OPG's DEEP GEOLOGIC

REPOSITORY

FOR LOW & INTERMEDIATE LEVEL WASTE

Postclosure Safety Assessment

March 2011

Prepared by: Quintessa Ltd., Geofirma Engineering Ltd.
and SENES Consultants Ltd.

NWMO DGR-TR-2011-25

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EXECUTIVE SUMMARY

Background

Ontario Power Generation (OPG) is proposing to build a Deep Geologic Repository (DGR) for Low and Intermediate Level Waste (L&ILW) near the existing Western Waste Management Facility at the Bruce nuclear site in the Municipality of Kincardine, Ontario. The Nuclear Waste Management Organization, on behalf of OPG, is preparing the Environmental Impact Statement (EIS) and Preliminary Safety Report (PSR) for the proposed repository.

The postclosure safety assessment evaluates the long-term safety of the proposed facility and provides supporting information for the EIS and PSR. Other aspects of the DGR work program (e.g., operational safety, inventory, facility design, site characterization and geosynthesis) are considered in separate technical reports. The PSR provides an integrated collection of arguments and evidence gathered from all these technical reports to demonstrate the safety of the DGR system.

This report provides a technical summary of the work undertaken and results obtained for the assessment of the postclosure radiological and non-radiological safety of the DGR. In particular, it provides an overview of the system assessed, and presents the scenarios evaluated and the key results from their detailed analyses. It identifies the main uncertainties and how they have been addressed.

Approach

The assessment has been undertaken using the following approach.

1. The assessment context is defined, documenting the high-level assumptions and the constraints, notably the regulatory requirements and the assessment timeframe.
2. The system is described, summarizing information on the waste, repository, geological setting and surface environment pertinent to postclosure safety.
3. A range of potential future scenarios is systematically identified, ranging from expected to “what if” scenarios.
4. Conceptual and mathematical models are developed to represent these scenarios.
5. The scenarios are analyzed and the results are assessed with respect to the performance of the system, its overall robustness, and the nature and role of key uncertainties.

Assessment Context

The purpose of the assessment is:

- To quantitatively assess the postclosure radiological and non-radiological safety of the proposed DGR;
- To identify those uncertainties that have the greatest potential impact on the long-term performance of the repository system; and
- To provide information that supports the EIS and PSR required for the DGR.

The other key components of the assessment context are summarized below.

Audiences:	Technical reviewers, including the Canadian Nuclear Safety Commission
Regulatory Requirements and Guidance:	Nuclear Safety and Control Act and associated regulations Canadian Nuclear Safety Commission regulatory guidance document G-320, “Assessing the Long Term Safety of Radioactive Waste Management” Canadian Environmental Assessment Agency and Canadian Nuclear Safety Commission guidelines for the preparation of the EIS for the DGR
Endpoints:	Radiation dose to humans Environmental concentrations of radionuclides and non-radioactive elements and chemical species Contaminant concentrations and fluxes in various spatial domains
Treatment of Uncertainties:	Consideration of a range of scenarios, from expected to “what if” scenarios Use of conservatism in scenarios, models and data Use of a stylized approach for the representation of future human actions and biosphere evolution Use of a range of deterministic calculation cases to explore uncertainties in models and data; limited probabilistic assessment for a reference case condition
Timeframe:	1 million years baseline Encompassing the period over which most radioactivity in the waste has decayed and the maximum risk is expected to occur Some analyses extended beyond 1 million years to estimate the maximum impacts from some scenarios

System Description

A high-level description of the DGR system considered in this postclosure safety assessment is provided below.

Waste:	The total emplaced volume of low and intermediate level waste (L&ILW) is approximately 200,000 m^3, comprised of operational and refurbishment wastes from Ontario Power Generation (OPG) owned or operated nuclear reactors. The wastes are emplaced in a range of steel and concrete waste containers and overpacks. The total activity at closure is about 16,000 TBq. Key radionuclides in terms of total activity include H-3, C-14, Ni-63, Nb-94 and Zr-93. The waste generates about 2 kW of decay heat at time of closure.
Repository:	The repository is at a depth of around 680 m and comprises two shafts, a shaft and services area, access and return ventilation tunnels, and 31 waste emplacement rooms in two panels. The repository is not backfilled. At closure, a concrete monolith is emplaced at the base of the shafts and then the shafts are backfilled with a sequence of materials (bentonite/sand, asphalt, concrete and engineered fill).
Geological Setting:	The DGR is located in low permeability Ordovician argillaceous limestones, with 230 m of shales above and 160 m of limestones below. Significant underpressures exist in the Ordovician rocks, whereas overpressures exist in

	the Cambrian below the DGR. Above the Ordovician shales, there are 325 m of Silurian shales, dolostones and evaporites. The porewater in the Silurian and Ordovician sediments is highly saline (total dissolved solids of 150 to 350 g/L) and reducing with pH buffered by carbonate minerals. Above the Silurian sediments, there are 105 m of Devonian dolostones, the upper portions of which contain fresh, oxidizing groundwater that discharges to Lake Huron. Site investigations at the Bruce nuclear site have not found commercially viable mineral or hydrocarbon resources.
Surface Environment:	The present-day topography is relatively flat and includes streams, a wetland, and, at a distance of approximately 1 km, Lake Huron. The annual average temperature is about 8°C with an average precipitation rate of around 1.1 m/a. The region around the Bruce nuclear site is mainly used for agriculture, recreation and some residential development. Groundwater is used for municipal and domestic water in this region, while the lake provides water for larger communities. The lake is used for recreation and commercial fishing. A significant aboriginal traditional activity in the region is fishing in Lake Huron.

The deep geologic repository provides the high-level safety functions of isolation and containment of the L&ILW. The site and design support these safety functions through a variety of safety relevant features or attributes, as summarized below.

Site Geology	- Multiple low-permeability bedrock formations enclose the DGR. - Predictable, horizontal geology with large lateral extent. - Stable deep diffusion-dominated groundwater system, even under glaciation. - Seismically quiet. - Geomechanically stable rock. - Low natural resource potential. - Low rock permeability limits the rate of repository resaturation. - Ordovician underpressures provide a convergent flow system. - Guelph and Salina A1 upper carbonate permeable formations can divert gas or solutes migrating upwards from repository via geosphere or shaft. - Chemical conditions limit contaminant mobility.
Layout	- DGR is located at 680 m depth in thick limestone formation. - Shafts are placed in an islanded arrangement separate from waste panels. - Waste emplacement rooms are not backfilled, providing space for gas. - Waste emplacement rooms are aligned with rock principal stress and have thick room pillars for mechanical robustness.
Shaft	- Concrete monolith at base of shafts provides long-term structural support of the shaft seals; it also helps delay water and gas flow. - The bentonite/sand mix in the shafts is the primary seal; it is a durable low-permeable material that can swell under DGR saline conditions. - The asphalt mix is a secondary shaft seal that provides an independent self-sealing barrier to transport. - The concrete bulkheads at the Guelph and Salina A1 levels isolate the bentonite from any flow in these units, and provide structural support for the overlying seals.

	- The shaft concrete liner and highly damaged zone (HDZ) are removed before the shaft seals are installed. - Engineered fill is used in the shaft in the shallow groundwater zone, and topped with a concrete cap. - Site characterization boreholes are sealed when no longer needed.
Waste and packaging	- Wastes and packaging are not designed for long-term integrity. - Corrosion-resistant Zircaloy delays release of the longer-lived radionuclides Nb-94 and Zr-93. - 80% of the waste volume is LLW. - Tritium is an important radionuclide at closure; it decays within a few hundred years. - The most important radionuclides at closure are tritium and C-14 due to their early release as gas. Tritium decays within a few hundred years; C-14 decays in about 60,000 years, before the onset of glaciation at the site.

Scenarios

The future evolution of the DGR system is assessed through a Normal Evolution Scenario and four Disruptive Scenarios. The Normal Evolution Scenario describes the expected long-term evolution of the repository and site following closure, and the Disruptive Scenarios consider events that could lead to possible penetration of barriers and abnormal degradation and loss of containment. These Disruptive Scenarios are unlikely or “what if” cases that test the robustness of the DGR system. The uncertainties associated with the future evolution of the DGR system are assessed in part through these scenarios, and in part through sensitivity cases considered within each scenario. A brief description of each scenario is given below.

Normal Evolution Scenario	After closure, the repository will quickly become anaerobic. The repository will start to fill slowly with water seeping in from the shafts and the surrounding rocks. The slow anaerobic degradation of the waste packages will result in the generation of gases, especially CH_4. The repository will remain mostly unsaturated, and the gas pressure will eventually equilibrate around the host rock steady-state hydraulic pressure. As the wastes degrade, C-14 and tritium will be released mostly as gas. Other contaminants will be released into repository water. Most contaminants will be contained within or near the repository by the low-permeability host rock, where they decay. Over timescales of many thousands of years some contaminants may slowly migrate via the sealed shafts and geosphere into the shallow geosphere, and then into the surface environment. People living on or near the site could potentially be exposed to these contaminants through the use of groundwater drawn from a well, through the use of local land for farming and hunting, and through fishing in the lake. Over long timescales glaciation could return, with ice-sheets covering the site with a periodicity of around 100,000 to 120,000 a. This would result in significant changes in the surface and shallow geosphere. However, the deep geosphere would remain largely stagnant, as during past glaciations.

		The region around the Bruce nuclear site is tectonically stable. Large earthquakes are very unlikely. The host rock is strong, and small earthquakes will have little effect. The primary effect of large earthquakes will be to cause rockfall in the repository, which will continue until the rooms and tunnels have filled. On long time scales, the radioactivity of the waste will decay to less than the natural activity of the rock directly overlying the repository.
Disruptive (“What if”) Scenarios	Human Intrusion	This scenario considers the impact of inadvertent human intrusion into the repository via an exploration borehole at some time in the future. Contaminants are released and humans are exposed to contaminated gas and drill core. If the exploration borehole is poorly sealed and penetrates into the pressurized Cambrian, contaminated groundwater could be released to the shallow geosphere resulting in the exposure of people using the groundwater.
	Severe Shaft Seal Failure	This scenario considers the consequences of rapid and complete seal degradation in the shafts, and the increased degradation of the repository/shaft excavation damaged zones (EDZs). Otherwise, the evolution of the DGR system is the same as the Normal Evolution Scenario.
	Poorly Sealed Borehole	This scenario considers the consequences of a poorly sealed deep site investigation borehole in close proximity to the DGR. The evolution of the DGR system and associated exposure pathways and groups are similar to those considered in the Normal Evolution Scenario. The key difference is that the borehole provides an enhanced permeability connection between the level of the repository, the overlying groundwater zones and the surface environment. The borehole is assumed to be 100 m from the DGR, consistent with the nearest borehole.
	Vertical Fault	This scenario considers the hypothetical case of “what if” a transmissive vertical fault exists, either undetected or representing the displacement of an existing structural discontinuity, which propagates from the Precambrian into the intermediate depth Silurian rocks in close proximity to the repository. Such a fault could provide an enhanced permeability pathway that bypasses the low-permeability deep geosphere. The fault is assumed to be 500 m to the northwest of the repository, i.e., beyond the area considered in detail in the site investigation program. An alternative location, 100 m southeast from the repository, is also considered.

Models, Data and Implementation

Conceptual and mathematical models and data are described. Data have primarily been taken from existing OPG waste characterization, DGR preliminary design, and Bruce nuclear site sub-surface and surface site information. These have been complemented with data from literature reviews for other parameters for the expected conditions in the DGR.

The models are implemented in three software codes.

- Assessment-level (system) models are implemented in AMBER 5.3, which is a compartment-model code that represents radioactive decay, package degradation, contaminant transport through the repository, geosphere and surface environment, and the associated impacts such as dose.
- Detailed groundwater flow and transport calculations are implemented in the 3-D finite-element/finite-difference code FRAC3DVS-OPG, the same code as used for DGR regional geosynthesis modelling.
- Detailed gas generation and transport calculations are implemented in T2GGM, a code that couples the Gas Generation Model (GGM) and TOUGH2. GGM is a project-specific code that models the generation of gas within the DGR due to corrosion and microbial degradation of the metals and organics present. TOUGH2 models the subsequent two-phase transport of gas through the repository and geosphere.

Results

Normal Evolution Scenario

The Normal Evolution Scenario Reference Case draws on the results of the site investigations and geosynthesis, and represents the site in the most detail. It includes the measured overpressure in the Cambrian sandstone below the DGR, and the measured underpressures and partial gas saturations in the Ordovician formations within which the DGR is located. Analyses included evaluation of water inflow from rock and shaft, gas generation and build up within the repository, corrosion and rockfall processes that would degrade waste packages, groundwater and gas flow through repository, host rock and shaft seals, and impacts on people living above and around the repository. Variant calculation cases are also assessed to explore uncertainties associated with the Normal Evolution Scenario.

The key results for these cases are as follows.

- The full resaturation of the repository with water is gradual, taking more than 1 million years, due to the low permeability of the host rock and gas generation in the repository. The majority of the water seeps into the repository from the surrounding host rock rather than the shafts.
- Contaminants are contained within the repository and host rock, thereby limiting their release into the surface environment and their subsequent impacts. Reference Case calculations estimate that less than 0.1% of the initial waste activity is released into the geosphere around the repository, and much less is released into the shafts.
- Gases are contained within the repository and geosphere. The gas pressure is anticipated to equilibrate at 7-9 MPa, i.e., around or somewhat above the 7.4 MPa equilibrium hydrostatic pressure at the repository level, and well below the lithostatic pressure of about 17 MPa. The gas will be primarily methane in the long term.

- The low-permeability geosphere and shaft attenuate the release of contaminants, providing time for radioactive decay to decrease the radioactivity in the repository.
- The maximum calculated dose for all calculated cases is more than five orders of magnitude below the 0.3 mSv/a public dose criterion (Figure E1). Calculated doses within the shaded range on Figure E1 are negligible and the magnitude of the values within this area is illustrative. In general, peak doses to children and infants are within a factor of three of the adult dose.
- These results apply to a hypothetical family assumed to be living on the site in the future, and obtaining all of its food from the area. The potential dose would decrease rapidly with distance from the site. For example, the calculated dose to a “downstream” group exposed via consumption of lake fish and water from Lake Huron are more than three orders of magnitude lower than the dose to the family living on the site.

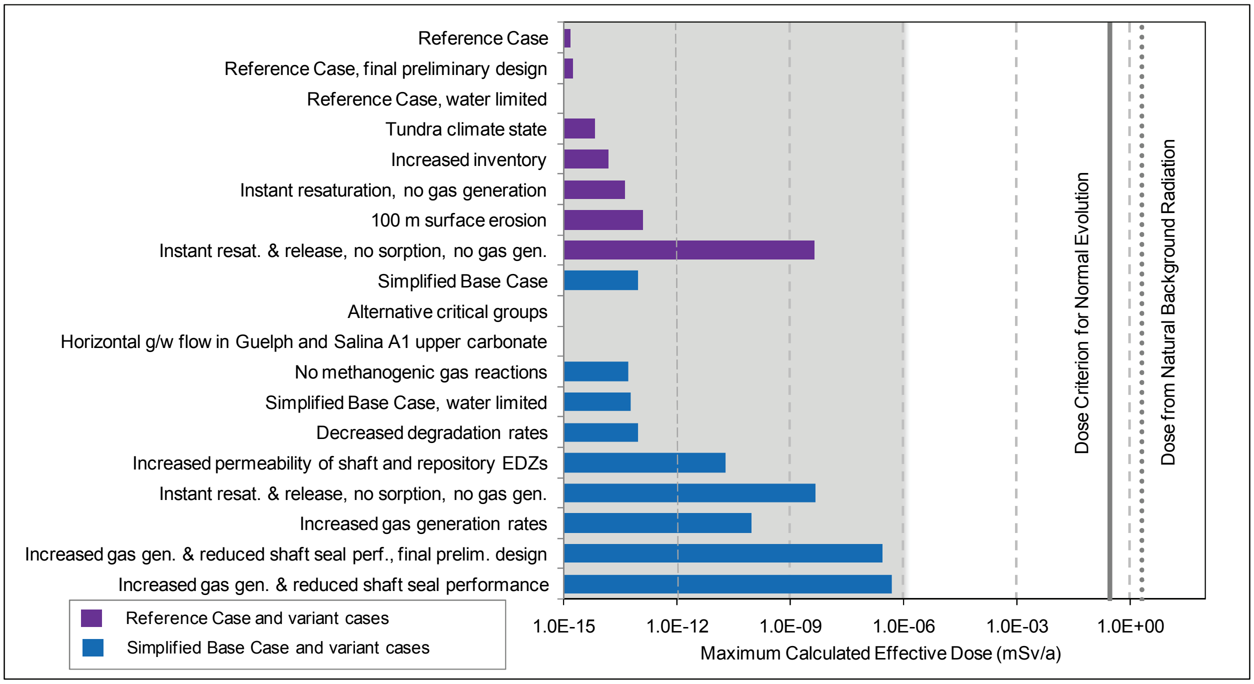


Figure E1: Normal Evolution Scenario: Maximum Calculated Doses for all Calculation Cases

Disruptive Scenarios

A tiered approach is adopted for disruptive scenarios, recognizing the speculative nature of some scenarios. First, a dose criterion of 1 mSv/a is used for radiological exposure of humans under credible scenarios. Second, if calculated doses exceed 1 mSv/a for a scenario, the acceptability of results from that 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 criterion. Where feasible, they are compared to a reference health risk of 10^{-5}/a.

Consistent with the Normal Evolution Scenario, a reference calculation is undertaken for each Disruptive Scenario. To avoid ambiguity with the Normal Evolution Scenario Reference Case, the reference calculation for each Disruptive Scenario is termed the Base Case calculation. In addition to the Base Case calculations, some variant calculations have been undertaken for each Disruptive Scenario.

The key results for these cases are summarized below and in Figure E2.

