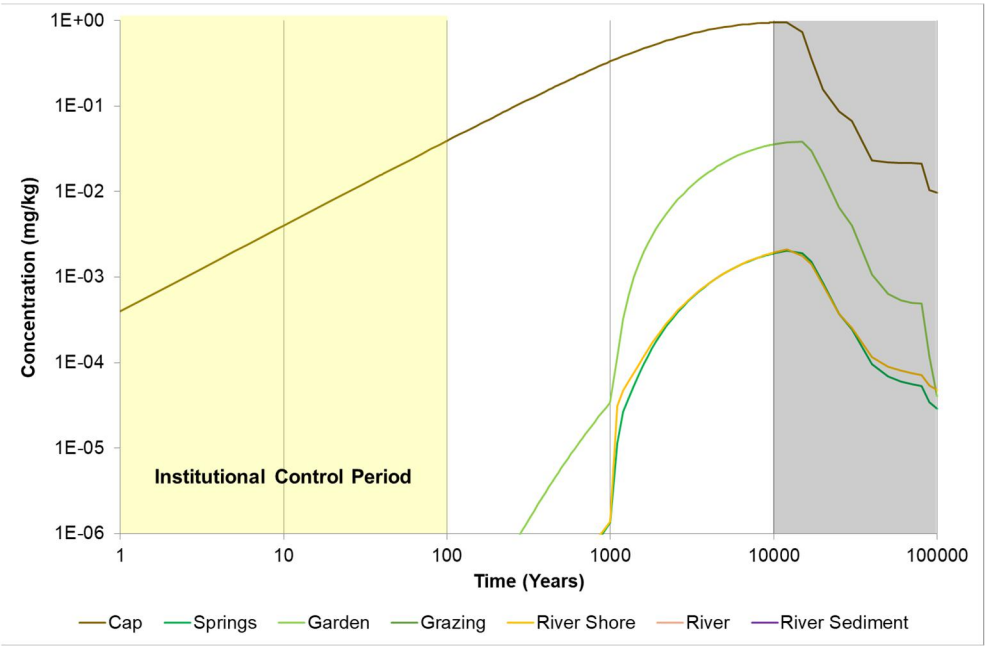


Table G-14 Lead Concentrations (mg/kg for solids, mg/L for water) in the Environment

Time (y)	Cap	Springs	Garden	River Shore	River Water	River Sediment
100	4E-02	6E-10	<1E-10	6E-09	<1E-10	<1E-10
300	1E-01	2E-09	1E-06	3E-09	<1E-10	<1E-10
1000	3E-01	3E-08	3E-05	3E-08	<1E-10	<1E-10
3000	7E-01	1E-05	1E-02	1E-05	<1E-10	<1E-10
10000	9E-01	4E-05	4E-02	4E-05	1E-10	<1E-10
30000	4E-02	4E-06	4E-03	5E-06	1E-11	2E-09
50000	2E-02	1E-06	7E-04	2E-06	5E-12	2E-08
Maximum (mg kg^{-1} or mg l^{-1})	9E-01	4E-05	4E-02	4E-05	1E-10	2E-08
Time of Peak (y)	12,000	12,000	12,000	12,000	12,000	50,000
EQS	45 mg kg^{-1}	0.001 mg l^{-1}	45 mg kg^{-1}	31 mg kg^{-1}	0.001 mg l^{-1}	31 mg kg^{-1}
Concentration Exceeding EQS?	No	No	No	No	No	No

G 2.2.2 Concentrations in Foodstuffs

A wide variety of foodstuffs have been assumed to be obtained from the immediate vicinity of the Facility on land that is irrigated with river water in order to cautiously maximise the potential exposure of the exposure groups considered. The calculated concentrations in the full set of foodstuffs included in the model are shown in Figure G-23. Cautiously, concentrations in foods have been calculated from the point of closure onwards, although in practice institutional controls would prevent the growing of food in locations that could become contaminated.

After institutional control, the highest concentrations of radionuclides in edible vegetables occurs in potatoes (0.2 Bq kg^{-1} after 12,000 y), dominated by Cl-36. In animal products, the highest concentrations are in chicken eggs (peaking at 0.2 Bq kg^{-1} from Cl-36 after 12,000 y) and the highest concentrations in meat occur in chicken and duck meat (peaking at 0.1 Bq kg^{-1} from C-14 after 1,500 y). Radionuclide concentrations in fish are much lower owing to the dilution offered by the river water, and peak at 0.07 Bq kg^{-1} from C-14 after 1,500 y.

The calculated concentrations of the radionuclides in potatoes, eggs, and fish are shown in Figure G-24 to Figure G-26. The radionuclides present with highest concentration in foodstuffs are presented in Table G-15 to Table G-17 for these foodstuffs. The uptake of non-radioactive contaminants into foods is not in the scope of the assessment as the environmental quality standard criteria for soil, sediment and water (see Appendix A) are designed to protect against adverse effects from exposure by food chain and other pathways.

Figure G-23 Calculated Concentrations of Radionuclides in Foodstuffs

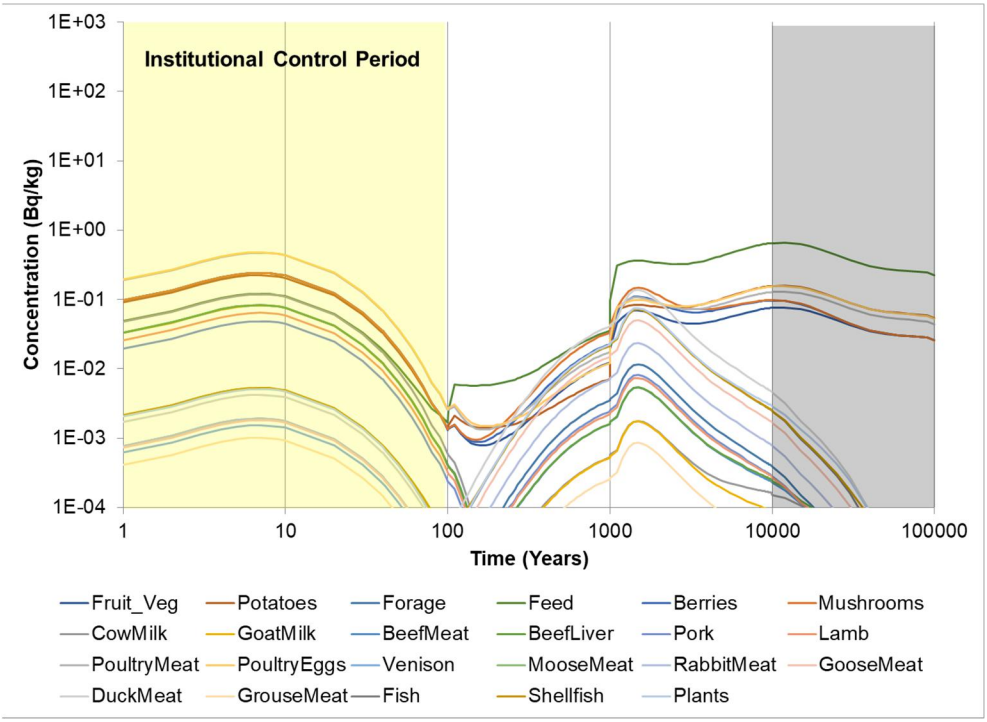


Figure G-24 Radionuclides in Potatoes

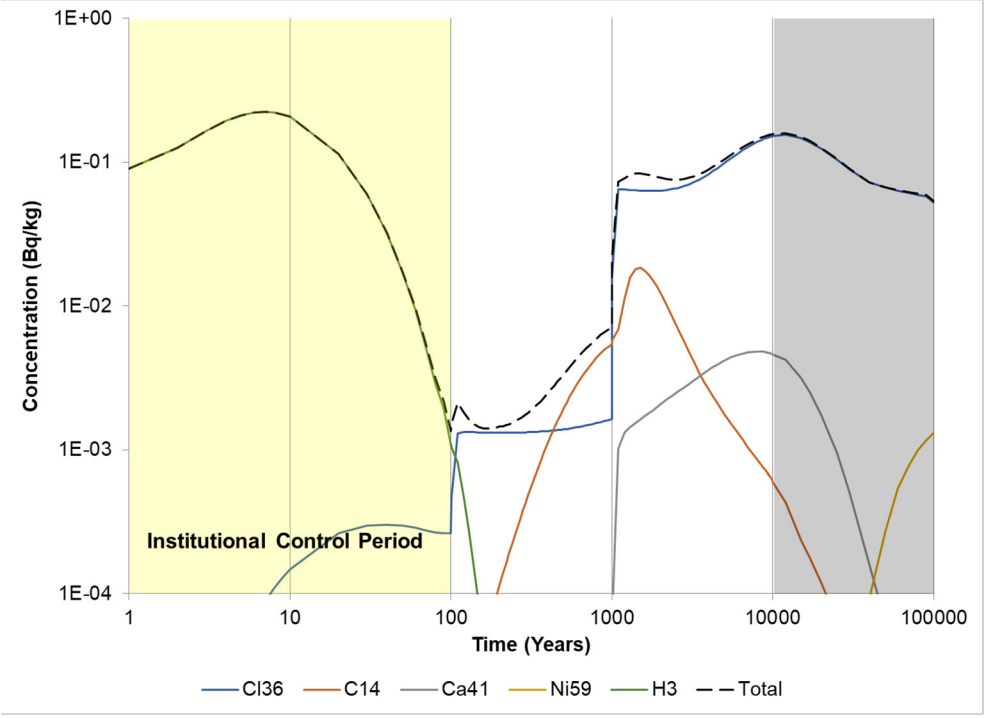


Figure G-25 Radionuclides in Chicken Eggs

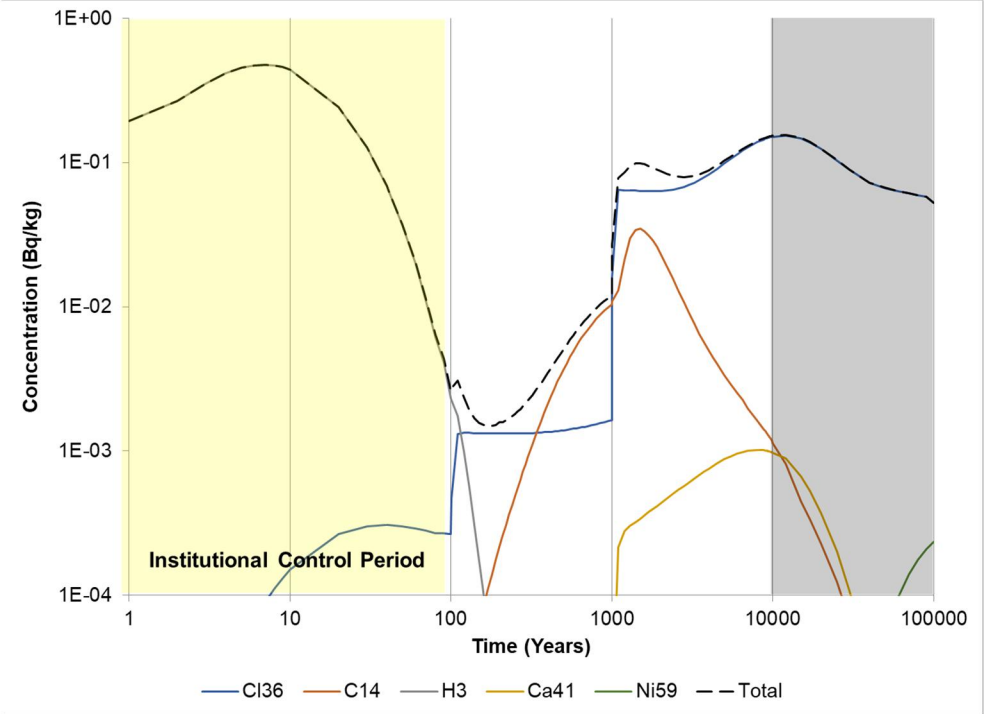


Figure G-26 Radionuclides in Fish

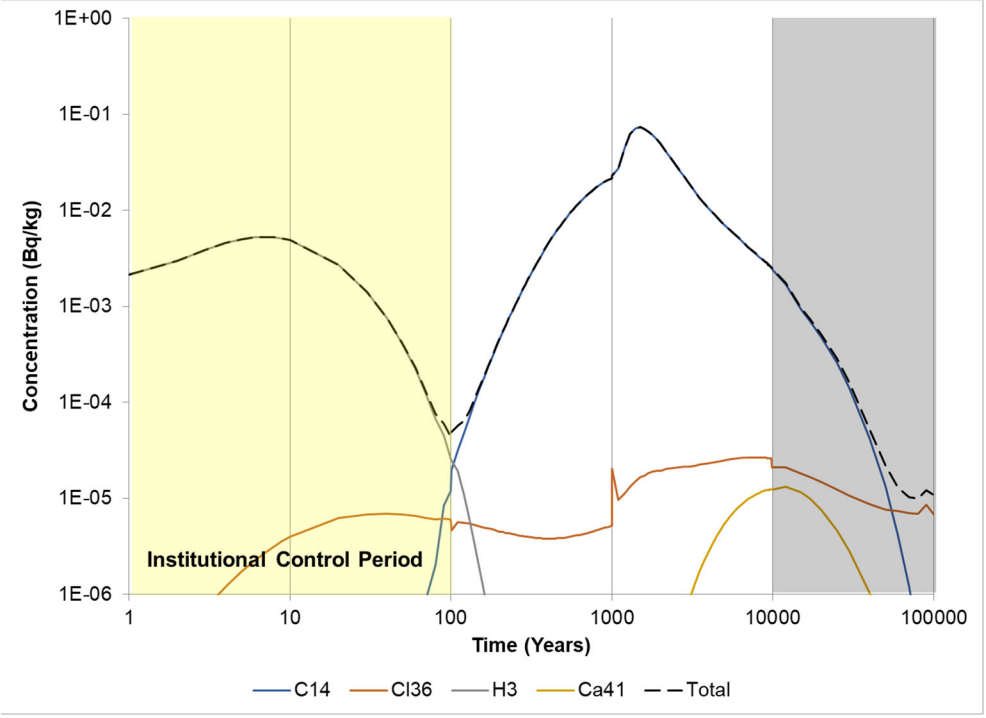


Table G-15 Radionuclides Present at the Highest Concentrations in Potatoes

Time (y)	Radionuclides (Bq kg^{-1})					
	Cl36	C14	Ca41	Ni59	H3	Total
100	3E-04	3E-06	8E-09	<1E-10	1E-03	1E-03
300	1E-03	5E-04	6E-06	<1E-10	2E-08	2E-03
1000	2E-03	5E-03	5E-05	<1E-10	<1E-10	7E-03
3000	7E-02	5E-03	3E-03	5E-09	<1E-10	8E-02
10000	2E-01	6E-04	5E-03	2E-06	<1E-10	2E-01
30000	9E-02	4E-05	5E-04	5E-05	<1E-10	9E-02
50000	7E-02	3E-06	6E-05	3E-04	<1E-10	7E-02
Maximum (Bq kg^{-1})	2E-01	2E-02	5E-03	3E-04	1E-03	2E-01
Time of Peak (y)	12,000	1,500	8,000	50,000	100	12,000

Table G-16 Radionuclides Present at the Highest Concentrations in Chicken Eggs

Time (y)	Radionuclides (Bq kg^{-1})					
	Cl36	C14	H3	Ca41	Ni59	Total
100	3E-04	6E-06	2E-03	2E-09	<1E-10	3E-03
300	1E-03	9E-04	5E-08	1E-06	<1E-10	2E-03
1000	2E-03	1E-02	<1E-10	1E-05	<1E-10	1E-02
3000	7E-02	9E-03	<1E-10	6E-04	1E-09	8E-02
10000	2E-01	1E-03	<1E-10	1E-03	3E-07	2E-01
30000	9E-02	7E-05	<1E-10	1E-04	9E-06	9E-02
50000	7E-02	6E-06	<1E-10	1E-05	5E-05	7E-02
Maximum (Bq kg^{-1})	2E-01	3E-02	2E-03	1E-03	5E-05	2E-01
Time of Peak (y)	12,000	1,500	100	8,000	50,000	12,000

Table G-17 Radionuclides Present at the Highest Concentrations in Fish

Time (y)	Radionuclides (Bq kg^{-1})					
	C14	Cl36	H3	Ca41	Se79	Total
100	1E-05	6E-06	3E-05	<1E-10	<1E-10	4E-05
300	2E-03	4E-06	2E-10	<1E-10	<1E-10	2E-03
1000	2E-02	5E-06	3E-08	7E-10	4E-08	2E-02
3000	2E-02	2E-05	<1E-10	8E-07	7E-06	2E-02
10000	2E-03	2E-05	<1E-10	1E-05	7E-06	2E-03
30000	1E-04	1E-05	<1E-10	3E-06	7E-06	2E-04
50000	1E-05	8E-06	<1E-10	4E-07	7E-08	2E-05
Maximum (Bq kg^{-1})	7E-02	3E-05	3E-05	1E-05	7E-06	7E-02
Time of Peak (y)	1,500	6,500	100	12,000	8,250	1,500

G 2.3 Doses to Human Receptors

Potential radiation doses to humans have been evaluated for four hypothetical receptors. These potential exposure groups have been selected, on the basis of the FEP analysis of the system, as being representative of the most exposed individuals to contaminants released from the facility.

- The Site Resident represents a small family group that lives on the site of the Facility and obtains all their food from the immediate vicinity, fish the river, and use the river recreationally. Exposures are maximised by assuming that they obtain contaminated water from the river and use it to irrigate

crops and to drink. They also raise livestock which drink water from the river and graze on land adjacent to the river.

- The Hunter exposure group represents a group of people whose recreational activities could lead to exposure to contaminants. Their exposure pathways include obtaining wild foods from the region of the facility, but they are not assumed to live on-site.
- The Indigenous exposure group, with habits based on a new study of the diet and harvest of the Algonquins of Pikwàkanagàn First Nation (AOPFN, 2021) which shows that today, their diet is more likely to be supplemented with additional groceries purchased from local shops.
- In addition to these exposure groups an Offsite Receptor is also considered, living downstream of the NPDDF. This receptor has more limited exposure pathways, using river water to drink and wash with.

An additional a 'Self-sufficient Indigenous' exposure group – representing a broadly self-sufficient group of people with conservative assumptions that bound the diet – is assessed as a Sensitivity Case (see Section G 3.10). It is based on the results of lifestyle surveys for an Indigenous community in the area, presented in SENES (2014).

A summary of the total doses calculated to these receptors for the Normal Evolution scenario is presented in Figure G-27. Doses to the offsite receptor peak at 3×10^{-10} mSv y^{-1} which is so low that it does not appear on the figure, given its scale.

Figure G-27 Total Dose to Receptors (Normal Evolution scenario)

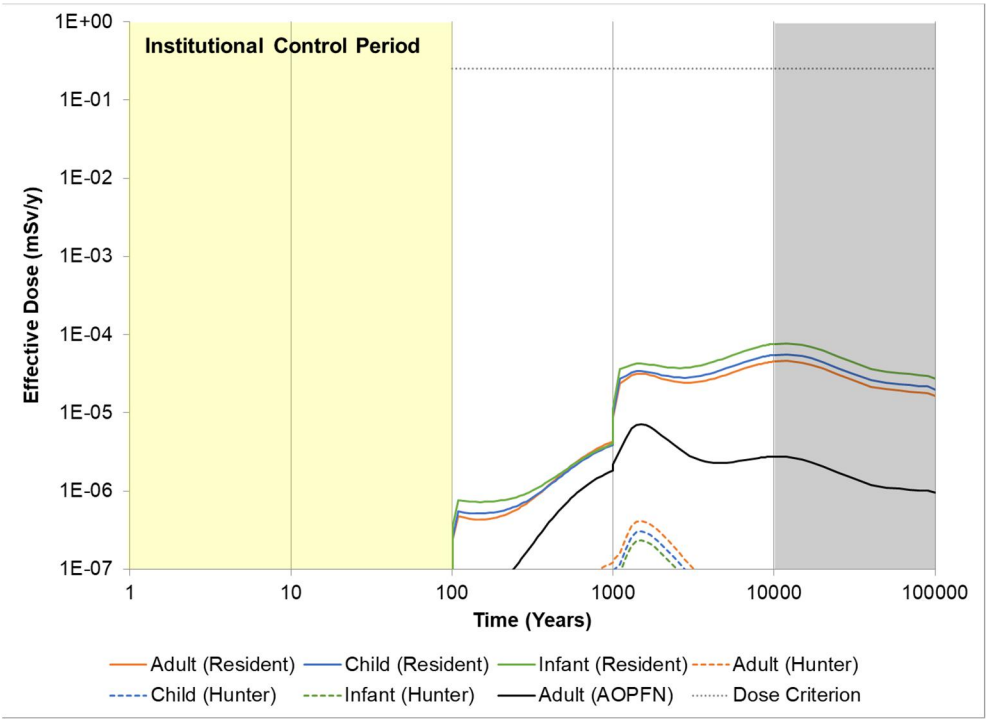
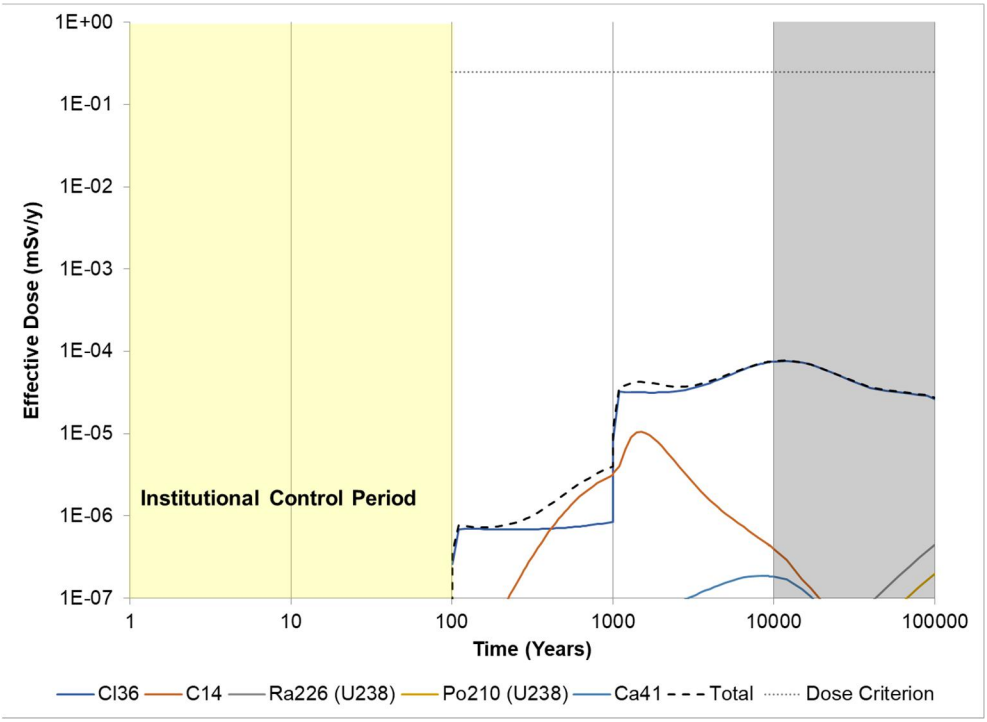


Figure G-27 shows that peak doses for the Normal Evolution scenario arise after 10,000 y, with the highest receptor dose being $8x10^{-5}$ mSv y^{-1} to an infant in the Resident exposure group. This is 3,000 times lower than the dose criterion of 0.25 mSv y^{-1}. These very low levels of exposure reflect the very low environmental concentrations, described in the previous section, and are illustrative of the fact that the main pathway for the release of contaminants is gradual leakage from the Facility, followed by transport in groundwater before release through springs and seepages, ultimately entering the river water. The doses to the key exposure groups are discussed in more detail in the following subsections.

G 2.3.1 Site Resident

The highest dose to the Site Resident exposure group is to an infant. The exposure is dominated by Cl-36 (peak at 12,000 y) (Figure G-28). The peak dose is $8x10^{-5}$ mSv y^{-1} with ingestion of vegetables being the most significant pathway contributing to dose (Figure G-29). Other radionuclides contribute less than $1x10^{-5}$ mSv y^{-1} from C-14 associated with eating animal products. In the far future (>40,000 y), radioactive daughters of U-238, Ra-226 and Po-210 have ingrown and become significant, primarily through exposure via external irradiation and inadvertent ingestion of soil. Cl-36 is dominant because it is mobile in the geological environment and is concentrated in foodstuffs.

Figure G-28 Total Dose to the Infant Site Resident (by Radionuclide)



Note: *A radionuclide that is followed by another in brackets indicates that it is a decay product of the parent radionuclide, in brackets, which was present at the time of closure.

Figure G-29 Total Dose to the Infant Site Resident (by Exposure Pathway)

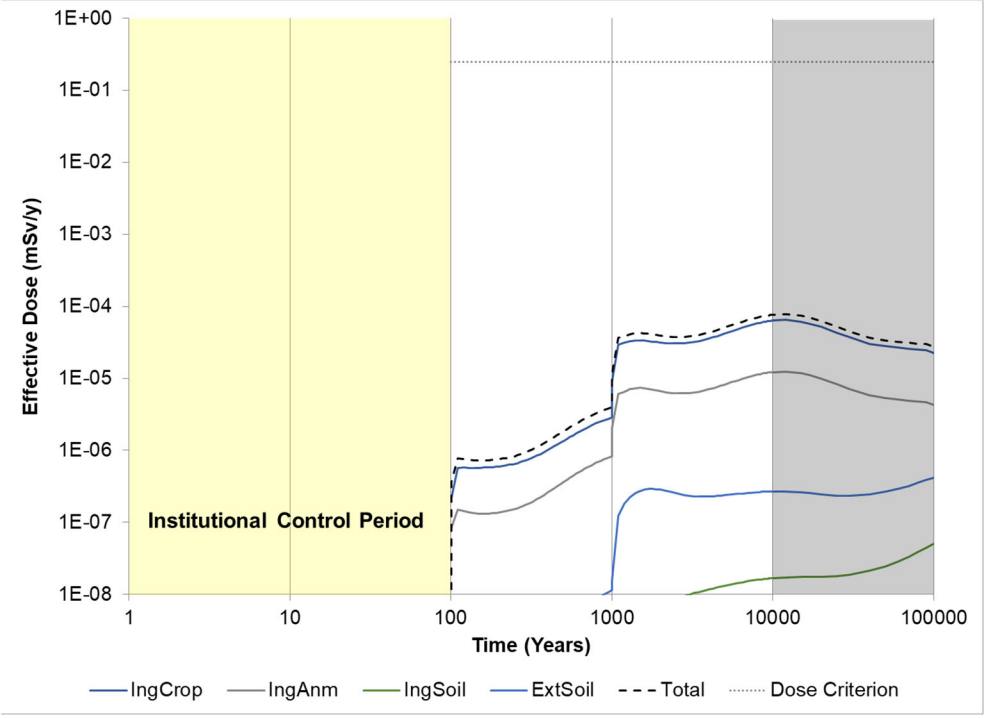


Table G-18 Summary of Dose (mSv y^{-1}) to the Infant Site Resident for the Five Radionuclides Contributing Most to the Dose

Time (y)	Cl36	C14	Ra226 (U238)*	Po210 (U238)*	Ca41	Total
100	3E-07	3E-09	<1E-10	<1E-10	<1E-10	4E-07
300	7E-07	3E-07	<1E-10	<1E-10	2E-10	1E-06
1000	8E-07	3E-06	<1E-10	<1E-10	2E-09	4E-06
3000	3E-05	3E-06	1E-10	<1E-10	1E-07	4E-05
10000	8E-05	4E-07	4E-09	2E-09	2E-07	8E-05
30000	4E-05	3E-08	5E-08	2E-08	2E-08	4E-05
50000	3E-05	3E-09	1E-07	6E-08	3E-09	3E-05
Maximum (mSv y^{-1})	8E-05	1E-05	1E-07	6E-08	2E-07	8E-05
Time of Peak (y)	12000	1500	50000	50000	8500	12000

Note: * Radionuclide is a daughter not present at closure that has ingrown from its parent, U-238.

Table G-19 Summary of Dose (mSv y^{-1}) to the Infant Site Resident for the Different Pathways Through Time

Time (y)	Ingestion of Crops	Ingestion of Honey	Ingestion of Animals	Ingestion of Fish	Ingestion of Water	Ingestion of Soil	External from Soil	External from Water	Inhalation of Gas	Total
100	2E-07	2E-09	8E-08	2E-10	6E-08	<1E-10	1E-10	<1E-10	<1E-10	4E-07
300	7E-07	1E-08	2E-07	8E-09	1E-08	<1E-10	2E-09	<1E-10	<1E-10	1E-06
1000	9E-06	2E-07	2E-06	9E-08	1E-07	2E-10	2E-08	<1E-10	<1E-10	1E-05
3000	3E-05	2E-07	6E-06	8E-08	1E-07	1E-08	2E-07	<1E-10	5E-10	4E-05
10000	6E-05	3E-07	1E-05	1E-08	6E-08	2E-08	3E-07	<1E-10	6E-10	8E-05
30000	4E-05	2E-07	7E-06	1E-09	2E-08	2E-08	2E-07	<1E-10	8E-11	4E-05
50000	3E-05	1E-07	5E-06	3E-10	2E-08	2E-08	3E-07	<1E-10	9E-12	3E-05
Max. (mSv y^{-1})	6E-05	5E-07	1E-05	3E-07	3E-07	5E-08	4E-07	2E-12	6E-10	8E-05
Time of Peak (y)	12000	1500	12000	1500	1500	100000	100000	1800	6000	12000

G 2.3.2 Hunter

The Hunter exposure group has different habits from the Site Resident, hence their exposure is dominated by C-14 in animal products (Figure G-30, Figure G-31, Table G-20 and Table G-21). The dose to the Hunter peaks at $4x10^{-7}$ mSv y^{-1} after 1,500 y. Their exposure to radionuclides is significantly lower than that of the Site Resident because the Hunter consumes smaller amounts of foods obtained from the vicinity of the NPDDF, since they do not farm. The Hunter also spends less time in the vicinity of the site as a whole than the resident, but spends longer time by the river, fishing.

Figure G-30 Total Dose to the Adult Hunter (by Radionuclide)

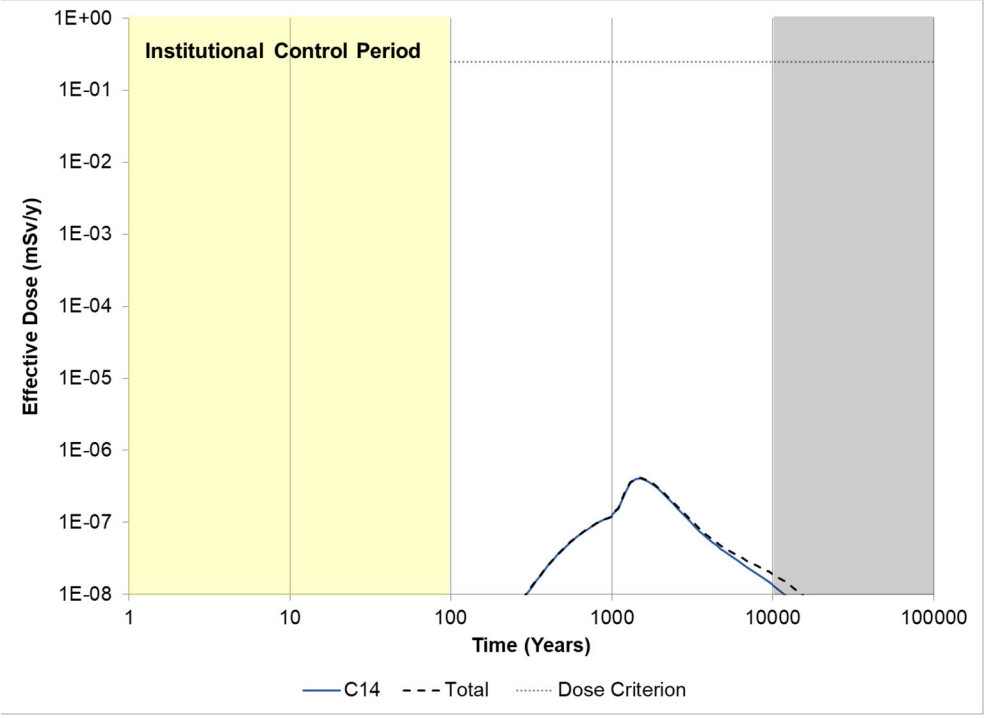


Figure G-31 Total Dose to the Adult Hunter (by Exposure Pathway)

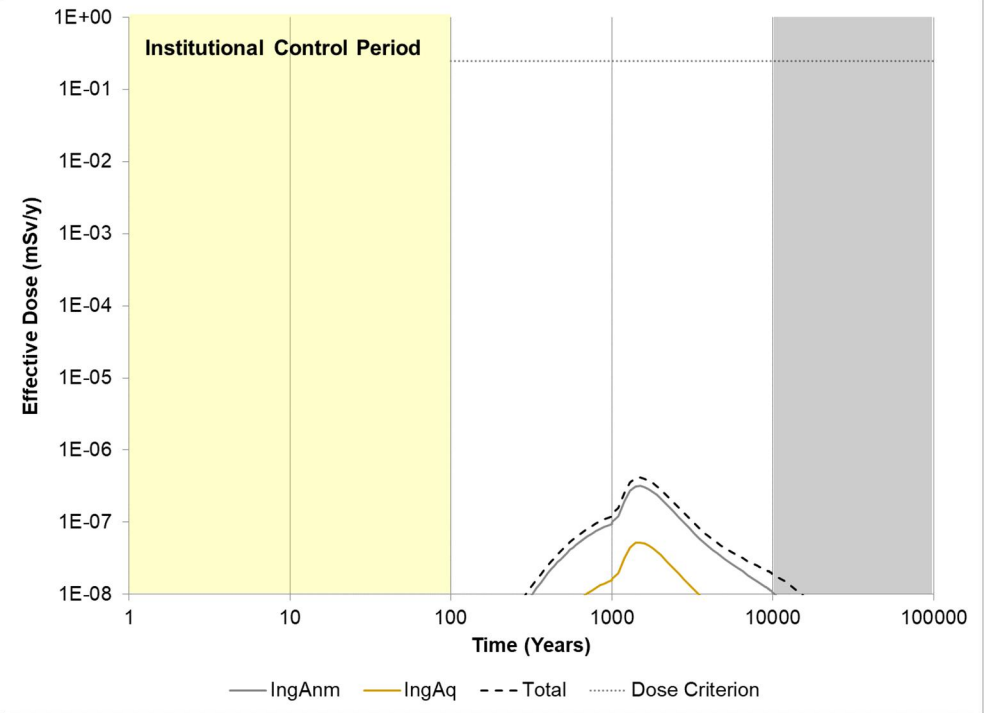


Table G-20 Summary of Dose (mSv y^{-1}) to the Adult Hunter for the Five Radionuclides Contributing Most to the Dose

Time (y)	C14	Ag108m	H3	Cl36	Ra226 (U238)*	Total
100	1E-10	1E-10	6E-09	5E-10	<1E-10	7E-09
300	1E-08	<1E-10	<1E-10	4E-10	<1E-10	1E-08
1000	1E-07	<1E-10	<1E-10	5E-10	<1E-10	1E-07
3000	1E-07	<1E-10	<1E-10	2E-09	<1E-10	1E-07
10000	1E-08	<1E-10	<1E-10	2E-09	<1E-10	2E-08
30000	8E-10	<1E-10	<1E-10	1E-09	3E-10	4E-09
50000	<1E-10	<1E-10	<1E-10	8E-10	9E-10	3E-09
Maximum (mSv y^{-1})	4E-07	9E-09	6E-09	3E-09	9E-10	4E-07
Time of Peak (y)	1500	1900	101	6500	50000	1500

Note: *A radionuclide that is followed by another in brackets indicates that it is a decay product of the parent radionuclide, in brackets, which was present at the time of closure.

Table G-21 Summary of Dose (mSv y^{-1}) to the Adult Hunter for the Different Pathways Through Time

Time (y)	Ingestion of animals	Ingestion of fish	Ingestion of water	Ingestion of soil	External from soil	External from water	Inhalation gas	Ingestion crops and honey	Total
100	1E-10	<1E-10	6E-09	<1E-10	1E-10	<1E-10	<1E-10	0E+00	7E-09
300	8E-09	1E-09	1E-09	<1E-10	<1E-10	<1E-10	<1E-10	0E+00	1E-08
1000	1E-07	2E-08	1E-08	<1E-10	9E-10	<1E-10	<1E-10	0E+00	1E-07
3000	8E-08	1E-08	1E-08	1E-09	4E-09	<1E-10	<1E-10	0E+00	1E-07
10000	1E-08	2E-09	4E-09	2E-09	1E-10	<1E-10	<1E-10	0E+00	2E-08
30000	7E-10	1E-10	2E-09	1E-09	3E-10	<1E-10	<1E-10	0E+00	4E-09
50000	1E-10	<1E-10	1E-09	8E-10	9E-10	5E-15	<1E-10	0E+00	3E-09
Max. (mSv y^{-1})	3E-07	5E-08	4E-08	2E-09	9E-09	3E-14	4E-13	0E+00	4E-07
Time of Peak (y)	1500	1500	1500	12000	1900	1800	1500	-	1500

G 2.3.3 Indigenous (AOPFN) Exposure Group

The Indigenous (AOPFN) exposure group has been based on a dietary survey performed by the AOPFN (AOPFN, 2021). Taking account of habits and customs, two additional exposure pathways are considered:

- Inhalation of smoke from burning plants; and
- Exposure of the skin through use of medicinal plants.

The group also consumes fish, game and wildfoods. The group is not assumed to be self-sufficient from the land, consistent with current habits. However, a generic Self-sufficient Indigenous group has been considered as a Sensitivity Case (see Section G 3.10).

Only doses to an adult are assessed as habits data are not available for younger ages. With a peak dose of 7×10^{-6} mSv y^{-1}, C-14 is the dominant radionuclide although there is a significant contribution from Cl-36 on timescales of more than about 5,000 y (see Figure G-32). As seen in Figure G-33, a range of exposure pathways are important, but ingestion of fish and vegetables are very similar, until the latter dominates after about 2,000 y, with Cl-36 in plants being most important. The summary of dose to an AOPFN adult for the five radionuclides contributing most to the dose and the summary of dose for the different pathways through time are given in Table G-22 and Table G-23, respectively.

Figure G-32 Total Dose to an Adult of the Indigenous (AOPFN) Exposure Group (by Radionuclide)

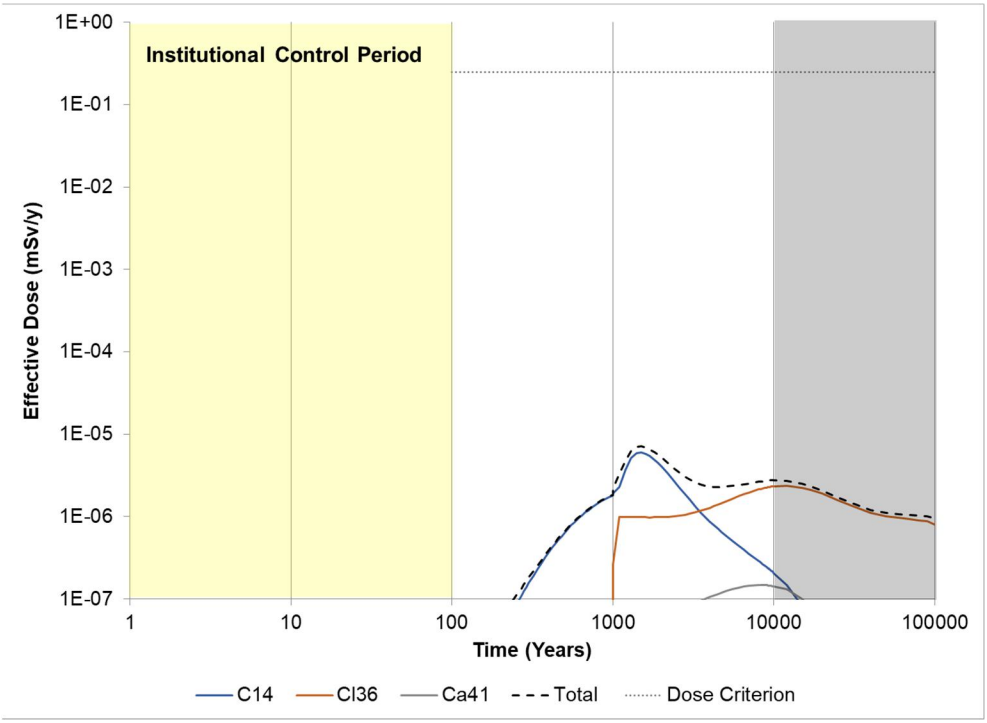


Figure G-33 Total Dose to an Adult of the Indigenous (AOPFN) Exposure Group (by Exposure Pathway)

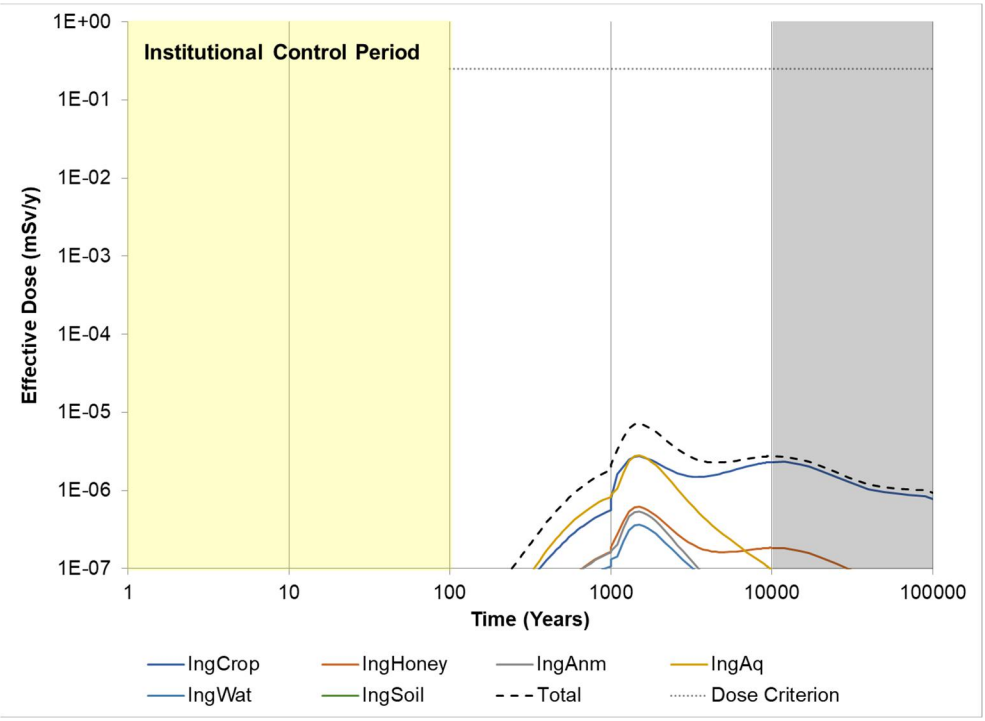


Table G-22 Summary of Dose (mSv y^{-1}) to an Adult of the Indigenous (AOPFN) Receptor Group - the Five Radionuclides Contributing Most to the Dose

Time (y)	C14	Cl36	Ca41	H3	Ra226 (U238)	Total
100	2E-09	1E-08	<1E-10	6E-08	<1E-10	8E-08
300	2E-07	2E-08	2E-10	<1E-10	<1E-10	2E-07
1000	2E-06	3E-08	2E-09	<1E-10	<1E-10	2E-06
3000	2E-06	1E-06	8E-08	<1E-10	<1E-10	3E-06
10000	2E-07	2E-06	1E-07	<1E-10	5E-10	3E-06
30000	1E-08	1E-06	2E-08	<1E-10	7E-09	1E-06
50000	1E-09	1E-06	2E-09	<1E-10	2E-08	1E-06
Maximum (mSv y^{-1})	6E-06	2E-06	1E-07	6E-08	2E-08	7E-06
Time of Peak (y)	1500	12000	8250	101	50000	1500

Note: *A radionuclide that is followed by another in brackets indicates that it is a decay product of the parent radionuclide, in brackets, which was present at the time of closure.

Table G-23 Summary of Dose (mSv y^{-1}) to an Adult of the Indigenous (AOPFN) Exposure Group - Different Pathways Through Time

Time (y)	Ingestion of Crops	Ingestion of Honey	Ingestion of Animals	Ingestion of Fish	Ingestion of Water	Ingestion of Soil	External from Soil	Inhalation of Smoke	Contamination of Skin	Total
100	9E-09	2E-09	2E-10	1E-09	6E-08	<1E-10	3E-10	<1E-10	<1E-10	8E-08
300	7E-08	2E-08	1E-08	7E-08	1E-08	<1E-10	3E-10	<1E-10	2E-10	2E-07
1000	8E-07	2E-07	2E-07	9E-07	1E-07	4E-10	5E-09	3E-10	3E-09	2E-06
3000	2E-06	2E-07	1E-07	7E-07	1E-07	2E-08	4E-08	2E-10	2E-09	3E-06
10000	2E-06	2E-07	2E-08	9E-08	4E-08	4E-08	4E-08	3E-11	3E-10	3E-06
30000	1E-06	1E-07	1E-09	8E-09	2E-08	3E-08	4E-08	<1E-10	<1E-10	1E-06
50000	1E-06	7E-08	2E-10	1E-09	1E-08	2E-08	4E-08	<1E-10	<1E-10	1E-06
Max. (mSv y^{-1})	3E-06	6E-07	5E-07	3E-06	4E-07	5E-08	7E-08	9E-10	9E-09	7E-06
Time of Peak (y)	1500	1500	1500	1500	1500	12000	100000	1500	1500	1500

G 2.3.4 Offsite Receptor

The offsite receptor is only assumed to be exposed to radionuclides in water from the Ottawa River. The only exposure pathways considered are ingestion of the contaminated water, and external radiation from the water (e.g., bathing and swimming). Two possible locations are considered for the offsite receptor: at Deep River, around 14 km downstream of the NPDDF, and at Ottawa, nearly 300 km downstream. The river flow rate at Deep River is assumed to be the same as that at NPDDF, but at Ottawa (i.e., at the Britannia hydrometric gauge) it is 1.5 times greater (see Appendix E) resulting in an additional dilution factor of 0.658. As the offsite receptor lives beyond any region that can be subject to institutional control, exposures may occur earlier than 100 y after closure. It can be seen, from Figure G-34, that the dominant radionuclide is H-3, and the peak dose of only $1x10^{-8}$ mSv y^{-1} occurs shortly after closure. The dose arises through ingestion of radionuclides in river water (see Figure G-35).

Figure G-34 Total Dose to the Adult Offsite Receptor (by Radionuclide)

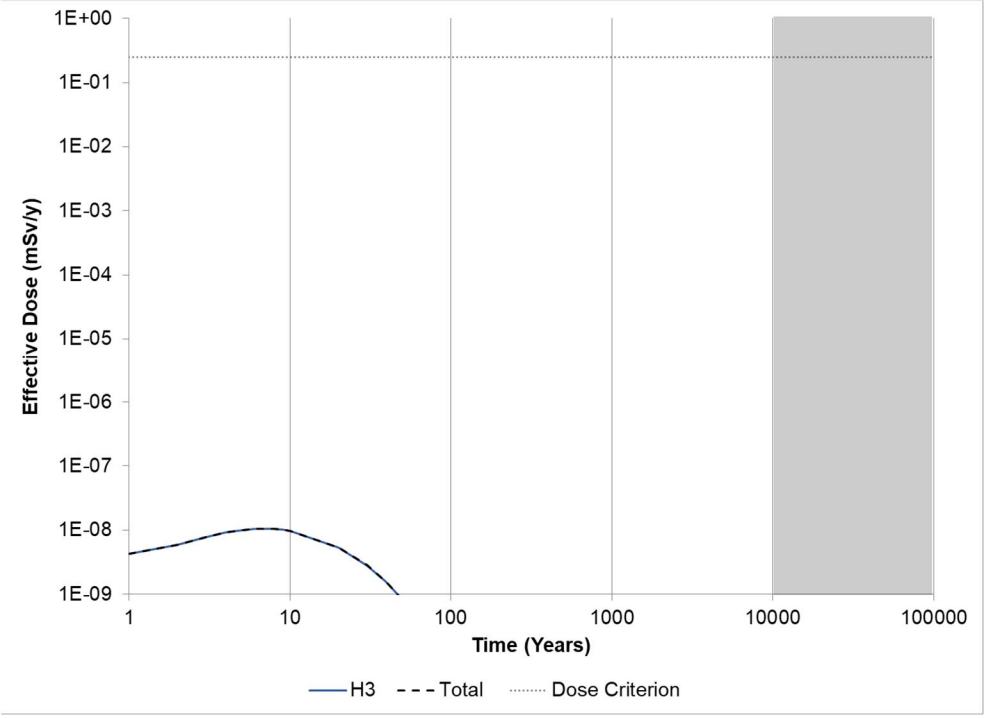


Figure G-35 Total Dose to the Adult Offsite Receptor (by Exposure Pathway)

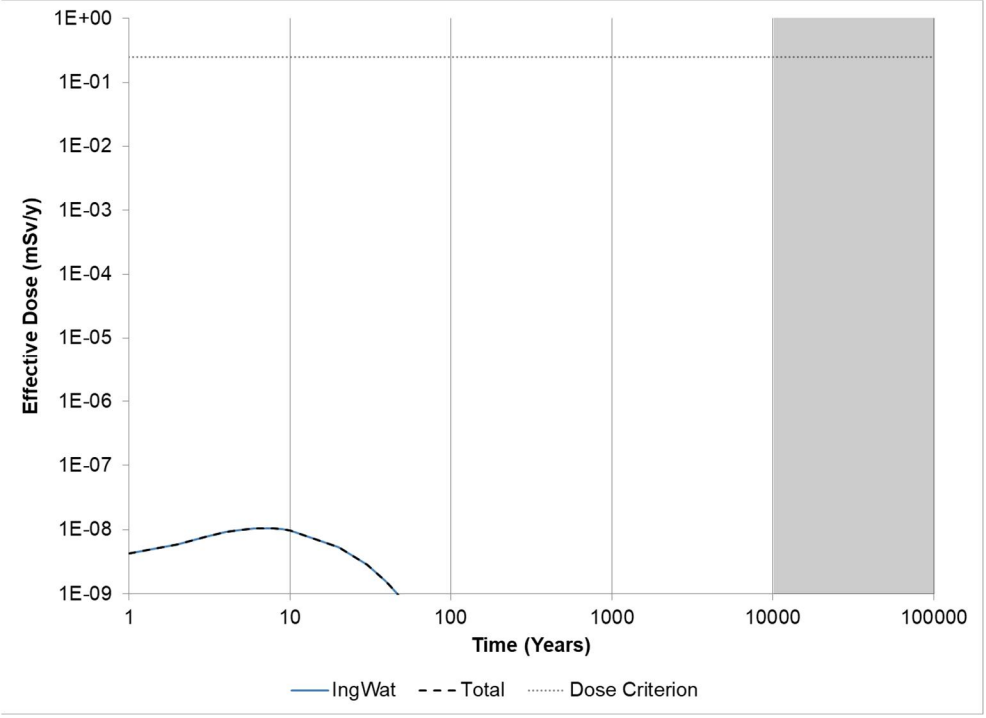


Table G-24 Summary of Dose (mSv y^{-1}) to the Adult Offsite Receptor at Deep River for the Five Radionuclides Contributing Most to the Dose

Time (y)	H3	C14	Cl36	Ca41	Tc99	Total
100	<1E-10	<1E-10	<1E-10	<1E-10	<1E-10	<1E-10
300	<1E-10	<1E-10	<1E-10	<1E-10	<1E-10	<1E-10
1000	<1E-10	<1E-10	<1E-10	<1E-10	<1E-10	<1E-10
3000	<1E-10	<1E-10	<1E-10	<1E-10	<1E-10	<1E-10
10000	<1E-10	<1E-10	<1E-10	<1E-10	<1E-10	<1E-10
30000	<1E-10	<1E-10	<1E-10	<1E-10	<1E-10	<1E-10
50000	<1E-10	<1E-10	<1E-10	<1E-10	<1E-10	<1E-10
Maximum (mSv y^{-1})	1E-08	3E-10	2E-11	8E-12	3E-12	1E-08
Time of Peak (y)	7	1500	6500	12000	1400	7

G 3 SENSITIVITY CASES

G 3.1 NES(a) – Measured Radionuclide Inventory

The Normal Evolution Scenario uses modelled data as a basis for the initial inventory of radionuclides in the NPDDF, which is anticipated to represent an upper bound. It is primarily based on the data sources and assumptions presented in Porter (2022) and references therein, and is discussed in detail in Appendix B and E. The inventory for some rooms also includes a conservative 'uncertainty factor' as there are limited data.

This sensitivity case uses the Measured Inventory where possible, without application of uncertainty factors, but is otherwise identical to the Normal Evolution Scenario. The inventory is based on information presented by NMNTI (2017) and Edwards (2018) for the Reactor Vault with supplementary assumptions for other rooms (as presented in Porter, 2022). Measurement data are the primary source of information although the fingerprint for the Primary Heat Transport (PHT) system is used to estimate the amounts of some difficult-to-measure radionuclides.

The activity concentrations in the Reactor Vault of the NPDDF are substantially lower in this calculation case than for the Normal Evolution scenario, as shown in Figure G-36. Initially, the total activity is a factor of six times lower at 4×10^{6} Bq kg^{-1}, but over time the difference increases, exceeding a factor of 10 after 500 y. This reflects the higher activity of some key radionuclides such as Ni-59 and Zr-93 in the inventory derived partly from modelling, compared with the measurement data used for this case.

The radionuclide concentrations outside of the NPDDF are also reduced. As shown in Figure G-37, the profile of concentrations is similar, indicating that the released radionuclides are the same as the Normal Evolution scenario. Releases to the deep groundwater pathway dominate but are a factor of 2-3 lower than in the Normal Evolution scenario. The dominant radionuclides are H-3 initially, C-14 (190 – 4,250 y) and Ca-41 (after 4,500 y). C-14 is most significant and is present in the activated metals in the Reactor Vault and generic contamination distributed through the structure.

Activity concentrations in surface environmental materials differ significantly from those in groundwater owing to the different sorption properties of the soils and sediments. C-14 is dominant after 120 y to timescales in excess of 10,000 y in the key medium of garden soil (Figure G-39). The vegetable ingestion pathway dominates the exposure of the Site Resident exposure group, for which the peak dose is eight times lower than in the Normal Evolution scenario, peaking at $1x10^{-5}$ mSv y^{-1}, well below the dose criterion of 0.25 mSv y^{-1} (Figure G-40). The lower doses for this case, relative to the NES, are due to the lower concentrations of Cl-36 in the metals in the Reactor Vault and, hence, in the environmental media such as the Garden.

Figure G-36 Radionuclide Inventory in the Reactor Vault (Measured Radionuclide Inventory Case)

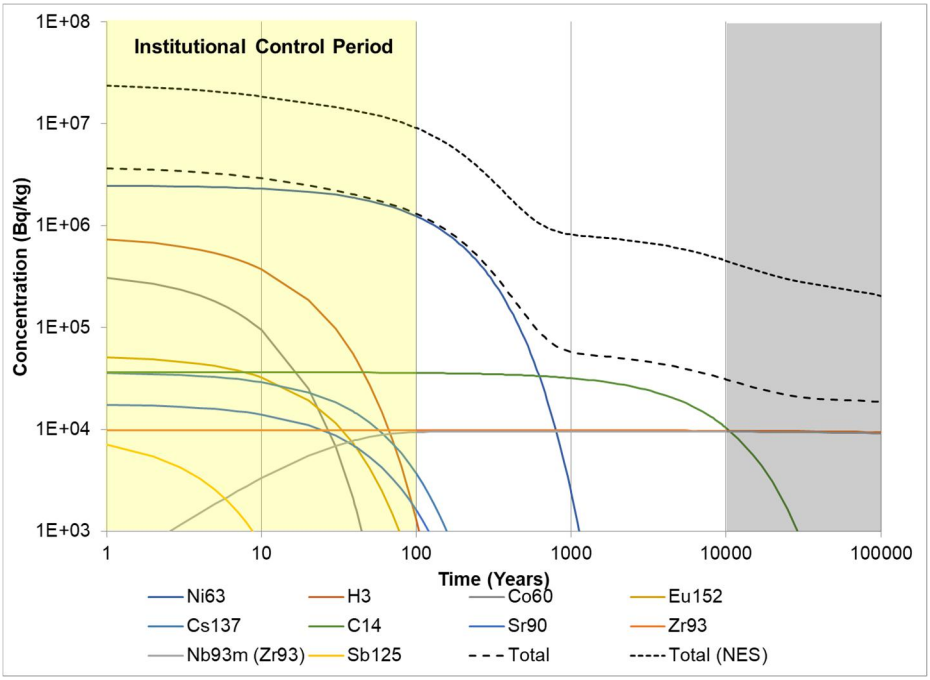


Figure G-37 Releases of Radionuclides from the NPDDF to the Geosphere (Measured Radionuclide Inventory Case)

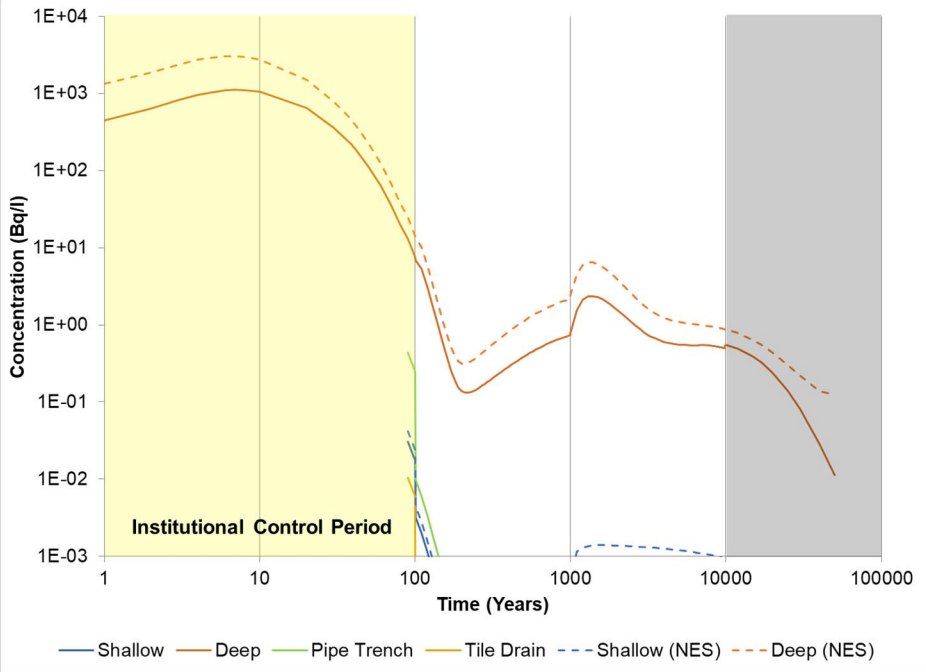


Figure G-38 Concentrations of Radionuclides in the Geosphere (Measured Radionuclide Inventory Case)

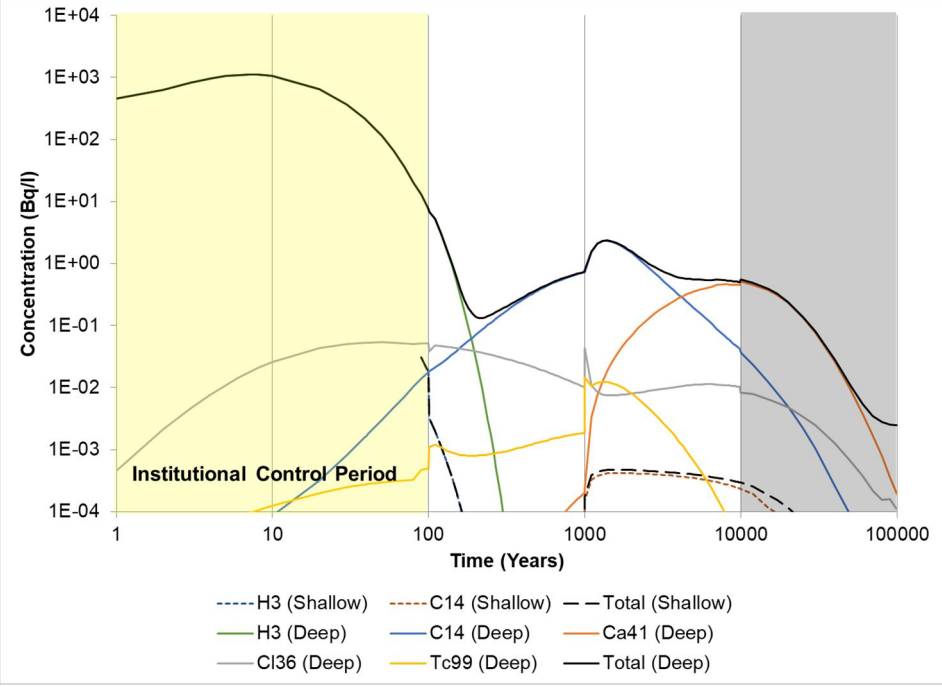
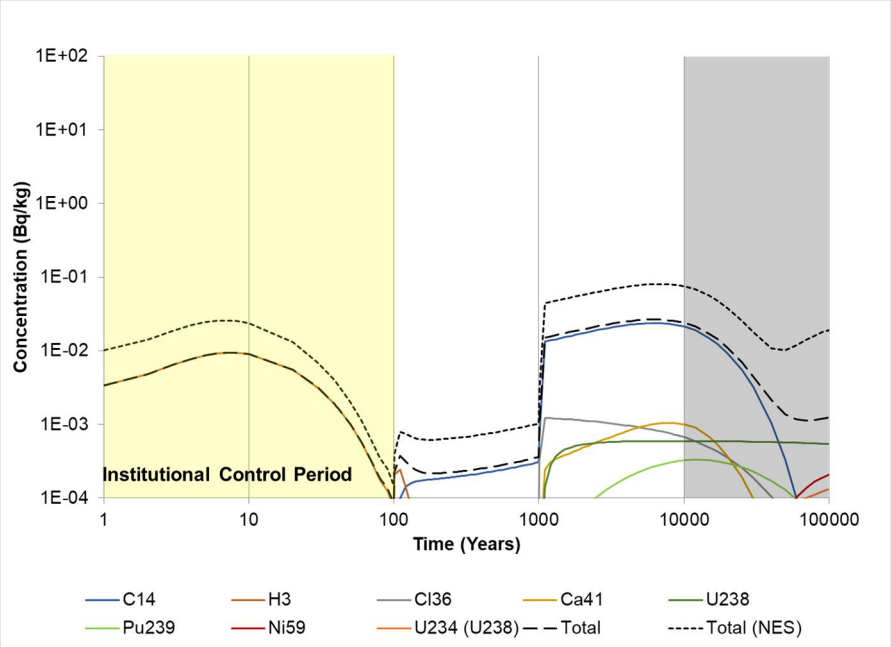
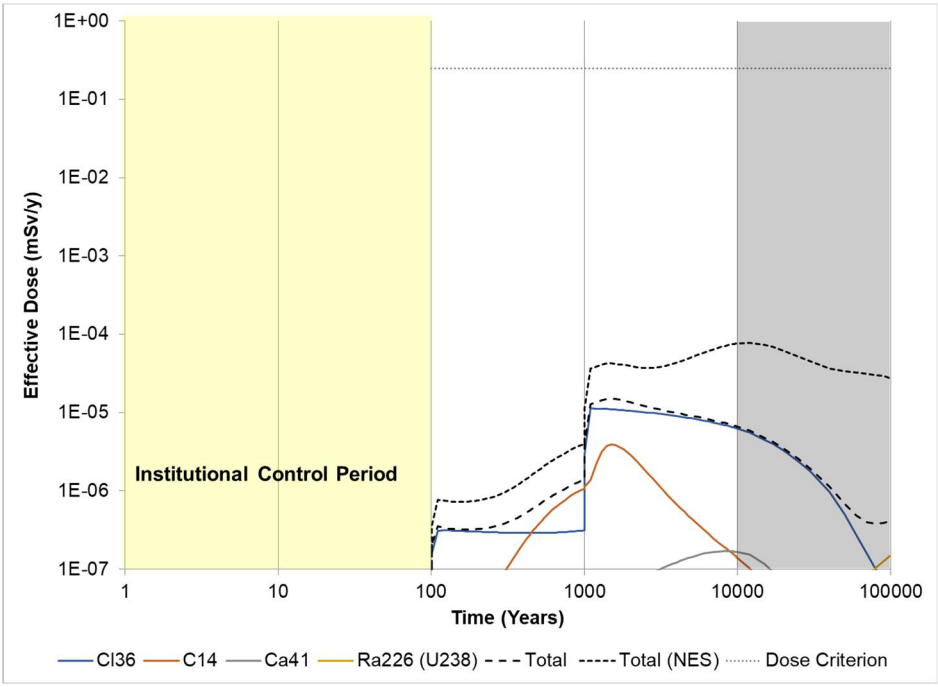


Figure G-39 Radionuclide Concentrations in Garden (Measured Radionuclide Inventory Case)



Note: A radionuclide that is followed by another in brackets indicates that it is a decay product of the parent radionuclide, in brackets, which was present at the time of closure.

Figure G-40 Total Doses to the Most Exposed Receptor – Site Resident Infant (Measured Radionuclide Inventory Case)

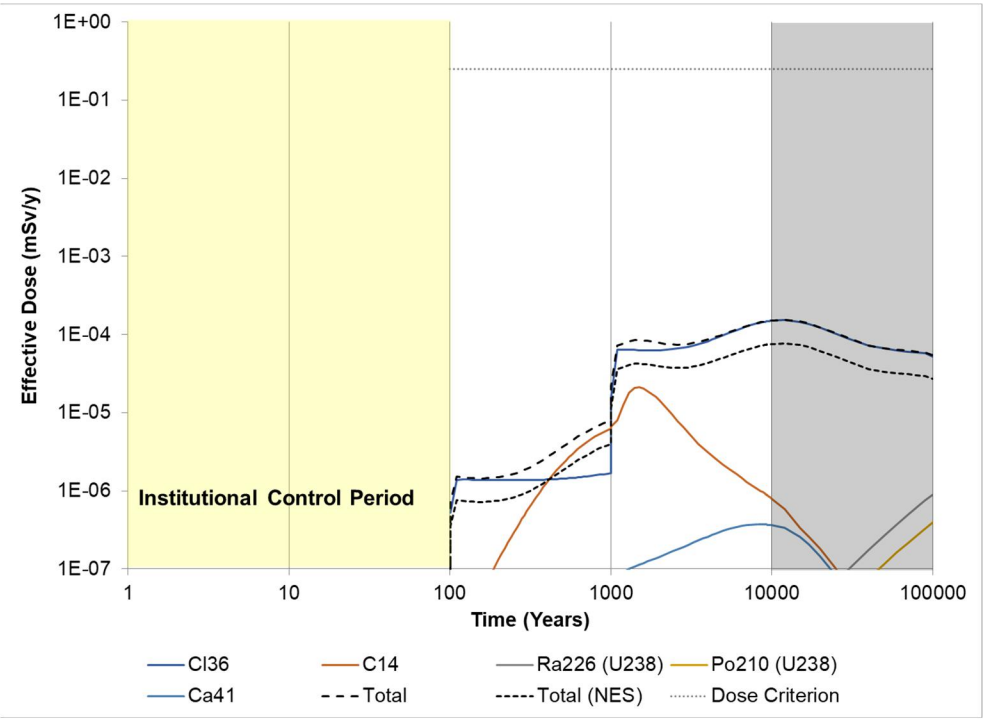


Note: A radionuclide that is followed by another in brackets indicates that it is a decay product of the parent radionuclide, in brackets, which was present at the time of closure.

G 3.2 NES(b) – Increased Radionuclide Inventory

For both the measured and modelled inventory data there are various uncertainties. These are associated with the knowledge of the extent and distribution of contamination in the plant and within the building, and the limitations in the detection of certain difficult to measure radionuclides. A conservative higher estimate of the inventory has therefore been considered in this sensitivity case. This is simply twice the modelled inventory (that considered in Normal Evolution scenario). As may be seen in Figure G-41, the doses follow the same pattern in time when compared with the Normal Evolution scenario but are twice as large. This shows that the calculated radiation dose simply scales with the assumed radionuclide inventory. This is because there are no significant non-linear effects in the model; these are generally only apparent for radionuclides that are subject to solubility limitation. This is not the case for the dominant radionuclides (C-14 and Cl-36). The peak dose occurs to an infant in the resident exposure group and is 2×10^{-4} mSv y^{-1}, 12,000 y after closure of the facility.