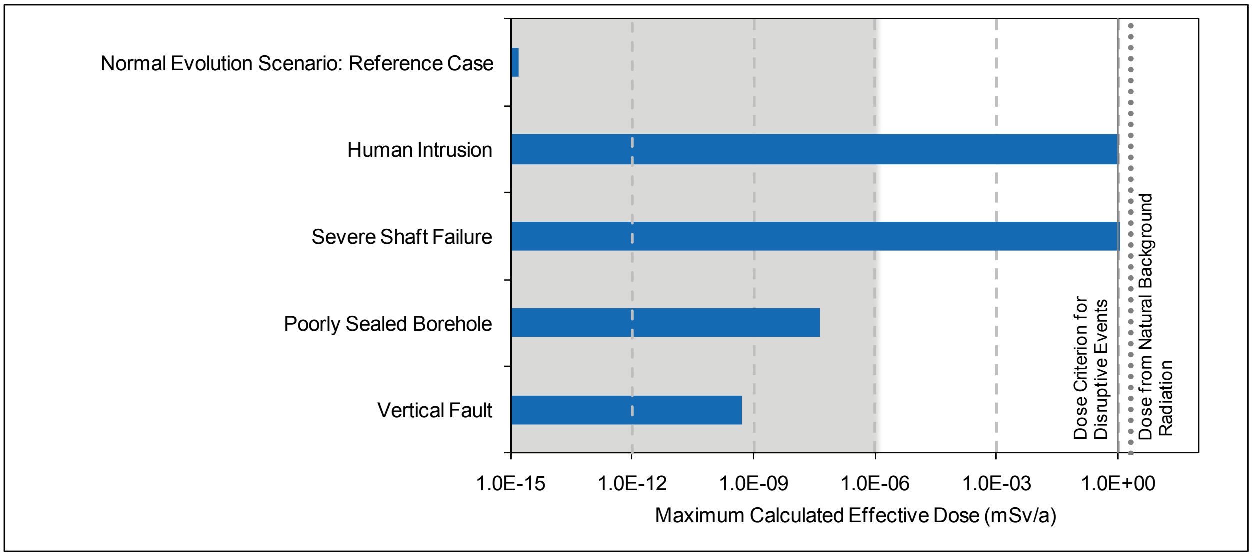


Figure E2: Disruptive Scenarios: Maximum Calculated Doses for Base Case Calculations

- For the *Human Intrusion Scenario*, if a borehole is drilled into the repository and gases and material from the repository are not appropriately contained, the calculated doses could be about 1 mSv for the drill crew and for a future person farming on the contaminated site for about 10,000 years after closure. The likelihood of drilling into the repository in any given year is very low due to the lack of mineral resources and the repository's small footprint and depth, and high contaminant releases are unlikely when following standard deep drilling practices. Thus the risk of serious health effects is low, and much less than the reference health risk value of 10^{-5}/a.
- For the *Severe Shaft Seal Failure Scenario*, the maximum calculated doses are about 1 mSv/a, based on immediate failure of 500 m of low-permeability shaft seals (to 10^{-9} m/s hydraulic conductivity), reduced sorption in the shafts, increased degradation of shaft and repository EDZs, and assuming a family is farming directly on top of the shafts (including a house located on the main shaft). The scenario is very unlikely. Therefore, the risk from the severe shaft seal failure scenario is low.
- Calculated peak annual doses for the *Poorly Sealed Borehole Scenario* and for the *Vertical Fault Scenario* are much less than the dose criterion.
- Additional cases were evaluated to determine the conditions necessary for a disruptive scenario to result in larger impacts than those resulting from its base case. For the Human Intrusion Scenario, the borehole would have to be extended down to the Cambrian and then be poorly sealed, so that there was water flowing up the borehole, through the repository and into the shallow groundwater system. For Severe Shaft Seal Failure Scenario, the hydraulic conductivity of all the shaft seals would have to degrade by 4-5 orders of magnitude beyond the design basis to 10^{-7} m/s, about equivalent to fine silt and sand. In these cases, the peak doses to someone living on top of the repository site could be tens of milliSieverts.

- The primary risk in the Disruptive Scenarios is from the release of bulk gas from the repository containing C-14. The potential impacts therefore decrease to well below the dose criterion after about 60,000 years due to C-14 decay. Since glaciation at the DGR site is not likely to occur prior to then, there is little risk that glaciation will cause larger impacts for the Disruptive Scenarios.

Key Radionuclides

- Most radionuclides are retained within the repository or geosphere.
- H-3, although a significant contributor to the waste radioactivity at closure, is fully retained within the repository and host rock, where it decays.
- For scenarios that could result in releases of contaminants to the surface environment within about 60,000 years of closure, C-14 (mostly from ILW moderator resins) is the key radionuclide, together with Nb-94 (mostly from ILW pressure tubes) for human intrusion.
- For releases that occur at later times, Cl-36 (mostly from ILW pressure tubes), and I-129 (mostly from ILW PHT resins) become more important due to their longer half-life and their mobility.
- Nb-94 and Zr-93 are slowly released and mostly retained within the shaft and geosphere and so are not significant contributors to the calculated doses for groundwater releases.

Impacts on Non-human Biota and Non-radiological Impacts

Calculations have been undertaken to assess the impact of radionuclides on non-human biota and the impact of non-radioactive elements and chemical species on humans and the environment. The key results are as follows.

- For the Normal Evolution Scenario, concentrations of radionuclides and of non-radioactive contaminants in surface media are well below the relevant environmental protection criteria.
- For Disruptive Scenarios, impacts are also low. All non-radioactive contaminants and most radionuclides have calculated concentrations in surface media that are well below their screening concentration criteria for the base cases.
- There are some local exceedances of screening criteria for the Human Intrusion Scenario and the Severe Shaft Seal Failure Scenario. In particular, C-14 and Nb-94 would locally exceed soil criteria by a factor of 20 if the drilling debris from the repository were to be dumped on the surface at the site in the Human Intrusion Scenario. Also, C-14 could locally exceed the surface water screening criteria by a factor of 1.4 in the Severe Shaft Seal Failure Scenario.
- Since these higher concentrations are local, the screening criteria are conservative, and the scenarios are very unlikely, the risk to biota from these scenarios is low.

Implications on Design

- Calculations indicate that there is no benefit to be gained from backfilling the repository due to the significant containment already provided by the host geology and the shaft seals. Backfilling results in a higher gas pressure within the repository after closure due to a reduction in void volume.
- The calculations have emphasized the importance of the shaft seals in limiting contaminant fluxes in groundwater and gas from the repository. The damaged zone in the rock around the concrete monolith at the shaft base is a key pathway to the shafts.
- Some contaminants that do migrate up the shafts as gas or dissolved species can be laterally diverted into the higher permeability Silurian units (Guelph and Salina A1 upper

carbonate). The low-permeability shaft seals in the Silurian are effective in directing contaminant transport into these features.

Uncertainties

The long timescales under consideration mean that there are uncertainties about the way in which the system will evolve. These uncertainties have been treated in the current assessment through: the assessment of a range of scenarios, models and data; the adoption of conservative scenarios, models and data; and the adoption of a stylized approach for the representation of future human actions and biosphere evolution. The key uncertainties in terms of their importance to potential impacts are as follows.

- **Gas pressure and repository saturation** are important in determining the release of radioactivity into repository water, and the potential for C-14 release through gas in the first 60,000 years. Therefore, the processes that control these parameters are important. They were approached in this safety assessment through use of a range of calculation cases to test the importance of uncertainties in those contributing processes.

- **Shaft seal and EDZ properties** and their evolution with time. Variant calculation cases for the Normal Evolution Scenario and the Severe Shaft Seal Failure Scenario calculations emphasize the importance of the shaft seals, particularly in the first 60,000 years following closure.

- **Glaciation effects.** Although geological evidence at the site indicates that the deep geosphere has not been affected by past glaciation events and that the deep groundwater system has remained stagnant, glaciation is expected to have a major effect on the surface and near-surface environment and it is not entirely predictable. It should, however, be noted that ice-sheet coverage of the site is likely to occur only after 60,000 to 100,000 years, at which point the primary remaining hazard will be long-lived radionuclides in groundwater rather than gaseous C-14. Calculations have shown that the deep groundwaters are stable and transport is diffusion-dominated, so dissolved radionuclides will be contained in the deep geosphere with large safety margins.

- **Chemical reactions**. Under the highly saline conditions of the deep geosphere at the DGR site, several aspects of the chemistry are uncertain due to the limited database. In particular, this includes the sorption of contaminants on seal materials and host rocks, as well as mineral precipitation/dissolution reactions. Generally, conservative values have been adopted in this assessment.

The geosphere is clearly key to the DGR safety. In general, the attributes of the geosphere are sufficiently well known to support the safety assessment. However, some aspects are still uncertain, such as the cause of the over/underpressures. These geosphere uncertainties have been considered in this assessment through a range of scenarios, calculation cases and conservative parameter values. Although further resolution of these uncertainties is desirable to increase confidence in the safety assessment, they have not been found to be important to the conclusions of this assessment.

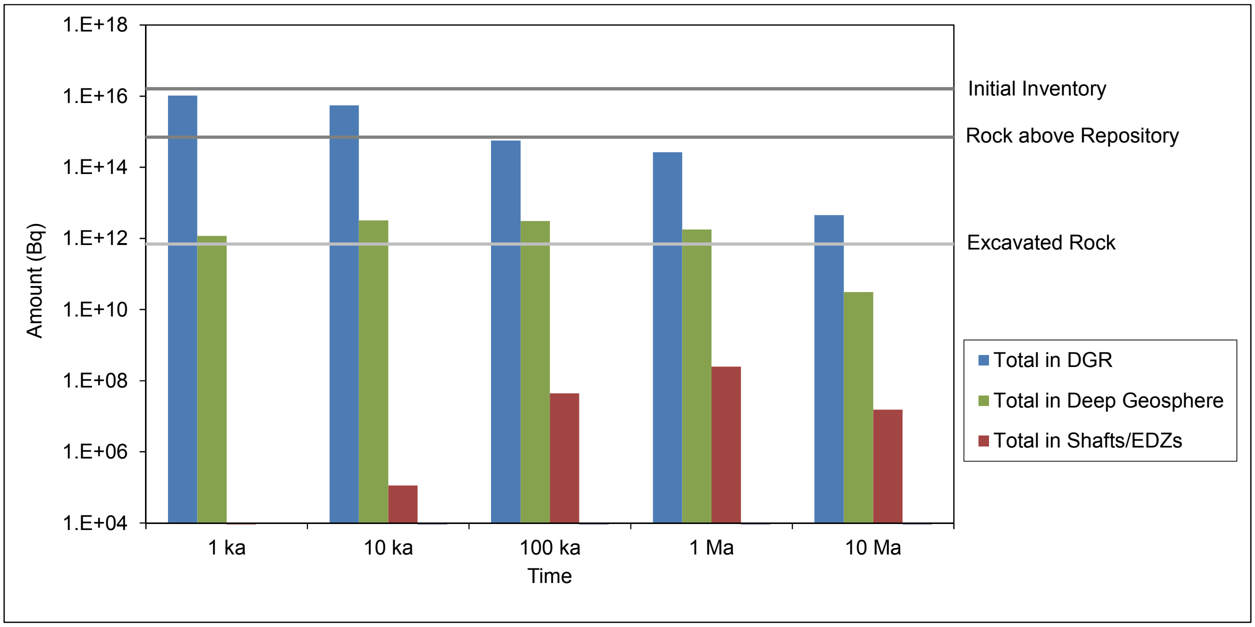
The Geoscientific Verification Plan outlines plans to initiate tests of important processes and materials in the rock during DGR construction - for example, EDZ measurements. Also, the shaft seal design will not be finalized until the decommissioning application several decades from now, and will take advantage of knowledge gained over the intervening period. While these tests plus further safety and geoscience modelling work will improve confidence in the assessment, the results presented here show that the DGR meets the postclosure safety criteria, that it provides isolation and containment of the wastes, and that the system safety is robust, i.e., the system will maintain its integrity and reliability under a range of conditions. The uncertainties should be interpreted in the context of the low calculated impacts; for example, calculated doses for all Normal Evolution Scenario variant cases are more than five orders of magnitude below the dose criterion.

Conclusions

Consistent with the guidelines for the preparation of the EIS for the DGR and the regulatory guide for assessing the long-term safety of radioactive waste management (G-320), the postclosure safety assessment has evaluated the DGR's ability to perform in a manner that will protect human health and the environment from the emplaced waste for an expected evolution scenario, as well as a number of disruptive ("what if") scenarios.

The assessment calculations for the Normal Evolution Scenario indicate that the DGR system provides effective containment of the emplaced contaminants. Most radionuclides decay within the repository or the deep geosphere (Figure E3). The amount of contaminants reaching the surface is very small, such that the maximum calculated impacts for the Normal Evolution Scenario are much less than the public dose criterion of 0.3 mSv/a for all calculation cases. In addition, potential impacts of radionuclides on biota and non-radioactive contaminants on humans and non-human biota are well below the relevant criteria.

The isolation afforded by the location and design of the DGR limits the likelihood of disruptive events potentially able to bypass the natural barriers to a small number of situations with very low probability. Even if these events were to occur, the analysis shows that the contaminants in the waste would continue to be contained effectively by the DGR system such that the risk criterion is met.



Note: The natural radioactivity in the rock above the repository footprint and in the excavated rock volume are shown.

Figure E3: Distribution of Activity in System at Different Times for the Normal Evolution Scenario Reference Case

TABLE OF CONTENTS

LIST OF TABLES

Page

LIST OF FIGURES

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1. INTRODUCTION

1.1 Background

Ontario Power Generation (OPG) is proposing to build a Deep Geologic Repository (DGR) for Low and Intermediate Level Waste (L&ILW) near the existing Western Waste Management Facility (WWMF) at the Bruce nuclear site in the Municipality of Kincardine, Ontario (Figure 1.1 and Figure 1.2). The Nuclear Waste Management Organization (NWMO), on behalf of OPG, is preparing the Environmental Impact Statement (EIS) and Preliminary Safety Report (PSR) for the proposed repository (Figure 1.3).

The postclosure safety assessment evaluates the long-term safety of the proposed facility and provides supporting information for the EIS (OPG 2011a) and PSR (OPG 2011b). It builds upon the previous assessment (QUINTESSA et al. 2009) and has been refined to take account of the revised waste inventory and repository design, and the greater understanding of the site that has been developed as the project has advanced.