Figure G-41 Total Doses to Most Exposed Receptor, the Infant Site Resident (Increased Modelled Radionuclide Inventory Case)



G 3.3 NES(c) – Reduced Near-field Sorption

Cement sorption coefficients can have significant uncertainty as they depend on characteristics that are specific to the location and nature of the cement. The values selected for the PostSA are based on a well-regarded compilation of data (Ochs *et al*., 2016), but retain this uncertainty. This can be significant as it determines the concentrations of radionuclides in water and thus the rate of release of radionuclides from the NPDDF. Ochs *et al*. (2016) show the values vary by differing amounts, sometimes in excess of an order of magnitude. This sensitivity case examines the implications of lower Kds by reducing all of those associated with cement and concrete. Lower limit values from Ochs *et al*. (2016) have been used, where possible. Where no lower limit data were available, the values were reduced by an order of magnitude. Lower Kds result in more of a contaminant being in solution and thus available for release from the Facility.

The consequences of the change are increased concentrations of radionuclides in the groundwater in the Reactor Vault including C-14 and Cl-36 (Figure G-42). Tritium concentrations are unchanged as this radionuclide is unsorbed (it is entirely present in solution) and is thus unaffected by the changes made in this sensitivity case.

The environmental concentrations are also significantly increased compared to the Normal Evolution scenario, mainly in relation to those radionuclides such as C-14, Cl-36 and Ca-41. The most important media for human exposures are the river water, which can be drunk directly by people and animals, and is used to irrigate crops (Figure G-43), and the soil in which crops are grown (Figure G-44). The significance of the change depends on the radionuclide and the uncertainty associated with the sorption of the specific element. For river water, where the dominant radionuclide is C-14 after institutional control, the peak concentration is notably increased in the period between 100 and 1000 y. C-14 is also important in the garden, but the highest concentrations occur after 1000 y.

The doses to humans reflect the changes in retention of radionuclides. Doses to all exposure groups are increased. The peak dose to the resident exposure group is increased from 8×10^{-5} mSv y^{-1} in the Normal Evolution scenario to 1×10^{-4} mSv y^{-1} and occurs much earlier, at 2,600 y after closure rather than at 12,000 y in the NES; Cl-36 remains the dominant radionuclide (Figure G-45). The most important pathway is the ingestion of vegetables.

Figure G-42 Radionuclide Concentrations in Water in the Reactor Vault (Reduced Near-field Sorption Case)

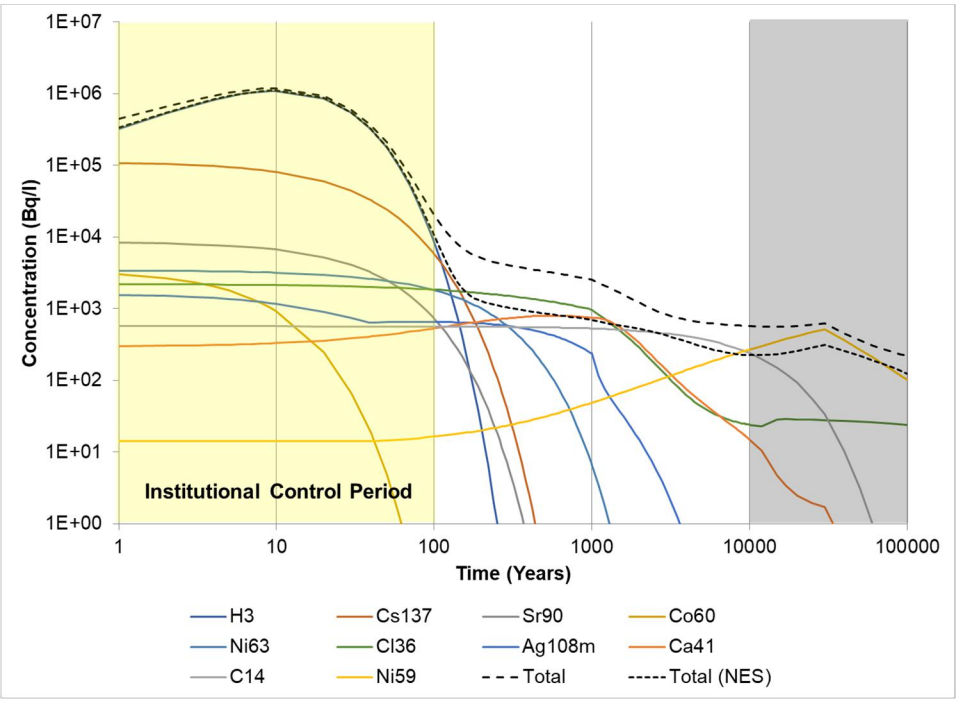
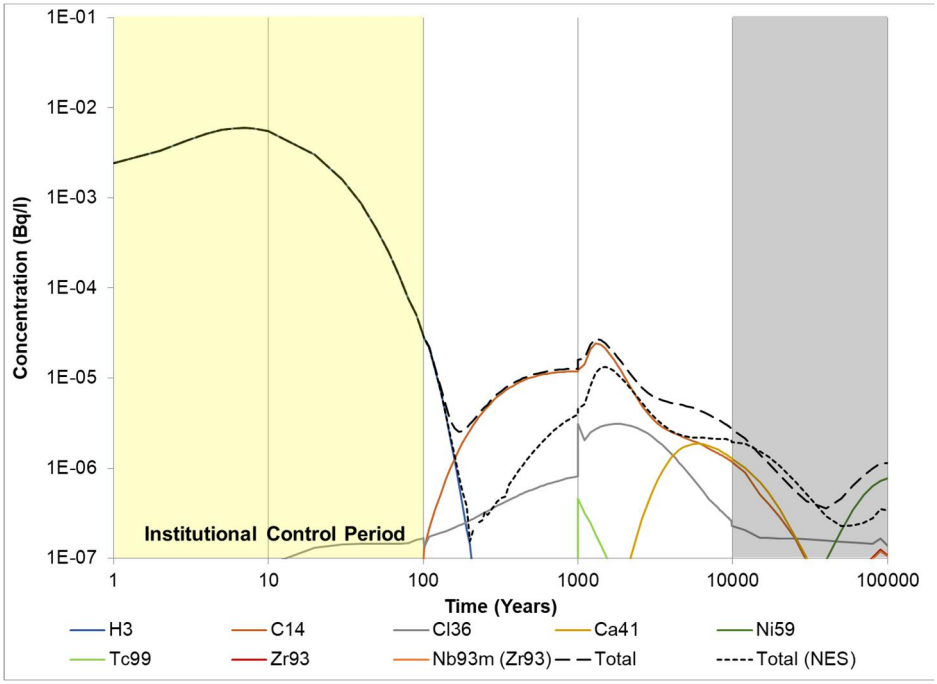
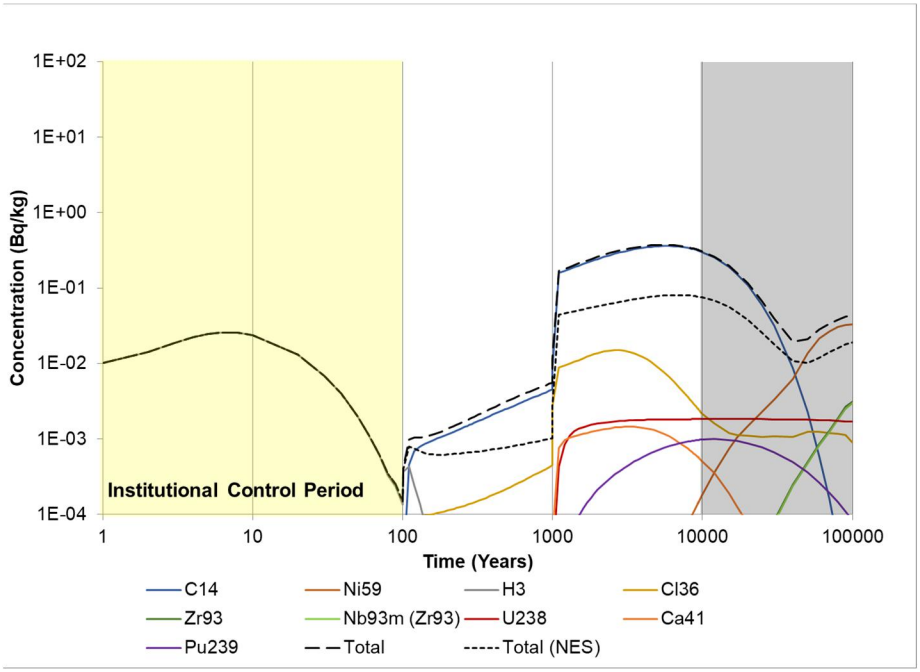


Figure G-43 Concentrations in the River Water (Reduced Near-field Sorption Case)



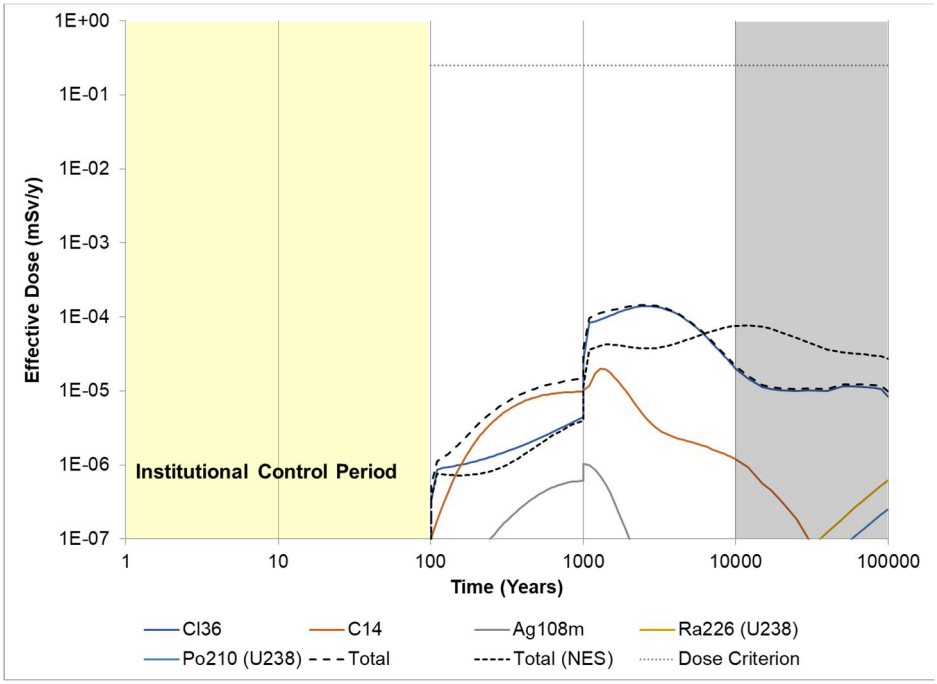
Note: Radionuclides in brackets indicate the parent of the radionuclide that was present in the initial radionuclide inventory of the NPDDF.

Figure G-44 Concentrations in the Garden (Reduced Near-field Sorption Case)



Note: Radionuclides in brackets indicate the parent of the radionuclide that was present in the initial radionuclide inventory of the NPDDF.

Figure G-45 Total Dose to the Most Exposed Receptor, Infant Site Resident (Reduced Near-field Sorption Case)



Note: Radionuclides in brackets indicate the parent of the radionuclide that was present in the initial radionuclide inventory of the NPDDF.

G 3.4 NES(d) – Reduced Far-field Sorption

Sorption also plays a significant role in the transport of contaminants in the geosphere (the “far-field”). The sorption values for the overburden and bedrock were therefore also reduced to determine the significance of uncertainties in sorption in these media. Because the data sources from which the reference values did not themselves provide ranges of values, for this case all sorption values were simply reduced by an order of magnitude to provide a conservative representation of sorption in the geosphere.

The concentrations in contaminated groundwater are almost identical to those calculated for the Normal Evolution scenario, as can be seen in Figure G-46.The effect of reduced geosphere sorption is not very significant, indicating that the dominant factor controlling the concentrations in the groundwater is the retention of contaminants in the NPDDF itself, rather than the geosphere. The environmental concentrations (Figure G-47) and resulting doses (Figure G-48) are also extremely similar to the Normal Evolution scenario, although lower geosphere sorption indicates that C-14 is more rapidly transported to the river in first few hundred years, resulting in higher concentrations in this period. The highest dose to the infant resident is unchanged from the Normal Evolution scenario, at $8x10^{-5}$ mSv y^{-1}.

Figure G-46 Radionuclide Concentrations in Groundwater Downstream of the NPDDF (Reduced Far-field Sorption Case)

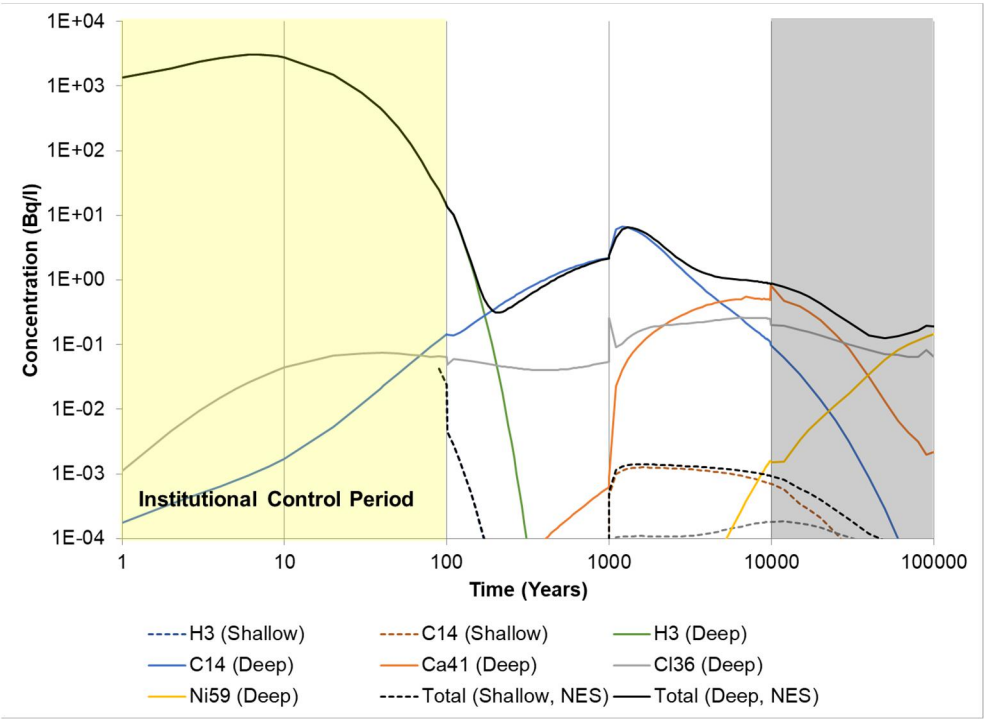


Figure G-47 Concentrations in the River Water (Reduced Far-field Sorption Case)

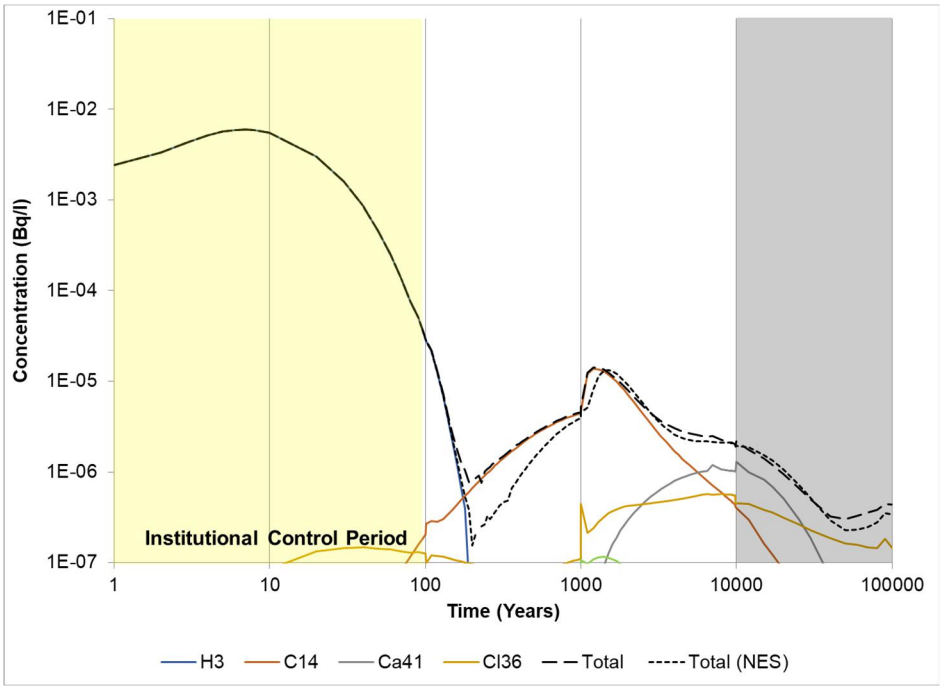
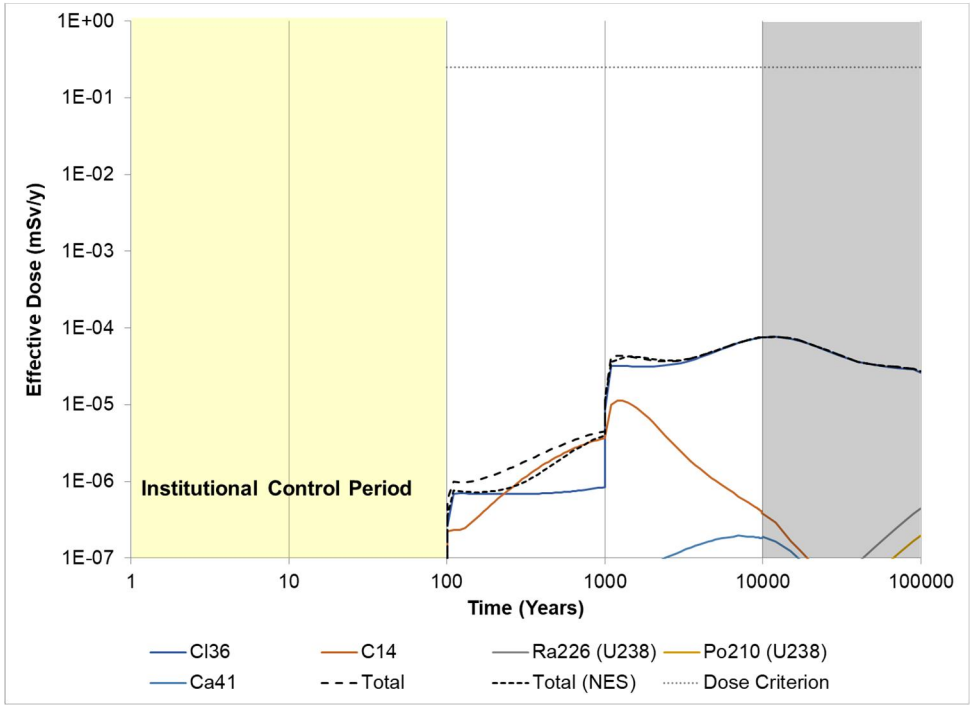


Figure G-48 Dose to the Most Exposed Group, the Infant Site Resident (Reduced Far-field Sorption Case)



Note: A radionuclide that is followed by another in brackets indicates that it is a decay product of the parent radionuclide, in brackets, which was present at the time of closure.

G 3.5 NES(e) – Reduced Sorption in Near-field and Far-field

The effects of reduced sorption in both the near-field and far-field have been explored with this case. This combines the lower sorption values for the near-field assumed for case NES(c) and the reduced geosphere sorption values used in NES(d). As may be expected, the results are very similar to those obtained for NES(c) as near-field sorption is dominant in controlling the environmental concentrations and doses.

The results presented below can be compared with those presented in Sections 0 and G 3.4. It is clear that the results calculated when both near-field and far-field sorption are both reduced (Figure G-49, Figure G-50, Figure G-51 and Figure G-52) most closely resemble those calculated with the lower near-field sorption values only (NES(c), Section 0). This is borne out most clearly in Figure G-53, which shows the calculated doses from the most exposed members (Infant Site Resident) of the four groups for whom radiation doses have been assessed and compares the results from this case, and the cases with near-field and far-field sorption only. However, it can be seen that the reduced sorption in both parts of the disposal does particularly influence the environmental concentrations of C-14, and thus doses, in the first few 100 y. As may be seen in Figure G-53, although there are differences in the rates of release in the period up to 1000 y, the results for this case are extremely similar to those calculated for the reduced near-field sorption case. The peak doses are compared with the Normal Evolution scenario and cases NES(c) and NES(d) in Table G-25 below.

Figure G-49 Release of Contaminants from the NPDDF to the Geosphere (Reduced Near-field and Far-field Sorption Case)

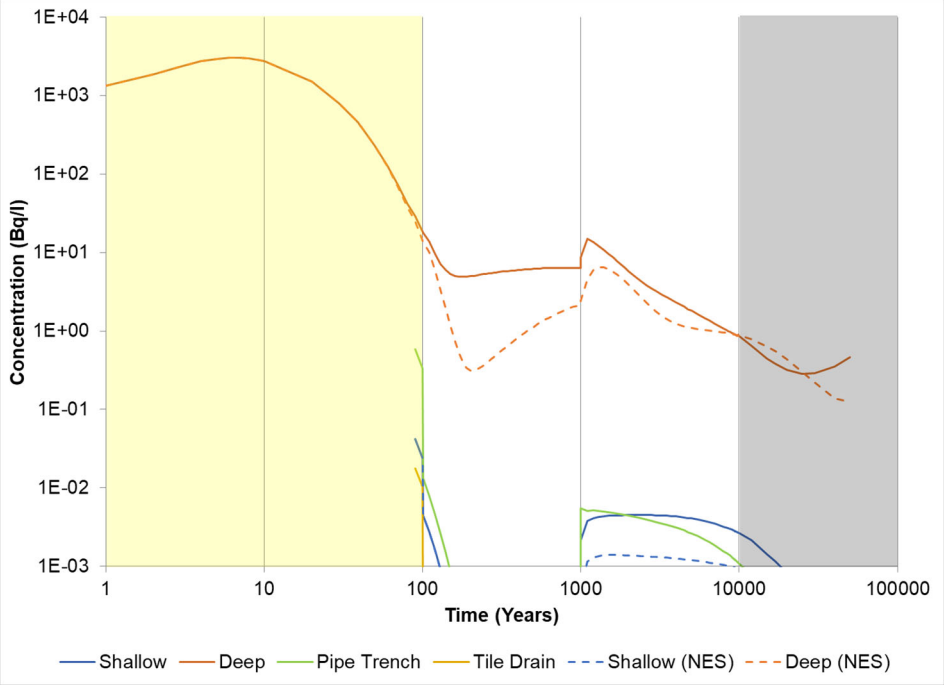


Figure G-50 Radionuclide Concentrations in Groundwater Downstream of the NPDDF (Reduced Near-field and Far-field Sorption Case)

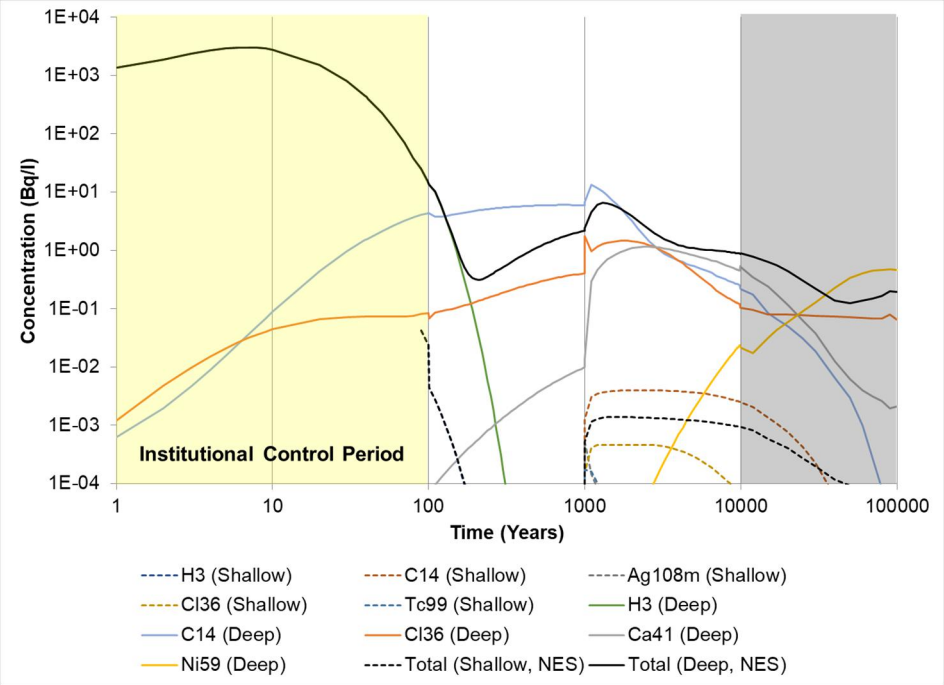


Figure G-51 Concentrations in the River Water (Reduced Near-field and Far-field Sorption Case)

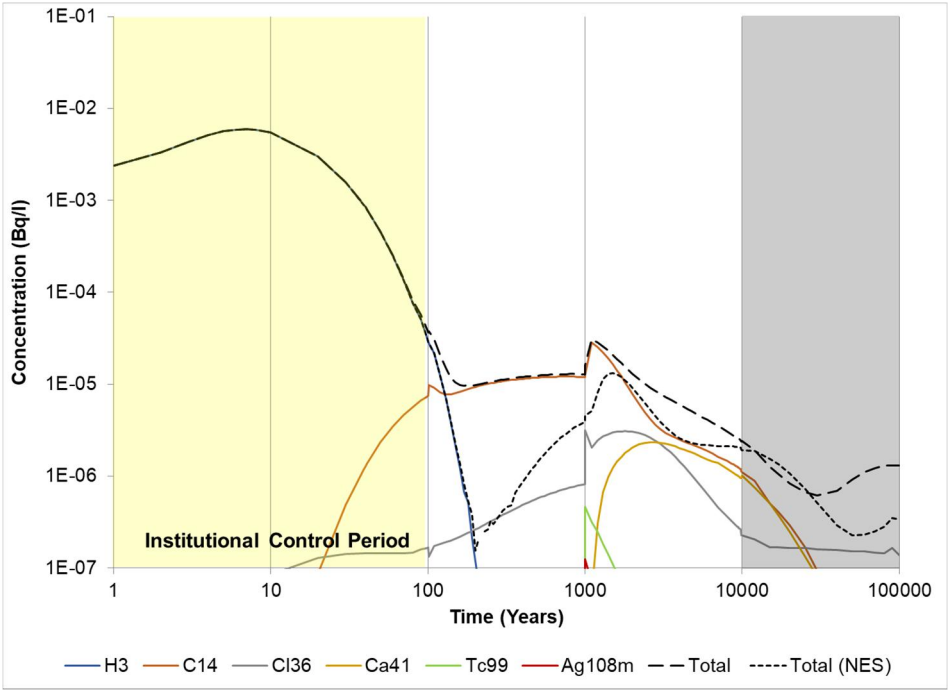
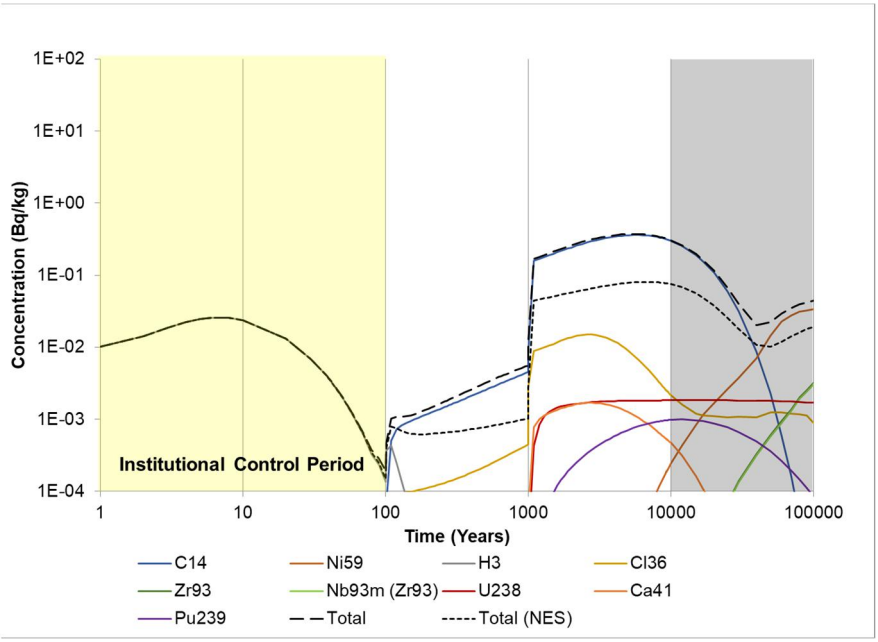
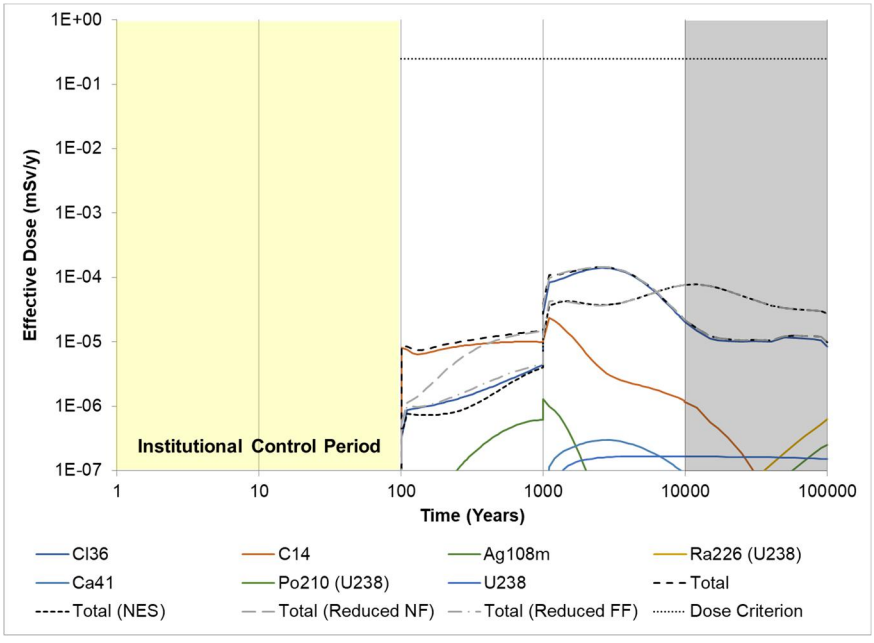


Figure G-52 Concentrations in the Garden (Reduced Near-field and Far-field Sorption Case)



Note: Radionuclides in brackets indicate the parent of the radionuclide that was present in the initial radionuclide inventory of the NPDDF.

Figure G-53 Dose to the Infant Site Resident (Reduced Near-field and Far-field Sorption Case) Compared with Normal Evolution scenario and Cases NES(c) (Reduced Near-field) and NES(d) (Reduced Far-field)



Note: Radionuclides in brackets indicate the parent of the radionuclide that was present in the initial radionuclide inventory of the NPDDF.

Table G-25 Summary of Peak Dose (mSv y^{-1}) to the Four Exposure Groups for the Normal Evolution Scenario and Cases NES(c), NES(d) and NES(e)

Calculation Case	Resident Group (Infant)	Hunter Group (Adult)	Offsite Group (Adult)	AOPFN Group (Adult)
Normal Evolution Scenario (NES)	8E-05 (12000 y)	4E-07	3E-10	7E-06
NES(c) (Reduced Near-field Sorption)	1E-04 (2600 y)	2E-06	7E-10	2E-05
NES(d) (Reduced Far-field Sorption)	8E-05 (12000 y)	4E-07	3E-10	8E-06
NES(e) (Reduced Near- and Far-field Sorption)	1E-04 (2600 y)	3E-06	7E-10	2E-05

G 3.6 NES(f) – Rapid Degradation

The scenario is based on the Normal Evolution scenario; however, it is assumed that the engineered barriers (the NPDDF structure and grout filling the rooms) are instantly in a physically degraded state at the end of the Institutional Control Period. The physical degradation of the engineered barriers in the NPDDF is not represented directly in the AMBER model. Rather, the model uses different sets of data on groundwater flow through the facility, based on detailed modelling undertaken by Arcadis & Geofirma (2023a,b). Detailed groundwater flow modelling provides calculated flows for undegraded and degraded structures, amongst other assumptions. In the Normal Evolution scenario, the engineered barriers are only assumed to be fully degraded after 1,000 y. In this case, this condition is assumed to be reached after only 100 y. A variety of situations could lead to such a condition, including a nearby severe seismic event which results in extensive cracking of concrete, or problems with the grouting of the facility that leads to poor curing of the backfill. The interest for this scenario is in the effect of the enhanced hydraulic conductivity of the engineered barriers on radionuclide releases from the NPDDF. The chemical effects of the cement on sorption remains the same as modelled in the Normal Evolution scenario but the increased flows through the Facility in the first 1,000 y affects the timescales for chemical degradation. These are shown in Table G-26 and Table G-27, and illustrated graphically as a timeline alongside the physical degradation in Figure G-54.

Table G-26 Time at Which Grout Degradation Stages Begin in the Rapid Degradation of Engineered Barriers Sensitivity Case

Room	Stage I	Stage II	Stage III	Stage IV
Above Bedrock				
Fuel Storage Room	0	25,000	>100,000	>100,000
Fuelling Room	0	12,000	>100,000	>100,000
Boiler Room	0	30,000	>100,000	>100,000
Turbine Room	0	12,000	>100,000	>100,000
Below Bedrock				
Fuel Storage Room	0	12,000	>100,000	>100,000
Reactor Vault	0	12,000	>100,000	>100,000
East of Reactor Vault	0	2,400	25,000	>100,000
West of Reactor Vault	0	6,000	60,000	>100,000
Dump Tank Pipe Room	0	8,000	80,000	>100,000
Boiler Room	0	9,000	90,000	>100,000
Boiler Room (deep)	0	6,000	60,000	>100,000

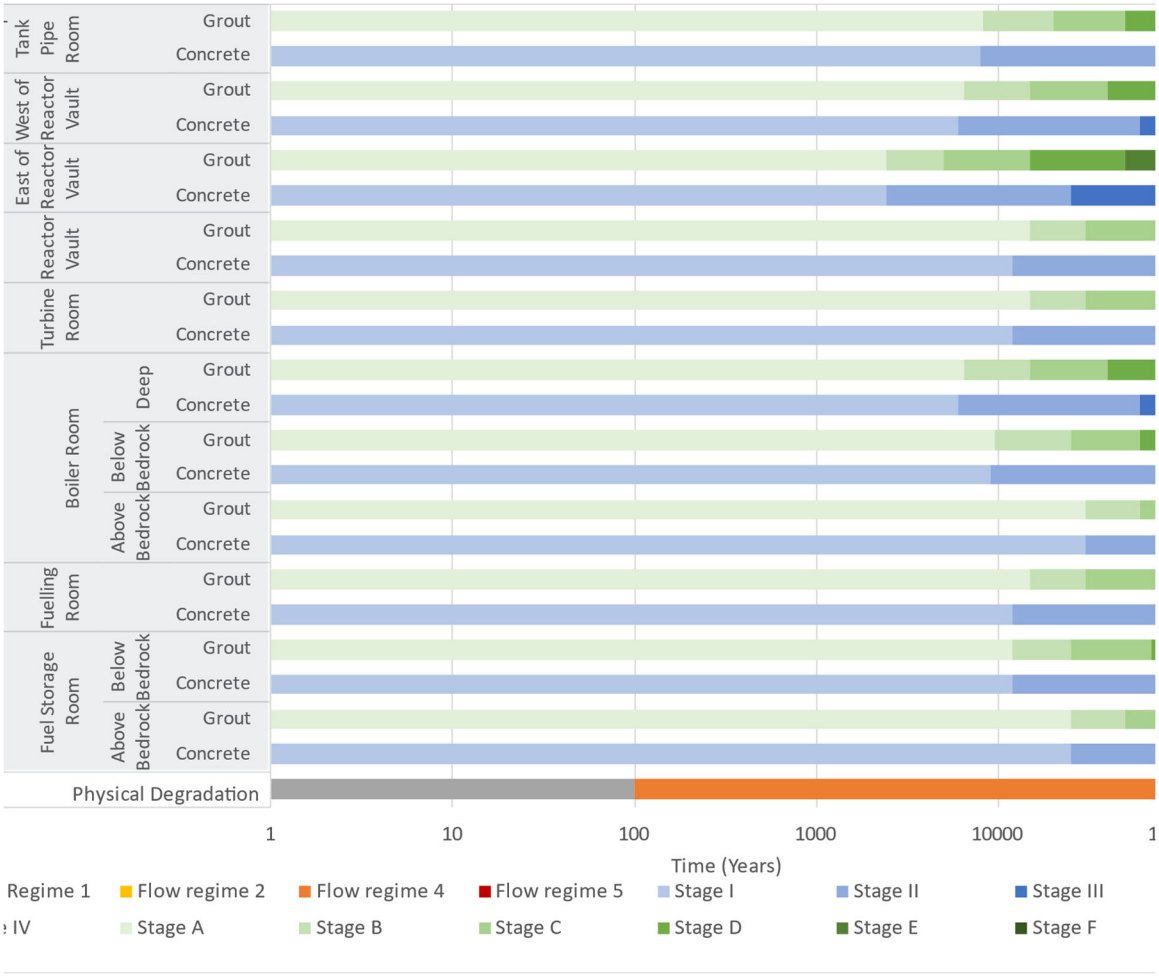
Note: Greyed-out cells are after the main assessment timeframe of 10,000 y.

Table G-27 Time at Which Grout Degradation Stages Begin in the Rapid Degradation of Engineered Barriers Sensitivity Case

Room	Stage A	Stage B	Stage C	Stage D	Stage E	Stage F
Above Bedrock						
Fuel Storage Room	0	25,000	50,000	#N/A	>100,000	>100,000
Fuelling Room	0	15,000	30,000	80,000	>100,000	>100,000
Boiler Room	0	30,000	60,000	#N/A	>100,000	>100,000
Turbine Room	0	15,000	30,000	80000	>100,000	>100,000
Below Bedrock						
Fuel Storage Room	0	12,000	25,000	70,000	>100,000	>100,000
Reactor Vault	0	15,000	30,000	80,000	>100,000	>100,000
East of Reactor Vault	0	2,400	5,000	15,000	50,000	100,000
West of Reactor Vault	0	6,500	15,000	40,000	>100,000	>100,000
Dump Tank Pipe Room	0	8,250	20,000	50,000	>100,000	>100,000
Boiler Room	0	9,475	25,000	60,000	>100,000	>100,000
Boiler Room (deep)	0	6,500	15,000	40,000	>100,000	>100,000

Note: Greyed-out cells are after the main assessment timeframe of 10,000 y.

Figure G-54 Timelines of Degradation in the Rapid Degradation of Engineered Barriers Sensitivity Case



The effect of switching to the "degraded" flows (Case 4 in Arcadis & Geofirma, 2023b) after 100 y rather than 1,000 y is shown clearly in Figure G-55. Immediately after 100 y there is a large increase in the release rate of tritium to the deep groundwater pathway, and increased releases of other radionuclides including C-14 (dominant after 160 y). From 1,000 y onwards the releases are similar to the Normal Evolution scenario, both for the shallow and deep groundwater pathways.

The effects on radionuclide concentrations in the surface environment are most important for the garden soils (which are assumed to be irrigated with contaminated river water). Figure G-56 shows that there are much higher concentrations of C-14 in soils in the 100 – 1,000 y period, whereas after this the calculated concentrations are almost identical to the Normal Evolution scenario. Other cases have established that Cl-36 is a key radionuclide from the perspective of exposures of people. As this is released more rapidly, from 100 y onwards, the radiation dose to a Site Resident is increased compared with the Normal Evolution scenario in the 100 – 1,000 y period. The peak dose, however, occurs much later (at 12,000 y) and is the same at 8×10^{-5} mSv y^{-1} (see Figure G-57).

Figure G-55 Release of Radionuclides from NPDDF to the Geosphere (Rapid Degradation of Engineered Barriers Case)

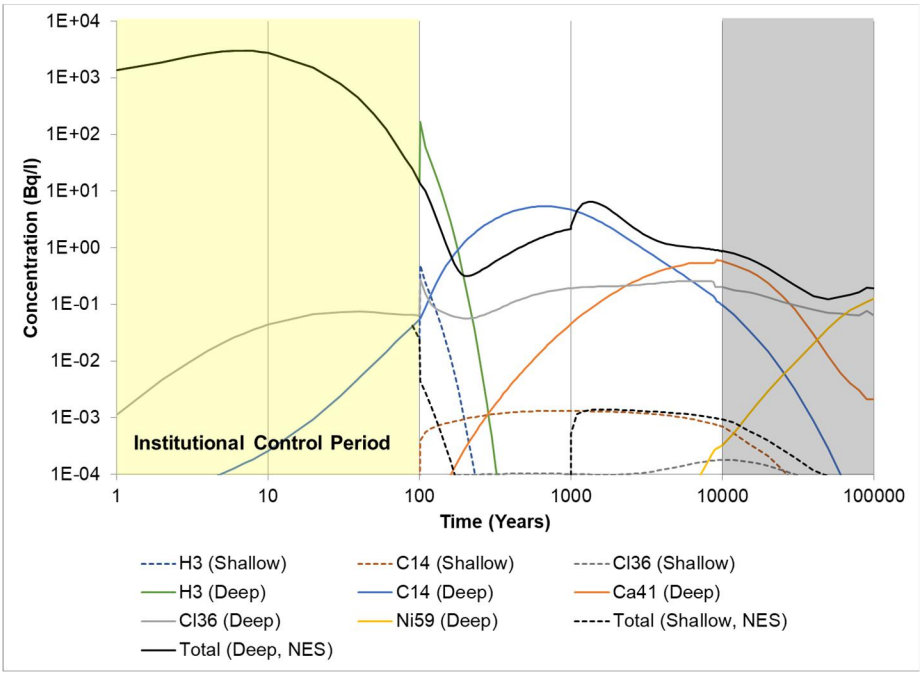
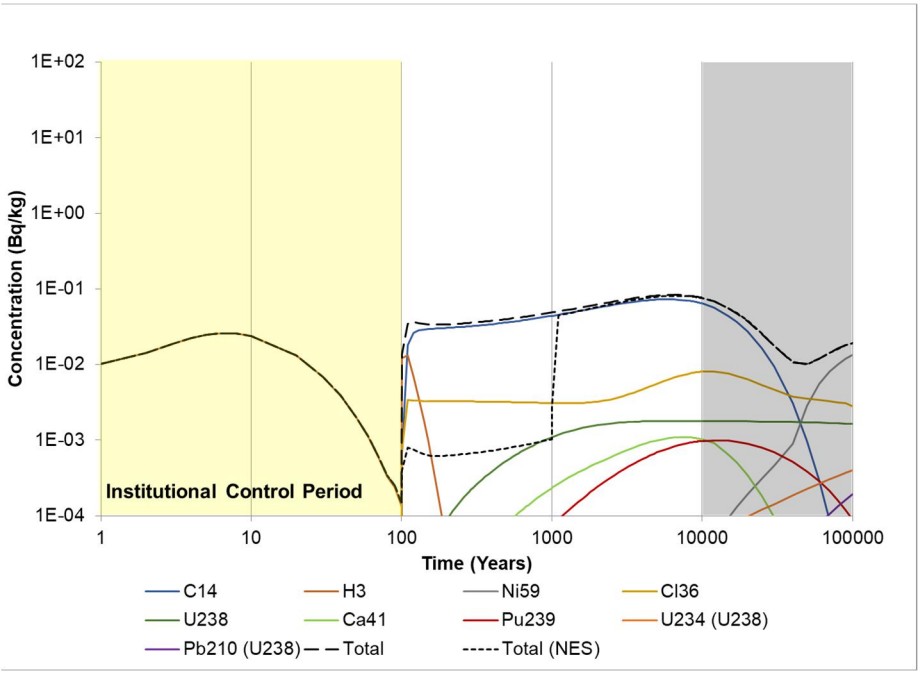
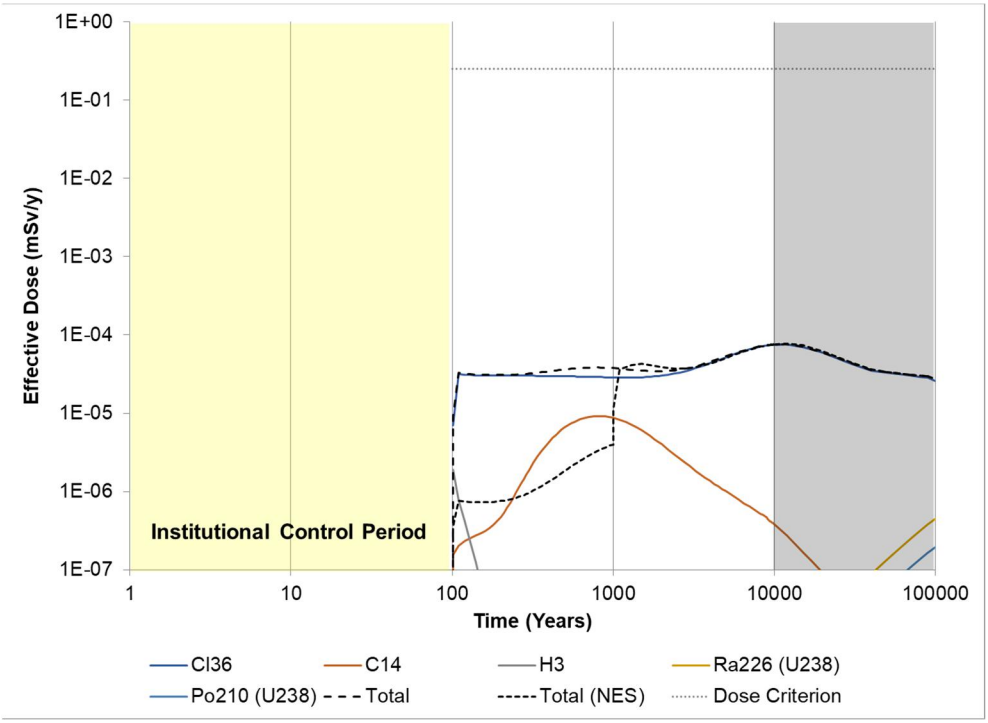


Figure G-56 Concentration of Radionuclides in Garden Soils (Rapid Degradation of Engineered Barriers Case)



Note: Radionuclides in brackets indicate the parent of the radionuclide that was present in the initial radionuclide inventory of the NPDDF.

Figure G-57 Dose to the Most Exposed Receptor - Infant Site Resident (Rapid Degradation of Engineered Barriers Case)



Note: Radionuclides in brackets indicate the parent of the radionuclide that was present in the initial radionuclide inventory of the NPDDF.

G 3.7 NES(g) – Geosphere Bedrock Hydraulic Conductivity

The Geosynthesis Report (Arcadis & Geofirma, 2022) outlines the hydraulic conductivity best estimates for each of the hydrostratigraphic units based on site characterization data, and compares these values to the final calibrated values generated by the groundwater model. The discussions indicate that the calibrated values generated by the groundwater flow model are reasonable. However, to reflect the uncertainties in hydrogeological properties, a sensitivity study has been undertaken in the NES(g) case. This examines the effect of increased hydraulic conductivity in bedrock compared to the Normal Evolution scenario. The change in hydraulic conductivity in bedrock is not represented directly in the AMBER model. Rather, the model uses different sets of data on groundwater flow through the facility, based on detailed modelling undertaken by Arcadis & Geofirma (2023a,b).

Most notably, the increased flows in the bedrock result in a general lowering of the water table, such that the parts of the NPDDF that sit in the overburden experience no groundwater transport. As a consequence, the only releases that occur are from the rooms that sit within the bedrock. Furthermore, the increased flow rates through the geosphere result in substantially greater dilution of the released contaminants. By way of

illustration, the volumetric flows through the bedrock compartment immediately beneath the Turbine Room at closure are increased from 1,000 m^3 y^{-1} in the Normal Evolution scenario to 50,000 m^3 y^{-1} for this sensitivity case.

The radionuclide concentrations in the geosphere are therefore much reduced in the bedrock, and there is no release to the overburden at all (as there is no flow through the parts of the NPDDF that sit in the overburden). The concentrations in the bedrock are substantially lower (see Figure G-58) with the peak concentration reducing from 3,000 to 70 Bq l^{-1}. However, the rate of discharge of contaminants to the river (in Bq y^{-1}, which is the product of the concentration of radionuclides in the water and the groundwater flow rate) is somewhat increased in the period 100 – 1000 y. Consequently, the river water concentrations in this timeframe are increased, as shown in Figure G-59. This does not, however, affect the doses to the most exposed receptor, the infant Site Resident (Figure G-61) as their dose is dominated by C-14. Concentrations in the soil are much reduced as there is no pathway for contaminants to reach the soil via the overburden as can be seen in Figure G-60, falling from a peak of $8x10^{-2}$ Bq kg^{-1} after 6,500 y in the NES to $8x10^{-4}$ Bq kg^{-1} after 60,000 y in this case. Consequently, the peak dose of $3x10^{-5}$ mSv y^{-1} is three times lower than that in the Normal Evolution scenario. This peak dose occurs 1100 y after closure and the radionuclide contributing most to the dose is C-14. In contrast, in the Normal Evolution scenario, the peak dose occurs much later, and the dominant radionuclide is Cl-36.

Figure G-58 Release of Contaminants from the NPDDF to the Geosphere (Geosphere Bedrock Hydraulic Conductivity Case)

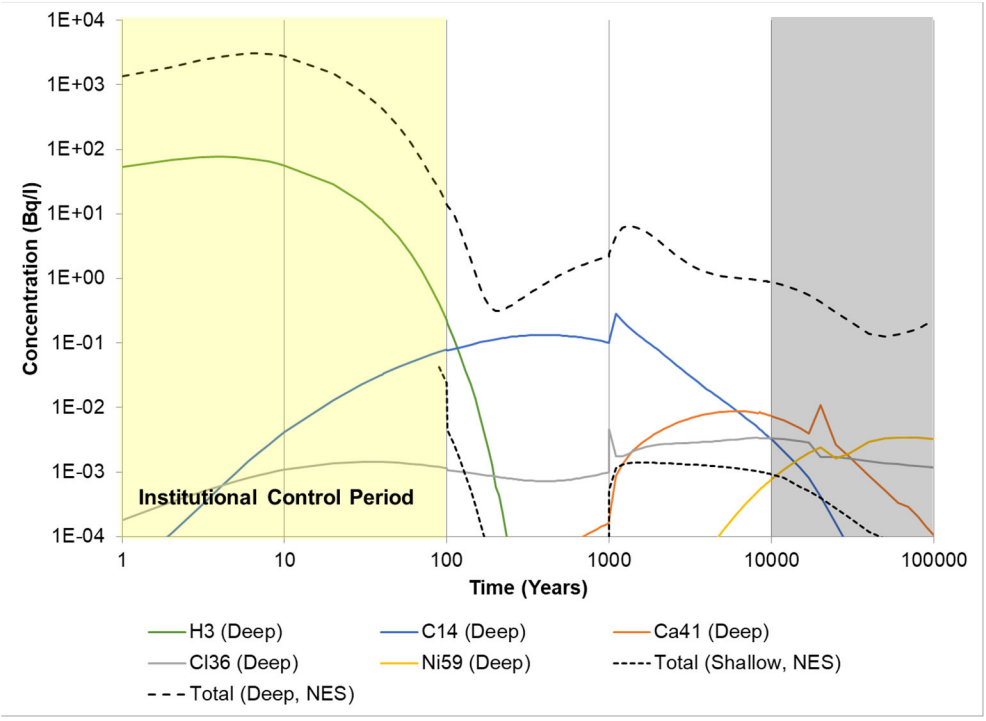


Figure G-59 Concentrations in the River Water (Bedrock Hydraulic Conductivity Case)

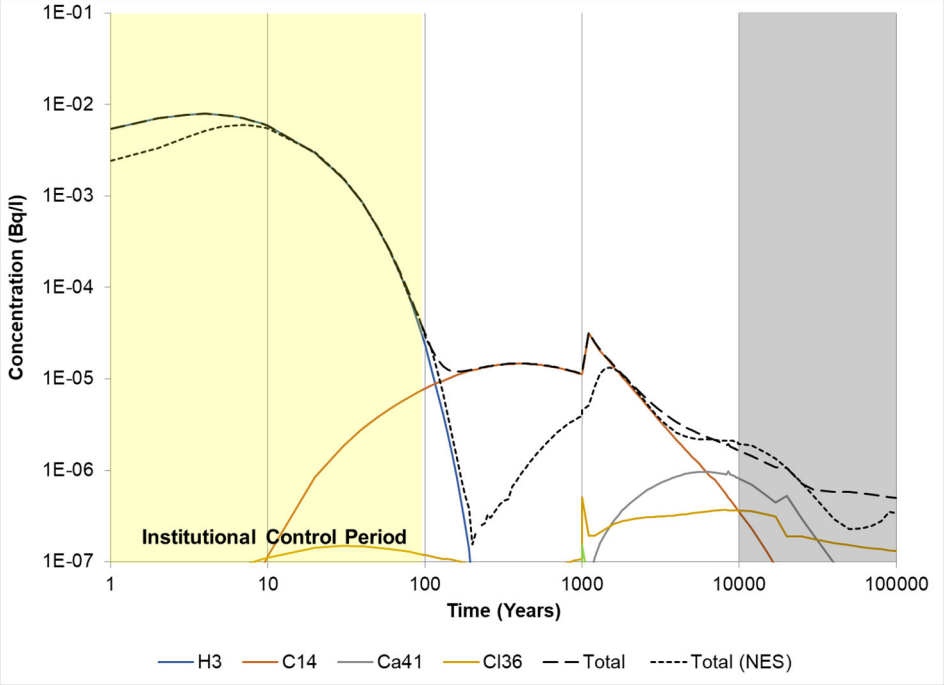


Figure G-60 Concentrations in the Garden (Bedrock Hydraulic Conductivity Case)

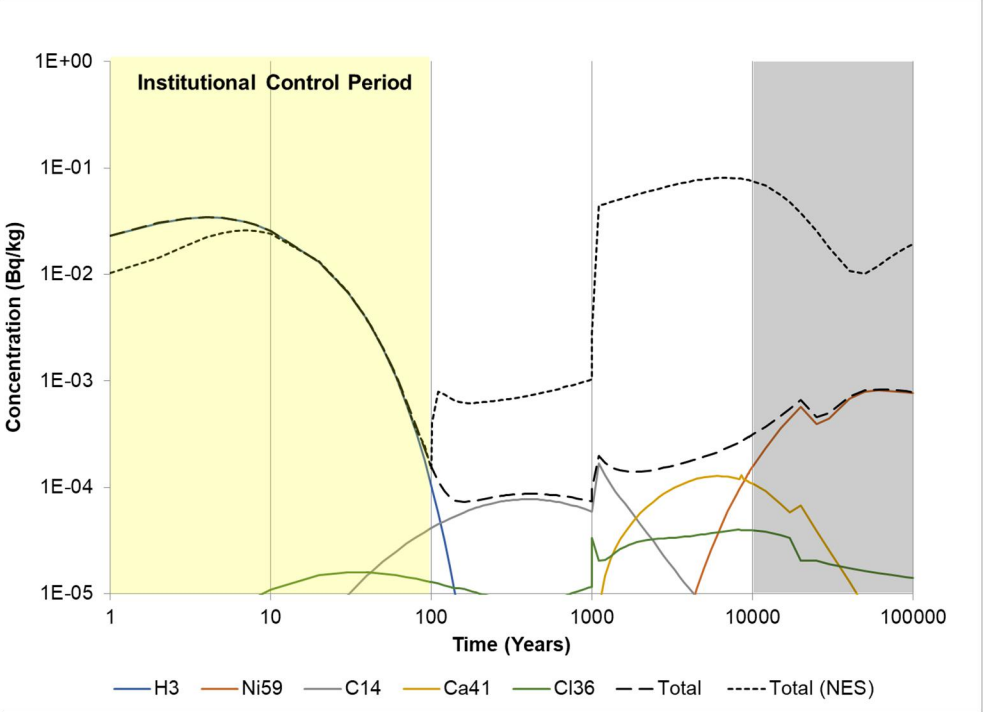
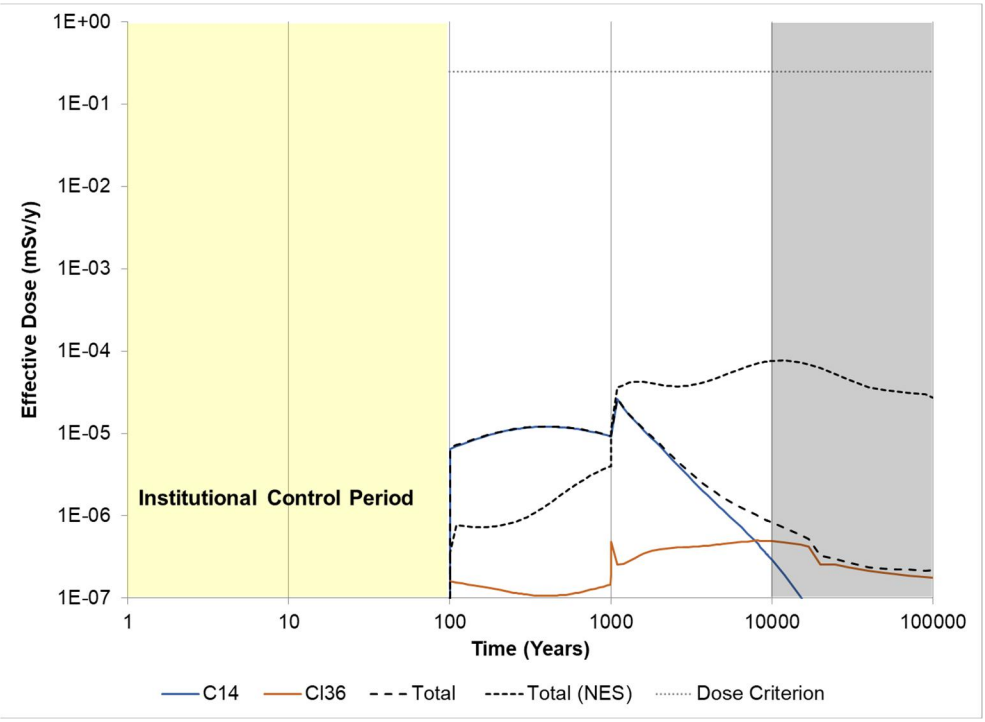


Figure G-61 Total Dose to the Most Exposed Receptor, Infant Site Resident (Geosphere Bedrock Hydraulic Conductivity Case)



G 3.8 NES(h) – Geosphere Overburden Hydraulic Conductivity

To reflect the uncertainties in hydrogeological properties of the overburden, this sensitivity study examines a case with increased hydraulic conductivity in the overburden fill material between the facility and the river, compared to Normal Evolution scenario. In the same manner as in the Geosphere Bedrock Hydraulic Conductivity Case (NES(g)), the change in hydraulic conductivity in overburden (till) is not represented directly in the AMBER model. Rather, the model uses different sets of data on groundwater flow through the facility, based on detailed modelling undertaken by Arcadis & Geofirma (2023b).

Figure G-62 shows that concentrations of radionuclides in the shallow groundwater are reduced compared with the Normal Evolution scenario because the higher flow rate increases the dilution of the contaminants. The concentrations in the bedrock pathway are very similar to those for the Normal Evolution scenario, as the flow rate in this part of the geosphere is unchanged. The overburden pathway is the most significant for human exposures as it leads to the release of contaminants (most importantly, Cl-36) to the Garden soil. The dose to the most exposed receptor, the Infant Site Resident, is shown in Figure G-63, and is reduced compared to that calculated for the Normal Evolution scenario. The main difference is that the increased overburden hydraulic conductivity reduces the concentrations of Cl-36. As a consequence, for this case the dominant radionuclide is C-14, and the peak dose is reduced to $1x10^{-5}$ mSv y^{-1} and occurs as 1400 y after closure.

Figure G-62 Concentrations in Groundwater Downstream from the NPDDF (Geosphere Overburden Hydraulic Conductivity Case)

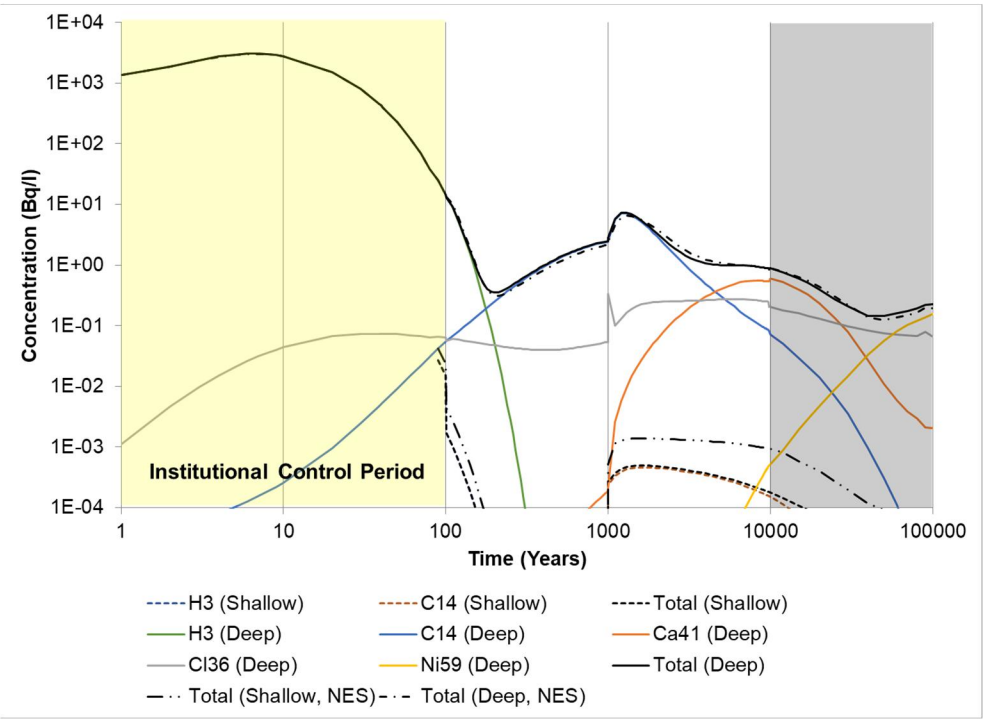
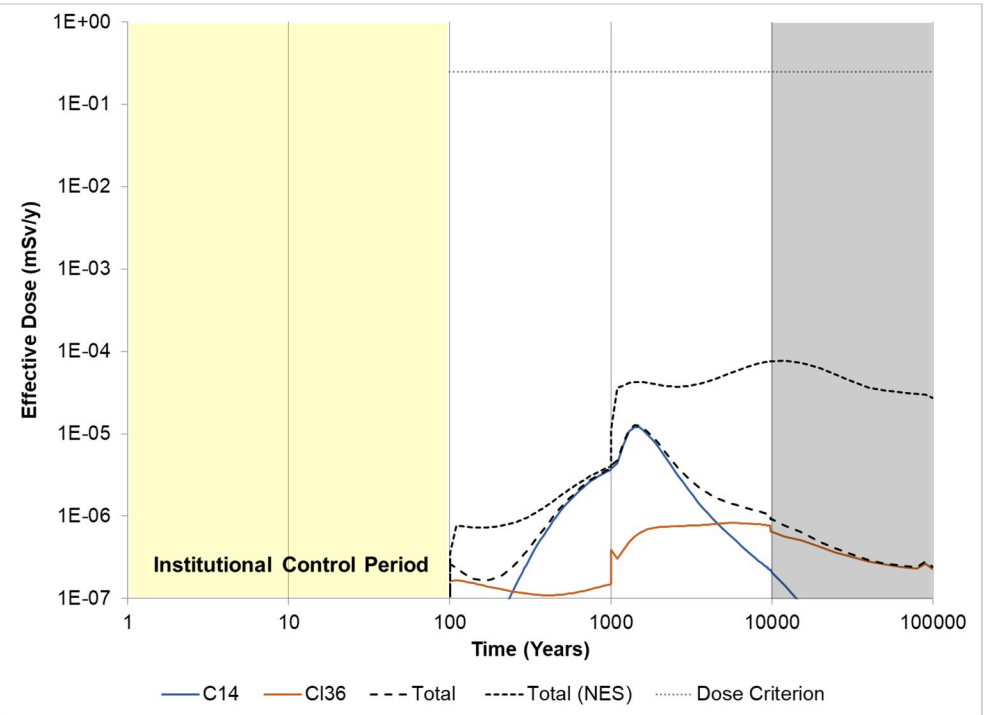


Figure G-63 Total Dose to the Most Exposed Receptor, Site Resident Infant (Geosphere Overburden Hydraulic Conductivity Case)



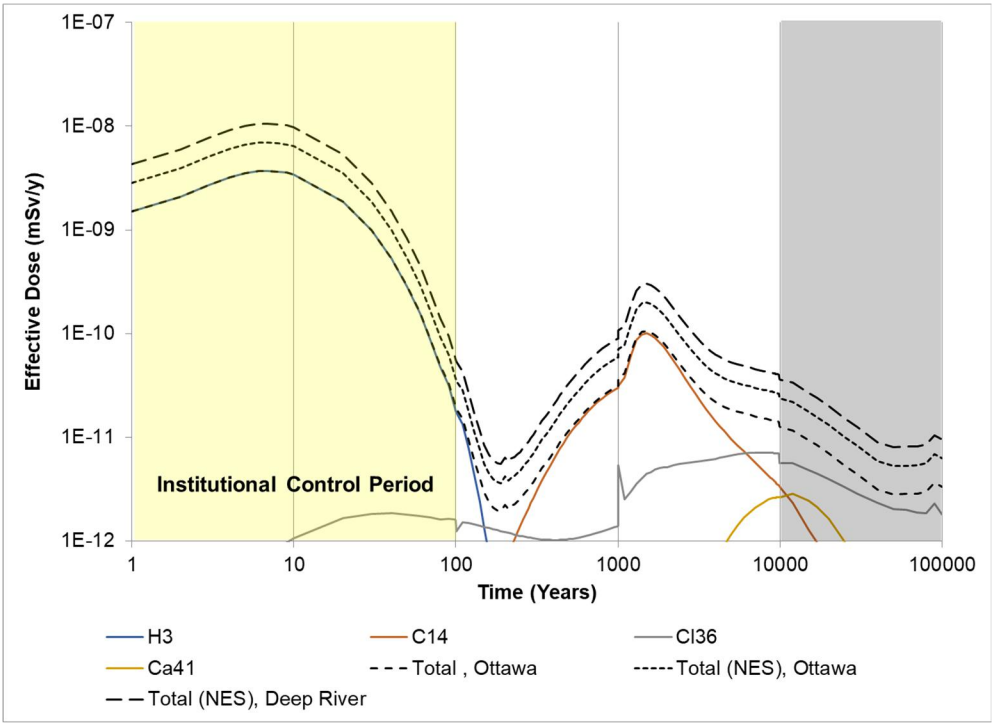
G 3.9 NES(i) – Increased Dilution in the River

The receptors who could use the site itself received the highest doses in the Normal Evolution scenario, but they may only be exposed after the period of institutional controls is concluded, which is assumed to be 100 y after closure. However, any contamination reaching the river can be dispersed and travel downstream where other people may be exposed earlier than this as there are no controls on their activities. Doses are therefore calculated to people exposed to river water, obtaining all their drinking water from the river and bathing in it for half an hour per day. Exposures via this route are assessed for a resident of Deep River, just downstream of NPDDF, and further downstream at the city of Ottawa.

For the Normal Evolution scenario, it is assumed that there is no additional flow in the river water at Deep River, given that it is only a short distance downstream from the NPDDF. Further downstream the river flow will increase due to additional inputs of water from tributaries. The concentrations at Ottawa are therefore determined by the ratio of the volumetric river flow rate at Des Joachims station (immediately upstream of NPDDF) and the reported volumetric flow rate measured at the Britannia hydrometric gauge just downstream of Gatineau, giving a dilution factor of 0.658.