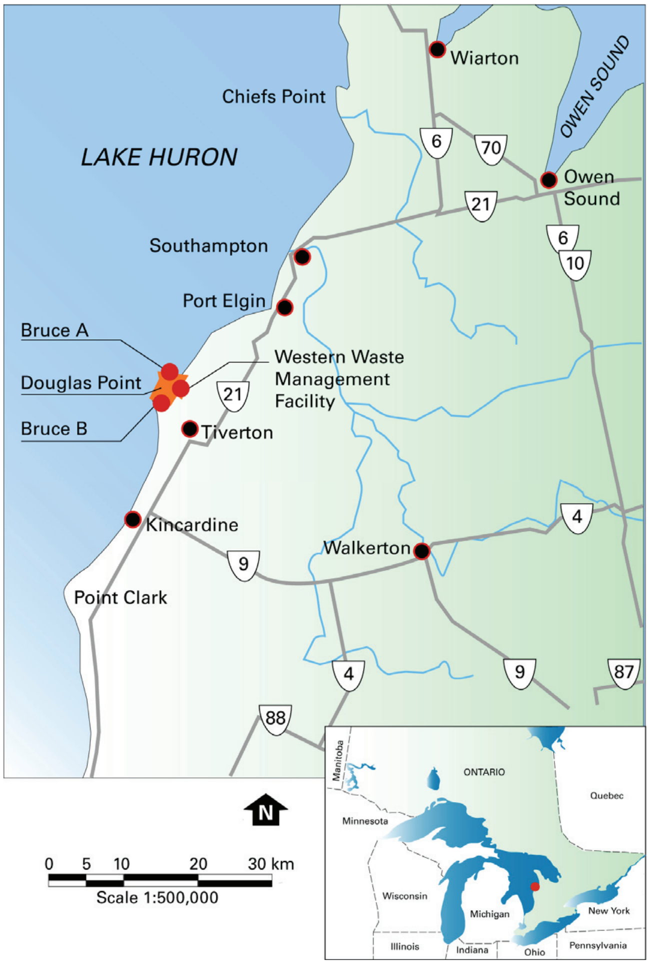

Figure 1.1: Location of the Bruce Nuclear Site, Ontario

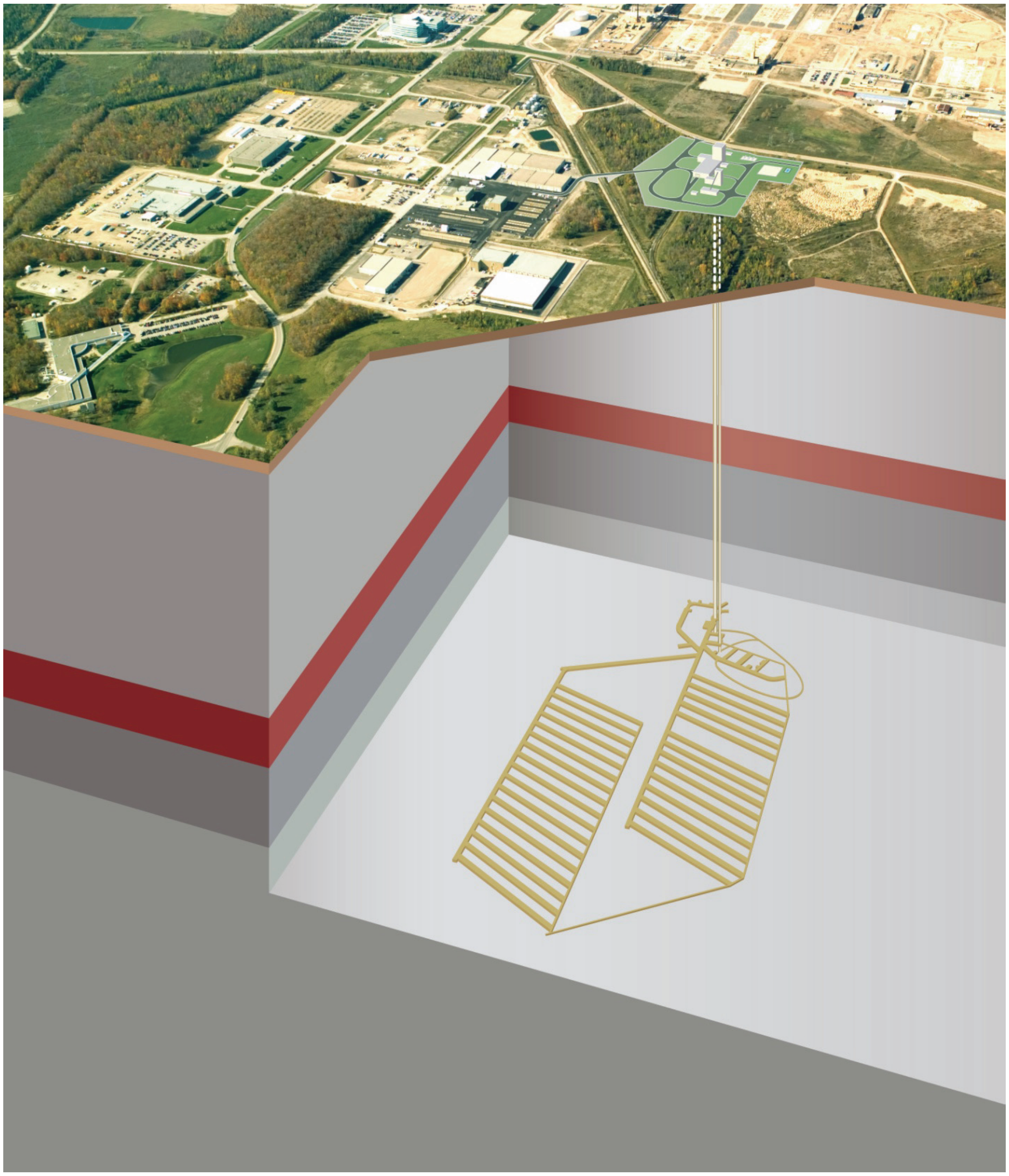

Figure 1.2: The DGR Concept at the Bruce Nuclear Site

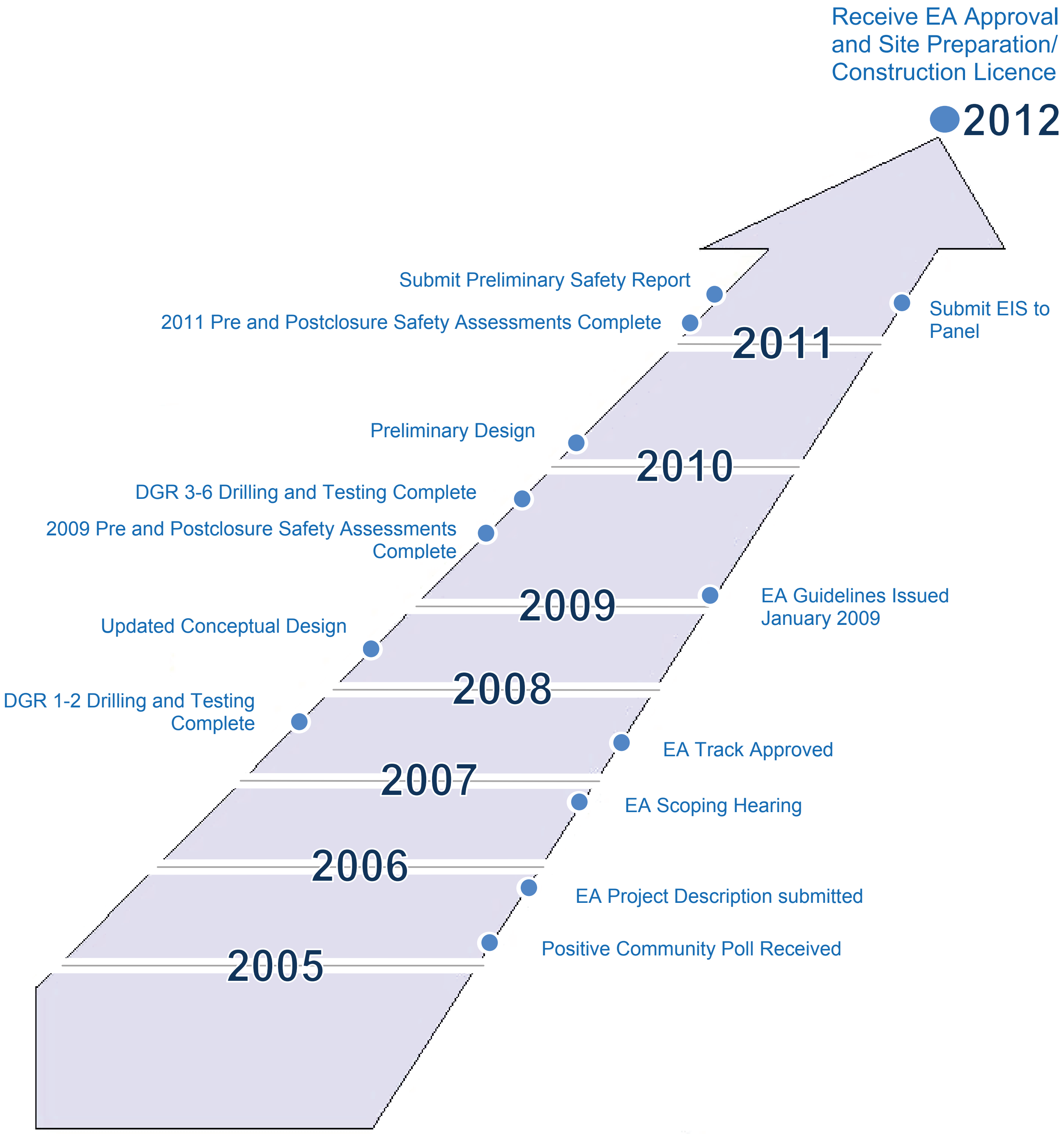

Figure 1.3: DGR Project Schedule

1.2 Purpose and Scope

The purpose of the current report is to provide a technical summary of the work undertaken and results obtained for the assessment of the postclosure radiological and non-radiological safety of the DGR. Other aspects of the DGR work program (e.g., operational safety, inventory, facility design, site characterization and geosynthesis) are considered in separate technical reports. The information provided in the current safety assessment report, together with information from these other technical reports, is synthesized to produce the overarching PSR (Figure 1.4). In particular, the PSR provides an integrated collection of arguments and evidence gathered from all these technical reports to demonstrate the safety of the DGR system (OPG 2011b).

The safety assessment report has been written for a technical audience that is familiar with the scope of the DGR project, the Bruce nuclear site, and the process of assessing the long-term safety of radioactive waste deep geologic repositories. The technical terms used in this report are consistent with those defined in the DGR project glossary (NWMO 2010a).

This report provides an overview of the postclosure safety assessment drawing upon technical arguments and evidence from the following set of supporting technical documents that present the detailed results and findings of the current postclosure safety assessment (Figure 1.5).

- The Analysis of the Normal Evolution Scenario report (QUINTESSA 2011a) describes the assessment of the Normal Evolution Scenario (i.e., the expected long-term evolution of the repository and site following closure). The associated conceptual and mathematical models and data are documented, and their implementation in and evaluation using the AMBER software tool is described.
- The Analysis of Human Intrusion and Other Disruptive Scenarios report (QUINTESSA and SENES 2011) describes the assessment of four Disruptive Scenarios (i.e., events that could lead to possible penetration of barriers and abnormal degradation and loss of containment). For each Disruptive Scenario, the associated conceptual and mathematical models and data are documented, and their implementation in and evaluation using AMBER is described.
- The System and Its Evolution report (QUINTESSA 2011b) describes the proposed repository, its waste, the site's geology and present-day surface environment. Their expected evolution over the postclosure period is described and the scenarios for assessment are identified.
- The Features, Events and Processes report (QUINTESSA et al. 2011) lists the feature, events and processes evaluated in the assessment and justifies their inclusion/exclusion.
- The Data report (QUINTESSA and GEOFIRMA 2011a) documents the waste, repository, geosphere, and surface environment data required for the postclosure safety assessment. Reference data values are justified and supporting references provided.
- The Groundwater Modelling report (GEOFIRMA 2011) describes the detailed groundwater flow and transport modelling work that has been undertaken using the FRAC3DVS-OPG code to support the assessment.
- The Gas Modelling report (GEOFIRMA and QUINTESSA 2011) describes the detailed gas generation and transport modelling work that has been undertaken using the T2GGM code to support the assessment.

These technical documents are cited at appropriate points in the current report and the reader is directed to relevant sections in them where a more detailed discussion is provided of the technical arguments and evidence summarized in the current report.

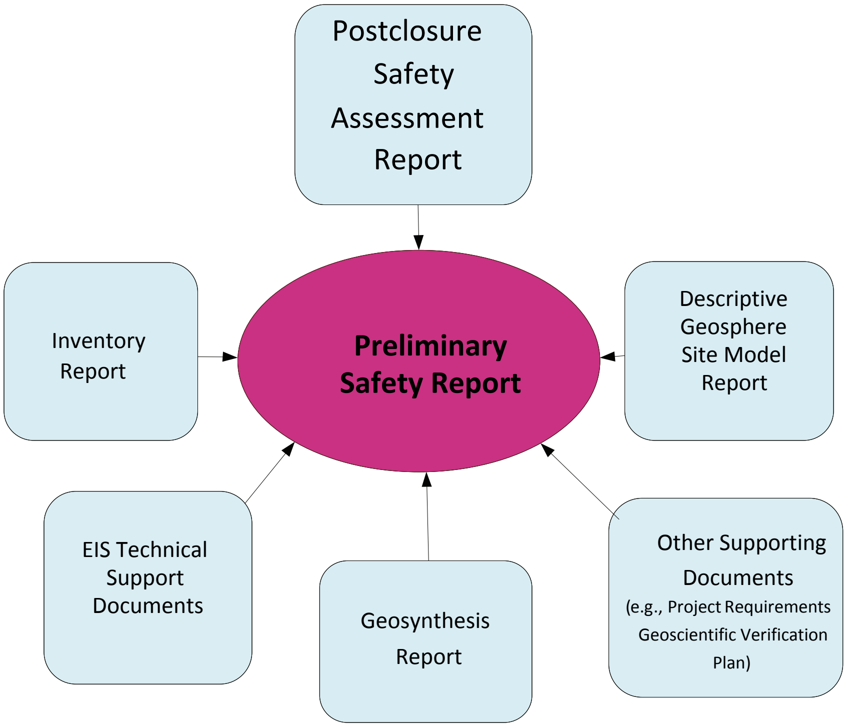

Figure 1.4: DGR Technical Reports Contributing to the Preliminary Safety Report

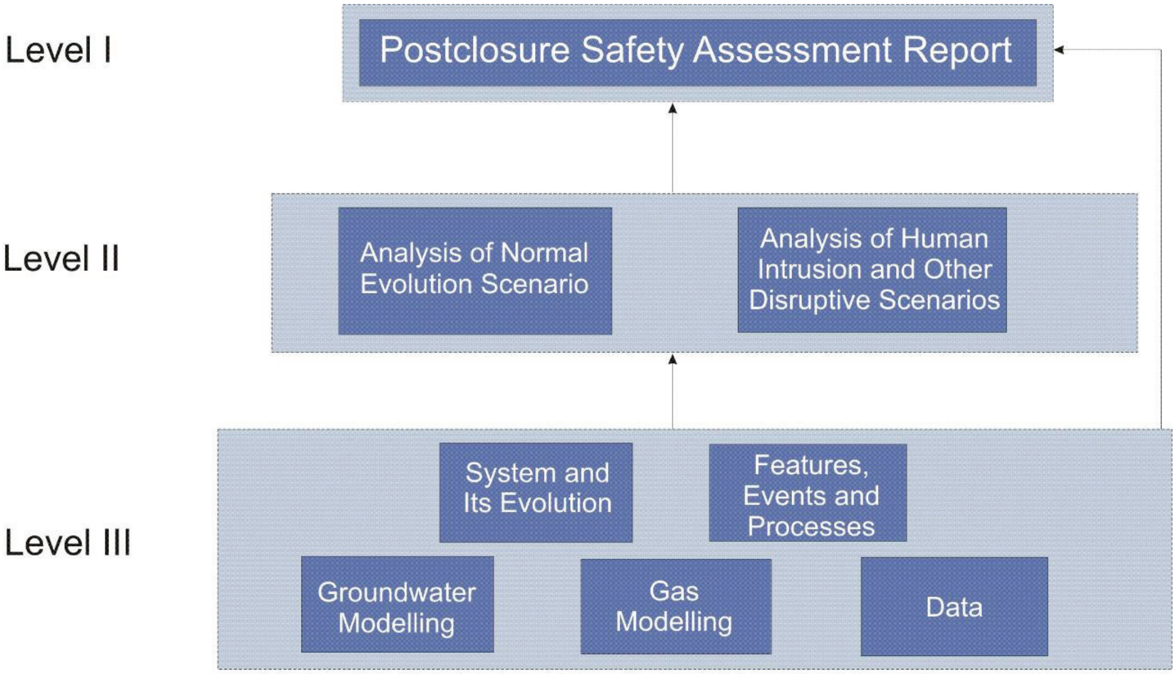

Figure 1.5: Document Structure for the Postclosure Safety Assessment

1.3 Report Outline

The approach used for the postclosure safety assessment is outlined in Chapter 2. The report is structured consistent with the steps of the approach, i.e.,:

- Assessment context, which consists of high-level assumptions and constraints that reflect the regulatory requirements, purpose and focus of the safety assessment (Chapter 3);
- System description (waste, repository, geological setting and surface environment) (Chapter 4);
- Scenario identification and description process (Chapter 5);
- The models assessed (Chapter 6);
- The results obtained (Chapter 7); and
- The summary and conclusions (Chapter 8).

2. ASSESSMENT APPROACH

The Canadian Nuclear Safety Commission (CNSC) has issued a regulatory guide (G-320) on assessing the long-term safety of radioactive waste management (CNSC 2006), which is cited in the Guidelines for the Preparation of the Environmental Impact Statement for the DGR for Low and Intermediate Level Radioactive Wastes (CEAA and CNSC 2009). The CNSC expects the applicant to use a well-structured, transparent and traceable approach to assess 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 analyzed; provide clear links to other components of the DGR program including the safety case and its associated safety functions and arguments; demonstrate use of appropriate quality assurance; be amenable to review; and provide a basis for future iterations.

The associated safety assessment documentation should be comprehensive and according to G-320 (CNSC 2006) should include:

- A selection of an appropriate methodology;
- The assessment context;
- The system description;
- The assessment timeframes;
- The assessment scenarios;
- The development and use of assessment models; and
- The interpretation of results.

The methodology used to assess the long-term performance of the DGR is outlined below; the approach is presented in detail in subsequent sections of this report, each of which deals with a specific step of the methodology.

The safety assessment has been carried out using an approach consistent with international best practice, as embodied in the draft safety standards on the safety case and safety assessment for radioactive waste disposal from the International Atomic Energy Agency (IAEA) (IAEA 2010) and the recommendations of the IAEA program for the Improvement of Safety Assessment Methodologies (ISAM) (IAEA 2004). It has been conducted as part of an iterative process in conjunction with site characterization, waste characterization and facility design. The quality management, including software and data control, is described further in QUINTESSA (2010).

As IAEA (2010) notes, the safety assessment is part of a larger safety case. This overall safety case, including in particular the integration of safety arguments, is presented in Section 14.2 of the PSR (OPG 2011b). The current report focuses on the safety assessment rather than the safety case.

The approach comprises the following basic steps (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 (presented in Chapter 3).
- The current information on the waste, repository, geological setting and surface environment relevant to postclosure safety is reported (presented in Chapter 4).
- A range of internally consistent potential future evolutions of the DGR system (scenarios) is systematically identified (presented in Chapter 5).

- 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 software tools (presented in Chapter 6).
- The results are analyzed, interpreted and discussed to inform on the performance of the system, its overall robustness, and the nature and role of key uncertainties (presented in Chapter 7). Particular emphasis is given to the comparison of the results for the identified safety and performance indicators against the relevant reference levels.

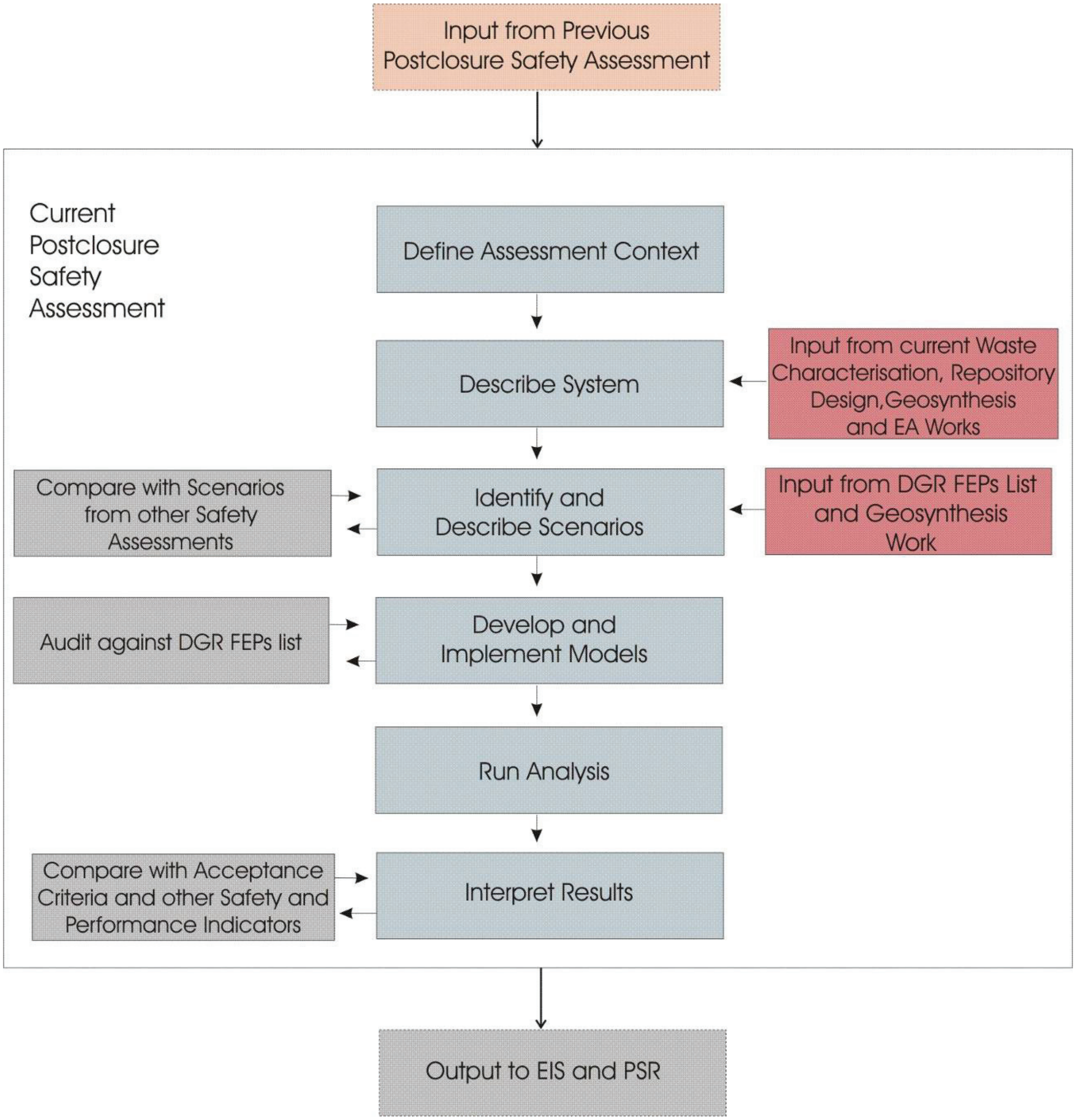

Figure 2.1: Approach Used in the Postclosure Safety Assessment

3. ASSESSMENT CONTEXT

3.1 Purpose of the Assessment

The purposes of the assessment are:

- To quantitatively assess the postclosure radiological and non-radiological safety of the proposed Deep Geologic Repository (DGR) at the Bruce nuclear site;
- To identify those uncertainties that have the greatest potential impact on the long-term performance of the DGR system; and
- To provide information that supports the Environmental Impact Statement (EIS) (OPG 2011a) and Preliminary Safety Report (PSR) (OPG 2011b).