A sensitivity case considers an alternative dilution factor of 0.35. These dilution factors simply scales the concentrations and hence the doses from the ingestion and external exposure pathways. The results are shown in Figure G-64. For the NES, the highest dose of $1x10^{-8}$ mSv y^{-1} occurs 7 y after closure at Deep River, through ingestion of water containing tritium. If a dilution factor of 0.658 is applied to calculate the dose in Ottawa the peak dose is $7x10^{-9}$ mSv y^{-1}, or $4x10^{-9}$ mSv y^{-1} with a dilution factor of 0.35.

Figure G-64 Total Dose to People Exposed to Contaminants in River Water at Ottawa, Considering Various Dilution Factors



G 3.10 NES(j) – Self-Sufficient Indigenous Receptor

A range of exposure groups have been chosen so as to provide an indication of the potential radiation doses to the most exposed people. The Normal Evolution scenario includes a hypothetical Site Resident, an Indigenous group representing habits based on a survey of the AOPFN, a Hunter group and an Offsite receptor.

In order to examine the sensitivity of the lifestyle assumptions, an additional exposure group has been considered, the Self-Sufficient Indigenous Group, assumed to live in the vicinity of the NPDDF and obtain food from that area. The characteristics of this group are conservatively-defined and based on Indigenous habits described in SENES (2014). The dietary intake rates for this receptor are taken from food intake data representing high energy intake rates (SENES, 2014). Their diet consists of deer and moose as well as wildfowl, fish, berries and mushrooms. This Indigenous group spends less time in the vicinity of the site as a whole than the Site Resident (as they are not living there), but spends longer by the river, fishing.

The peak dose to the Self-sufficient Indigenous exposure group is $4x10^{-5}$ mSv y^{-1} to an infant, dominated by C-14 at 1,500 y (similar to the time of the peak dose for the AOPFN exposure group). After 2,200 y Cl-36 is the dominant radionuclide and second peak dose of $3x10^{-5}$ mSv y^{-1} is reached after 10,000 y due mainly to Cl-36. As shown, these doses remain lower than for the Site Resident ($8x10^{-5}$ mSv y^{-1}) but greater than that to the AOPFN exposure group ($7x10^{-6}$ mSv y^{-1}), as shown in Figure G-65 and Figure G-66.

Compared to the AOPFN exposure group, the conservative intake rates for the Self-sufficient Indigenous group are taken from a large population survey for each foodstuff, whereas the AOPFN rates are based on targeted dietary surveys and are expected to be more representative. Even when accounting for a local fraction of <1, the intake rates of moose, grouse, duck, fish and berries are significantly higher than for the AOPFN receptor. Foodstuff pathways dominate the doses (Figure G-67), therefore the AOPFN receptor receives a lower dose.

The summary of dose to an infant in the Indigenous Self-Sufficient Group for the five radionuclides contributing most to the dose and the summary of dose to an infant in the Indigenous Self-Sufficient for the different pathways through time are given in Table G-28 and Table G-29, respectively.

Figure G-65 Total Dose to the Indigenous Self-Sufficient Group, Compared with Exposure Groups Considered in the Normal Evolution Scenario

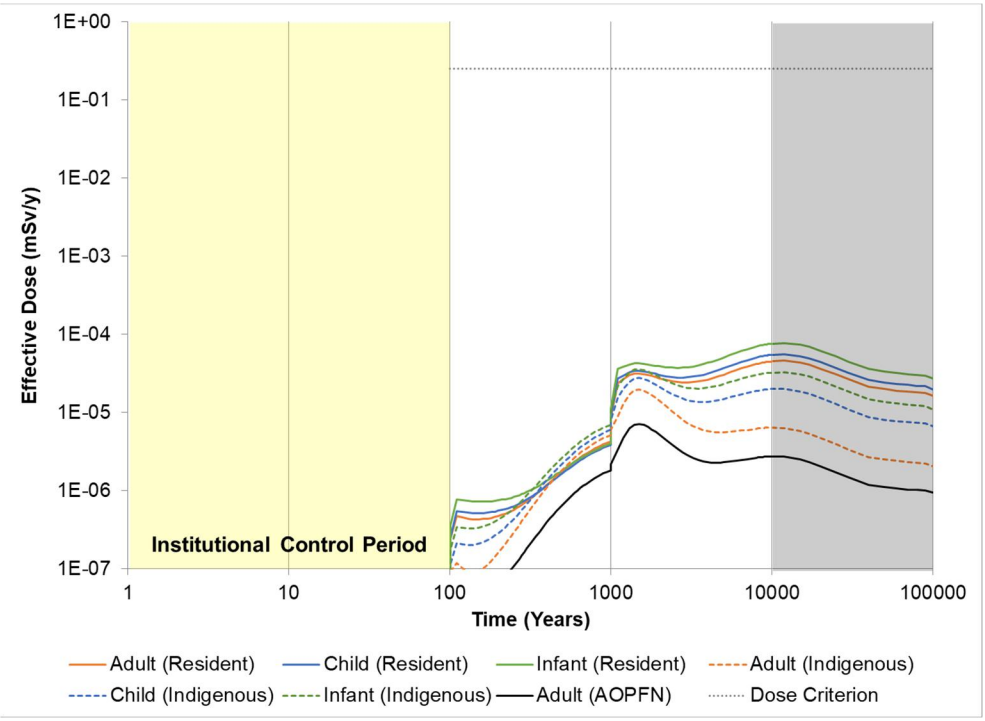


Figure G-66 Total Dose to an Infant in the Indigenous Self-Sufficient Group (by Radionuclide)

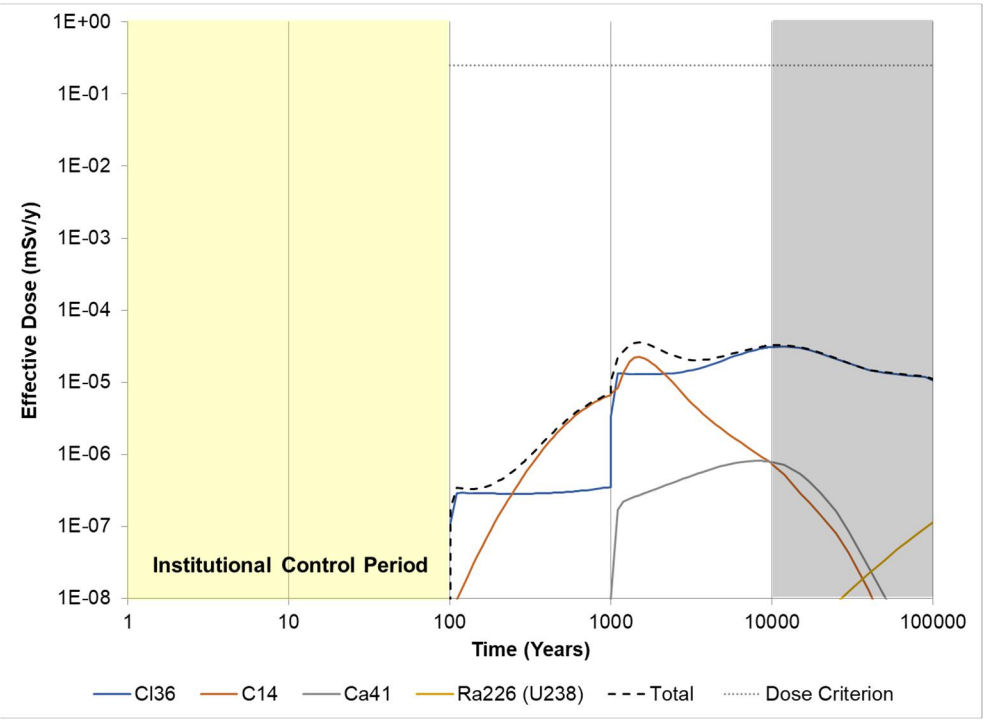


Figure G-67 Total Dose to an Infant in the Indigenous Self-Sufficient Group (by Exposure Pathway)

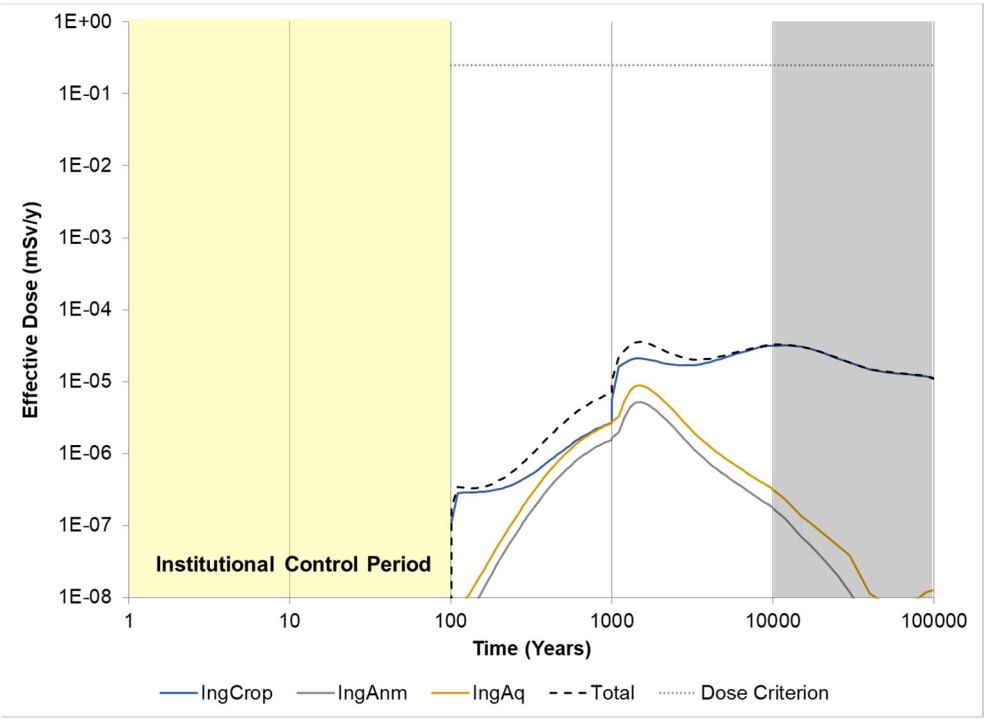


Table G-28 Summary of Dose (mSv y^{-1}) to an Infant in the Indigenous Self-Sufficient Group for the Five Radionuclides Contributing Most to the Dose

Time (y)	Cl36	C14	Ca41	Ra226 (U238)*	Po210 (U238)*	Total
100	1E-07	6E-09	<1E-10	<1E-10	<1E-10	2E-07
300	3E-07	6E-07	1E-09	<1E-10	<1E-10	9E-07
1000	4E-07	7E-06	9E-09	<1E-10	<1E-10	7E-06
3000	1E-05	6E-06	5E-07	<1E-10	<1E-10	2E-05
10000	3E-05	7E-07	8E-07	1E-09	9E-10	3E-05
30000	2E-05	4E-08	9E-08	1E-08	9E-09	2E-05
50000	1E-05	4E-09	1E-08	3E-08	3E-08	1E-05
Maximum (mSv y^{-1})	3E-05	2E-05	8E-07	3E-08	3E-08	4E-05
Time of Peak (y)	12000	1500	8000	50000	50000	1500

Note: * Radionuclide is a daughter not present at closure that has ingrown from its parent, U-238.

Table G-29 Summary of Dose (mSv y^{-1}) to an Infant in the Indigenous Self-Sufficient Group for the Different Pathways Through Time

Time (y)	Ingestion of Crops	Ingestion of Honey	Ingestion of Animals	Ingestion of Fish	Ingestion of Water	Inhalation of Gas	Total
100	1E-07	1E-09	2E-09	5E-09	6E-08	<1E-10	2E-07
300	5E-07	7E-09	1E-07	2E-07	1E-08	<1E-10	9E-07
1000	6E-06	9E-08	2E-06	3E-06	1E-07	<1E-10	1E-05
3000	2E-05	1E-07	1E-06	2E-06	1E-07	<1E-10	2E-05
10000	3E-05	2E-07	2E-07	3E-07	6E-08	<1E-10	3E-05
30000	2E-05	1E-07	1E-08	4E-08	2E-08	<1E-10	2E-05
50000	1E-05	7E-08	3E-09	8E-09	2E-08	<1E-10	1E-05
Max. (mSv y^{-1})	3E-05	3E-07	5E-06	9E-06	3E-07	4E-13	4E-05
Time of Peak (y)	12000	1500	1500	1500	1500	1500	1500

G 4 DISRUPTIVE EVENT CASES

G 4.1 DE(a) – Site Investigation (Inadvertent Human Intrusion)

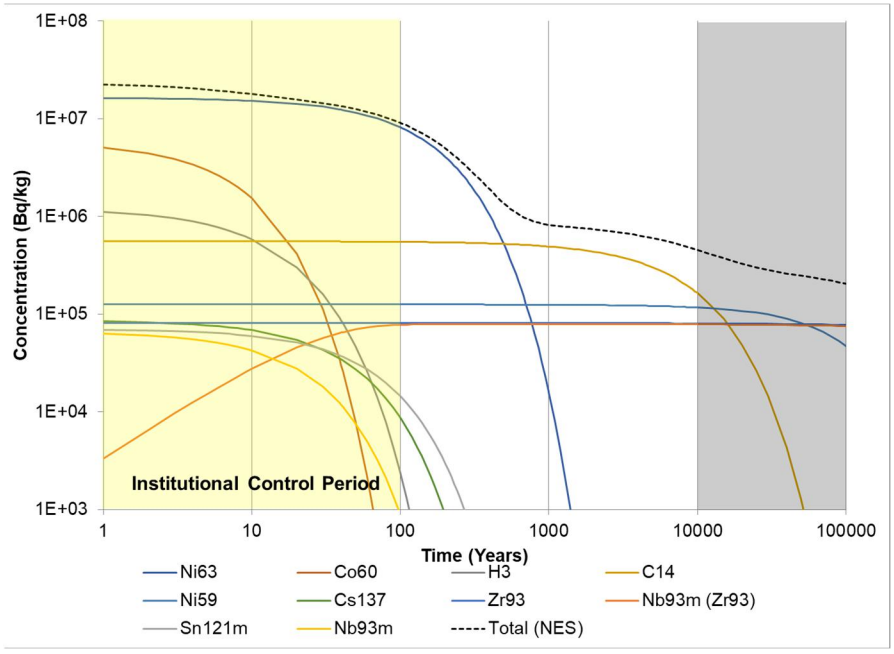
Site investigation is a Disruptive Event scenario that represents the possible consequences of people, in the future, locating and investigating the NPDDF without knowledge of its contents. Even if it were found in the future, the monolithic nature of the Facility at closure means that inadvertent disruption by humans would be very difficult and therefore relatively unlikely to occur without a significant degree of careful investigation which could reveal the presence of waste. Barriers to human intrusion will include a concrete cap over the nuclear area with an engineered cover. Beneath the concrete cap the Facility rooms will be filled with grout. For the purposes of this calculation case, however, these barriers are assumed to be overcome. Access to the NPDDF rooms would require machinery and facilities, usually deployed for geological excavations, to penetrate the many metres of concrete. The scenario is therefore modelled by assuming that at some time after the Institutional Control period a person may drill into the NPDDF and retrieve a 5 kg sample of material containing some radioactive waste. The “Borehole Driller” is assumed to be directly exposed to the most contaminated material (which would be retrieved from the Reactor Vault). It is then assumed to be inspected (by the drilling crew), left on site and subsequently become mixed with soil used for farming by the Site Resident exposure group. Cautiously, the additional contamination is assumed not to be leached from the soil.

It is noted that the 5 kg value of metal used is a factor of 10 more conservative than would be expected as it is estimated that the mass of Zircaloy in the core sample is 0.437 kg in 16.25 kg of grout, dictated by the core sample size of 4.5 m.

For the purposes of the dose assessment, the average concentration in the Reactor Vault is taken (Figure G-68). This ranges from $9x10^{6}$ Bq kg^{-1} after 100 y, decreasing to $5x10^{5}$ Bq kg^{-1} after 10,000 y. The peak dose rate from external radiation, after 100 y, is 0.04 μSv h^{-1}, initially dominated by Ag-108m (Figure G-69). The half-life of Ag-108m means that a substantial decrease does not occur until more than 1,000 y after closure of the NPDDF. The radionuclide has a half-life of 418 y and is dominant due to its presence as an activation product with a strong gamma emission. After 1,200 y the dominant radionuclide is Nb-94, also present in activated metal reactor components.

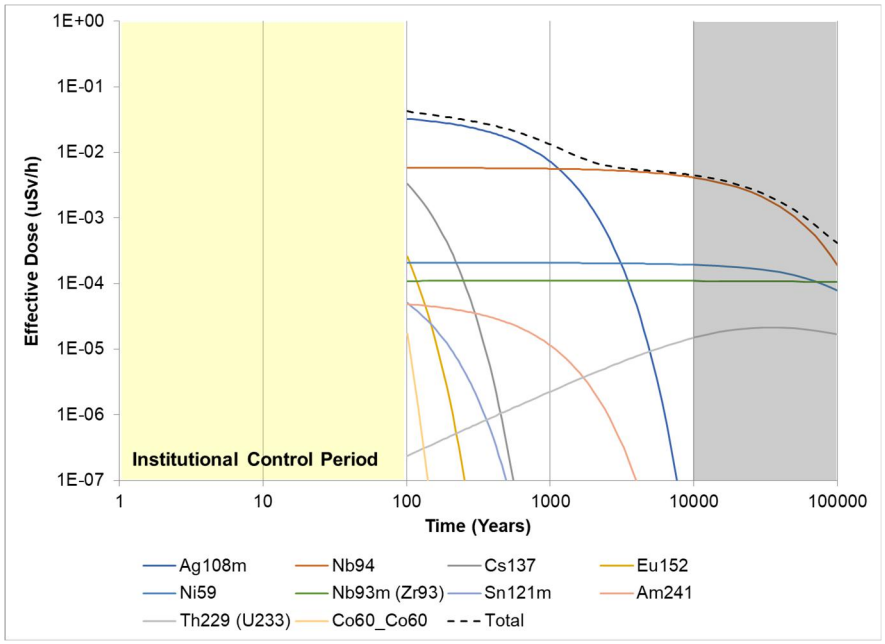
As discussed in Appendix A, a dose criteria is not defined by CNSC for human intrusion exposures. Instead, reasonable efforts are expected to limit the dose from a high-consequence intrusion scenario and to reduce the probability of the intrusion occurring. In this respect, the in-situ disposal concept provides a substantial deterrent and limits the range of situations that could lead to intrusion. Radiation doses to the Borehole Driller and to the Site Resident group following intrusion are shown in Figure G-70 and can be seen to be well below the public dose limit of 1 mSv y^{-1}. The highest doses, which occur if the intrusion happens immediately after the end of institutional control, are $5x10^{-4}$ mSv y^{-1} to the Borehole Driller, while an infant Site Resident receives $4x10^{-4}$ mSv y^{-1}. (These peak doses occur at 100 y after closure, i.e., immediately following intrusion.) The dominant exposure pathway for the Borehole Driller is external irradiation by Ag-108m and Nb-94 in the retrieved drill core (Figure G-71). Food chain pathways dominate the dose to the infant Site Resident living on land contaminated with the retrieved contaminants (Figure G-72). Cl-36 is the dominant radionuclide owing to its high uptake factor for terrestrial biota (Figure G-73).

Figure G-68 Average Concentration of Radionuclides in the Reactor Vault (Note: Total and Total NES are identical here)



Note: Radionuclides in brackets indicate the parent of the radionuclide that was present in the initial radionuclide inventory of the NPDDF.

Figure G-69 Dose Rate to a Person at 1 m Distance from a 5 kg Core Sample at Average Concentration in the Reactor Vault (Site Investigation Scenario)



Note: Radionuclides in brackets indicate the parent of the radionuclide that was present in the initial radionuclide inventory of the NPDDF.

Figure G-70 Dose to Exposure Groups (Site Investigation Case)

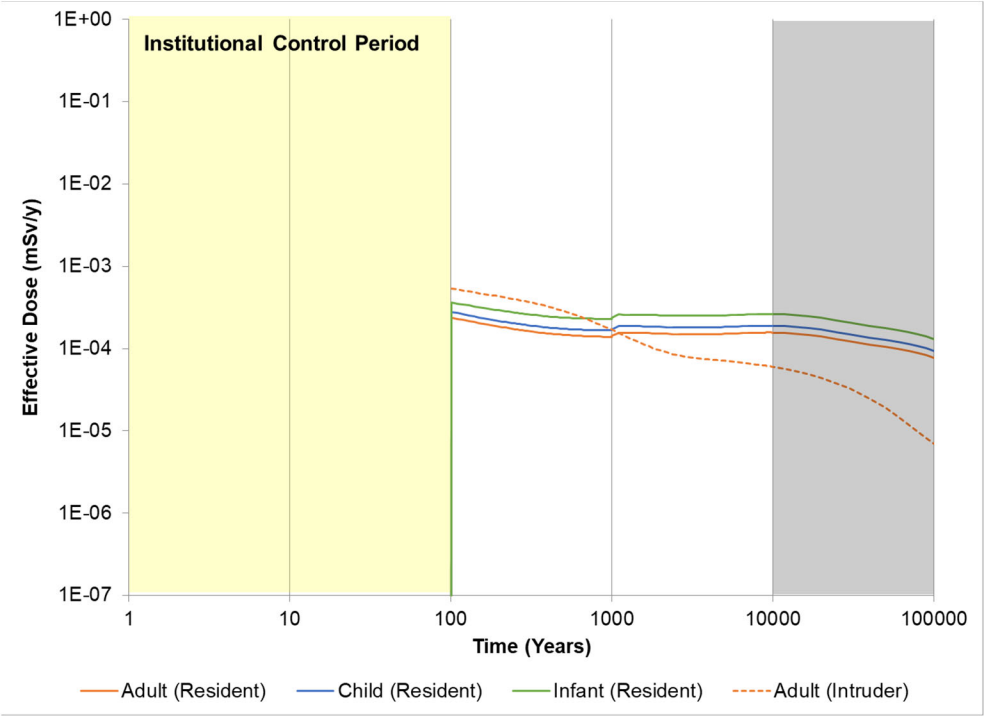


Figure G-71 Dose to Borehole Driller, by Radionuclide (Site Investigation Case)

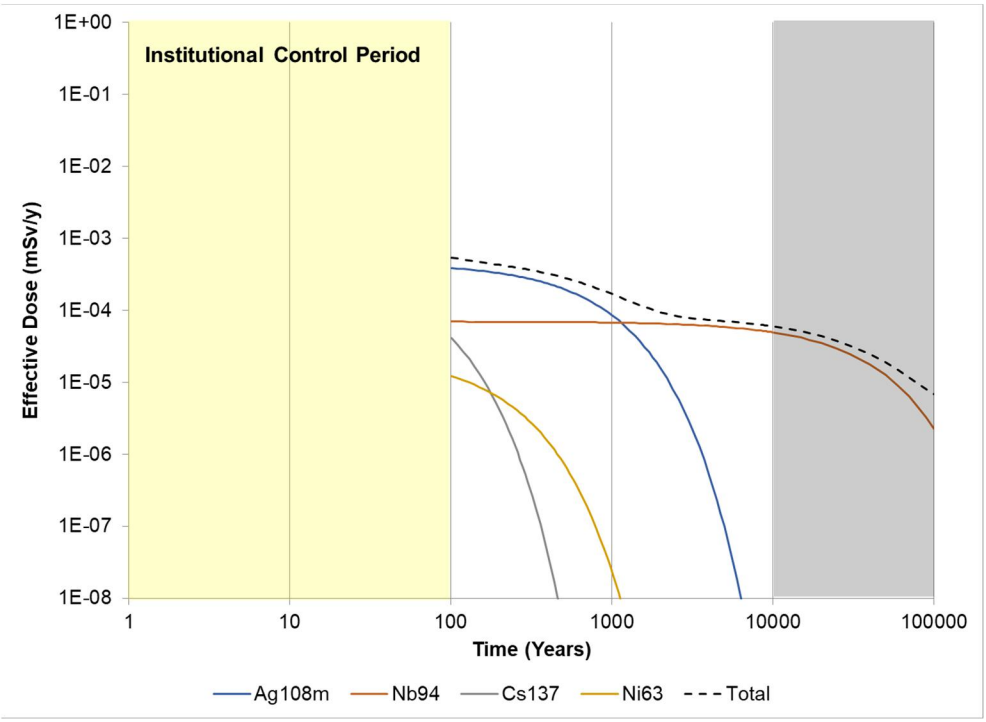


Figure G-72 Dose to Infant Site Resident on Contaminated Ground, by Pathway (Site Investigation Case)

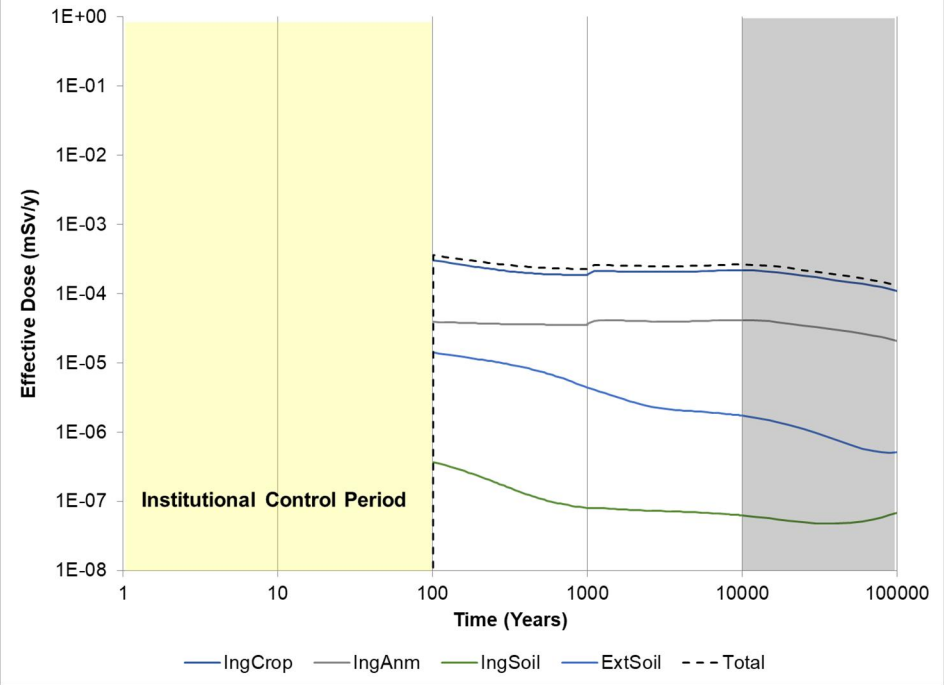
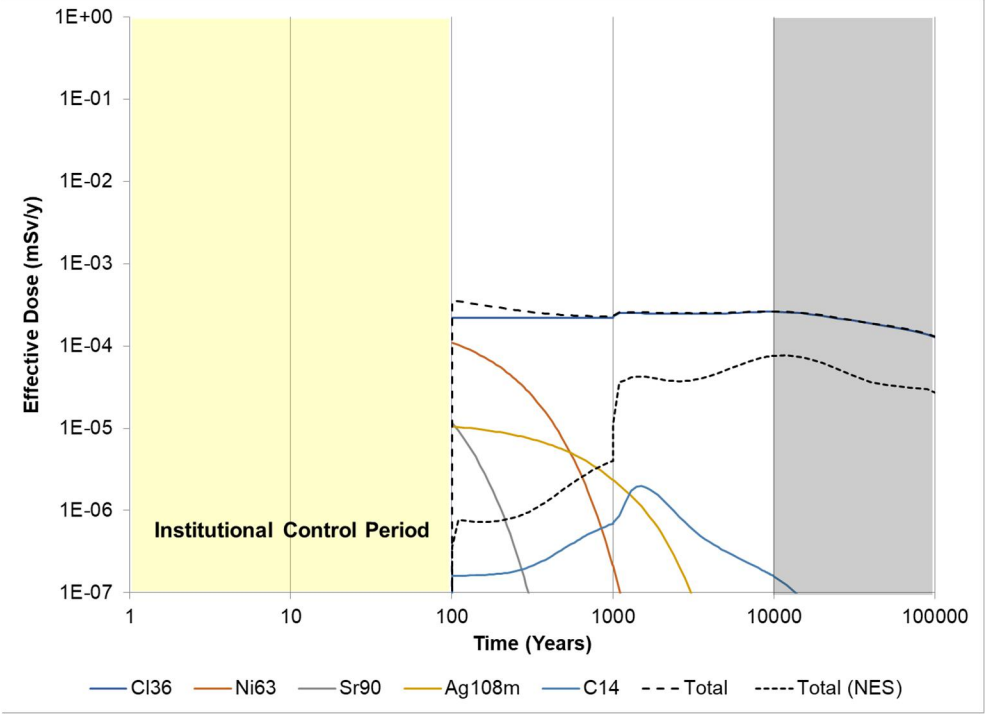


Figure G-73 Dose to Infant Site Resident on Contaminated Ground, by Radionuclide (Site Investigation Case)



G 4.2 DE(b) – Surface Erosion

The surface erosion event considers the occurrence of a flood or some other event that scours the surface of the riverbank. Highly conservatively, it assumes that the superficial overburden material is removed and that people could be directly exposed to the contaminated bedrock. This is modelled by assuming that the "Garden" is located on the contaminated part of the geosphere, with radionuclide concentrations in the Garden set equal to those in the geosphere materials through which the contaminated groundwater has flowed. Cautiously, the concentrations in the bedrock are used in the calculation, as these are higher than those in the overburden. There are no other changes to the model; the radionuclide releases and transport are the same as modelled in the Normal Evolution scenario, as are the exposure groups.

The surface erosion event is assumed to occur after 100 y. As can be seen in Figure G-74, there is immediately an increase in concentrations in the part of the model assumed to be used for vegetables ("Garden") with tritium peaking at 2 Bq kg^{-1} at 100 y. Thereafter, the dominant radionuclide is C-14 out to 4,000 y with a peak concentration of 26 Bq kg^{-1} after 1,300 y. In the very far future, the radionuclide concentration in the Garden could reach 39 Bq kg^{-1} with Ni-59 dominating.

The radionuclide concentrations in certain foodstuffs (vegetables and poultry) are much increased as they are assumed to come from this area of contaminated ground. Concentrations in pigs, cows and goats are unaffected as they are assumed to use a larger area of grazing land. In practice, growing vegetables on the small area of ground downslope of the NPDDF would not be feasible in the Surface Erosion case because the material is rock not soil, the area of ground contaminated by groundwater is small (around 100 m by a few 10s of m), and it is steeply sloping.

The highest dose of $4x10^{-3}$ mSv y^{-1} is to a child in the Site Resident receptor group, from ingestion of plants and crops (compared with $8x10^{-5}$ mSv y^{-1} to the Site Resident infant in the Normal Evolution scenario), while the doses are dominated by Ca-41 and peak at 10,000 y (Figure G-75 and Figure G-76).

Figure G-74 Concentration Assumed in Garden (Surface Erosion Case)

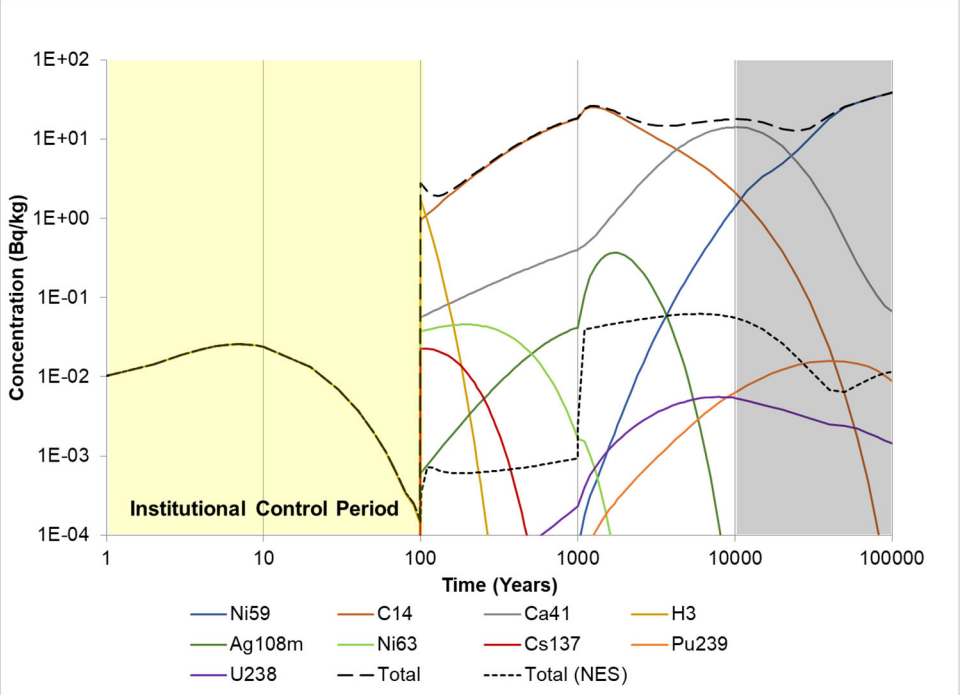


Figure G-75 Dose to the Most Exposed Receptor - Child Site Resident, by Radionuclide (Surface Erosion Case)

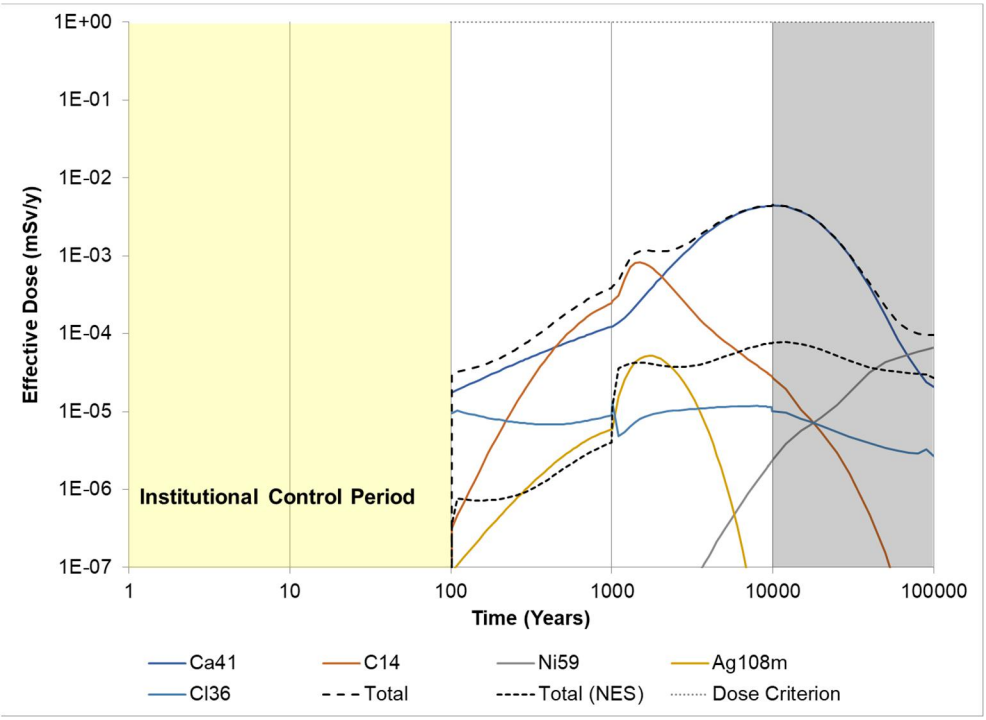
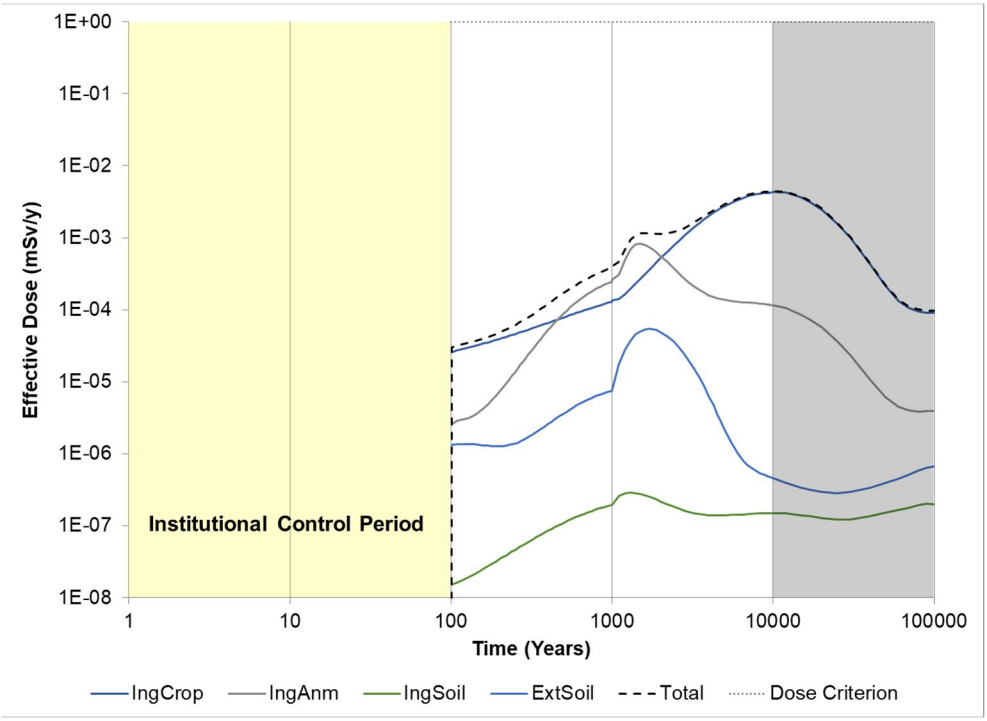


Figure G-76 Dose to the Most Exposed Receptor - Child Site Resident, by Pathway (Surface Erosion Case)



G 4.3 DE(c) – Extreme Degradation

The structure of the NPDDF, and the grout planned to be added to the Facility, play two key roles in the overall function of the disposal system. The barriers both physically limit water flow through the wastes, and also provide chemical conditions that limit the release of radionuclides into solution. This scenario is designed to examine the consequences of the extreme degradation of these barriers. It is based on the Normal Evolution scenario, with the difference that the above-bedrock engineered barriers are reduced to an extremely physically degraded state after 1,000 y. This is not represented directly but water flow through the Facility is based on detailed groundwater modelling undertaken by Arcadis & Geofirma (2023a,b).

The hydraulic conductivity of the above bedrock concrete and grout was increased to $1x10^{-6}$ m s^{-1} after 1,000 y. The portion of the NPDDF that sits within the bedrock is assumed to be protected by the bedrock mass and the concrete and grout only degrades to a hydraulic conductivity of $1x10^{-8}$ m s^{-1}. By comparison, the Rapid Degradation case (NES(f)) assumes that the concrete and grout both above and below bedrock reach the degraded state of $1x10^{-8}$ m s^{-1} earlier, after 100 y rather than 1,000 y.

The key change from the Normal Evolution scenario is that the very much higher hydraulic conductivity of the above-bedrock barriers allows much more water flow through the above-bedrock parts of the Facility. This in turn increases the rate of release of contaminants. Importantly, it also reduces the duration that the chemical effects of the cement persist, which reduces the period in which high-pH conditions lead to

increased sorption of key radionuclides. This is because the duration of the chemical degradation stages depends on the total volume of water flowing through each part of the structure. Table G-30 and Table G-31 present the times at which the different concrete and grout degradation stages begin in this case. Comparing the times presented in Table G-30 and Table G-31 to those of the NES (shown earlier in Table G-3 and Table G-4) shows that the duration of the key concrete and grout degradation stages in the above-bedrock parts of the facility are much shorter than those calculated for the Normal Evolution scenario. The timescales for the chemical degradation of the below-bedrock parts of the NPDDF are similar to those for the NES. The degradation timescales are illustrated graphically as a timeline alongside the physical degradation in Figure G-77.

Table G-30 Time at Which Concrete Degradation Stages Begin – DE(c) Extreme Degradation Case

Room	Stage 1	Stage 2	Stage 3	Stage 4
Above Bedrock				
Fuel Storage Room	0	1,900	9,700	70,000
Fueling Room	0	1,700	8,000	60,000
Boiler Room	0	1,600	6,500	40,000
Turbine Room	0	2,200	15,000	90,000
Below Bedrock				
Fuel Storage Room	0	12,000	>100,000	>100,000
Reactor Vault	0	12,000	>100,000	>100,000
East of Reactor Vault	0	3,000	25,000	>100,000
West of Reactor Vault	0	8,000	70,000	>100,000
Dump Tank Pipe Room	0	8,000	70,000	>100,000
Boiler Room	0	8,500	80,000	>100,000
Boiler Room (deep)	0	7,000	70,000	>100,000

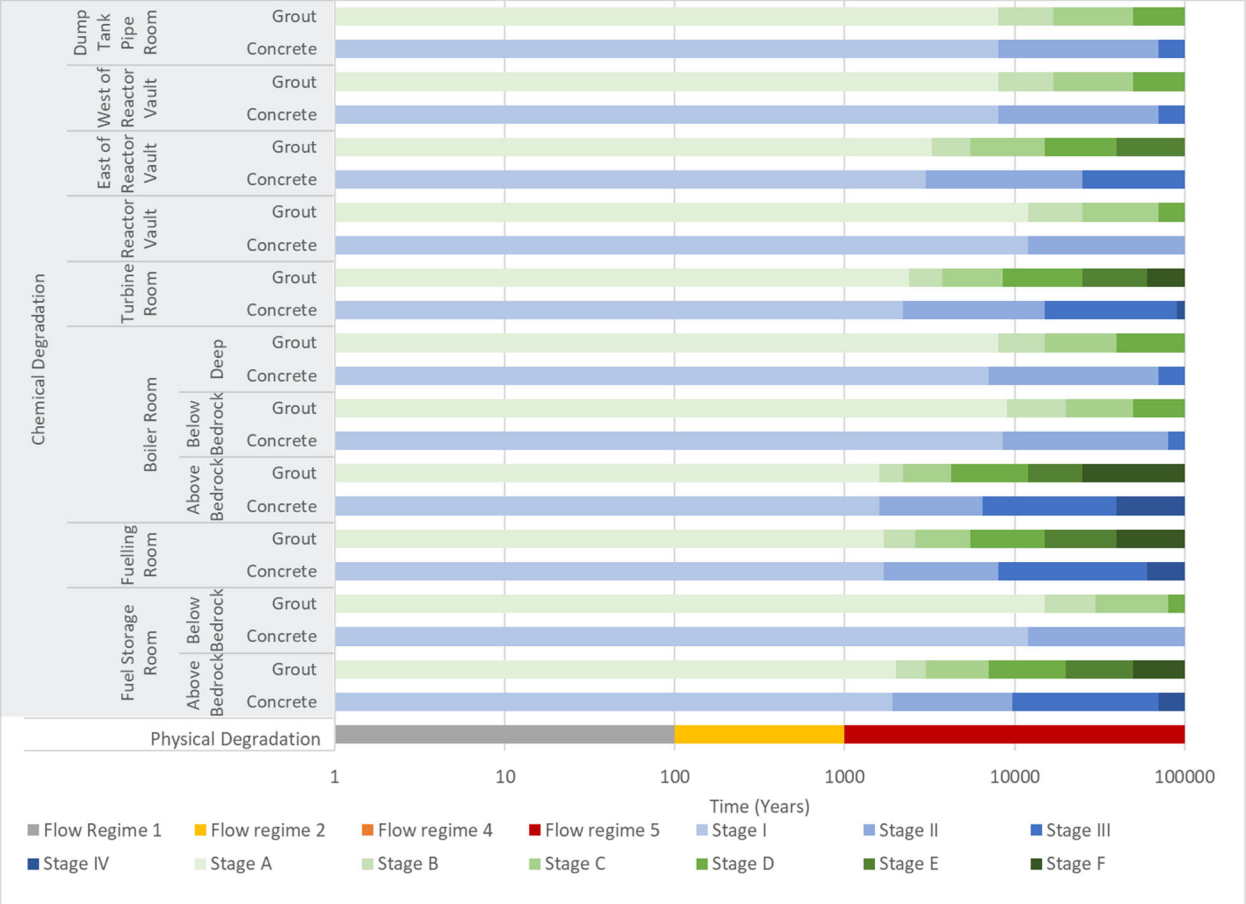
Note: Greyed-out cells are after the main assessment timeframe of 10,000 y.

Table G-31 Time at Which Grout Degradation Stages Begin – DE(c) Extreme Degradation Case

Room	Stage A	Stage B	Stage C	Stage D	Stage E	Stage F
Above Bedrock						
Fuel Storage Room	0	2,000	3,000	7,000	20,000	50,000
Fueling Room	0	1,700	2,600	5,500	15,000	40,000
Boiler Room	0	1,600	2,200	4,250	12,000	25,000
Turbine Room	0	2,400	3,750	8,500	25,000	60,000
Below Bedrock						
Fuel Storage Room	0	15,000	30,000	80,000	>100,000	>100,000
Reactor Vault	0	12,000	25,000	70,000	>100,000	>100,000
East of Reactor Vault	0	3,250	5,500	15,000	40,000	100,000
West of Reactor Vault	0	8,000	17,000	50,000	>100,000	>100,000
Dump Tank Pipe Room	0	8,000	17,000	50,000	>100,000	>100,000
Boiler Room	0	9,000	20,000	50,000	>100,000	>100,000
Boiler Room (deep)	0	8,000	15,000	40,000	>100,000	>100,000

Note: Greyed-out cells are after the main assessment timeframe of 10,000 y.

Figure G-77 Timelines of Degradation in the Extreme Degradation of Engineered Barriers Case



The effect of higher flows and the more rapid chemical degradation of the cementitious structures is seen in Figure G-78 in which the greater releases of radionuclides is most noticeable in the overburden. The more significant physical degradation can be seen in a sharp increase in concentrations at 1,000 y and the more rapid chemical degradation in the "lumpy" nature of the releases after 10,000 y. The latter reflects a sequence of transitions in sorption coefficient, as the chemical degradation of the cementitious materials moves through successive stages of reduced pH. As flows through each room are different, these transitions occur at different times (see Table G-30 and Table G-31). The initial peak concentration in groundwater (Figure G-78), associated with H-3, is identical. The second peak, after 1,200 y, is increased only slightly, from 6 Bq l^{-1} in the Normal Evolution scenario to 10 Bq l^{-1} in the bedrock, associated with C-14. The increase is much larger in the shallow groundwater (in the overburden), where the peak concentration increases 20 times from 0.001 Bq kg^{-1} to 0.02 Bq l^{-1}. Particularly notable is the sudden increase in the Cl-36 concentrations in overburden groundwater at 12,000 – 15,000 y, when grout degradation transitions from Stage D to E in the Boiler Room and Fuelling Room, and the sorption of Cl changes from 0.02 m^3 kg^{-1} to 0 m^3 kg^{-1} (unsorbed).

The key environmental media are river water (Figure G-79) and the garden soil (Figure G-80). The primary source of contamination in the river is the bedrock pathway and peak concentrations of radionuclides (after 1,000 y, when extreme degradation occurs) are increased by a factor of 3 from that calculated for the Normal Evolution scenario to $3x10^{-5}$ Bq l^{-1}. The peak concentration in the garden is increased by a greater amount, from $6x10^{-2}$ Bq kg^{-1} to 1 Bq kg^{-1} as some contaminants released to the overburden can enter the soil adjacent to the NPDDF directly. The peak dose (to an infant Site Resident, see Figure G-81) is increased to $3x10^{-4}$ mSv y^{-1} due to higher concentrations of Cl-36 in foodstuffs. The spike in the dose at 12,000 y, resulting from the reduction in Cl-36 sorption in the boiler room as the grout transitions from Stage D to Stage E is particularly noticeable.

Figure G-78 Release of Radionuclides from the NPDDF to the Geosphere (Extreme Degradation of Engineered Barriers Case)

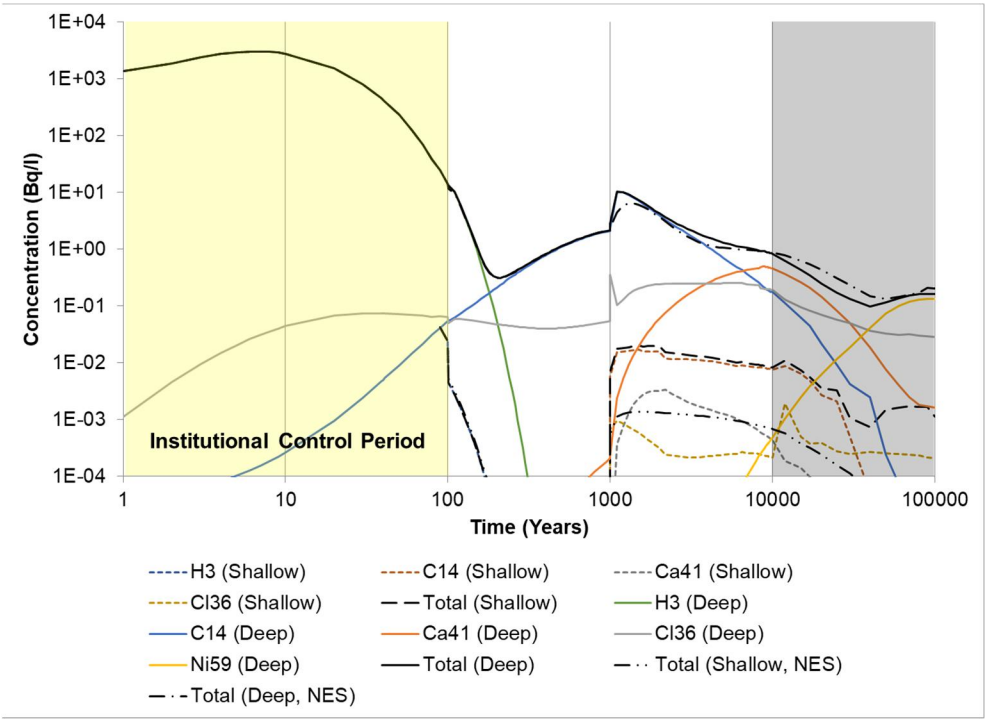


Figure G-79 Concentrations of Radionuclides in River Water (Extreme Degradation of Engineered Barriers Case)

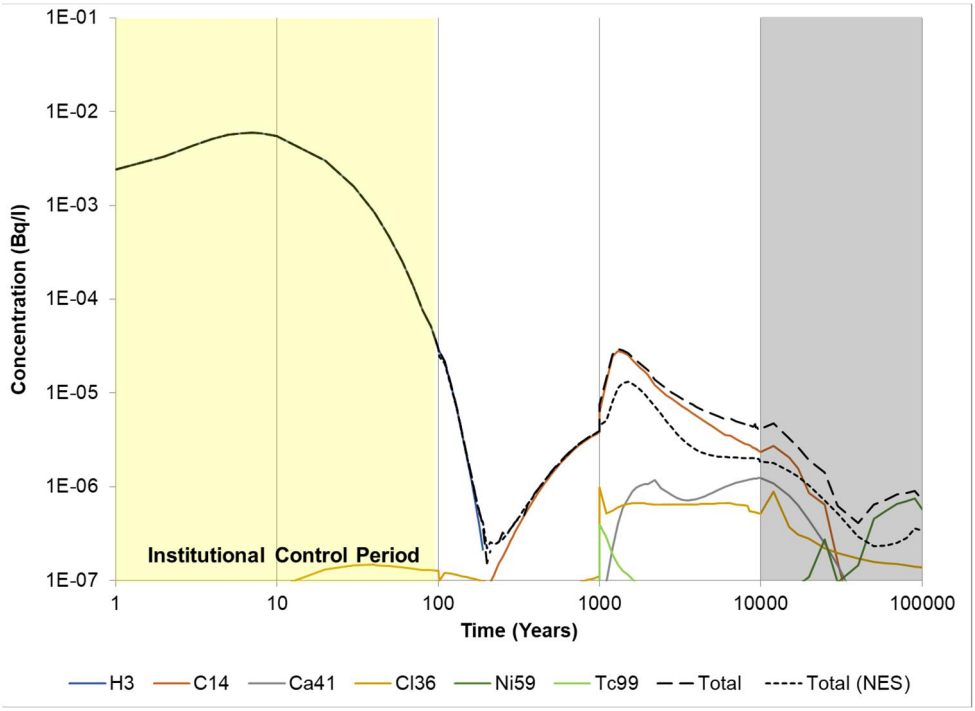


Figure G-80 Concentrations of Radionuclides in the Garden (Extreme Degradation of Engineered Barriers Case)

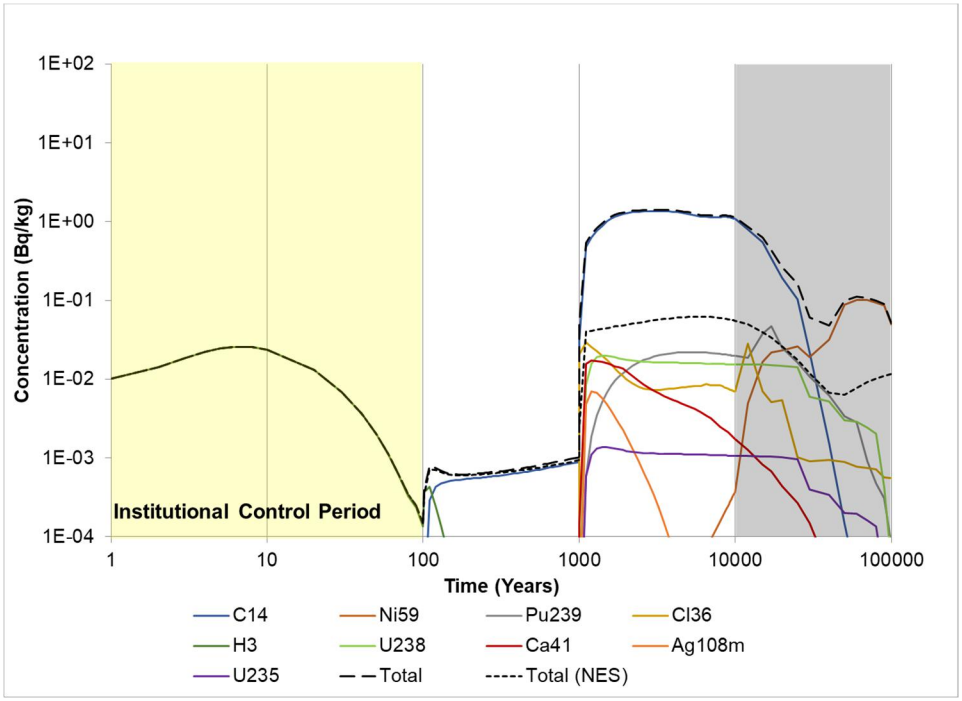
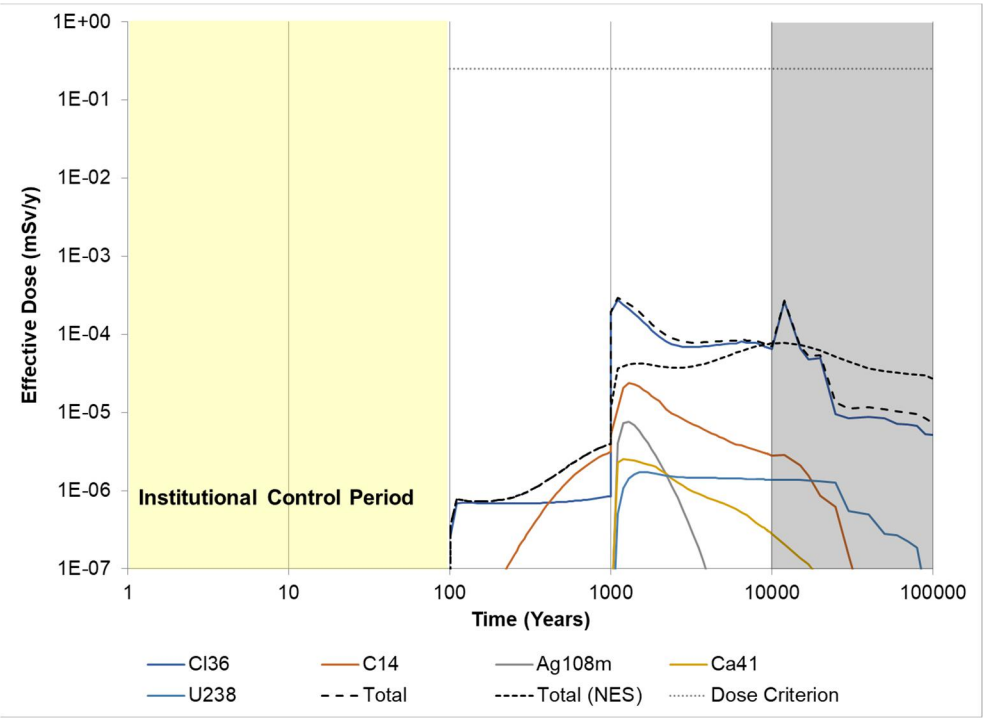


Figure G-81 Dose to Most Exposed Receptor - Infant Site Resident, by Radionuclide (Extreme Degradation of Engineered Barriers Case)



G 4.4 DE(d) – Fault Zone Activation

In the Normal Evolution scenario, it is assumed that the Facility experiences a 1-in-10,000-y seismic event. However, seismic events of even greater magnitudes (such as a 1-in-50,000-y event) may have further impacts on the Facility's long-term performance and safety (through early degradation of engineered barriers) and also induce a fault zone of higher conductivity in the geosphere.

This Disruptive Event case therefore builds on the assumptions made in the Extreme Degradation case (DE(c)), and assumes that there is more comprehensive damage to the NPDDF and in addition a fault zone has been created in the bedrock. This is assumed to occur due to a large seismic event occurring after 1,000 y. The entire Facility structure is assumed to be extremely degraded (hydraulic conductivity increased from $1x10^{-11}$ m s^{-1} to $1x10^{-6}$ m s^{-1} in concrete and grout, above and below the bedrock surface). The fault zone is represented using a higher hydraulic conductivity in the bedrock between the facility and the river compared to that of the Normal Evolution scenario. The higher conductivity is not represented directly in the model but is based on detailed groundwater flow modelling undertaken by Geofirma & Arcadis (2023a,b), on the basis of which increased flows through the bedrock are specified. These much higher flows lead to much more rapid chemical degradation of the structures in the NPDDF, with the below-bedrock parts of the NPDDF entirely losing the chemical effects of the cements by 15,000 y, and the degradation well advanced in the above bedrock parts by 10,000 y (see Table G-32 and Table G-33).

Table G-32 Time at Which Concrete Degradation Stages Begin – DE(d) Fault Zone Activation Case

Room	Stage 1	Stage 2	Stage 3	Stage 4
Above Bedrock				
Fuel Storage Room	0	1,400	4,250	25,000
Fueling Room	0	1,200	3,000	17,000
Boiler Room	0	1,700	8,000	50,000
Turbine Room	0	1,300	3,500	20,000
Below Bedrock				
Fuel Storage Room	0	1,200	2,800	15,000
Reactor Vault	0	1,200	2,800	15,000
East of Reactor Vault	0	1,100	1,500	4,250
West of Reactor Vault	0	1,100	2,000	8,000
Dump Tank Pipe Room	0	1,200	2,200	9,000
Boiler Room	0	1,200	2,600	15,000
Boiler Room (deep)	0	1,100	2,000	8,000

Note: Greyed-out cells are after the main assessment timeframe of 10,000 y.

Table G-33 Time at Which Grout Degradation Stages Begin– DE(d) Fault Zone Activation Case

Room	Stage A	Stage B	Stage C	Stage D	Stage E	Stage F
Above Bedrock						
Fuel Storage Room	0	1,400	1,700	3,000	8,000	17,000
Fueling Room	0	1,300	1,500	2,400	5,000	12,000
Boiler Room	0	1,700	2,600	5,500	15,000	40,000
Turbine Room	0	1,300	1,600	2,600	6,000	15,000
Below Bedrock						
Fuel Storage Room	0	1,200	1,400	2,200	4,500	9,200
Reactor Vault	0	1,200	1,400	2,200	4,500	9,100
East of Reactor Vault	0	-*	1,100	1,300	1,900	3,000
West of Reactor Vault	0	1,100	1,300	1,600	3,000	5,500
Dump Tank Pipe Room	0	1,200	1,300	1,700	3,250	6,000
Boiler Room	0	1,200	1,400	2,000	4,000	8,250
Boiler Room (deep)	0	1,100	1,300	1,700	3,000	5,500

Note: Greyed-out cells are after the main assessment timeframe of 10,000 y.

*Transition through Stage B is not resolved in the model output as it occurs between timesteps at 1,001 y and 1,100 y

In the first 1000 y the results are the same as the NES as there is no difference with the scenario, therefore this period is not discussed further. After degradation occurs, however, the higher conductivity of the Facility and the bedrock groundwater path leads to very different pattern of releases than the Normal Evolution scenario and indeed the Extreme Degradation case (Section G 4.3). Because the whole facility is assumed to be extremely degraded, rather than the above bedrock portion, there is a greater flux of water through the structure and grout. This leads to more rapid chemical degradation of these materials, resulting in 'spikes' as there are transitions that involve changes to the sorption of key radionuclides like C-14. However, the higher flow rates also increase the dilution of the radionuclides that have been released from the NPDDF into the bedrock meaning that the peak concentrations are similar in this period (albeit peaking at 8,000 y rather than 1,300 y). This is illustrated in Figure G-82 where the peak concentration in the bedrock after degradation has occurred is 8 Bq l^{-1}, similar to the peak of 6 Bq l^{-1} for the NES and 10 Bq l^{-1} for the Extreme Degradation case. The overall greater releases of contaminants induced by the higher bedrock flow rates do, however, result in an increased peak concentration in the overburden of 0.1 Bq l^{-1} compared with 0.001 Bq l^{-1} in the Normal Evolution Scenario and 0.02 Bq l^{-1} for the Extreme Degradation case.

The total flux of radionuclide releases is increased, resulting in higher concentrations in the river (Figure G-83). Particularly notable is the very 'spiky' releases of C-14, in particular the peak at 8,000 y which corresponds to a transition in the chemical regime in the deep Boiler Room and rooms surrounding the Reactor Vault. The peak, occurring at 8,000 y, is $5x10^{-4}$ Bq l^{-1}, compared with the Normal Evolution scenario ($1x10^{-5}$ Bq l^{-1}) or the Extreme Degradation case ($3x10^{-5}$ Bq l^{-1}). As with the Extreme Degradation case, the more rapid chemical degradation of the cement and concrete leads to changes in the sorption coefficient which in turn leads to spikes in the profile of concentrations of radionuclides such as C-14 and Cl-36 at times later than 1000 y.

The resulting doses are similar to those calculated for the Extreme Degradation case (see Figure G-81) although slightly higher resulting from the more rapid release induced by the higher bedrock flow rates. In addition, the key radionuclide, and time of peak, differs. In this case the dose is dominated by C-14 rather than Cl-36 and occurs significantly later, owing to the different pattern of chemical degradation, particularly in the below bedrock rooms such as the deep Boiler Room and Reactor Vault. The peak dose, shown in Figure G-84, is $5x10^{-4}$ mSv y^{-1} after 8,000 y to an adult Site Resident, dominated by C-14 via ingestion of vegetables.

Figure G-82 Release of Radionuclides from the NPDDF to the Geosphere (Fault Zone Activation Case)

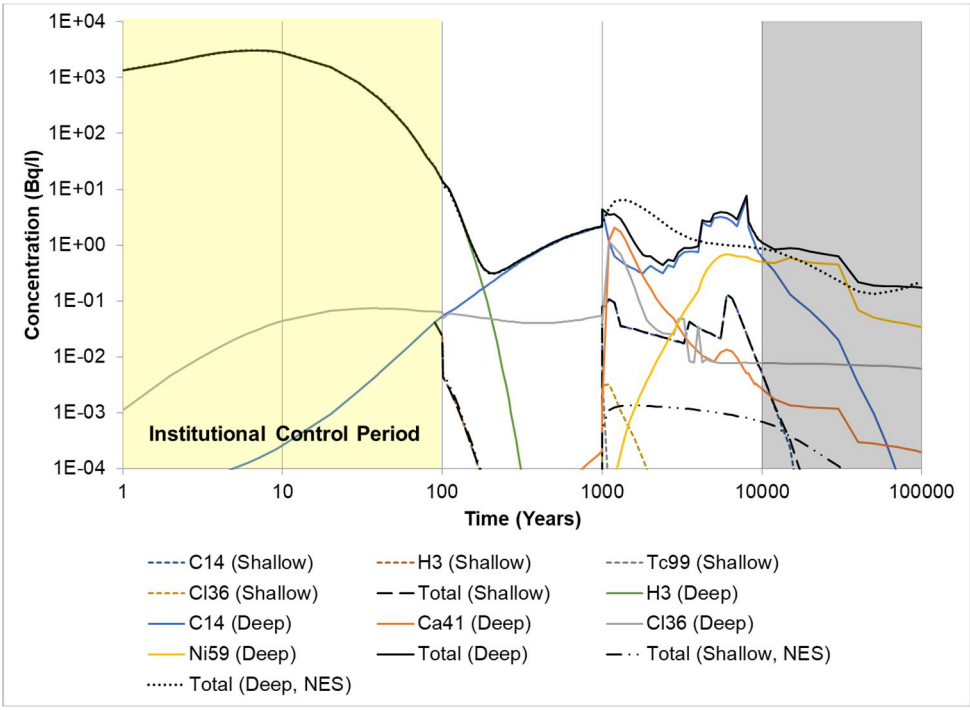


Figure G-83 Concentrations of Radionuclides in River Water (Fault Zone Activation)

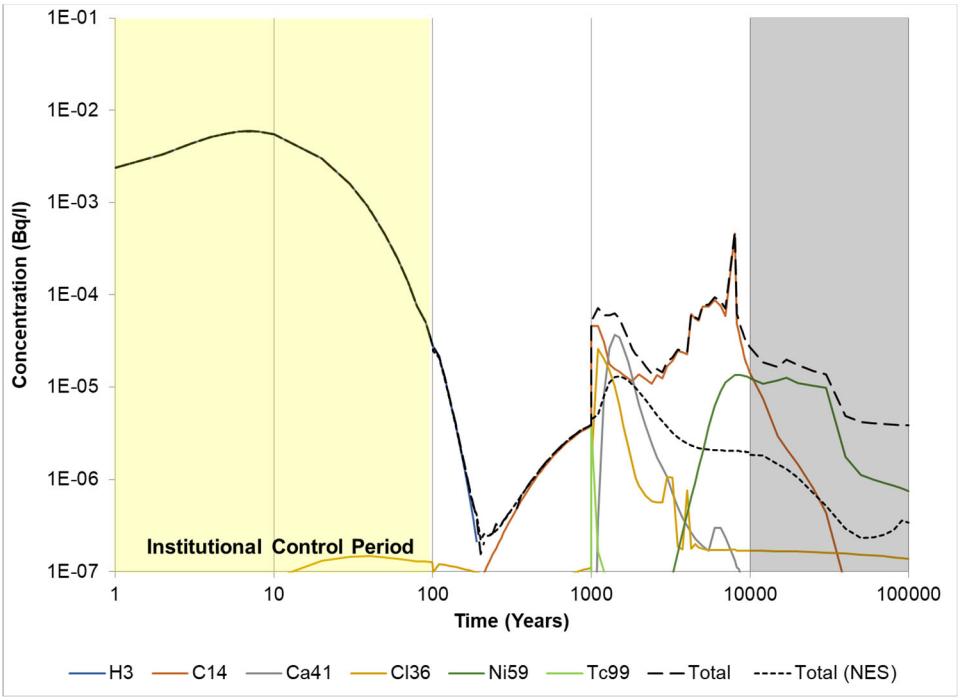
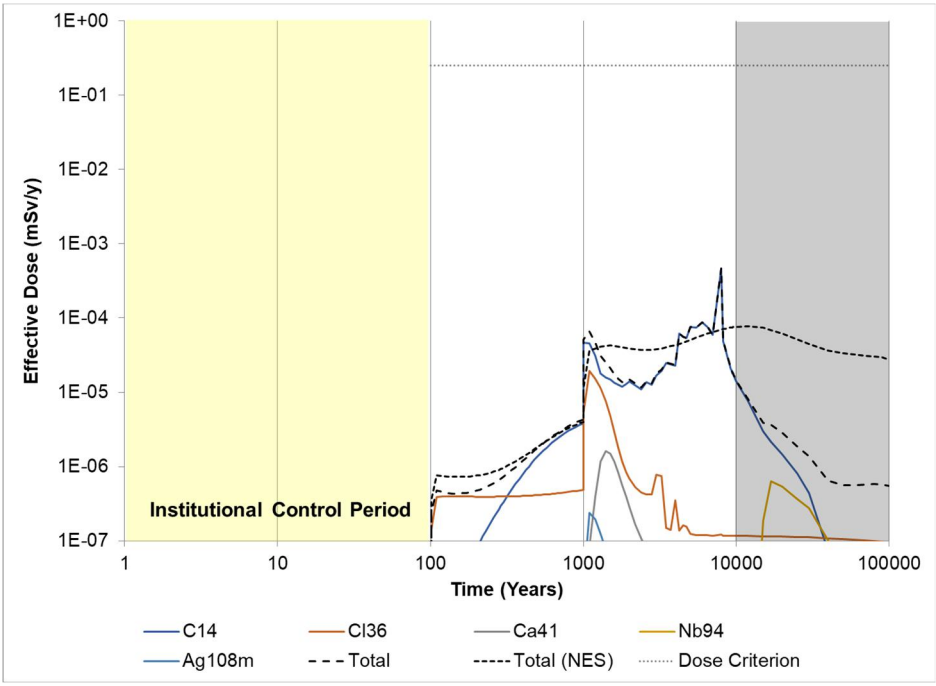


Figure G-84 Dose to Most Exposed Receptor - Adult Site Resident, by Radionuclide (Fault Zone Activation Case)



G 4.5 DE(e) – Excavation of Above-Bedrock Facility

The mass excavation of the entire Facility is deemed unlikely as the concrete structure would retain sufficient structural integrity to make it extremely difficult. Furthermore, relatively limited examination (as considered in Section G 4.1) would be sufficient to reveal the characteristics of the Facility and deter any more large-scale disruption. Nevertheless, the consequences of the partial disruption and excavation of the NPDDF is of interest, where the above-bedrock portion of the facility is excavated and mixed with soil (at a ratio of 1:10 grout and concrete to soil). The Excavation of Above Bedrock Facility Disruptive event case considers such scenario and, the entire inventory present in the Facility above the bedrock is assumed to be mixed into the modelled volume of garden and grazing soil (approximately 16,400 m^3) at the ratio of 10% waste to 90% soil. The assumption is that there is no house built inside of the excavated hole and only the Site Resident receptor is assumed to be exposed. Note that a “What if” case examines the consequences of the mass excavation of the entire facility even though this is deemed to be extremely unlikely (see Section G 6.1).