3.2 Audience

This report is written for technical reviewers of the DGR project, such as the Canadian Nuclear Safety Commission (CNSC), to provide more supporting technical detail than provided in the EIS and PSR.

3.3 Regulatory Requirements and Guidance

The DGR will be classified as a Class 1B nuclear facility under the *Nuclear Safety and Control Act* (NSCA), being “a facility for the disposal of a nuclear substance generated at another nuclear facility”. Under the NSCA, OPG will require licences from the CNSC to prepare a site, and to construct, operate, decommission and abandon the DGR. It is also necessary for OPG to address the *Canadian Environmental Assessment Act* (CEAA) which requires an Environmental Impact Statement (EIS) for a project before the CNSC (as the federal authority) issues a licence (CEAA, Paragraph 5 (1) (d)). The Canadian Environmental Assessment Agency and CNSC, in consultation with other agencies such as Health Canada, has prepared guidelines for the preparation of the EIS for the DGR (CEAA and CNSC 2009). These guidelines require the whole lifecycle of the DGR to be assessed in the EIS. A description of how the facility would perform over the long-term is required to help determine the safety of the facility and its potential impact on human health and the environment.

A Joint Review Panel will be convened to review the EIS, the Application for the Site Preparation and Construction Licences, and other supporting documentation. The decision to grant the Licences would be made by the Joint Review Panel after it receives and reviews the documentation, holds public hearings, and obtains environmental impact statement acceptance by the Governor in Council[2].

Section 13 of the EIS guidelines is of particular relevance to the current report, since it discusses the assessment of the long-term safety of the DGR. The section identifies a number of topics that need to be addressed in the postclosure safety assessment. These are listed in Table 3.1.

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[2] Separate licences will be required for the operation, decommissioning, and abandonment of the DGR.

Table 3.1: Relevant Guidance from the EIS Guidelines for the DGR[3]

Issue	Guidance
Demonstration of long-term safety	• Need to provide reasonable assurance that the DGR will perform in a manner that protects human health and the environment from the emplaced waste through the use of a long-term safety assessment based on a pathways analysis of contaminant releases, contaminant transport, receptor exposure and potential effects based on a scenario of expected evolution of the disposal facility and site.
Selection of scenarios	• Long-term assessment of scenarios should be sufficiently comprehensive to account for all of the potential future states of the site and the environment. Scenarios should be developed in a systematic, transparent and traceable manner. • The anticipated evolution of the repository under different scenarios has to be supported by a combination of expert judgment, field data on the past evolution of the site, and also mathematical models that might need to couple chemical, thermal, hydrologic, hydrogeologic and mechanical processes that play key roles in the repository evolution. • The safety assessment should include a central scenario of the normal (or expected) evolution of the site and facility with time. It should be based on reasonable extrapolation of present-day site features and receptors lifestyles. It should include the expected evolution of the site and degradation of the waste disposal system (gradual or total loss of barrier function) as it ages. • Additional scenarios should be assessed that examine the impacts of low-probability disruptive events or modes of containment failure that lead to the possible abnormal degradation and loss of containment. • The approach and screening criteria used to exclude or include scenarios should be justified and well documented.
Provision of additional arguments and multiple lines of reasoning	• Use of different safety assessment strategies: e.g., using a combination of approaches such as scoping and bounding calculations, deterministic and probabilistic approaches. • Demonstrating that the waste disposal system will maintain its safety function under extreme conditions, disruptive events or unexpected containment failure. • Use of complementary safety indicators to doses and environmental concentrations such as: waste dissolution rates; groundwater age and travel time; fluxes of contaminants; concentrations of contaminants in specific environmental media; and changes in toxicity of the waste.
Demonstration of confidence in mathematical models	• Performing independent predictions using entirely different assessment strategies and computer tools. • Demonstrating consistency amongst the results of the long-term assessment model and complementary scoping and bounding assessments. • Applying the assessment model to an analog of the waste management system to build confidence through a post audit of the real data available from an analog. • Performing model intercomparison studies of benchmark problems. • The choice of solute transport modelling codes used should be justified and supporting information on code verification and validation provided. • Scientific peer review by publication in open literature and widespread use by the scientific and technical community will add to the confidence in the assessment model.

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[3] See Table 7.24 for summary of how these were addressed.

Issue	Guidance
Interpretation of results and comparison with acceptance criteria	• The proponent will establish and justify the acceptance criteria adopted for the assessment • Compliance with the acceptance criteria and with regulatory guidance must be evaluated, and the uncertainties associated with the assessment should be analyzed. • Demonstration of a thorough understanding of the underlying science and engineering principles, which are controlling the assessment results. • An uncertainty analysis of the predictions should be performed to identify the sources of uncertainty and determine the effects of these uncertainties on safety. This analysis should distinguish between uncertainties arising from uncertainties in site characterization data, in the conceptual site descriptive model, in assumptions of the scenario, and in the mathematics of the assessment model. • For the uncertainties, which have important impact on long-term safety, follow-up field and laboratory investigation programs in combination with refinement of mathematical models should be proposed.

Further generic guidance on assessing long-term safety of radioactive waste management is set out in the regulatory guide G-320 (CNSC 2006). This provides guidance on performing long-term assessments and interpreting the results. Recommendations from G-320 relevant to the postclosure safety assessment are summarized in Table 3.2.

3.4 Acceptance Criteria

Section 6.1 of G-320 states that “the applicant is expected to propose justified and scientifically defensible benchmarks and acceptance criteria for the assessment” (CNSC 2006). It is noted that acceptance criteria can be derived from current values of regulatory limits, standards, objectives, and benchmarks, which may be reduced by applying an additional margin of safety, such as a dose constraint or a safety factor.

In light of the Canadian regulatory requirements and guidance (Section 3.3) and international standards and guidance from organizations such as the International Commission on Radiological Protection (ICRP) and the International Atomic Energy Agency (IAEA), the acceptance criteria discussed below have been proposed to CNSC for application to the postclosure safety assessment (OPG 2008, NWMO 2009, 2010b). Specific criteria have been proposed for:

- The radiation exposure of people that may arise from the expected evolution of the DGR 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 repository system, “Disruptive Scenarios”;
- The radiation effects on non-human biota; and
- The effects of non-radioactive contaminants.

The CNSC review of the radiological criteria for the Normal Evolution Scenario (see Section 3.4.1) and for the Disruptive Scenarios (see Section 3.4.2) (CNSC 2008) concluded that CNSC staff found the proposed approach to be consistent with the information and recommendations made in the regulatory guide G-320 (CNSC 2006), the ICRP’s 2007 recommendation (ICRP 2007), and the IAEA safety requirements for geological disposal of radioactive waste (IAEA 2006a).

Table 3.2: Relevant G-320 CNSC Expectations and Recommended Approaches[4]

Issue	Guidance
Assessment approach	The CNSC expects the safety assessment to demonstrate the applicant's understanding of the waste management system through a well-structured, transparent, and traceable methodology. 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.
Hazardous substances, non-human biota	Long-term assessments should address the impact on humans and on non-human biota from both radioactive and hazardous non-radioactive constituents of the radioactive waste.
Time frame	Assessments of the future impact that may arise from the radioactive waste are expected to include the period of time during which the maximum impact is predicted to occur. The assumed performance time frames of engineered barriers and the evolution of their safety function with time should be documented and justified, with reference to current national or international standards where appropriate.
Institutional controls	A submission from a licence applicant should identify the role that institutional controls play in waste management system safety, and how that role is taken into account in the safety assessment.
Assessment end points	The principal regulatory requirements are those that address radiation dose and environmental concentrations. Several other safety indicators, such as those that reflect containment barrier effectiveness or site-specific characteristics that can be directly related to contaminant release and transport phenomena, can also be presented to illustrate the long-term performance of a waste management system.
Radiation protection	Long term safety assessments of a facility or contaminated site should provide reasonable assurance that the regulatory radiation dose limit for public exposure will not be exceeded. However, to account for the possibility of exposure to multiple sources and to help ensure that doses resulting from the facility being assessed are as low as reasonably achievable (ALARA), an acceptance criterion that is less than the regulatory limit of 1 mSv/a should be used.
Environmental concentrations of hazardous substances	Benchmark values for protection from hazardous substances can be found in federal and provincial environmental objectives and guidelines. Where available, the Canadian Council of Ministers of the Environment's (CCME's) Canadian Environmental Quality Guidelines 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 provincial guidelines should be used. Where Canadian jurisdiction has not established human health-based guidelines, benchmarks may be based on those of the United States Environmental Protection Agency. Benchmarks that are proposed based on sources of information other than those identified above may need additional justification for their use.

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[4] See Table 7.25 for summary of how these were addressed.

Issue	Guidance
Optimization	The design of a nuclear facility should be optimized to exceed all applicable requirements. In particular, a radioactive waste management facility should more than meet the regulatory limits, remaining below those limits by a margin that provides assurance of safety for the long term.
Scenarios	A long-term assessment scenario should be sufficiently comprehensive to account for all of the potential future states of the site and the biosphere. It is common for a safety assessment to include a central scenario of the normal, or expected, evolution of the site and the facility over time, and additional scenarios that examine the potential impact of disruptive events or modes of containment failure. Scenarios should be developed in a systematic, transparent, and traceable manner through a structured analysis of relevant features, events, and processes (FEPs) that are based on current and future conditions of site characteristics, waste properties, and receptor characteristics and their lifestyles.
Intrusion scenarios	Scenarios concerning inadvertent human intrusion into a waste facility could predict doses that are greater than the regulatory limit of 1 mSv/a. 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 risk from the intrusion should, therefore, be reported. Reasonable efforts should be made to limit the dose from a high-consequence intrusion scenario, and to reduce the probability of the intrusion occurring.
Receptors	Receptors may be identified through the FEP analysis or from evaluation of valued ecosystem components (VECs). The human receptors in a scenario may be based on the ICRP concept of a critical group for radiological protection of persons. The habits and characteristics that are assumed for the human critical group should be based on reasonably conservative and plausible assumptions that consider current lifestyles and available site-specific or region-specific information. Non-human receptors usually include a range of different plants and animals occurring at various levels of biological organization (e.g., organism, population, community, or ecosystem). Among other criteria, the receptors should represent the taxonomic groups most likely to receive a higher exposure from a particular pathway.
Data	The use of generic or default data in place of site-specific data in developing the conceptual and computer models may be acceptable when there is no site-specific data available, such as in early stages of development; however, with the acquisition of as-built information and operational data, and increased understanding of site characteristics throughout the facility lifecycle, site-specific data should be used.
Conceptual and mathematical models	A conceptual model of the waste management system should be developed to the rigour and level of detail that is appropriate for the purpose of the assessment. The conceptual model should account for uncertainties, incomplete information in the system description, and simplifications and assumptions adopted during interpretation of the site characterization data. These simplifications and assumptions, and any resulting restrictions or limitations in the model, should be identified and discussed in the assessment. Justification for rejecting alternate interpretations should be discussed.
Computing tools	All software used in an assessment should conform to accepted quality assurance (QA) standards.

Issue	Guidance
Understanding	Demonstrate a thorough understanding of the underlying science and engineering principles that are controlling the assessment results.
Uncertainties	A formal uncertainty analysis of the predictions should be performed to identify the sources of uncertainty. This analysis should distinguish between uncertainties arising from input data; scenario assumptions; the mathematics of the assessment model; and the conceptual models.
Confidence building	Claims of long-term safety submitted to support a licence application may be evaluated by way of the 'weight of evidence' and confidence-building arguments (i.e., scientific evidence, multiple lines of reasoning, reasoned arguments, and other complementary arguments) that support the assessment and its conclusions.
Compliance	Interpretation should include evaluation of compliance with the acceptance criteria and analysis of the uncertainties associated with the assessment. Comparison of the assessment results with acceptance criteria to provide a reasonable assurance of future safety should include discussion of the conservatism of the model results and the conservatism built into the acceptance criteria for the safety indicators.

3.4.1 Radiological Criteria for the Normal Evolution Scenario

The Normal Evolution Scenario describes the expected long-term evolution of the repository and site following closure based on reasonable extrapolations of present-day site features and receptors' lifestyles, and including its expected degradation (loss of barrier functions) with time (see Section 5.1).

The criteria adopted for public radiological exposure as a result of the Normal Evolution Scenario are (OPG 2008):

- A dose constraint of 0.3 mSv/a to the critical group (i.e., the group of people representative of those individuals in the population that are expected to receive the highest annual radiological dose);
- Optimization below dose constraint[5];
- Doses are calculated for an average adult member of the critical group; and
- The assessment encompasses the time of maximum calculated impact.

The above dose constraint is approximately an order of magnitude below the annual Canadian individual dose received from natural background radiation (Grasty and LaMarre 2004) and is set at a level that is below the regulatory dose limit of 1 mSv/a for public exposure to allow for the potential exposure to multiple sources of radioactivity, and to help ensure that doses resulting from the facility are as low as reasonably achievable.

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[5] CNSC (2006) states that the design of a radioactive waste management facility should be optimized by ensuring that it more than meets the regulatory limits, remaining below those limits by a margin that provides assurance of safety for the long term.

3.4.2 Radiological Criteria for Disruptive Scenarios

Disruptive Scenarios postulate the occurrence of unlikely events or situations leading to possible penetration of barriers and abnormal loss of containment (CNSC 2006, Section 7.5.2). They include speculative or "what if" calculations that test the robustness of the DGR system.

A tiered approach is adopted for disruptive scenarios, recognizing the speculative nature of some scenarios (OPG 2008). First, a dose criterion of 1 mSv/a is used for radiological exposure of humans under credible scenarios. Second, if calculated doses exceed 1 mSv/a for a scenario, the acceptability of results from that 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 criterion. Where the probability of exposure can be quantified without excessive uncertainty, a measure of risk can be calculated based on the probability of exposure and the health effects if the exposure occurs. As a general guide, this can be compared with a reference health risk value of 10^{-5}/a (OPG 2008).

Human intrusion is a special case. According to G-320 (CNSC 2006), “human intrusion scenarios are to be assessed separately, and the intrusion scenario probability should be considered in interpreting dose results. Reasonable efforts should be made to limit the dose from a high-consequence intrusion scenario and to reduce the probability of the intrusion occurring.” In this regard, it should be noted that the fundamental design feature of the DGR is that the wastes are isolated at 680 m depth, which specifically reduces the probability of intrusion.

3.4.3 Radiological Criteria for Non-human Biota

Potential radiological impacts on non-human biota are assessed for both Normal Evolution and Disruptive Scenarios. The proposed screening criteria, which have been accepted by the CNSC (CNSC 2009), are expressed as No Effect Concentrations (NECs) for radionuclides of interest in the postclosure safety assessment (Table 3.3). These NECs are documented in Garisto et al. (2008) and are derived from Estimated No Effect Values (ENEVs) for indicator species. The ENEVs used are the most conservative values provided by ENVIRONMENT CANADA and HEALTH CANADA (2003) and UNSCEAR (1996). The radionuclide concentration corresponding to each radionuclide’s ENEV is calculated for each indicator species in each applicable medium (surface water, groundwater, soil and sediment), assuming nil concentration in the other media. The NEC is then defined as the lowest concentration in each medium for all indicator species.

If any radionuclide concentrations exceed the NECs under the Normal Evolution Scenario, an Ecological Risk Assessment (ERA) will be carried out for the radionuclides that exceed the criteria. The ERA will take into account uncertainties and the potential need for the effect of several radionuclides to be summed. If any concentrations exceed these NECs under Disruptive Scenarios, then the acceptability would be 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 dose criterion.

Table 3.3: No Effect Concentrations for Non-Human Biota

Radionuclide	Media			
	Groundwater (Bq/L)	Soil (Bq/kg)	Surface Water (Bq/L)	Sediment (Bq/kg)
C-14	1.6E+6	3.5E+2	2.4E-1	2.8E+5
Cl-36	3.0E+5	5.0E+0	3.1E+0	4.1E+4
Zr-93	5.9E+6	2.8E+5	1.8E+0	5.0E+6
Nb-94	3.6E+4	1.3E+2	1.6E-2	2.6E+4
Tc-99	8.1E+5	6.0E+1	8.0E-1	3.0E+6
I-129	9.0E+5	1.9E+4	3.2E+0	1.2E+6
Ra-226	5.9E+2	2.8E+2	5.9E-4	9.3E+2
Np-237	5.8E+2	5.0E+1	5.8E-2	1.1E+3
U-238	5.6E+2	4.9E+1	2.3E-2	6.6E+4
Pb-210	1.8E+5	3.7E+3	5.0E+0	6.3E+3
Po-210	5.4E+2	3.0E+1	7.0E-3	1.1E+5

3.4.4 Criteria for Non-radioactive Contaminants

Potential impacts from non-radioactive elements or chemical species are assessed for both Normal Evolution and Disruptive Scenarios in environmental media relevant to human health and environmental protection.

The proposed criteria (NWMO 2010b), which have been accepted by the CNSC (CNSC 2010), are based on federal (Canadian Council of Ministers for the Environment - CCME) and provincial (Ontario Ministry of the Environment - MoE) guideline concentrations for groundwater, surface water, soil and sediment (Table 3.4). Guideline concentrations for groundwater, soil and sediment are provided primarily from MoE (2009), since these are the most conservative. The most conservative guideline concentrations values between MoEE (1994) and CCME (2007) are used for surface waters. For several elements of potential interest, no criteria were provided in MoEE (1994), CCME (2007) or MoE (2009). In these cases, the exposure is evaluated based solely on surface water criteria from Sneller et al. (2000), Suter and Tsao (1996), ODEQ (2001) and CCOHS (2009).

The impacts from hazardous substances released from the DGR are assessed in a tiered approach. Contaminants are screened first based on a comparison of estimated environmental concentrations with the criteria given in Table 3.4. If any concentrations exceed these criteria under the Normal Evolution Scenario, these species will be assessed further in a tiered approach with decreased conservatism in models. If any concentrations exceed these criteria under Disruptive Scenarios, then the acceptability would be 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 3.4: Environmental Quality Standards for Non-Radioactive Elements and Chemical Species

Species	Groundwater (µg/L)	Note	Soil (µg/g)	Note	Surface Water (µg/L)	Note	Sediment (µg/g)	Note
Ag	0.3	A	0.5	A	0.1	H, P	0.5	A
As	13	A	11	A	5	I, P	6	A
B	1700	A	36	A	200	I	-	B
Ba	610	A	210	A	-	B	-	B
Be	0.5	A	2.5	A	11	J	-	B
Br	-	B	-	B	1700	T	-	B
Cd	0.5	A	1	A	0.017	Q	0.6	A
Chloro-benzene	0.01	C	0.01	C	0.0065	K	0.02	C
Chloro-phenol	0.2	D	0.1	D	0.2	L	-	B
Co	3.8	A	19	A	0.9	H	50	A
Cr	11	E	67	E	1	M	26	E
Cu	5	A	62	A	1	J	16	A
Dioxins/ Furans	1.5E-5	F	7E-6	F	0.3	N	-	-
Gd	-	B	-	B	7.1	U	-	B
Hf	-	B	-	B	4	V	-	B
Hg	0.1	A	0.16	A	0.004	R	0.2	A
I	-	B	-	B	100	I	-	B
Li	-	B	-	B	2500	S	-	B
Mn	-	B	-	B	200	S	-	B
Mo	23	A	2	A	40	I	-	B
Nb	-	B	-	B	600	W	-	B
Ni	14	A	37	A	25	H	16	A
PAH	0.1	G	0.05	G	0.0008	O	0.22	G
Pb	1.9	A	45	A	1	J	31	A
PCB	0.2	A	0.3	A	0.001	H	0.07	A
Sb	1.5	A	1	A	20	I	-	B
Sc	-	B	-	B	1.8	X	-	B
Se	5	A	1.2	A	1	P	-	B
Sn	-	B	-	B	73	Y	-	B
Sr	-	B	-	B	1500	Y	-	B
Te	-	B	-	B	20	T	-	B
Tl	0.5	A	1.0	A	0.3	I	-	B
U	8.9	A	1.9	A	5	I	-	B
V	3.9	A	86	A	6	I	-	B
W	-	B	-	B	30	I	-	B
Zn	160	A	290	A	20	J	120	A
Zr	-	B	-	B	4	I	-	B

Notes:

A ‘Full depth background site condition standard’ for Ontario from MoE (2009).
B No value available.
C As note A; values for hexachlorobenzene used.
D As note A; values for trichlorophenol used.

E As note A; values for total chromium used.
F As note A; values represent standard toxic equivalents (TEQ).
G As note A; values for anthracene used.
H Provincial Water Quality Objective (PWQO) for Ontario from MoEE (1994).
I Interim PWQO from MoEE (1994).
J Lowest PWQO/Interim PWQO conservatively adopted from MoEE (1994).
K PWQO for hexachlorobenzene from MoEE (1994).
L PWQO for dichlorophenols from MoEE (1994).
M PWQO for Cr (VI) from MoEE (1994).
N PWQO for dibenzofuran in MoEE (1994).
O Interim PWQO for anthracene in MoEE (1994).
P Freshwater CEQG from CCME (2007).
Q Cadmium interim freshwater CEQG from CCME (2007).
R Interim freshwater CEQG for methylmercury from CCME (2007).
S Irrigation water value from the Canadian Water Quality Guidelines for the Protection of Agricultural Water Uses from CCME (2007).
T Calculated from minimum of Oral rate/mouse LD50s from CCOHS (2009).
U Maximum Permissible Concentration (MPC) for freshwater from Sneller et al. (2000).
V Value for Zr used.
W Lowest available from ODEQ (2001).
X Lowest available MPC for freshwater for all rare earth elements from Sneller et al. (2000).
Y Tier II secondary chronic value from Suter and Tsao (1996).

3.5 Assessment End Points

The safety case for the DGR is presented in the Preliminary Safety Report, drawing on information from this safety assessment, from the geosynthesis work, and from other supporting activities (see Chapter 14, OPG 2011b). Compliance with the overall safety objective is achieved through demonstration that:

1. Postclosure and preclosure safety criteria are met;
2. The DGR provides long-term isolation and containment;
3. The DGR system is robust; and
4. The DGR can be constructed, operated and decommissioned safely.

The postclosure safety assessment provides supporting evidence for the first three of the above points through the calculation of various assessment end points.

Assessment end points are quantities used in a safety assessment to measure the impact of a repository and its performance in relation to its safety functions of long-term isolation and containment. They allow potential hazards or the performance of the repository system or its components to be evaluated and can be used to provide understanding of the system performance and confidence in the safety of the repository (IAEA 2003). Assessment end points can be categorized as either safety indicators or performance indicators (see, for example, the discussion in Marivoet et al. 2008).

In order to demonstrate that the postclosure acceptance criteria are met (Compliance condition #1), as given in Section 3.4, the following safety indicators are calculated:

- Radiation dose to humans to a “representative person”;
- Environmental concentrations of radionuclides; and
- Environmental concentrations of non-radioactive hazardous substances.

In addition, the following performance indicators are calculated in order to help demonstrate compliance conditions #2 and #3:

- Radiotoxicity of the waste[6];
- Contaminant amounts within various spatial domains (e.g., the repository, the host rock, and the wider geosphere) and temporal domains; and
- Fluxes of contaminants at various points in the DGR system.

"Radiation dose" refers to the sum of effective dose equivalents from external irradiation in a year plus the committed effective dose equivalent from intakes of radionuclides in the same year calculated using the recommendations developed by the ICRP. The most recent ICRP recommendations include an evaluation of new information on the risk of radiation exposure (ICRP 2007). The recommendation is largely the same as that presented in the ICRP's last main recommendations (ICRP 1991, 1996). However, the values for some important parameters like tissue weighting factors and the dose-risk factor have been updated. Although dose coefficients have not yet been updated with the ICRP's latest recommendation, the ICRP has noted that the dose coefficients given in ICRP Publication 72 (ICRP 1996) remain adequate (ICRP 2007).

The dose from each scenario is calculated for one or more hypothetical "representative persons". For the purposes of the protection of the public, a "representative person" is defined as an individual receiving a dose that is representative of the more highly exposed individuals in the population (ICRP 2006). The representative person is, therefore, the equivalent of the "average member of a critical group" defined in previous publications (e.g., ICRP 2000). Representative person(s) are identified and justified for each scenario under consideration.

Because the potential contamination of the biosphere would be chronic in its nature, the annual dose averaged over the lifetime of the representative person is a reasonable measure of radiological impact. This average is adequately represented by the annual dose to an adult (ICRP 2006). In addition, sensitivity cases are analyzed to indicate the dose to other age groups.

The timescale considered in this safety assessment is very long (see Section 3.6) and the reliability of quantitative predictions diminishes with increasing time (CNSC 2006). Therefore the long-term quantitative estimates of impacts such as dose should be seen as indicators rather than absolute measures of impacts.

3.6 Treatment of Uncertainties

The treatment of uncertainty is central to any assessment to establish the safety of a radioactive waste repository. Marivoet et al. (2008) note that many organizations use the following three broad categories to structure their analysis of uncertainties in postclosure safety assessments[7].

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[6] Sum of the radionuclide concentrations (Bq/kg) in waste multiplied by their respective ingestion dose conversion coefficients (Sv/Bq).

[7] The boundaries between these categories can overlap in that, depending upon how models are formulated, an uncertainty may be classed as a model or a data uncertainty.

- **Future or scenario uncertainty:** uncertainty in the evolution of the repository system and human behaviour over the timescales of interest;
- **Model uncertainty:** uncertainty in the conceptual, mathematical and computer models used to simulate the behaviour of the repository system (e.g., due to approximations used to represent the system); and
- **Data uncertainty:** uncertainty in the data and parameters used as inputs in the modelling (e.g., due to incomplete site-specific data, and parameter estimation errors from interpretation of test results).

Uncertainties are accounted for in the current assessment through:

- The assessment of a range of scenarios, models and data with deterministic, and limited probabilistic, calculation cases (Section 3.6.1);
- The adoption of conservative scenarios, models and data (Section 3.6.2); and
- The adoption of a stylized approach for the representation of future human actions and biosphere evolution (Section 3.6.3).

3.6.1 Range of Scenarios, Models and Data

In the assessment, uncertainty in the future evolution of the site and human behaviour is addressed by assessing an appropriate range of scenarios that describe the potential evolution of the system. The scenario identification process, described in Chapter 5, ensures that key uncertainties are identified, and scenarios are defined to explore their consequences. Some future uncertainties may be amenable to representation with parameter values, in which case they can be explored in the same way as other data uncertainties (see below).

Conceptual and mathematical model uncertainties are identified in the model development process described in Chapter 6, making use of Feature/Event/Process (FEP) arguments and taking into account conceptual uncertainties in supporting work (e.g., geosphere characterization). Key uncertainties are addressed by using alternative conceptual representations of the system. This is facilitated by the availability of a range of computer codes (e.g., FRAC3DVS-OPG and AMBER) that are capable of representing different conceptualizations and mathematical descriptions of the system[8]. Once again, some conceptual and mathematical model uncertainties may be amenable to representation with parameter values, and can be investigated using the methods applied to data uncertainties.

Uncertainties in data have been identified and characterized in the Data report (QUINTESSA and GEOFIRMA 2011a). Two approaches can be used to analyze data uncertainties.

- Multiple deterministic calculations – in which alternative sets of parameter values, which provide a self-consistent representation of the system, are adopted. The results are then compared to the Reference Case and the differences explored providing a clear illustration of the impact of specific uncertainties or uncertainty combinations. Often a set of calculation cases whose parameters span the range of interest is evaluated in order to build up an appreciation of possible impacts of varying parameter values, and to develop an

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[8] Uncertainties related to the codes themselves are reduced through verification and validation.

understanding of the system. A limitation of the deterministic approach is that there is often no systematic or complete coverage of the uncertainty space in parameter values.

- Probabilistic calculations – in which a range of key parameters is assigned probability distribution functions that describe the uncertainty. The model is evaluated a large number of times, in each case using randomly selected values from the distributions. The model output is a distribution of results. The strength of the probabilistic approach lies in its ability to be comprehensive in exploring the space of the phenomena considered, and their associated model parameters. Its weakness is the need to make use of simplified models and the possibility that the statistical sampling may choose parameter combinations outside their range of validity.

Both approaches are used in the current assessment, but with emphasis on deterministic calculations.

3.6.2 Conservative Scenarios, Models and Data

Throughout the assessment process, it is necessary to make various assumptions that influence the design of the assessment – whether they relate to scenarios, models or data. Assumptions are often categorized as 'realistic'[9] or 'conservative'[10], although care needs to be taken when using such terms. The key is to ensure that each major assumption used in the assessment is considered and documented, and that the potential implications are understood. This approach underlies the current assessment work and key assumptions are summarized in Table 7.2 to Table 7.6.

However, it is also important to define a general attitude towards conservatism that is applied throughout the assessment. While it may superficially appear sensible to adopt a conservative approach to ensure that the potential impacts are not under-estimated, care is needed. The net effect of an aggregation of many conservative assumptions can be an unrealistic estimate of impacts, which could result in the unnecessary rejection of a satisfactory system. Furthermore, some analyses (e.g., evaluation of potential design improvements) can be meaningless if the assessment is dominated by conservative assumptions.

Therefore, the assessment documented in this report has adopted scientifically informed, physically realistic assumptions for processes and data that are understood and can be justified on the basis of the results of research and/or site investigation. Where there are high levels of uncertainty associated with processes and data, conservative assumptions have been adopted to allow the impacts of uncertainties to be bounded.

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[9] Realism is defined as "the representation of an element of the system (scenario, model or data), made in light of the current state of system knowledge and associated uncertainties, such that the safety assessment incorporates all that is known about the element under consideration and leads to an estimate of the expected performance of the system attributable to that element" (IAEA 2006b).

[10] Conservatism is defined as "the conscious decision, made in light of the current state of system knowledge and associated uncertainties, to represent an element of the system (scenario, model or data) such that it provides an under-estimate of system performance attributable to that element and thereby an over-estimate of the associated radiological impact (i.e., dose or risk)" (IAEA 2006b).

3.6.3 Stylized Approach

It is unrealistic to predict human habits and behaviour over the timescale of relevance to the DGR system. Further, major changes to the surface and near-surface environment are also likely as a result of natural changes such as ice-sheet advance/retreat or as a result of future human actions. Thus, in order to estimate the potential future impacts of the DGR, a 'reference' biosphere approach has been adopted, consistent with the recommendations of the international BIOMASS and BIOCLIM programs (IAEA 2003, BIOCLIM 2004). In this approach, stylized representations[11] of the biosphere are used to allow illustrative estimates of repository impact to be made (see Chapters 6, 7 and 8 of the System and Its Evolution report, QUINTESSA 2011b). Each stylized biosphere acts as a 'measuring instrument' for evaluating the safety and performance indicators identified in Section 3.5.

3.7 Building of Confidence

It is important that any safety assessment is developed in a manner that builds confidence of all stakeholders in the relevance of its outcomes. Confidence building can be achieved by (NEA 1999a; IAEA 1999):

- The use of a systematic assessment methodology that allows the assessment to be undertaken using a well-structured, transparent and traceable manner;
- The use of an iterative approach that allows the results of previous assessments to be used to inform the current assessment;
- The use of a range of strategies to identify and manage the various uncertainties associated with the assessment;
- The demonstration that the repository system will maintain its integrity and reliability under extreme conditions (i.e., the system is robust);
- The use of multiple lines of evidence to support key findings;
- The application of a quality management system to the assessment;
- The peer review of the assessment and its results; and
- The comparison of the repository system with natural systems that have evolved over relevant timescales.

Confidence of stakeholders in a postclosure safety assessment can be established at two levels. The first level involves establishing confidence within each stage of the assessment process (i.e., assessment context, system description, development and justification of scenarios, formulation and implementation of models and associated data, analysis of the results, and review and modification). The second level involves gaining overall confidence in the postclosure safety assessment and associated implications for further data gathering, assessment and design optimization. Various measures and attributes that can be used to develop confidence in the assessment at these two levels are summarized in Table 3.5.

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[11] A stylized representation of the biosphere, and human habits and behaviour is a representation that has been simplified to reduce the natural complexity to a level consistent with the objectives of the analysis using assumptions that are intended to be plausible and internally consistent but that will tend to err on the side of conservatism.

Further confidence can be built in the assessment by ensuring that it addresses the postclosure safety assessment issues identified in the EIS guidelines for the DGR (Table 3.1) and G-320 (Table 3.2).

Table 3.5: Confidence Building Measures and Attributes

Confidence in each Stage of the Assessment Process		Confidence in the Overall Safety of the DGR
Assessment Stage	**Confidence Building Measures and Attributes**	
Assessment Context	• Demonstration of understanding of the key components of the assessment context.	• Use of a systematic approach consistent with international practice and recommendations. • Adequate understanding of the DGR system and its uncertainties. • Use of multiple safety and performance indicators. • Clear presentation of the assessment and its results. • Application of a quality management system. • Peer review of the assessment. • Involvement of stakeholders in the development of the assessment.
System Description	• Demonstration of adequate understanding of engineered and natural aspects of the DGR system (repository, geosphere and biosphere) and associated uncertainties. • Linkage to geosynthesis, waste characterization, and repository design.	
Scenarios	• The set of scenarios is sufficiently comprehensive and is developed in a systematic, transparent and traceable manner. • The approach used to exclude or include scenarios are justified and well documented. • Scenarios are consistent with the geosynthesis, waste characterization, and repository design.	
Models and Data	• The conceptual models and associated data are consistent with the assessment context, DGR system and scenarios. • The software tools have the ability to adequately solve the problems under consideration. • Alternative models, codes, data and approaches are considered. • Models are consistent with the geoscience assessment, site characterization, waste characterization, and repository design.	
Analysis of Results	• Key assumptions are documented and justified. • Results are plausible and explainable. • Uncertainties are adequately addressed. • Compliance with regulatory requirements and recommendations is analyzed.	
Review and Modification	• Modifications are implemented in a structured and well-documented manner.	

3.8 Timeframes of Interest

The construction phase of the DGR is expected to take approximately 5 years. The operations phase will then last about 35 years. This will be followed by a closure phase (including dismantling surface facilities and sealing the shafts), which is expected to take about 10 years. For the purposes of this postclosure assessment, it is assumed that the DGR is closed (i.e., decommissioning is completed) by the end of 2062. This is the start time for the assessment and the waste inventory is decay corrected to this date.

Following closure of the repository, institutional controls will be put in place as a safety feature to reduce the likelihood of future human actions that could compromise the repository. During this control period, radioactive decay will reduce the concentrations of radionuclides in the repository, and inadvertent human intrusion will not occur. A period of 300 years is assumed over which such controls, as well as societal memory, are effective, consistent with current international practice (e.g., SKB 2006). Beyond this period, there are no expectations in this safety assessment with respect to any ongoing societal control, monitoring or memory of the site.

Canadian regulatory policy P-290 requires that "the assessment of future impacts of radioactive waste on the health and safety of persons and the environment encompasses the period of time when the maximum impact is predicted to occur" (CNSC 2004). Therefore, a time period of 1,000,000 years is selected as a baseline for the postclosure calculations. This encompasses the period of highest radioactivity (~10,000 years), including in particular the decay of C-14 (~60,000 years), as well as the timeframe in which the residual radioactivity drops below that of the overlying rock at the Bruce nuclear site (100,000 – 1,000,000 years).

However, calculated peak impacts associated with releases in groundwater might occur after more than 1,000,000 years due to the isolation and containment provided by the repository system. Therefore, some calculations are extended for timescales in excess of 1,000,000 years.

In light of the above discussion, the following timeframes are considered in the safety assessment.

- **0 – 10,000 years**: Conditions in the repository will gradually evolve with the ingress of some water, degradation of wastes packages and generation of gas. All waste packages have degraded by the end of the period. Most radionuclides of operational safety concern such as H-3 or Co-60 decay.
- **10,000 – 100,000 years**: C-14 will decay. The repository and geological evolution, and health and environmental impacts are analyzed through one glacial cycle with cooling and subsequent ice-sheet development expected in the period from 60,000 to 100,000 years.
- **100,000 – 1,000,000 years**: By 1,000,000 years, the residual activity in the repository will be approximately equal to that in the overlying rock with only long-lived radionuclides such as Cl-36, Zr-93, I-129 and U-238 remaining. Glacial cycling occurs with a periodicity of approximately 100,000 years with ice-sheets advancing and retreating over the site. Geological events, repository evolution and health and environmental impacts are quantified or numerically bounded in the assessment for this period.
- **Beyond 1,000,000 years**: Some calculations are extended beyond 1,000,000 years to provide evidence that the peak impacts have been identified. Given the significant uncertainties associated with such timescales that could affect the geosphere as well as the biosphere, the results of the calculations should be seen as being indicative.