The concentrations of radionuclides in the soil which is assumed to be used for growing crops (“Garden”) is much higher than in the Normal Evolution scenario, owing to its contamination with excavated material. As shown in Figure G-85, the peak concentration is 600 Bq kg^{-1} compared with 0.06 Bq kg^{-1} for the Normal Evolution scenario. Furthermore, the soil concentrations would be above 100 Bq kg^{-1} if the excavation took place at any time between 100 and 10,000 y after closure, dominated by C-14. The doses are, however, dominated by the long-lived radionuclide Cl-36, and peak at 0.01 mSv y^{-1} at 10,000 y to the Site Resident Infant, via ingestion of plants. Despite the conservative assumptions, the dose remains below the public

dose limit of 1 mSv y^{-1}. As discussed in Appendix A, a dose criterion is not defined by CNSC for human intrusion exposures although reasonable efforts are expected to limit the probability of the intrusion occurring and the dose if it does occur.

Figure G-85 Concentrations of Radionuclides in Soil Contaminated with Radioactivity from the Excavated Facility (Excavation of Above-Bedrock Facility Case)

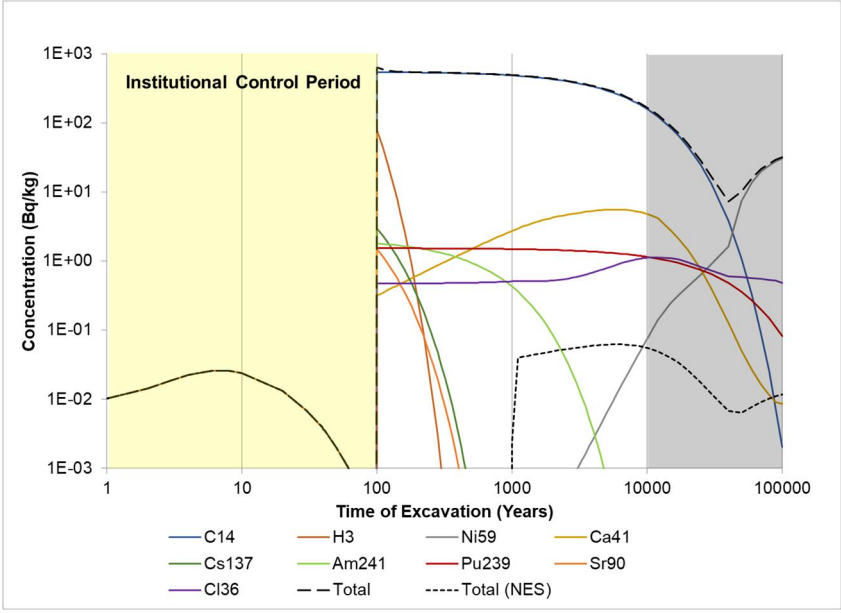
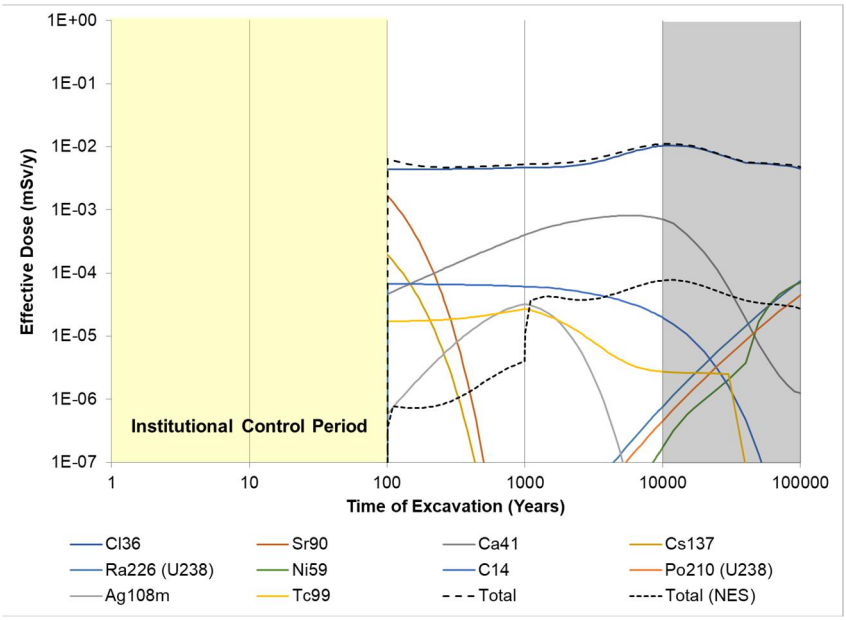


Figure G-86 Dose to Most Exposed Receptor - Infant Site Resident, by Radionuclide (Excavation of Above-Bedrock Facility Case)



Note: Radionuclides in brackets indicate the parent of the radionuclide that was present in the initial radionuclide inventory of the NPDDF.

G 4.6 DE(f) – Overburden Well

A well provides a route by which radionuclides in groundwater can be released directly into soil that is subsequently used for farming. Wells are used by people living in the region of the NPDDF, but they are typically into deeper aquifers than those which could be affected by the NPDDF. The plume from the Facility is expected to be no more than a few tens of metres wide and around 100 m in length, as demonstrated by Arcadis & Geofirma (2023a,b), and so would be unlikely to be intercepted. It is also beneath relatively steeply sloping ground, and close to the river, a location in which a well would be difficult to install. Nevertheless, domestic use of well water is of interest in constraining the potential calculated doses that could arise from exposure to contaminated groundwater. Hence, the possibility of a well in the overburden is treated as a Disruptive Event case.

The contaminated groundwater has been assumed to be extracted from the overburden immediately downstream of the Facility and be used, rather than river water, for drinking (people and animals) and irrigation of crops. The concentrations in well water and river water are compared in Figure G-87, which shows that concentrations are much higher in well water particularly after 1,000 y ($1x10^{-3}$ Bq l^{-1} compared with $1x10^{-5}$ Bq l^{-1}). The concentration of radionuclides in irrigated garden soil is shown in Figure G-88. Although irrigation well water has substantially higher radionuclide concentrations, this is not reflected in the garden soil concentrations, because (in the current case) garden soil is predominantly contaminated by radionuclide released from the NPDDF to the soil via the overburden, rather than by irrigation water. Thus, radionuclide concentrations in the garden are not substantially increased compared to the Normal Evolution scenario (the peak is unchanged at 0.08 Bq kg^{-1} from C-14 at 7,000 y).

In terms of human exposures, the increase in radionuclide concentrations in the water used by the Site Resident does nevertheless lead to a significantly increased dose. This is principally because the livestock raised by the Site Resident is assumed to consume well water rather than river water, and as a result becomes more contaminated. The peak dose is increased to $1x10^{-4}$ mSv y^{-1}, peaking at 10,000 y (see Figure G-89).

Figure G-87 Concentration of Radionuclides in Well Water Compared with the River Water Used for Irrigation and Drinking in the NES (Overburden Well Case)

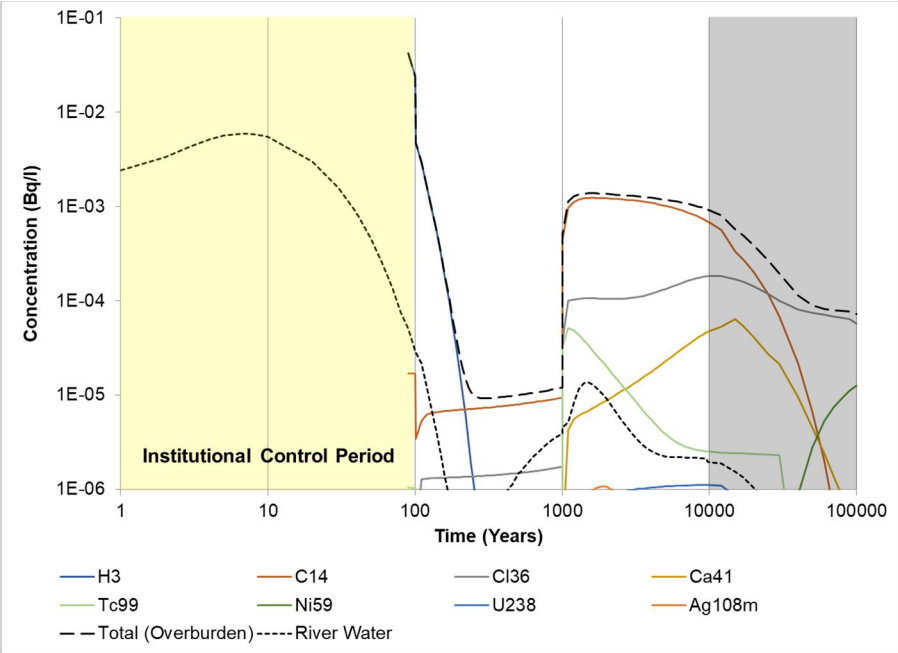
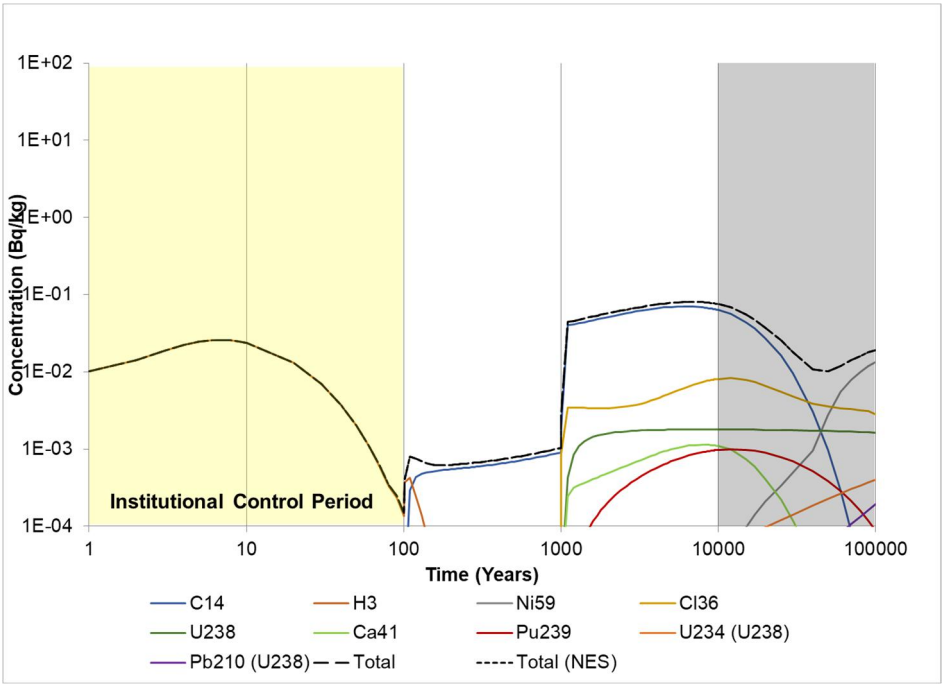
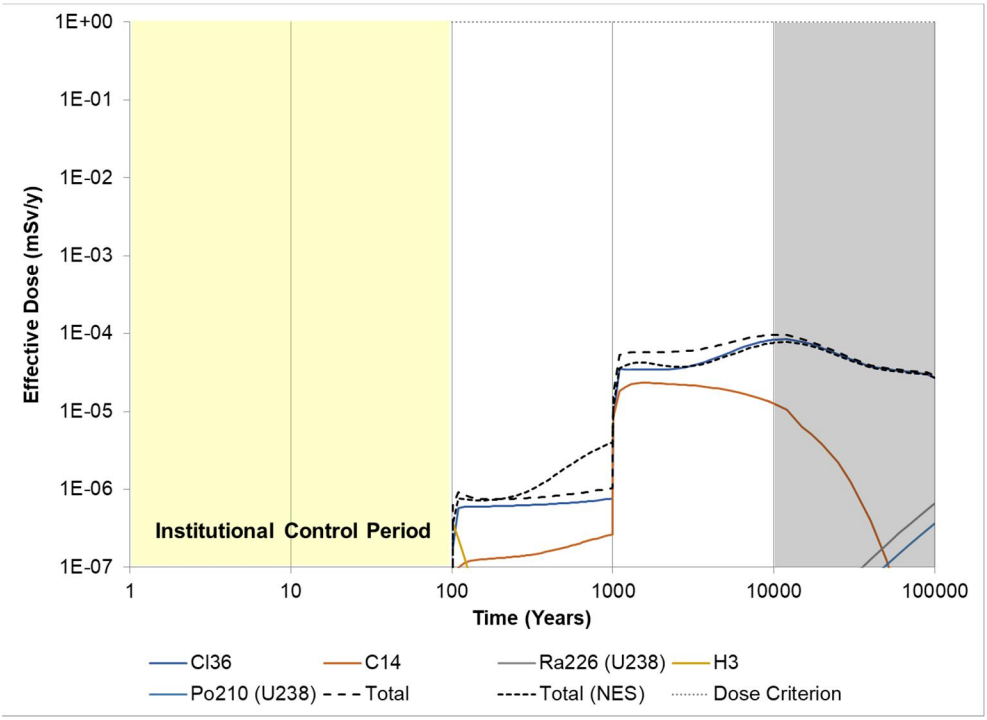


Figure G-88 Concentration of Radionuclides in Garden Soil Irrigated with Groundwater (Overburden Well Case)



Note: Radionuclides in brackets indicate the parent of the radionuclide that was present in the initial radionuclide inventory of the NPDDF.

Figure G-89 Radiation Dose to Most Exposed Receptor - Infant Site Resident, by Radionuclide (Overburden Well Case)



Note: Radionuclides in brackets indicate the parent of the radionuclide that was present in the initial radionuclide inventory of the NPDDF.

G 4.7 DE(g) – Bedrock Well

As outlined in the preceding subsection, the potential for exposure to well water by its domestic use is of interest even though the likelihood of intercepting a plume of contaminated groundwater from the NPDDF is very small. As concentrations of radionuclides differ in the overburden and bedrock, this case considers a well abstracting water from the bedrock, to complement the DE(f) case presented in Section G 4.6. As with the previous case, it is assumed that well water is used for irrigation, and drinking water by animals and humans.

Radionuclide concentrations in the well water from the bedrock far exceed those in the river, as can be seen from Figure G-90, owing to the very high dilution offered by the river, and exceed those in well water from the overburden (see Figure G-86). The volumes of water flowing through the bedrock are very small, to the extent that it would be difficult to abstract sufficient quantities for use. The peak concentration in the bedrock groundwater after the period of institutional control is 14 Bq l^{-1}, almost entirely due to tritium. A later peak of 3 Bq l^{-1} occurs after 1,300 y due to C-14. These compare with a peak concentration in the river water of 0.006 Bq l^{-1} (this is within the institutional control period; after that time the highest concentration

in the river is $1x10^{-5}$ Bq l^{-1} after 1,500 y) and a peak concentration in well water from the overburden of $1x10^{-3}$ Bq l^{-1} after 1,000 y. As a consequence, the concentration of radionuclides in soil in the Garden are substantially increased, as illustrated in Figure G-91, as in this case the garden is predominantly contaminated via irrigation water. As sorption dictates the extent to which contaminants accumulate in the soil, the mix of radionuclides differs, with the peak concentration being 0.9 Bq kg^{-1}, dominated by Ca-41 in the period up to 10,000 y. In the far future the highest concentration to occur is 4 Bq kg^{-1} from Pu-239.

The high concentrations in the well-water significantly increase the dose to a Site Resident, peaking at 0.03 mSv y^{-1} at 1,300 y. The main exposure pathway is via irrigated crops, dominated by C-14. While this is more than 20 times greater than the highest dose in the Normal Evolution scenario, it remains nearly an order of magnitude below the dose criterion applied in the NES and more than 30 times below 1 mSv y^{-1}.

Figure G-90 Concentration of Radionuclides in Well Water Compared with the River Water Used for Irrigation and Drinking in the NES (Bedrock Well Case)

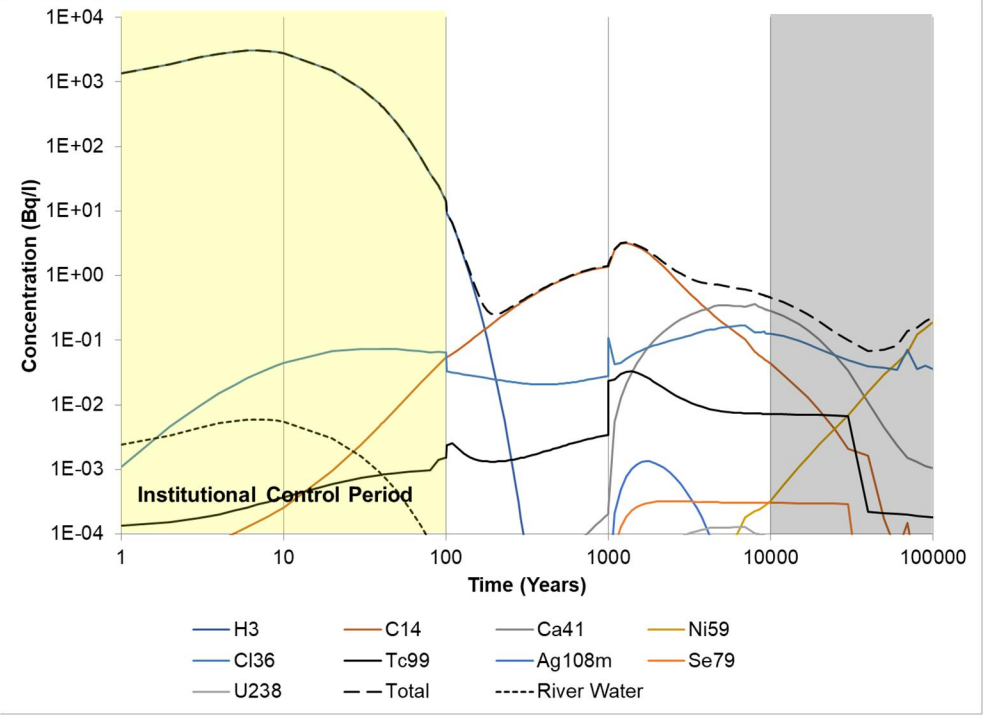


Figure G-91 Concentration of Radionuclides in Garden Soil Irrigated with Groundwater (Bedrock Well Case)

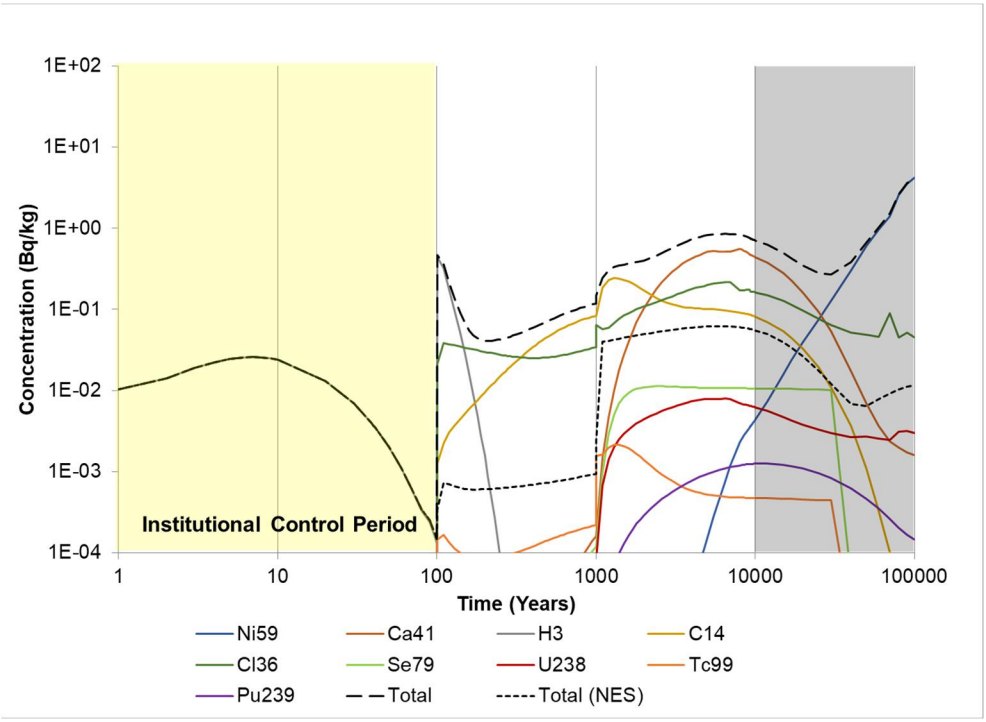
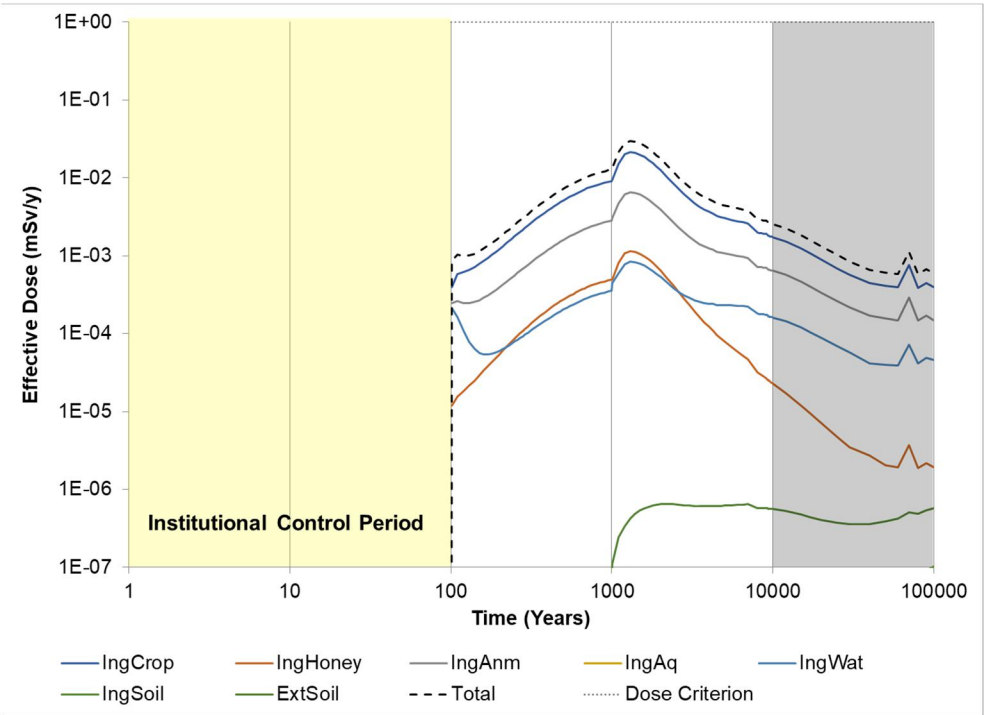


Figure G-92 Radiation Dose to Infant Site Resident, by Pathway (Bedrock Well Case)



G 5 DEFENCE-IN-DEPTH CASES

G 5.1 DD(a) – Role of Existing Facility Structure

The concrete structure of the NPDDF is a key barrier to the release of radionuclides. There is existing evidence of its effectiveness in preventing ingress of water into the Facility given by the relatively limited amounts of water collected in the sump at its base. This case seeks to quantify its importance in the context of the long-term performance of the disposal system. The case is modelled by assigning the properties of fully degraded concrete in all the model compartments that represent the NPDDF walls in the Normal Evolution scenario. The grouted rooms, however, are assumed to perform in the same way as represented in the Normal Evolution scenario.

The reduction in the effectiveness of the concrete structure at controlling flows through the NPDDF is shown in the calculated concentrations in groundwater immediately downstream of the Facility, shown in Figure G-93. The concentrations of radionuclides in both the bedrock groundwater, and particularly the overburden groundwater, are significantly higher than for the Normal Evolution scenario, most notably in the period 100 – 1,000 y when the role of the structure is most significant. The peak concentration in the bedrock is 40 Bq l^{-1} compared with 6 Bq l^{-1} in the Normal Evolution scenario, and it also occurs much earlier after only 170 y. Even more markedly, the peak concentration in the overburden is 2 Bq l^{-1} immediately after institutional control ends, compared with 0.001 Bq l^{-1}.

The effect of the increased rates of release in the 100 – 1,000 y period are evident when considering the environmental concentrations (e.g. the river water concentrations, Figure G-94, and the garden, Figure G-95). For the river water, a sharp increase can be seen after 40 y due to the much earlier resaturation of the facility when the structure is not assumed to be an effective hydraulic barrier, mainly due to tritium. The peak concentration at 40 y is 0.04 Bq l^{-1} (from tritium) and the concentration is 0.002 after 100 y (dominated by C-14), and much higher than the $1x10^{-5}$ Bq l^{-1} peak concentration in the Normal Evolution scenario. In the garden, the peak concentration is 2 Bq kg^{-1} from C-14 at 1,100 y compared with 0.06 Bq kg^{-1} at 6,000 y in the Normal Evolution scenario.

Both river water and garden concentrations are important in determining the dose to a receptor. The highest doses in this case are received by the Indigenous (AOPFN) receptor immediately after the end of Institutional Control. The peak dose after institutional control is 0.004 mSv y^{-1} at 100 y, dominantly from external irradiation by Cs-137 and Ag-108m in soil (Figure G-96). After about 130 y, these radionuclides have decayed and migrated, and the highest doses are to Site Residents via C-14 in crops (see Figure G-97).

Figure G-93 Release of Contaminants from the NPDDF to the Geosphere (Role of Existing Facility Structure Case)

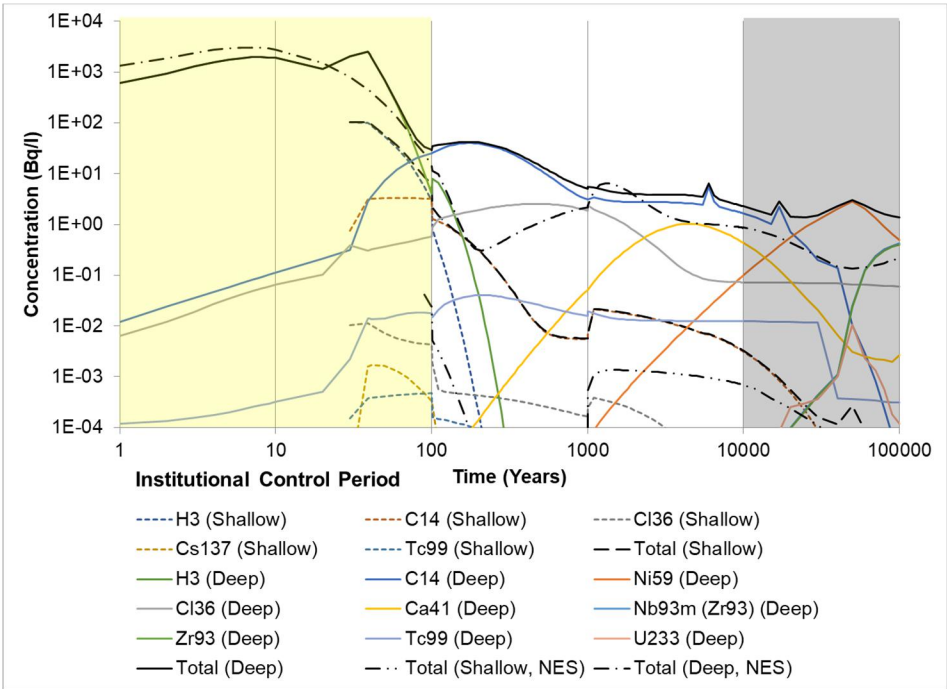


Figure G-94 Concentrations in the River Water (Role of Existing Facility Structure Case)

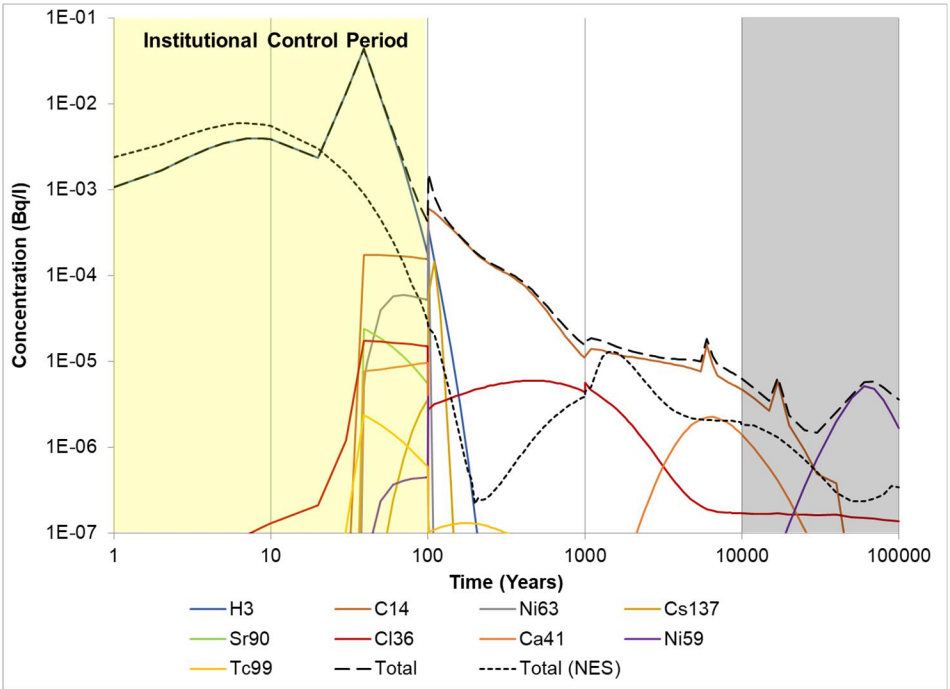
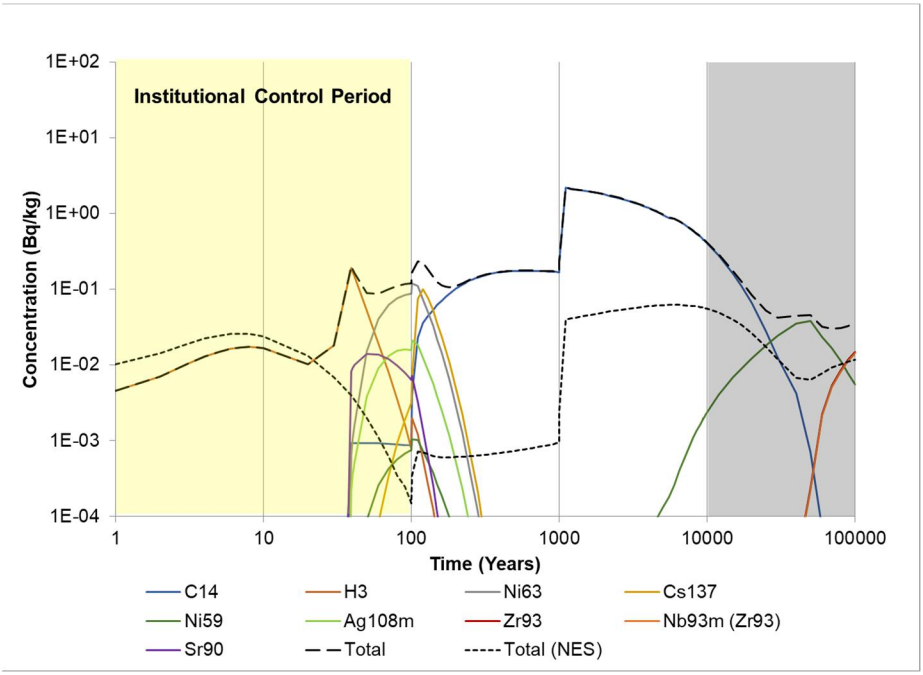


Figure G-95 Concentrations in the Garden Soil (Role of Existing Facility Structure Case)



Note: Radionuclides in brackets indicate the parent of the radionuclide that was present in the initial radionuclide inventory of the NPDDF.

Figure G-96 Dose to Most Exposed Receptor - an Adult Indigenous (AOPFN) Receptor (Role of Existing Facility Structure Case)

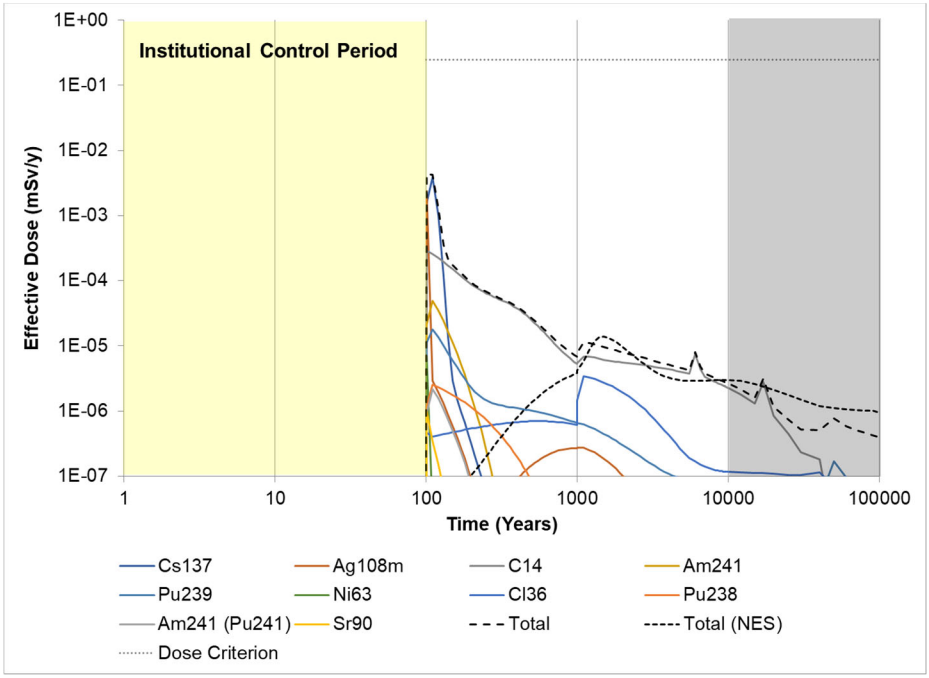
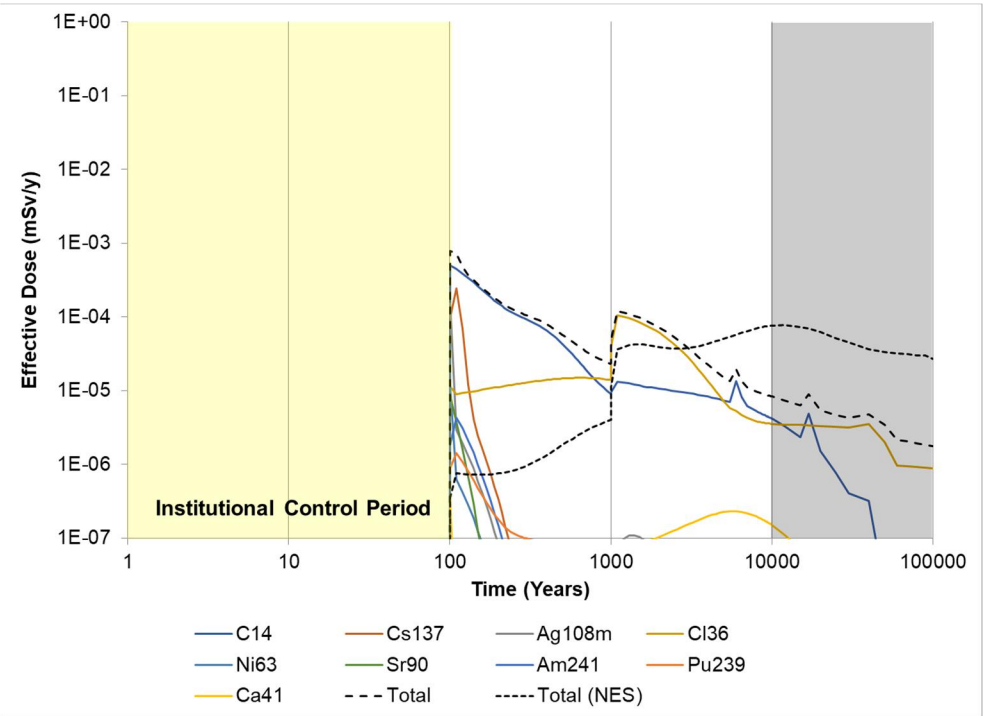


Figure G-97 Dose to an Infant Site Resident Receptor (Role of Existing Facility Structure Case)



G 5.2 DD(b) – Role of Grout

The calculation case DD(b) is intended to illustrate the role of grout within the NPDDF as a barrier to the release of radionuclides. It complements DD(a) which examines the role of the structure and uses the same method of assigning the properties of fully degraded grout in all the model compartments that are represented as grout in the Normal Evolution scenario. The structure is assumed to perform in the same way as represented in the Normal Evolution scenario.

Figure G-98 shows the groundwater concentrations that result from the release of radionuclides from the NPDDF into the geosphere. These are initially similar in the bedrock, dominated by tritium and then C-14 in the first 1,000 y. At this point, the concrete structure is assumed to degrade, exposing the degraded grout to higher water flows. The result is increased concentrations in bedrock groundwater, from a peak of 6 Bq l^{-1} in the Normal Evolution scenario to 50 Bq l^{-1} in this case. The concentrations in the overburden groundwater are also increased, peaking at 0.09 Bq l^{-1} just after 1000 y, compared with $1x10^{-3}$ Bq l^{-1} in the Normal Evolution scenario. In both cases C-14 dominates after around 200 y out to 10,000 y.

The environmental concentrations reflect the higher groundwater concentrations in both pathways. Figure G-99 shows that the peak concentration in river water increases by around one order of magnitude compared to the Normal Evolution scenario, peaking at 1,500 y to $1x10^{-4}$ Bq l^{-1}, dominated by C-14. An

earlier peak, during the institutional control period, is increased from $6x10^{-3}$ Bq l^{-1} in the Normal Evolution scenario to 0.02 Bq l^{-1} (due to tritium). The increase in concentrations in garden soil (Figure G-100) are even greater, from 0.06 Bq kg^{-1} in the Normal Evolution scenario to more than 10 Bq kg^{-1} in this case. The increase is greater than in other environmental materials because the lack of grout means C-14 is much less sorbed in the Facility (only on the concrete structure). C-14 is, however, sorbed to in the bedrock (the dominant pathway to the river) which retards the radionuclide. In contrast, C-14 released to soils surrounding the Facility via the overburden has much less opportunity for sorption, and therefore concentrations are much higher immediately after the concrete structure degrades.

The highest doses, to the infant Site Resident, reflect the Garden soil concentrations as the key pathway is the ingestion of vegetables, with Cl-36 being the most significant radionuclide (see Figure G-101). The peak dose is $9x10^{-4}$ mSv y^{-1} at 1,000y, increased from $8x10^{-5}$ mSv y^{-1} in the Normal Evolution scenario at 12,000 y.

Figure G-98 Release of Contaminants from the NPDDF to the Geosphere (Role of Grout Case)

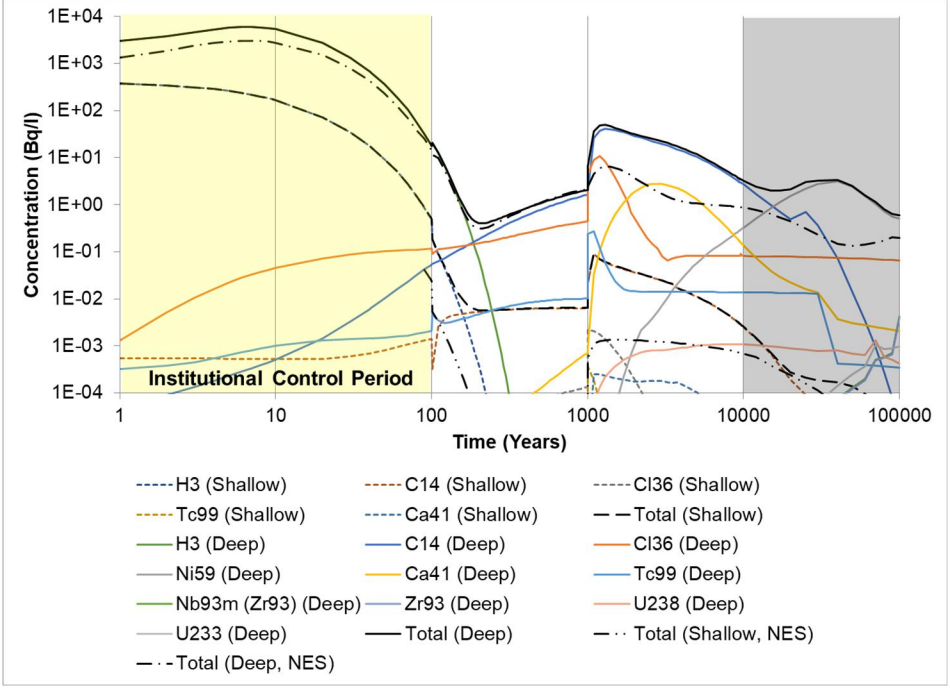


Figure G-99 Concentrations in the River Water (Role of Grout Case)

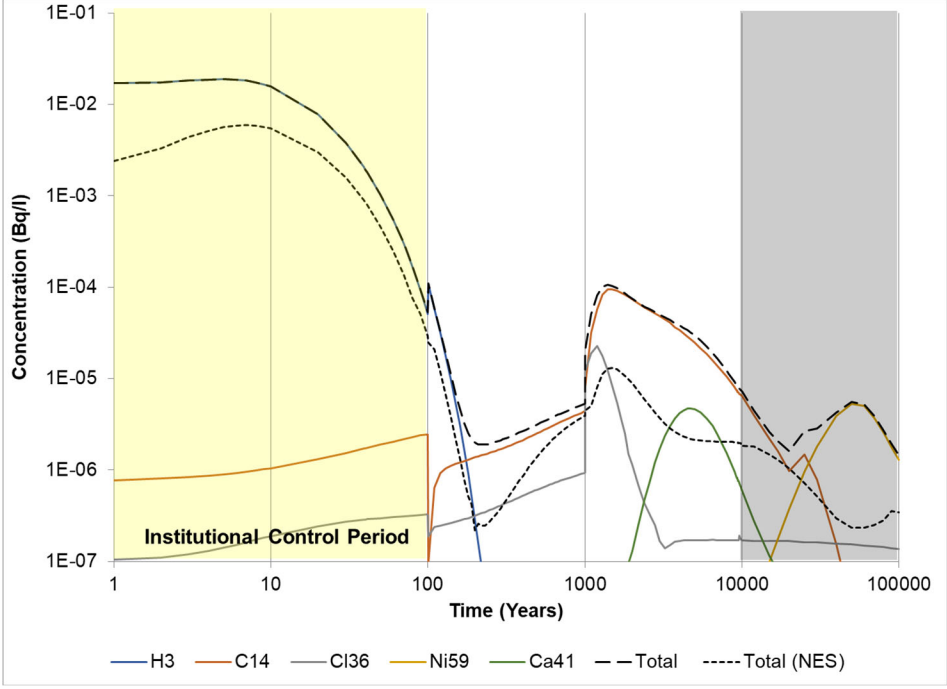


Figure G-100 Concentrations in the Garden Soil (Role of Grout Case)

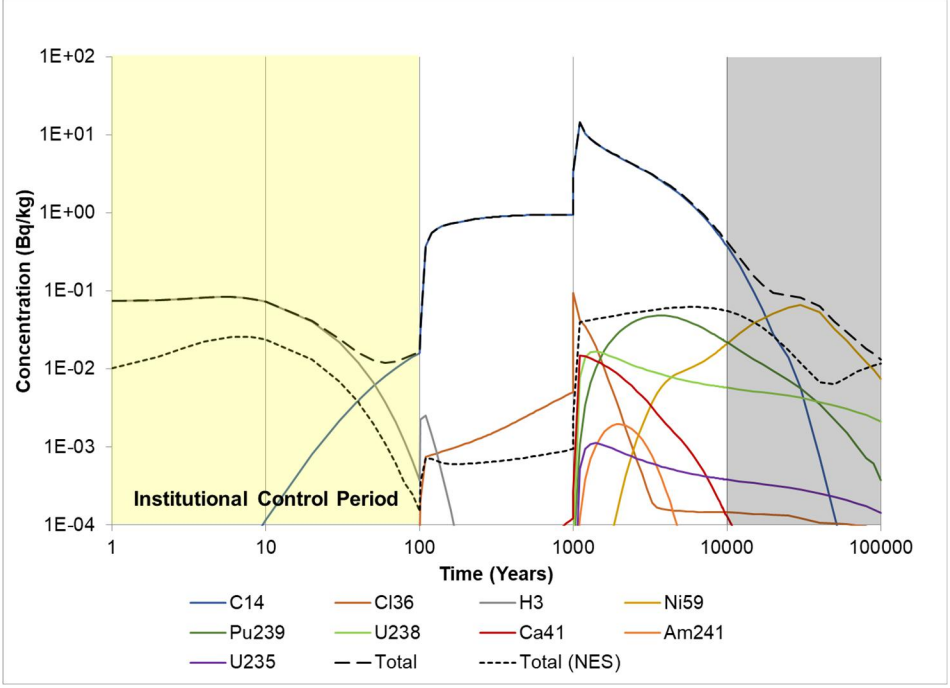
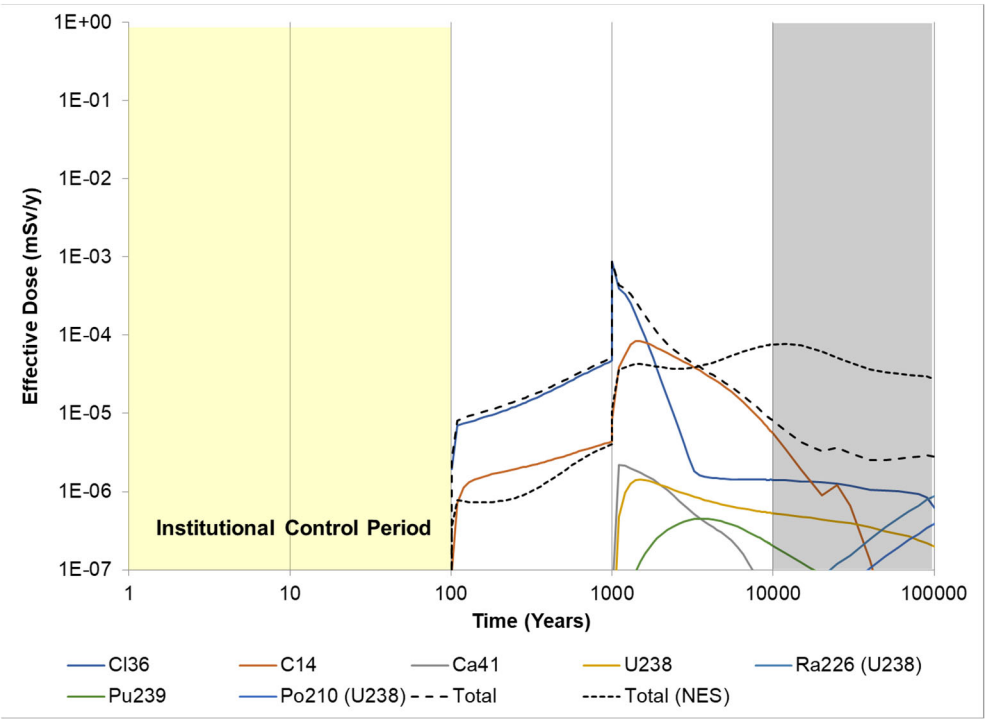


Figure G-101 Dose to Most Exposed Receptor – Infant Site Resident (Role of Grout Case)



Note: Radionuclides in brackets indicate the parent of the radionuclide that was present in the initial radionuclide inventory of the NPDDF.

G 6 WHAT-IF CASES

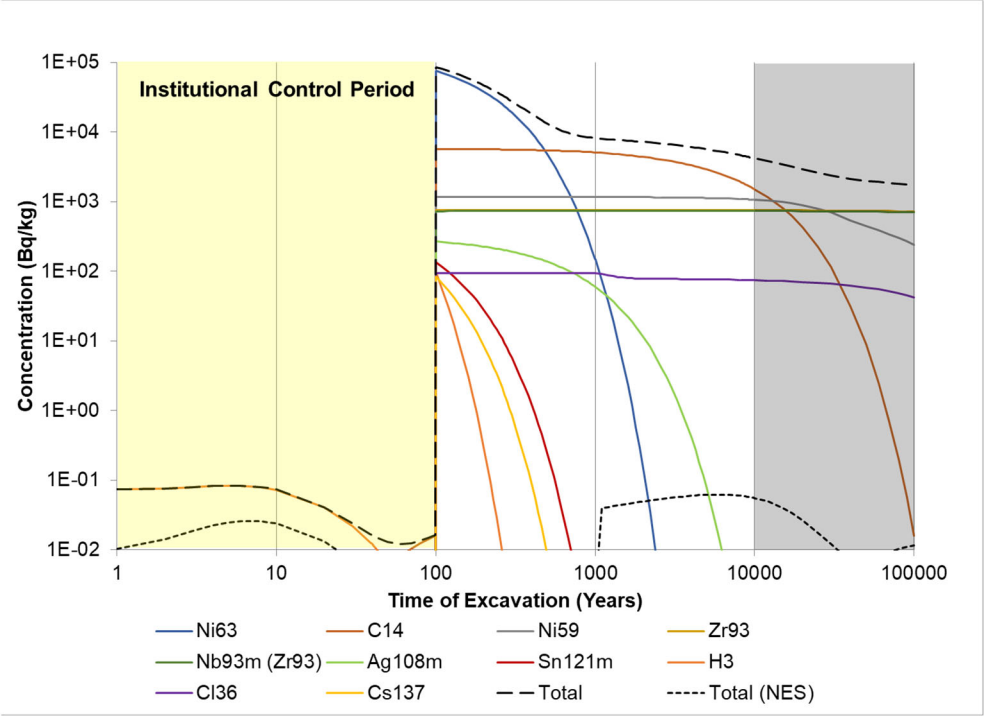
G 6.1 WI(a) – Facility Mass Excavation

The calculation case WI(a) examines the potential effects of the most extreme disruption that could occur to the NPDDF. It provides an indication of the limit to the dose that could occur due to such a situation. The case assumes that at some time after 100 y the entire Facility is excavated and its contents, including all radionuclides, are dispersed in a small patch of surface soils. This case is therefore more extreme in its assumptions that the Disruptive Event case that considered the excavation of the above-bedrock parts of the facility, presented in Section G 4.5. Most notably, this case evaluates the consequence of the excavation, and dispersal in surface soils of the entire inventory of the Reactor Vault. The excavated material (approximately 24,400 m^3) is assumed to be mixed with the Garden soil, at a 10% loading. Very conservatively, a person is assumed to live on and cultivate the contaminated soil, as this offers the highest potential for exposure.

The peak concentration in soil of $9x10^4$ Bq kg^{-1} (see Figure G-102) is much higher than in other cases owing to the presence of waste material from, primarily, the Reactor Vault and the contribution of shorter-lived radionuclides should excavation occur shortly after the end of institutional control. This compares with just 0.06 Bq kg^{-1} for the Normal Evolution case. Because radionuclides in the wastes are transferred directly into soil, rather than via groundwater, the dominant radionuclides differ from previous cases. Ni-63 is most significant until 500 y, thereafter C-14 until 15,000 y, then Ni-59, Zr-93 and Nb-93m.

The most important radionuclide from the perspective of dose, however, is Cl-36 via ingestion of crops (see Figure G-103 and Figure G-104). The peak dose in this case is just over 1 mSv y^{-1} to an infant Site Resident if excavation occurred immediately after institutional control ceases. The dose is not compared with any criteria as the case is extremely conservative, but does provide an indication of the likely maximum level of dose.

Figure G-102 Radionuclide Concentrations in the Garden Soil (Facility Mass Excavation Case, no Leaching of Soil)



Note: Radionuclides in brackets indicate the parent of the radionuclide that was present in the initial radionuclide inventory of the NPDDF.

Figure G-103 Dose to an Infant Site Resident, by Radionuclide (Facility Mass Excavation Case, no Leaching of Garden Soil)

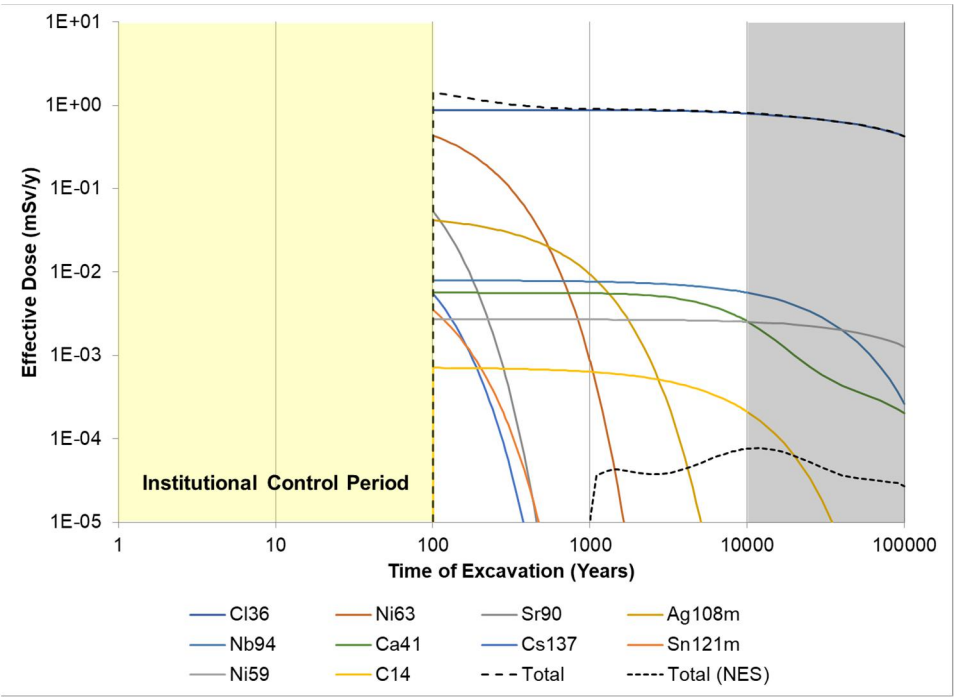
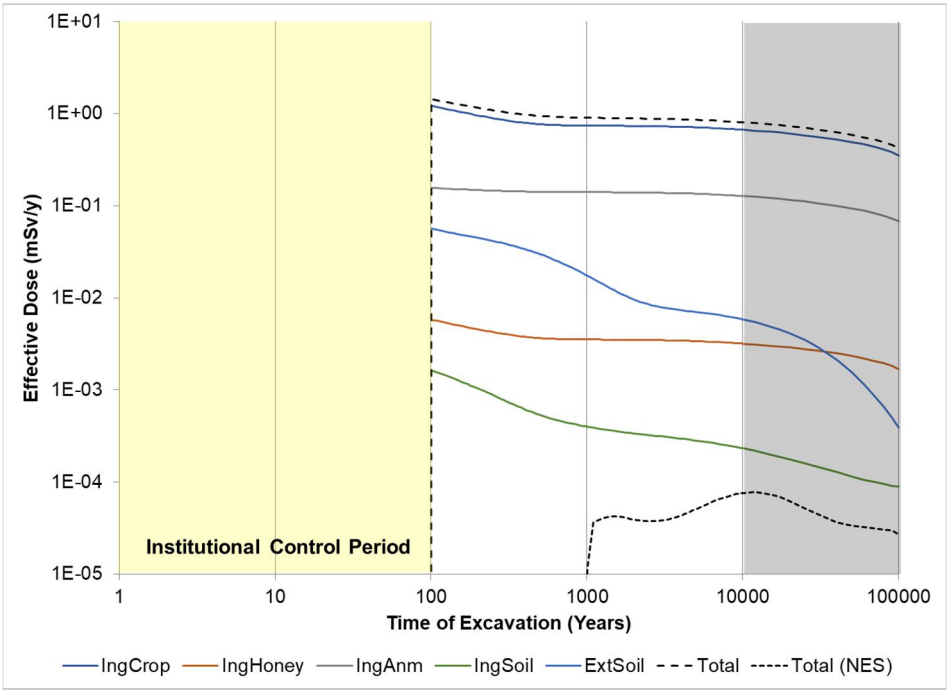


Figure G-104 Dose to an Infant Site Resident, by Pathway (Facility Mass Excavation Case, no Leaching of Garden Soil)



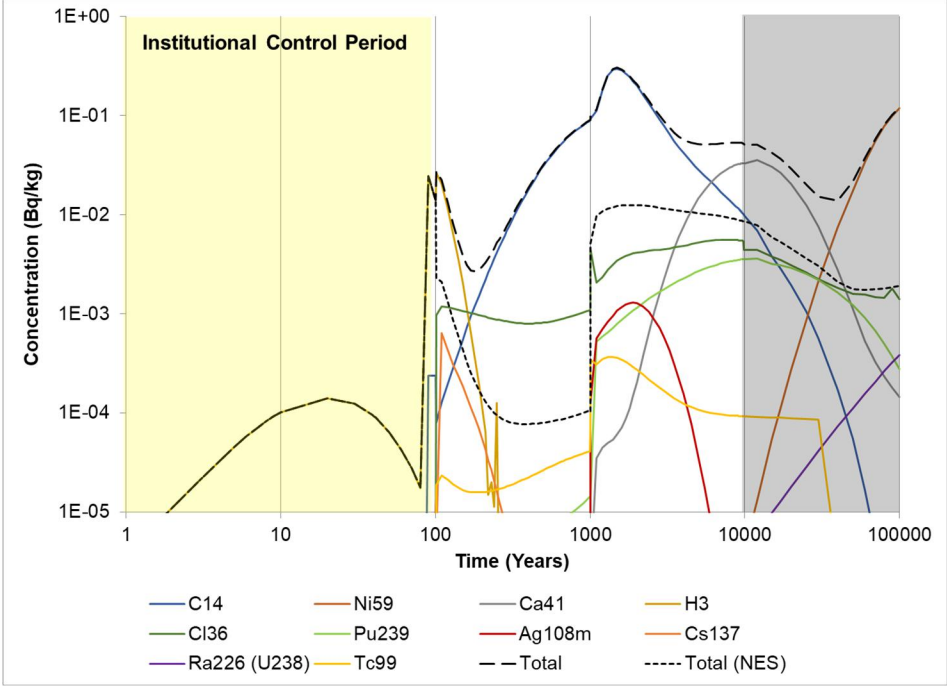
G 6.2 WI(b) – River Level Fall

The Ottawa River is the primary receptor for contaminants migrating in the bedrock groundwater. This "What If" calculation case examines the possibility of a significant change to the location and nature of these groundwater releases. Although it is expected that the river will remain similar in size and location in the future due to the very large catchment, extreme environmental change could involve reduced precipitation over a wide area (e.g., in the onset of a glaciation) and reduce the river level. In such a situation, the groundwater from the bedrock might be released on the banks of the river. The "What If" WI(b) case assesses this by assuming that contaminated groundwater from the bedrock is released into a patch of shoreline sediments rather than to the riverbed sediments. This is assumed to occur at the end of the period of institutional control, although this is in reality implausible.

The most affected part of the model is the shoreline sediments, into which bedrock groundwater is assumed to flow from 100 y onwards. The concentrations are presented in Figure G-105 and shows that the peak concentration in these sediments is increased from 0.01 Bq kg^{-1} in the Normal Evolution scenario to 0.3 Bq kg^{-1}, dominated by C-14 at 1,500 y.

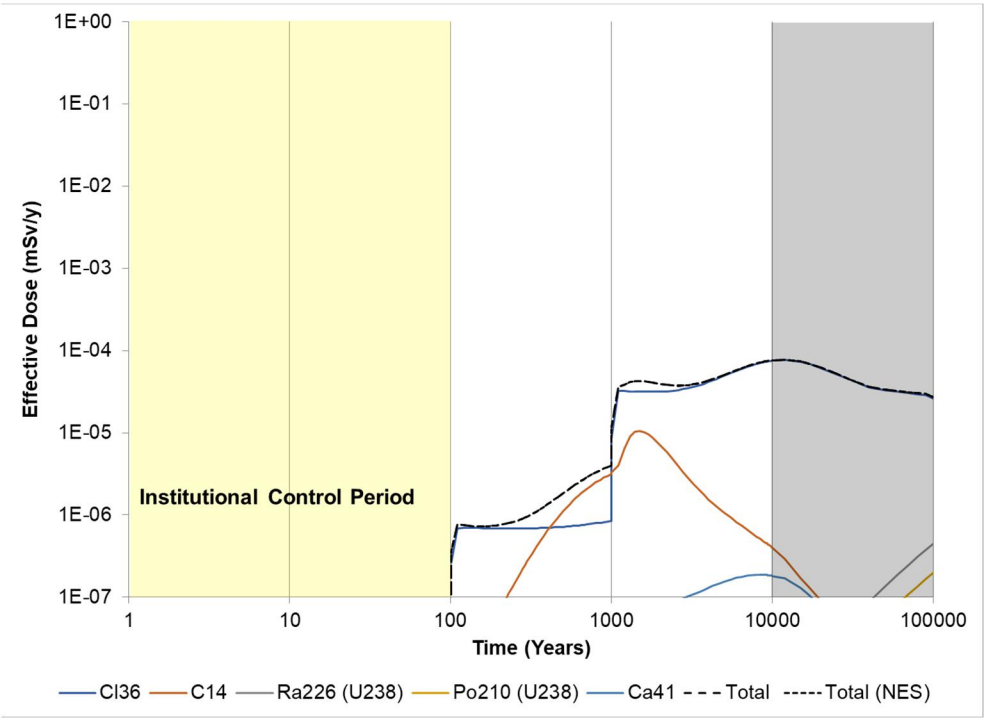
The shoreline sediments are not, however, a major contributor to the exposure pathways for receptors. Consequently, the peak dose is unchanged from the Normal Evolution scenario as shown in Figure G-106.

Figure G-105 Concentration of Radionuclides in the Shore Sediments (River Level Fall Case)



Note: Radionuclides in brackets indicate the parent of the radionuclide that was present in the initial radionuclide inventory of the NPDDF.

Figure G-106 Total Radiation Doses to the Most Exposed Receptor, Site Resident Infant (River Level Fall Case)



Note: Radionuclides in brackets indicate the parent of the radionuclide that was present in the initial radionuclide inventory of the NPDDF.

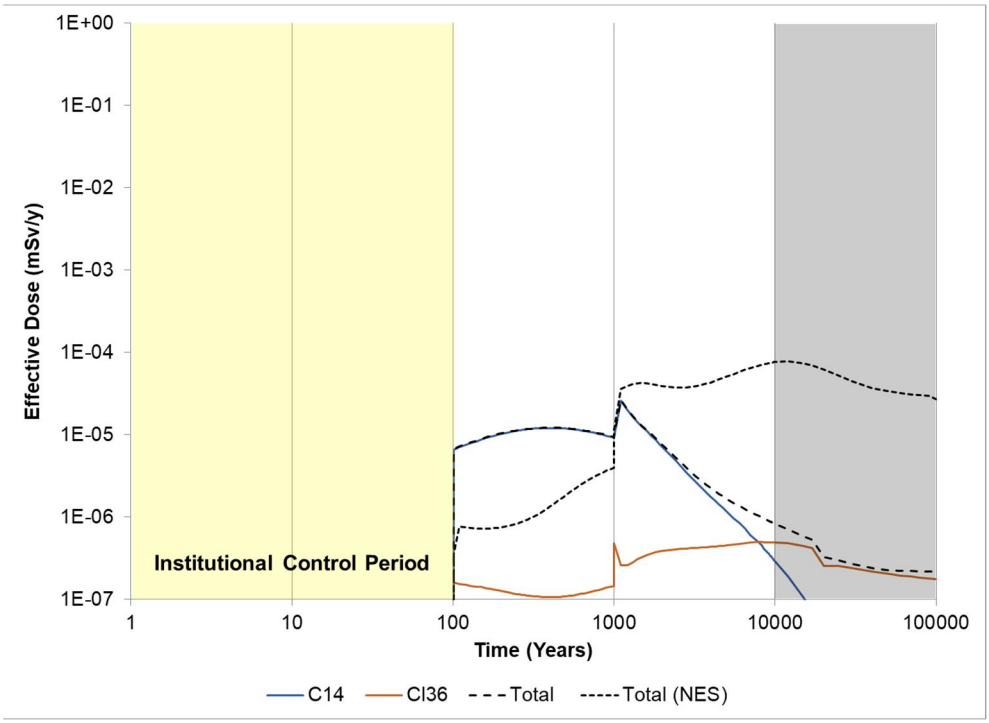
G 6.3 WI(c) – Undetected Fracture Zone

This “What If” case considers the possibility of features being present within the geosphere that are not detected prior to closure of the NPDDF (e.g., fracture zones, faults, boreholes). Such features could play a role in the transport of groundwater to and from the Facility and the associated migration of contaminants. This case examines the impact of such a situation by applying the higher bedrock conductivity to all bedrock downgradient of the facility. This is a conservative approach, rather than limiting the higher bedrock conductivity to a defined area. Practically, the combination of conditions considered in this “What If” case is the same as modelled in the Sensitivity Case that assesses the impact of a higher geosphere bedrock hydraulic conductivity (see Section G 3.7).

As discussed earlier, the increased flows in the bedrock (in this case due to an undetected feature) lead to greater dilution of the released contaminants. Consequently, radionuclide concentrations in groundwater are lower. However, the rate of discharge of contaminants to the river (the product of the concentration of radionuclides in the water and the groundwater flow rate) is notably higher in the period 100 – 1000 y. Consequently, the river water concentrations in this timeframe are increased, as shown in Figure G-59.

The increased flows in the bedrock also result in a general lowering of the water table, such that the parts of the NPDDF that sit in the overburden experience no groundwater transport. Thus, there is no radionuclide releases from the NPDDF to the overburden and, consequently, no releases from the overburden to the Garden, an important pathway for contamination of the garden soil. As a result, radionuclide concentrations in the garden soil are much reduced (see Figure G-60). The doses to the most exposed receptor, the infant Site Resident (Figure G-107) are therefore reduced. The peak dose of $3x10^{-5}$ mSv y^{-1} is three times lower than that in the Normal Evolution scenario and occurs after 1,100 y.

Figure G-107 Total Dose to the Site Resident Infant Receptor (Undetected Fracture Zone Case)



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