4. SYSTEM DESCRIPTION

This chapter summarizes the key features of the DGR system – which comprises the waste and its packaging, the engineered repository, the geological setting (geosphere), and the surface environment (biosphere). An overview of each of these components is presented below – further details are provided in the System and Its Evolution report (QUINTESSA 2011b) and the Data report (QUINTESSA and GEOFIRMA 2011a). The primary data sources are:

- The Reference L&ILW Inventory Report (OPG 2010) for the waste and waste packaging;
- Chapter 6 (Facility Description) of the Preliminary Safety Report (OPG 2011b) for the repository design;
- The Geosynthesis Report (NWMO 2011a) and the Descriptive Geosphere Site Model (DGSM) Report (INTERA 2011) for the geological setting; and
- The Technical Support Documents (TSDs) supporting the Environmental Assessment (EA) for the DGR (GOLDER 2011a-g, AMEC NSS 2011) and the EA Study Report for the WWMF (OPG 2005) for the surface environment.

The following subsections describe the DGR system as it exists at present, or during the operational period of the DGR.

4.1 Waste

4.1.1 Categories and Characteristics

The DGR will accept operational and refurbishment wastes from OPG owned or operated nuclear power plants. The wastes to be accepted are classified as solid low-level or intermediate-level, consistent with Canadian Standard CSA N292.3 (CSA 2008a). The DGR will not accept used nuclear fuel.

The waste is categorized in the Reference L&ILW Inventory Report (OPG 2010) according to the characteristics of the waste. These categories and the waste characteristics are summarized in Table 4.1. Most waste categories are relatively homogeneous in their physical characteristics, especially incinerator ash, resins and sludges, and reactor fuel channel wastes (e.g., pressure tubes, calandria tubes, and end fittings) from reactor refurbishment (retubing).

Certain wastes will be conditioned at the WWMF prior to being sent to the DGR. This is current practice at the WWMF. The main waste conditioning practices undertaken at WWMF are incineration (resulting in the generation of bottom ash and baghouse ash) and compaction (resulting in the generation of compacted waste bales and boxes). In addition, the steam generators from reactor refurbishment are assumed to be grouted and cut into smaller pieces.

4.1.2 Packaging

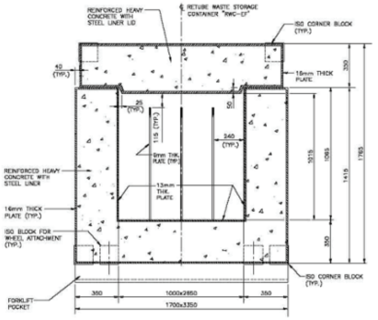
The range of waste containers and overpacks that will be used by OPG for the storage and eventual emplacement of L&ILW in the DGR is described in the Reference L&ILW Inventory Report (OPG 2010). It is recognised that each waste category may use several types of waste containers and overpacks, and conversely each waste container/overpack may not be exclusive to a single waste category. Furthermore, there is ongoing evolution of the package designs. However, for the safety assessment, the most common waste containers and overpacks for each waste category have been identified as “reference”, as described in Section 3.2 of the Data Report (QUINTESSA and GEOFIRMA 2011a) and summarized in Table 4.2.

Table 4.1: Waste Categories

Waste Category	**Description**
LLW Wastes	
Bottom ash	Heterogeneous ash and clinker from waste incineration.
Baghouse ash	Fine homogeneous ash from waste incineration.
Compacted wastes (bales)	Generally compactable solid LLW; for example, compacted empty waste drums, rubber hoses, rubber area floor matting, light gauge metals, welding rods, plastic conduit, fire blankets and fire retardant material, metal cans, insulation, ventilation filters, air hoses, metal mop buckets and presses, electric cable (<1/4” diameter), lathe turnings, metal filings, glass, plastic suits (Mark III/IV), rubbers, Vicraft hoods, rubber gloves.
Compacted wastes (boxes)	Same as compacted bales.
Non-Processible (boxes)	Solid LLW that is non-compactable or has a contact dose rate greater than 2 mSv/h; for example, heavy gauge metal (e.g., beams, ion exchange (IX) vessels, angle iron, plate metal), concrete and cement blocks, metal components (e.g., pipe, scaffolding pipes, metal planks, motors, flanges, valves), wire cables and slings, electric cables (>1/4” diameter), Comfo respirator filters, tools, paper, plastic, absorbent products, laboratory sealed sources, feeder pipes.
Non-Processible (drums)	Generally small, granular or solidified LLW; for example, floor sweepings, cleaners and absorbents (e.g., Dust Bane, Stay Dry), metal filings, glassware, light bulbs, bituminized low-level waste.
Non-Processible (other)	Large and irregularly shaped objects such as heat exchangers, encapsulated tile holes, shield plugs, and other miscellaneous large objects (e.g., fume hoods, glove boxes, processing equipment).
LL/ALW Resins	Spent Low-Level (LL) ion exchange resin arising from light water auxiliary systems, and/or Active Liquid Waste (ALW) treatment systems.
ALW sludges	Sludge containing clay sorbent arising from the liquid effluent treatment plant at Bruce A.
Steam generators	Redundant steam generators from refurbishment. The steam generators consist of Inconel 600 tubes, carbon steel shell, shroud, head and tubesheet.
ILW Wastes	
Moderator resins	Spent IX resin arising from moderator purification systems.
PHT resins	Spent IX resin arising from PHT (Primary Heat Transport) purification systems.
Misc. Resins	Spent IX resin arising from station auxiliary systems (e.g., heavy water upgraders).
CANDECON resins	Spent IX resin from chemical decontamination process for nuclear heat transport systems.
Irradiated core components	Various replaced core components, notably flux detectors and liquid zone control rods.
Filters and filter elements	Filters and filter elements from various station process systems.
IX columns	Spent IX resin mainly arising from the Pickering PHT purification system, comes as package with steel container.
Retube - Pressure Tubes	Fuel channel waste from large scale retube.
Retube - End Fittings	Fuel channel waste from large scale retube.
Retube - Calandria Tubes	Fuel channel waste from large scale retube.
Retube - Calandria Tube Inserts	Fuel channel waste from large scale retube.

Table 4.2: Reference Containers and Overpacks

Container Name, Wastes and Overpack	Picture	Container Name, Wastes and Overpack	Picture
Carbon steel ash bin (AIBN) • Bottom ash • Baghouse ash Reference overpack • LLW sheet metal overpack (BINOPK)		Mild steel bale rack (BRACK) • Compacted waste (bales) Reference overpack • To be overpacked but details not yet specified. Assumed to be simple sheet metal cover	
Mild steel compactor box (B25) • Compacted waste (boxes) Reference overpack • None		Carbon steel drum bin (DBIN) • Non-processible waste (drummed) Reference overpack • 10% overpacked in LLW sheet metal overpack (BINOPK)	
Non-pro box (NBP47) • Non-processible waste (boxes) Reference overpack • None		Low Level resin pallet Tank (RTK) • ALW resins • LLW resins Reference overpack • To be overpacked but details not yet specified. Assumed to be simple sheet metal cover	

Container Name, Wastes and Overpack	Picture	Container Name, Wastes and Overpack	Picture
ALW sludge box (NPBSB) • ALW sludges Reference overpack • LLW sheet metal overpack (BINOPK)		Resin liner (RL) • CANDECON resins • Moderator resins • PHT resins • Miscellaneous resins Reference shield (RLSHLD1) • Concrete cylinder each holding two resin liners	
Tile hole equivalent liner (THLIC18)* • Filters and elements • Irradiated core components • IX columns Reference overpack* • Transported in a re-usable shield and inserted into a concrete pipe array in the emplacement room		Retube waste container (RWC-EF) • Retube wastes (end fittings)	
Retube waste container (RWC-PT) • Retube wastes (pressure tubes) • Retube wastes (calandria tubes) • Retube wastes (calandria tube inserts)		Notes: This table presents a simplified description of waste containers and overpacks. Pictures generally show the containers as they appear during storage at the WWMF. All containers will be lidded and overpacked if necessary. Steam Generators are not shown in the table as they will not be placed in containers. * Original preliminary design. Replaced by steel and concrete ATHEL and ILW Shield containers in final preliminary design (OPG 2010).	

4.1.3 Volumes

The reference volume of L&ILW to be placed in the DGR has been estimated in the Reference L&ILW Inventory Report (OPG 2010) and is presented in Table 4.3 (based on data in Tables 2.1 and 3.1 of OPG 2010). The raw or net volume refers to the waste material itself, whereas the emplaced volume is the volume occupied by the waste packages in the repository including an allowance for the waste containers and any overpacks.

Table 4.3: Reference Forecast Waste Volumes

Waste Categories	Raw (Net) Volume (m^3)	Number of DGR Containers	Emplaced Volume (m^3)
LLW			
Bottom ash	2,033	882	7,497
Baghouse ash	364	218	1,853
Compacted wastes (bales)	2,268	1,383	4,702
Compacted wastes (boxes)	14,110	6,135	17,177
Non-processible (boxes)	56,713	24,190	73,792
Non-processible (drums)	9,408	7,840	25,532
Non-processible (other)	3,279	164	3,279
LLW and ALW resins	3,393	2,165	6,307
ALW sludges	3,569	1,709	14,527
Steam generators	8,387	512	8,387
Sub-total LLW	**103,524**	**45,198**	**163,053**
ILW			
Moderator resins	1,929	430	4,779
PHT resins	1,348	301	3,340
Misc. resins	1,808	403	4,480
CANDECON resins	2,257	503	5,592
Irradiated core components	27	4,459(1) 4,453(2)	6,101(1) 9,453(2)
Filters and filter elements	1,344		
IX columns	544		
Retube Wastes (Pressure Tubes)	193	242	1,860
Retube Wastes (Calandria Tubes)	133	167	1,285
Retube Wastes (Calandria Tube Inserts)	36	45	349
Retube Wastes (End Fittings)	2,429	899	9,804
Sub-total ILW	**12,048**	**7,449(1)** **7,443(2)**	**37,590(1)** **40,942(2)**
Total	**115,572**	**52,647(1)** **52,641(2)**	**200,643(1)** **203,995(2)**

Notes:

1. Based on waste packages proposed for original preliminary design (NWMO 2010c).
2. Based on waste packages proposed for final preliminary design (OPG 2010).

4.1.4 Contaminants and Other Materials

A large number of radioactive and non-radioactive species are present in L&ILW wastes, but most of these are present in small amounts and only a subset needs to be considered in safety assessment calculations. Screening calculations have been conducted that included the full set of contaminants identified in the Reference L&ILW Inventory Report (OPG 2010), and identified potentially important contaminants for consideration in the safety assessment (see Appendix A of the Data report, QUINTESSA and GEOFIRMA 2011a). Table 4.4 summarizes the total amounts of radionuclides, elements and chemical species in the LLW and ILW considered in this safety assessment based on the Reference L&ILW Inventory Report (OPG 2010).

Figure 4.1 shows the time dependence of radioactivity in the waste due to decay. For comparison, the figure also shows the natural radioactivity in the rock above the repository as a horizontal grey band, mostly from K-40 and the U-238 decay chain. The upper part of this band corresponds to the Bruce nuclear site area, the lower part to the DGR repository footprint.

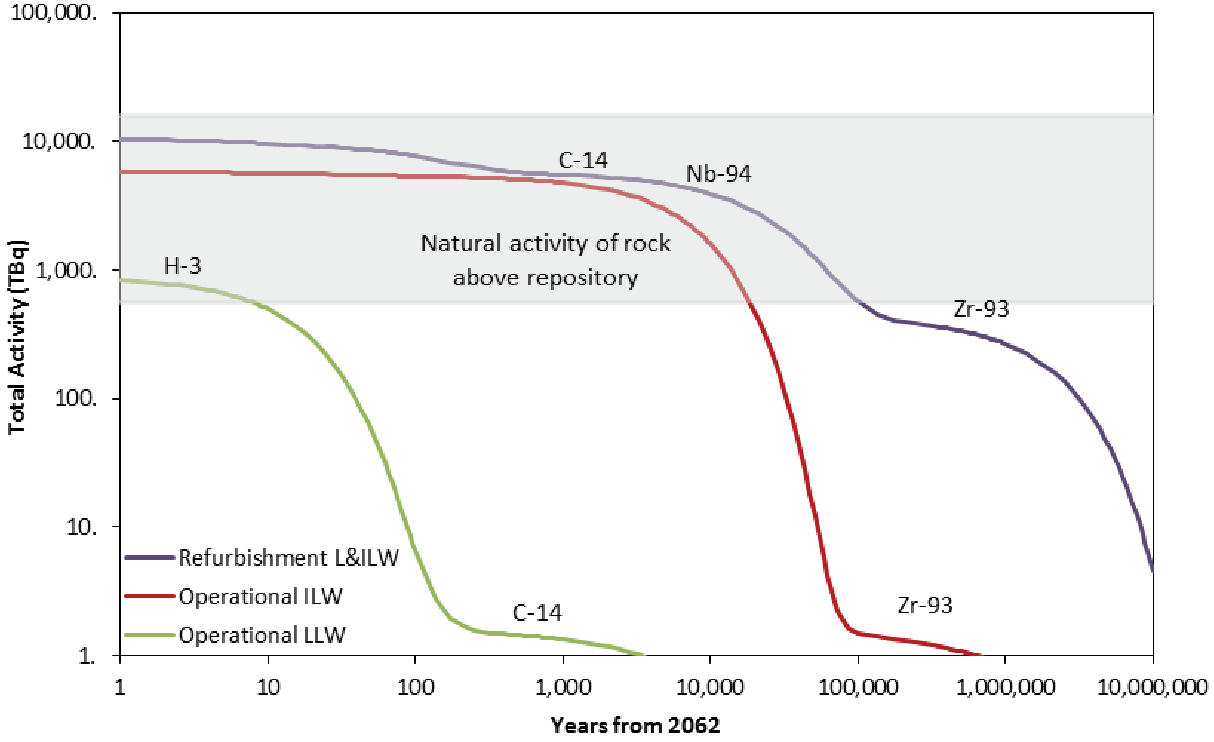


Figure 4.1: Time Dependence of Radioactivity in the Waste Due to Decay

Figure 4.2 similarly shows the decrease in radiotoxicity with time due to decay. This parameter takes into account the relative ingestion hazard of the different radionuclides. The natural rock radiotoxicity is also shown, with Po-210 from U-238 as a key radionuclide.

These figures show that the 80% of the waste volume that is LLW will have largely decayed to low levels in a few hundred years. It is the 10% of the waste volume in the refurbishment (retube) ILW that contains most of the long-lived radioactivity – in particular Zr-93. Figure 4.1 shows that the total radioactivity of the wastes is less than that of the rock within about 100,000 years. Figure 4.2 shows that wastes remain more concentrated, with the radiotoxicity of the retube waste about 100 times that of the rock per cubic metre at longer times.

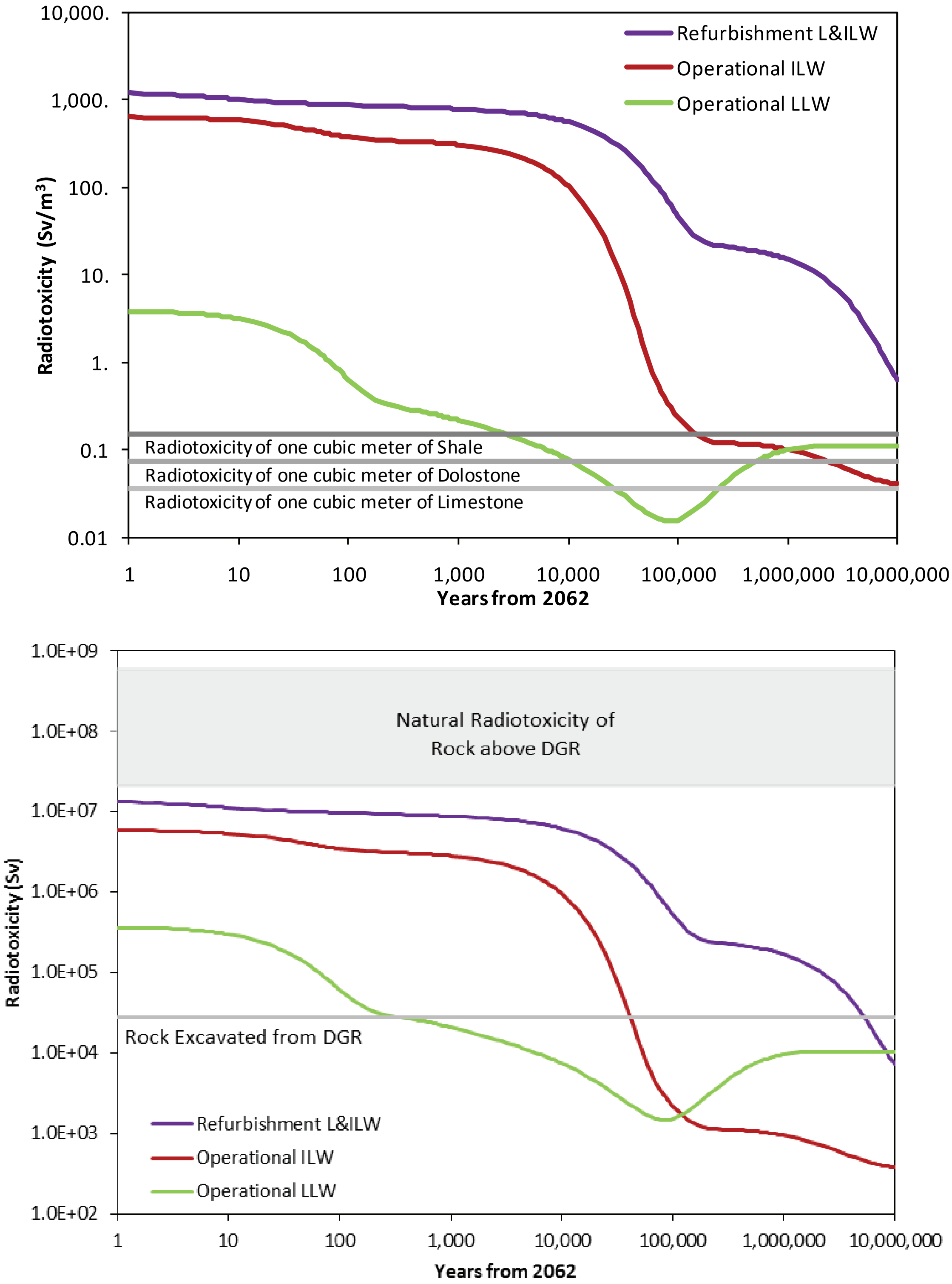


Figure 4.2: Time Dependence of Radiotoxicity in the Waste: (a) Per m^3 of Net Waste Volume and (b) Total in Repository

Table 4.4: Amounts of Potentially Important Radionuclides, Elements and Chemicals in Waste

Radio-nuclide(1)	Amount (Bq) at 2062			Elements/ Chemicals	Amount (kg)		
	LLW	ILW	Total		LLW	ILW	Total
H-3	8.49E+14	1.56E+14	1.00E+15	Antimony	3.23E+03	2.35E+01	3.25E+03
C-14	2.42E+12	6.07E+15	6.07E+15	Arsenic	2.83E+02	1.42E+02	4.25E+02
Cl-36	6.01E+08	1.42E+12	1.42E+12	Barium	9.42E+03	1.59E+02	9.58E+03
Ni-59	5.01E+10	3.63E+13	3.64E+13	Beryllium	1.11E+02	2.10E+01	1.32E+02
Ni-63	5.04E+12	3.95E+15	3.96E+15	Boron	1.53E+03	5.25E+03	6.78E+03
Se-79	1.54E+06	1.25E+10	1.25E+10	Bromine	1.30E+02	4.62E-01	1.30E+02
Sr-90(2)	8.96E+12	4.52E+13	5.42E+13	Cadmium	1.12E+04	1.96E+01	1.12E+04
Mo-93	0.00E+00	1.00E+12	1.00E+12	Chromium	7.85E+05	1.98E+05	9.84E+05
Zr-93	4.54E+06	2.13E+14	2.13E+14	Cobalt	3.42E+02	3.01E+02	6.44E+02
Nb-93m	0.00E+00	9.26E+12	9.26E+12	Copper	3.35E+06	7.01E+03	3.35E+06
Nb-94	2.46E+10	4.60E+15	4.60E+15	Gadolinium	0.00E+00	5.41E+03	5.41E+03
Tc-99	6.28E+07	6.10E+10	6.10E+10	Hafnium	0.00E+00	2.58E+02	2.58E+02
Ag-108m	3.43E+07	1.97E+13	1.97E+13	Iodine	6.60E+01	1.19E-01	6.61E+01
Sn-121m	0.00E+00	7.76E+13	7.76E+13	Lead	1.52E+06	2.85E+02	1.52E+06
I-129	1.21E+06	1.33E+08	1.34E+08	Lithium	4.47E+01	5.89E+03	5.94E+03
Cs-137(2)	1.32E+13	9.37E+13	1.07E+14	Manganese	8.32E+05	1.71E+04	8.49E+05
Ir-192m	0.00E+00	1.14E+10	1.14E+10	Mercury	6.83E+01	3.73E-01	6.87E+01
Pt-193	0.00E+00	1.15E+13	1.15E+13	Molybdenum	2.15E+02	9.78E+02	1.19E+03
Pb-210	3.20E+10	0.00E+00	3.20E+10	Nickel	1.63E+06	4.92E+04	1.68E+06
Ra-226	3.80E+09	0.00E+00	3.80E+09	Niobium	1.02E+02	1.10E+04	1.11E+04
U-232	2.25E+08	7.71E+06	2.33E+08	Scandium	2.29E+01	6.16E-01	2.35E+01
U-233	3.07E+08	8.88E+06	3.15E+08	Selenium	8.14E+01	5.06E+00	8.64E+01
U-234	1.34E+09	1.30E+08	1.47E+09	Silver	5.13E+00	2.13E+00	7.26E+00
U-235	2.16E+07	2.08E+06	2.36E+07	Strontium	3.24E+03	3.35E+01	3.27E+03
U-236	2.56E+08	2.38E+07	2.80E+08	Tellurium	2.03E+02	6.63E-02	2.03E+02
U-238	5.91E+09	1.60E+08	6.07E+09	Thallium	2.41E-01	3.04E-01	5.45E-01
Np-237	1.23E+08	1.07E+07	1.34E+08	Tin	1.37E+02	2.37E+03	2.51E+03
Pu-238	4.69E+11	2.77E+10(3)	4.96E+11(3)	Tungsten	1.18E+00	1.48E+02	1.49E+02
Pu-239	8.32E+11	8.51E+10	9.18E+11	Uranium	3.34E+02	2.49E+01	3.59E+02
Pu-240	1.23E+12	1.24E+11	1.35E+12	Vanadium	8.97E+01	9.56E+02	1.05E+03
Pu-241	6.75E+10(3)	1.76E+12	1.83E+12(3)	Zinc	1.47E+05	2.06E+03	1.49E+05
Pu-242	1.23E+09	1.26E+08	1.36E+09	Zirconium	7.42E+02	5.95E+05	5.96E+05
Am-241	2.16E+12	2.30E+11	2.39E+12	PAHs	3.43E+00	0.00E+00	3.43E+00
Am-242m	2.35E+09	2.39E+07	2.37E+09	Cl-Benzenes & Cl-Phenols	2.76E+00	0.00E+00	2.76E+00
Am-243	2.67E+09	4.31E+08	3.10E+09				
Cm-243	2.70E+09	5.30E+08	3.23E+09	Dioxins & Furans	9.25E-02	0.00E+00	9.25E-02
Cm-244	1.93E+11	1.25E+11	3.18E+11	PCBs	1.31E-01	0.00E+00	1.31E-01
Total	8.83E+14(3)	1.53E+16	1.62E+16				

Notes:
1. Radioactive progeny are not listed in the table but are included in the safety assessment calculations.
2. Sr-90 and Cs-137 activities are total including their respective progeny.
3. Value from interim version of the Reference L&ILW Inventory Report at the time of the data freeze for the safety assessment (summer 2010). Values from final version of Reference L&ILW Inventory Report (OPG 2010) are: Pu-238 - 3.23E+10 Bq (ILW) and 5.01E+11 Bq (total); Pu-241 - 2.87E+12 Bq (LLW) and 4.63E+12 Bq (total); and Total 8.86E+14 Bq (LLW).

Table 4.5 summarizes the amount of organics, metals and concrete in the wastes and their containers and overpacks, derived from data presented in the Reference L&ILW Inventory Report (OPG 2010) and presented in Section 3.4.1 of the Data report (QUINTESSA and GEOFIRMA 2011a).

Table 4.5: Amounts of Organics, Metals and Concrete in Wastes and Their Containers and Overpacks

Material		Amount (kg)			
		LLW		ILW	
		Wastes	Containers and Overpacks	Wastes	Containers and Overpacks (1)
Organics	Cellulose	8.2E+06	-	-	-
	Rubber and Plastics	8.2E+06	2.1E+05	-	-
	Resins	1.5E+06	-	4.2E+06	-
Metals	Carbon steel	4.1E+06	3.4E+07	9.1E+05	2.4E+06
	Stainless steel	5.3E+06	2.8E+06	2.4E+06	9.8E+06
	Zircaloy	-	-	6.0E+05	-
Concrete		1.1E+06	3.5E+06	-	5.7E+07

Notes:

1. Values from interim version of the Reference L&ILW Inventory Report at the time of data freeze for the safety assessment (summer 2010). Values in final version of Reference L&ILW Inventory Report are 2.1E+06 kg (carbon steel), 1.0E+07 kg (stainless steel) and 6.3E+07 kg (concrete) due to change in T-H-E Liner disposal concept.

4.1.5 Safety Relevant Features

The principal postclosure safety feature associated with the waste is the **wasteform** itself. Specifically, a significant fraction of the long-lived radionuclides, including in particular Nb-94 and Zr-93, are neutron activation products bound within the corrosion-resistant Zircaloy pressure tubes (Shoesmith and Zagidulin 2010) (which in turn are overpacked in robust steel and concrete containers). For other wastes, the wasteform has little long-term safety role.

The wastes are contained in a variety of steel or concrete waste **containers**. This packaging can provide a physical barrier to water contacting the waste and, in the case of concrete packaging, a chemical barrier to the subsequent migration of contaminants. However, in the postclosure safety assessment, the packaging is not credited with any barrier function, since the packages are not designed to provide any long-term isolation and containment of wastes.

4.1.6 Uncertainties

The total volume of wastes is relatively well constrained, being based on waste volumes already stored, plus experience of reactor operation combined with OPG's forecast scenario based essentially on the life of the current nuclear fleet. Uncertainties associated with the reference forecast scenario could be large, but ultimately are constrained by the excavated volume to approximately 200,000 m^3 of emplaced waste packages. Uncertainties associated with changes to inventory volumes, within the general reference forecast scenario, could result in a change of perhaps up to 10% to the inventory volume, since over 50% of the projected volumes are already present at WWMF.

OPG's waste packages are mostly well defined. Potential changes include the amount of overpacked waste and the possibility of pre-processing the steam generators. However, while these changes would somewhat affect the total amount of steel and concrete in the repository, the amount of radioactivity would be little changed. One change that has occurred since the assessment calculations were undertaken is the change from the T-H-E (Tile Hole Equivalent) liner packaging to the ILW shield for certain ILW waste categories (see Table 4.1). This has had a limited effect on emplaced volumes (Table 4.3) and metal and cement amounts in the DGR (Table 4.5), and no impact on radioactive waste inventory.

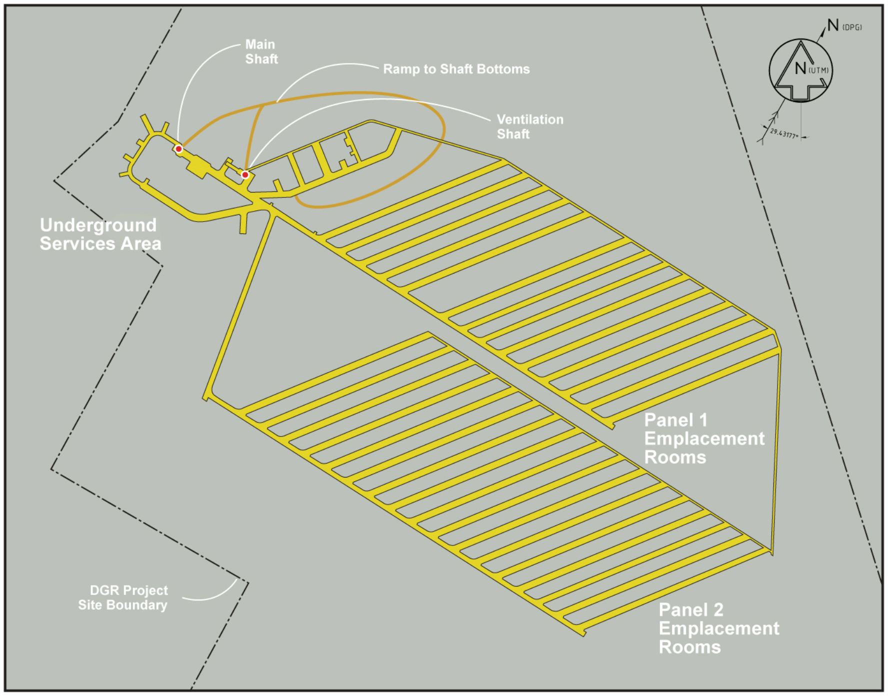
Most waste categories are relatively homogeneous in their physical characteristics, especially incinerator ash, resins and sludges, and retube wastes. However, non-processible wastes could be quite diverse in characteristics. The volumes of metal and concrete are well defined, but quantities of other materials (e.g., cellulosics and chemical contaminants in some waste categories) are uncertain. Some physical characteristics of wastes, such as moisture content and hydraulic conductivity, have been estimated and are uncertain; however, it is unlikely that these parameters will have a significant effect on overall postclosure impacts.

Concentrations of radionuclides and non-radioactive contaminants are subject to a degree of uncertainty as they are based on waste-type-specific sampling and scaling factors, rather than direct measurement of each waste package. This approach is routinely used by other waste management organizations (IAEA 2009). The contaminants of most interest are present in the wastes at low levels, and they can vary significantly between packages (OPG 2010). However, summed across the many packages in the repository, the total inventories have much less uncertainty. In this safety assessment, the impact of a factor of ten higher inventories is assessed.

4.2 Repository

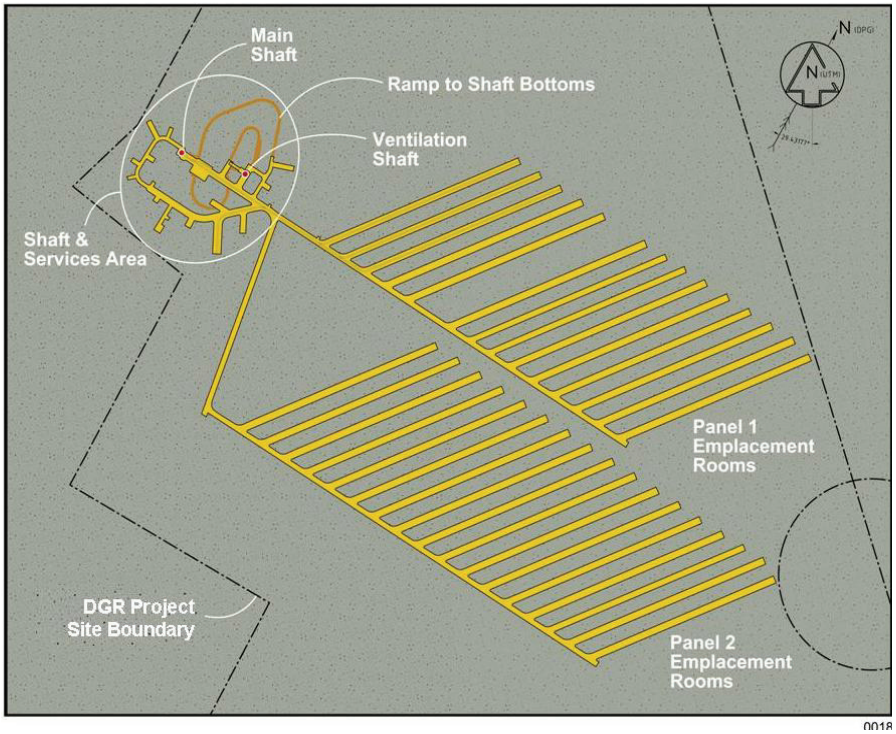
The final preliminary design for the repository is shown in Figure 4.3, and is described in the Chapter 6 of the Preliminary Safety Report (OPG 2011b).

However, the postclosure safety assessment was initiated using the original preliminary design shown in Figure 4.4 (NWMO 2010c). The key changes from the original to the final preliminary design relate to the ventilation system and disposal option for certain ILW waste categories. They are summarized in Table 4.6. It should be noted that these changes have been made for operational safety and reliability reasons rather than postclosure safety reasons.



Note: Figure 6-7 in OPG (2011b).

Figure 4.3: General Layout of the Final Preliminary Design Repository



Note: Figure from NWMO (2010c).

Figure 4.4: General Layout of the Original Preliminary Design Repository

Table 4.6: Summary of Changes from the Original to the Final Preliminary Design for the DGR

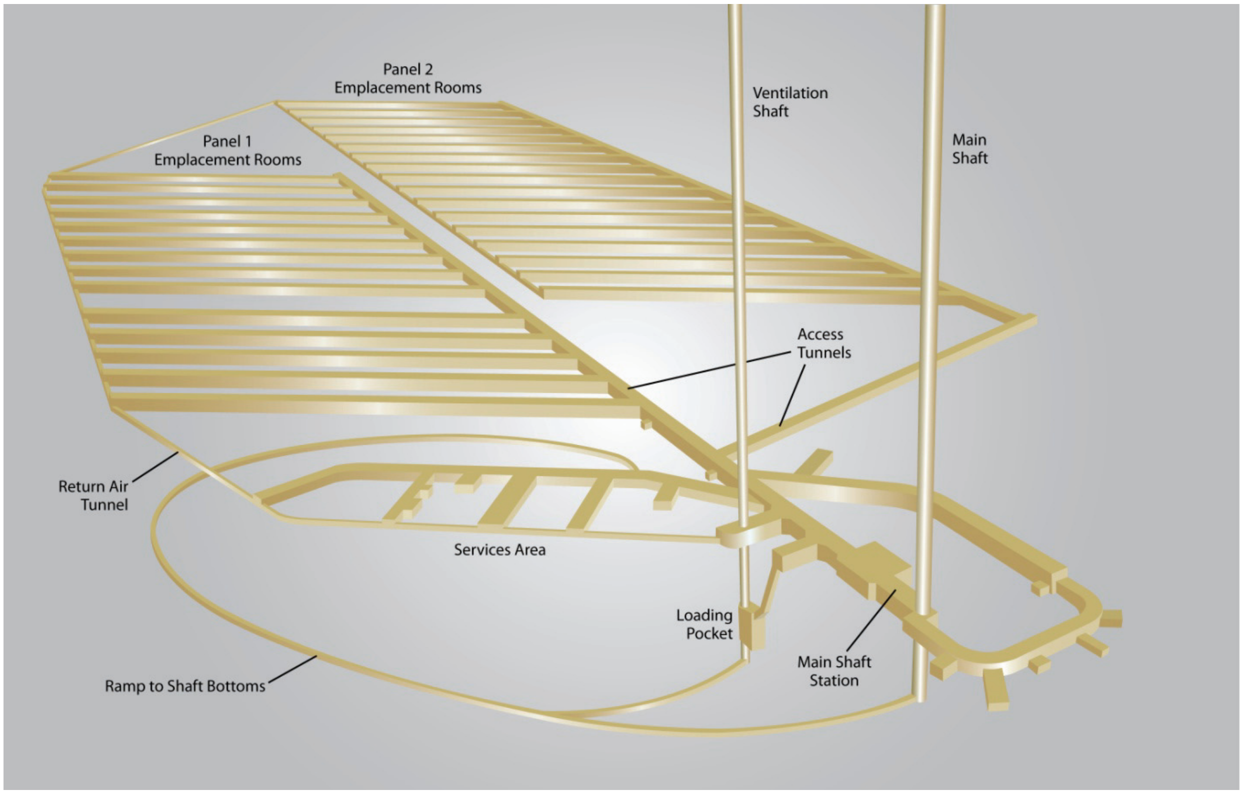
Feature	Change	Comment
Waste Capacity	Not changed	-
Surface structures	Not changed	-
Shafts	Not changed	-
Shaft Service Area	Rearranged for better air flow Lower height	Larger volume Lower height tunnels are more stable
Access Tunnels	No ventilation duct Lower height	Less excavated volume No ventilation duct maintenance Easier tunnel roof maintenance Better for tunnel excavation and stability
Emplacement Rooms	Ventilation duct removed Dimensions not changed Capacity not changed Backwall connects to return air drift	Simpler air flow No ventilation duct lifetime limit
T-H-E placement	Changed from horizontal concrete arrays in rooms, to steel & concrete packages similar to resin liners.	Easier handling
Ventilation drifts	Added	Increased excavated volume
Panel closure	Added closure plugs	Added on ventilation drifts
Monolith	Extended into services area to north east of ventilation shaft	Consistent with the change in shaft service area
Shaft seal	Not changed	-

The design is likely to evolve further prior to the construction of the DGR, as the detailed design is prepared. Since the primary barrier is the geosphere and since long-term safety is a design requirement, it is expected that any changes would not substantively affect the postclosure safety conclusions.

The key features of the repository design relevant to postclosure safety assessment are described in the subsections below.

4.2.1 Layout and Construction

The depth of the repository floor is around 680 m below ground surface in competent and tight limestone (the Cobourg Formation), which lies within the 400 m thick sequence of Ordovician rocks. The repository comprises two shafts, a shaft and services area, two access tunnels, 31 waste emplacement rooms (14 rooms in the Panel 1 and 17 rooms in the Panel 2), and, in the case of final preliminary design, ventilation drifts (Figure 4.3 and Figure 4.5). The waste emplacement rooms will be oriented in the direction of major principal horizontal stress, so as to maximize stability.



Note: Figure 6-6 in OPG (2011b).

Figure 4.5: Isometric View of the Final Preliminary Design Repository

Access to the repository will be by shaft, which will be excavated using controlled drill and blast techniques. A main shaft will be used to transfer waste packages from receipt facilities on the surface to the repository and to supply conditioned air to the repository. Exhaust air will be drawn from the repository via a ventilation shaft.

The underground layout of the repository has the main and ventilation shafts as an islanded arrangement within a shaft and services area. A main access tunnel extends from the main shafts to the east, passing the ventilation shaft and then proceeding towards the two panels of waste emplacement room panels, as shown in Figure 4.3. Underground support facilities (offices, workshops, refuge stations, maintenance areas, etc.) will be located in the shaft and services area.

Access to the emplacement rooms in the Panels 1 and 2 will be via tunnels with a total length of approximately 500 m and 800 m, respectively (Section 4.2 of the Data report, QUINTESSA and GEOFIRMA 2011a). A rail line will run along the access tunnel into the first three emplacement rooms in Panel 1. The emplacement rooms will be divided into six size profiles (P1 to P6) of varying widths (7.4 to 8.6 m) and heights (5.8 to 7.2 m), but a constant length (250 m) (see Section 4.2 of the Data report, QUINTESSA and GEOFIRMA 2011a, for details).

It is expected that the shaft and services area, the access tunnels and the emplacement rooms will be excavated using controlled drill and blast. They will have concrete floors with shotcrete on the roofs and extending down the walls, and rockbolts placed as needed in the roofs to provide roof support. The total repository void volume of the original and final preliminary designs are 4.18 x 10^5 m^3 and 4.49 x 10^5 m^3, respectively (see Table 4-5 of the Data report, QUINTESSA and GEOFIRMA 2011a).

4.2.2 Waste Emplacement

Panel 2 will be filled prior to Panel 1, over the first several years of the DGR's operation, with the wastes currently in storage at the WWMF. Then, the nine rooms in Panel 1 that are furthest from the shaft and services area will be filled over about 15 years. Finally, the five rooms closest to the shaft and services area will be filled. The allocation of wastes in the emplacement rooms adopted for the purposes of the current assessment is summarized in Table 4.7.

Waste packages destined for Panel 2 emplacement rooms will be moved using forklifts. Most of the waste packages destined for Panel 1 will be similarly moved, but some will be of sufficient size and weight to require movement on self-powered rail carts.

Six sizes of emplacement room are envisaged, with each type being used for the placement of particular types of waste package. Examples of stacking layouts are illustrated in Figure 4.6 and Figure 4.7.

Table 4.7: Number of Emplacement Rooms Occupied by Each Waste Category in the Repository Panels

Waste Category	Panel 1		Panel 2 (Rooms 1 – 17)
	Rooms 1 – 5	Rooms 6 – 14	
LLW Non-Processible (other)	1	-	-
LLW Steam generators	-	1	1 (1)
All other LLW categories	1	3	13
All ILW categories	3	5	4

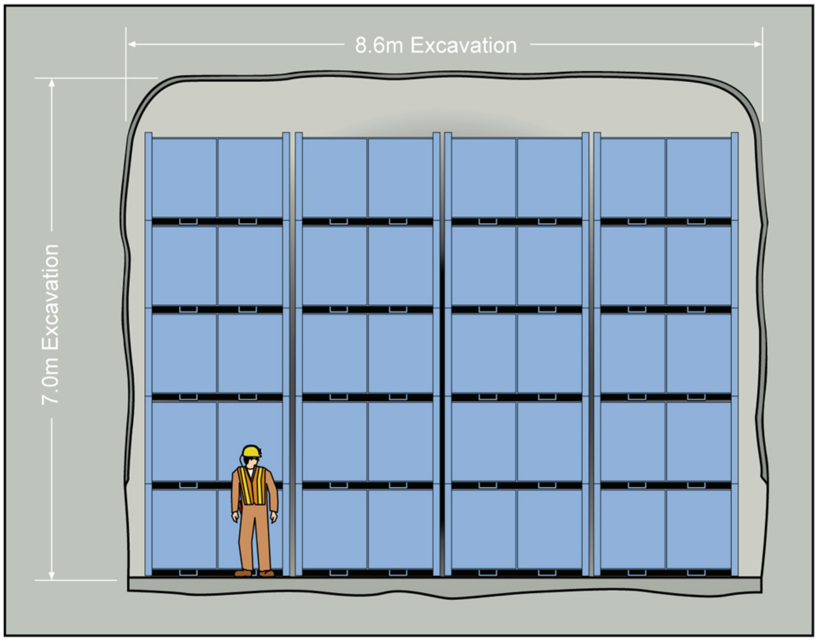
Notes:

1. Emplaced in same room as ILW.

4.2.3 Closure

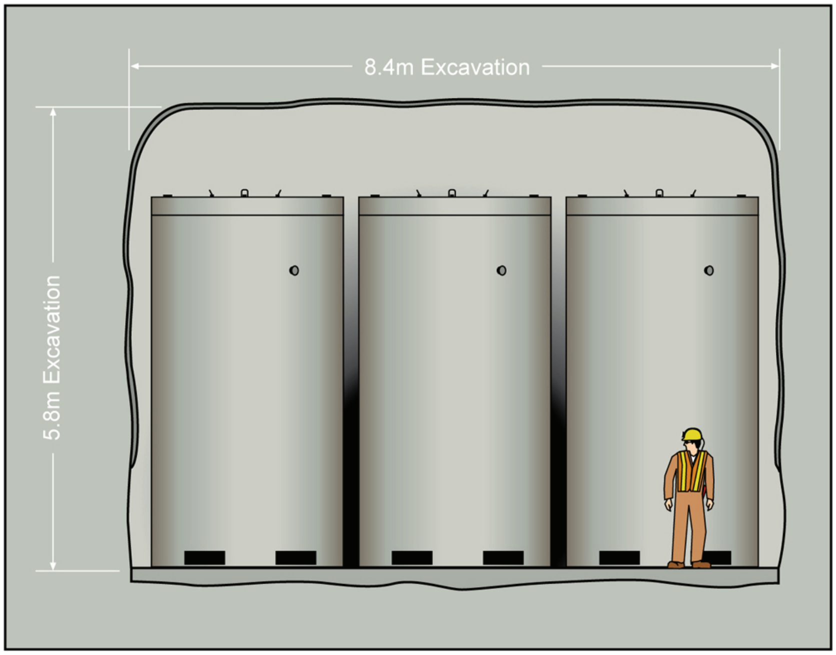
4.2.3.1 Repository Level

The emplacement rooms, access tunnels and, in the case of the final preliminary design, ventilation drifts will not be backfilled. This is for several reasons, including postclosure safety, as is discussed later in this report. After a group of emplacement rooms have been filled with waste packages, thick concrete closure walls will be constructed in the access tunnel to isolate this group of rooms. The walls will be designed to limit the release of gases and any potentially contaminated water during the operational period but will not be designed to provide any long-term postclosure isolation and containment. There may be six closure walls in place at the end of repository operations in the final preliminary design. The rail lines will remain in the rooms and tunnels.



Note: Figure 6-17 in OPG (2011b).

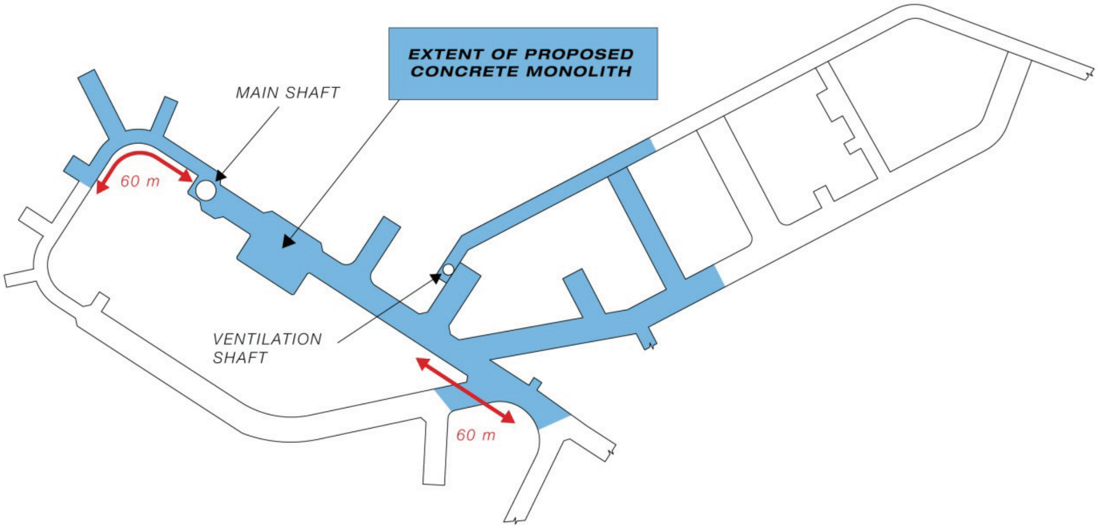
Figure 4.6: Emplacement Room Section View – P1 Profile for Bin Type Waste Packages



Note: Figure 6-18 in OPG (2011b).

Figure 4.7: Emplacement Room Section View – P3 Profile for Resin Liner Type Waste Packages

At final closure, any equipment that has been used within the shaft and services area will remain in the area. In addition, the steel work and shaft concrete liner removed during the closure of the ventilation shaft might be placed in the area. Concrete monoliths created at the base of each shaft will extend into the repository tunnels to form a single monolith at the repository level (Figure 4.8).



Note: Figure 13-1 in OPG (2011b).

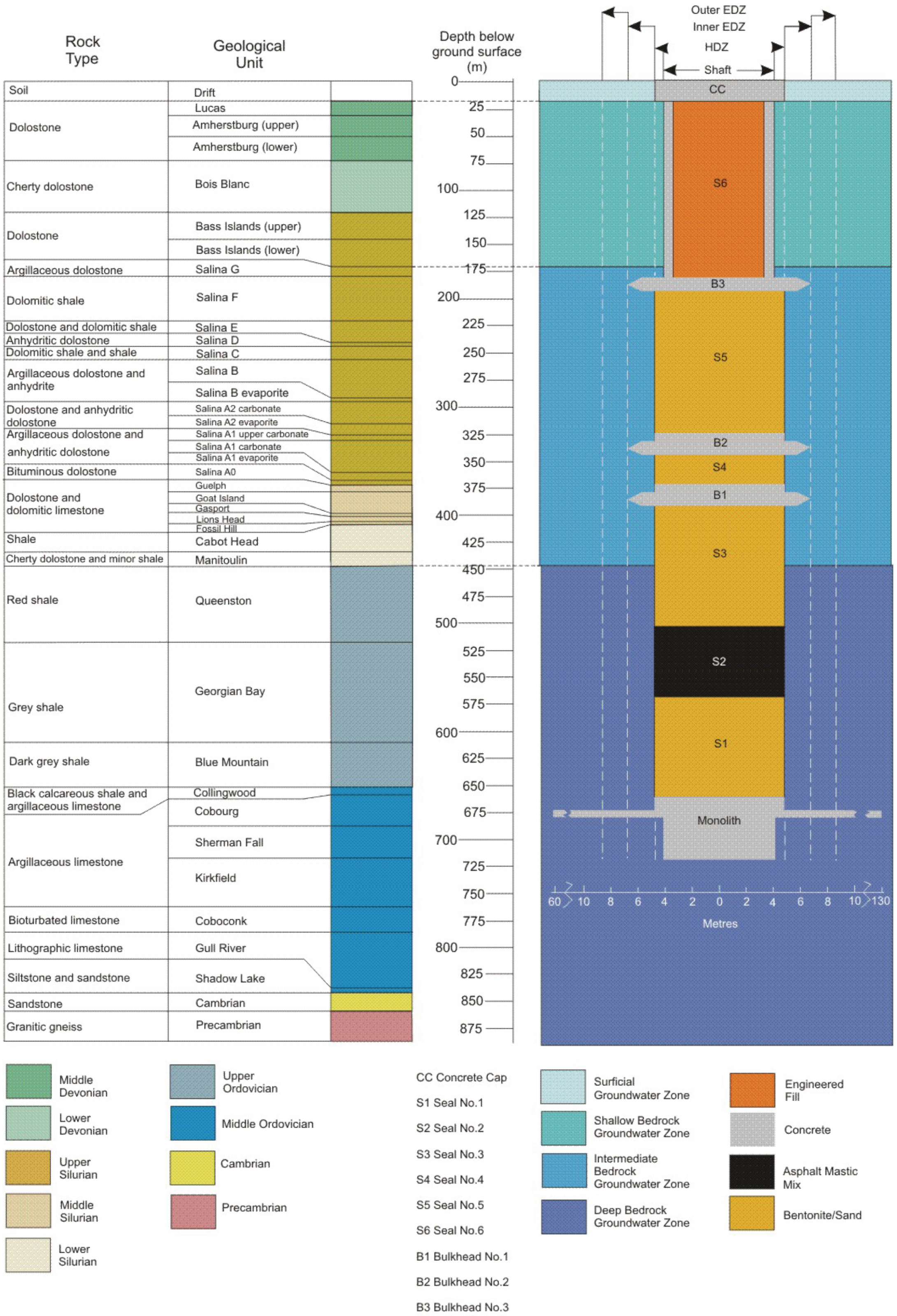
Figure 4.8: Location of Monolith in Repository Tunnels

The total amount of concrete and steel associated with the emplacement rooms (excluding the wastes and their packaging), the access tunnels and the ventilation drifts (including closure walls), the shaft and services area (including equipment and material removed from the ventilation shaft), and the monolith in the shafts and repository is estimated to be 160,000 tonnes of concrete and 3,500 tonnes of steel for the original preliminary design, and 140,000 tonnes of concrete and 3,300 tonnes of steel for the final preliminary design (see Section 4.3.1 of the Data report, QUINTESSA and GEOFIRMA 2011a).

4.2.3.2 Shafts

Decommissioning of the shafts will consist of: the removal of shaft infrastructure; the removal of the concrete shaft liner and highly damaged zone (HDZ) from the repository horizon up to about 180 m below ground surface (mBGS); and the installation of shaft seals.

The shaft seal concept is based on durable materials and is consistent with international practice, e.g., the Waste Isolation Pilot Plant facility (Hansen and Knowles 2000). The shaft seal design is illustrated in Figure 4.9, described in Section 13.6.3.1 of the Preliminary Safety Report (OPG 2011b) and summarized below.



Note: Figure 4.7 in QUINTESSA and GEOFIRMA (2011a).

Figure 4.9: Illustration Showing Sequence of Shaft Sealing Materials

- A **concrete monolith** containing Low Heat High Performance Cement (LHHPC) will be placed at the base of each shaft to provide a stable foundation for the overlying seal materials and support to the repository openings in the vicinity of the shafts.

- **Concrete bulkheads** containing LHHPC will be placed in each shaft at specific points, to provide permeability control and structural support. One bulkhead will be located towards the top of the Silurian rock formations at the boundary between the saline lower rock formations and the upper freshwater formations. Two other bulkheads will be located around the two more permeable zones in the Silurian rock formations. Other bulkheads may be added for further structural support, or if needed to separate the bentonite/sand and asphalt seals.

- The shaft will be sealed with durable materials. A 70:30 **bentonite/sand** mix will be used for the majority of seals[12]. An **asphalt mastic mix** will be used in one section to provide a different low-permeable material barrier that has the ability to creep and self-heal. The shaft in the upper formations will be filled with compacted **engineered fill** such as sand.

- A **concrete cap** will be constructed at the top of each shaft, consistent with the requirements for the decommissioning of a mine shaft. Even though the DGR does not meet the legal definition of a mine, it is considered good practice to meeting these requirements (Section 13.5 of the PSR, OPG 2011b).

The approximate total amount of materials used for shaft sealing has been estimated in Tables 4-8 and 4-15 of the Data report (QUINTESSA and GEOFIRMA 2011a) as: 59,000 tonnes of concrete for the concrete monoliths; 41,000 tonnes of concrete for the concrete bulkheads; 13,000 tonnes of asphalt mastic mix; 66,000 tonnes of bentonite/sand; and 17,000 tonnes of engineered fill.

4.2.3.3 Other Excavations

The DGR design includes excavations below repository level for rock handling and ramp access to the shaft bottoms (Figure 4.3). These excavations will be backfilled with LHHPC at closure and there will be no removal of any associated excavation damaged zone.

4.2.4 Safety Relevant Features

The following potential postclosure safety features and associated functions can be identified relating to the repository and shaft.

- The **waste emplacement rooms** are located at 680 m depth in a thick limestone formation under 200 m of shale caprock. They are not backfilled and their HDZs are not removed at closure so they are not expected to provide any barrier to contaminant migration. However, they do provide space for gas that might be generated from the corrosion and degradation of the wastes. Furthermore, the rooms are aligned with the principal stresses in the rock and, in conjunction with the thick room pillars, are mechanically robust.

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[12] A 70:30 mix was selected for a number of reasons: sufficient clay content for good swelling even under saline groundwater conditions; ease of handling compared with 100% clay (greater likelihood of quality placement); and improved mechanical properties compared to 100% clay.

- The **closure walls** could act as a barrier to migration of contaminants. However, these are designed for operational safety and are not intended to have a postclosure safety role.
- The **shafts** have been placed in an "island" arrangement to maximize their separation from the waste panels, and the HDZ in the shafts is removed before the shaft seals are installed.
- The **concrete monolith** at the base of the shafts provides long-term structural support to the shaft seals and the repository tunnels in the vicinity of the shafts. It can also limit water and gas flow into/from the DGR and shafts.
- The **bentonite/sand mix** in the shaft acts as the primary shaft seal. It limits groundwater and gas flow in the shaft and acts as a durable physical and chemical barrier to the migration of contaminants that can swell under DGR saline conditions.
- The **asphalt mastic mix** acts as a secondary shaft seal that provides an independent, self-sealing, low-permeable barrier to limit groundwater and gas flow and contaminant migration.
- The **concrete bulkheads** at the Guelph and Salina A1 levels isolate the bentonite/sand from any flow in these units, and provide structural support for the overlying bentonite/sand seals. These can help limit groundwater and gas flow in the shaft, but are not durable transport barriers in the long term.

4.2.5 Uncertainties

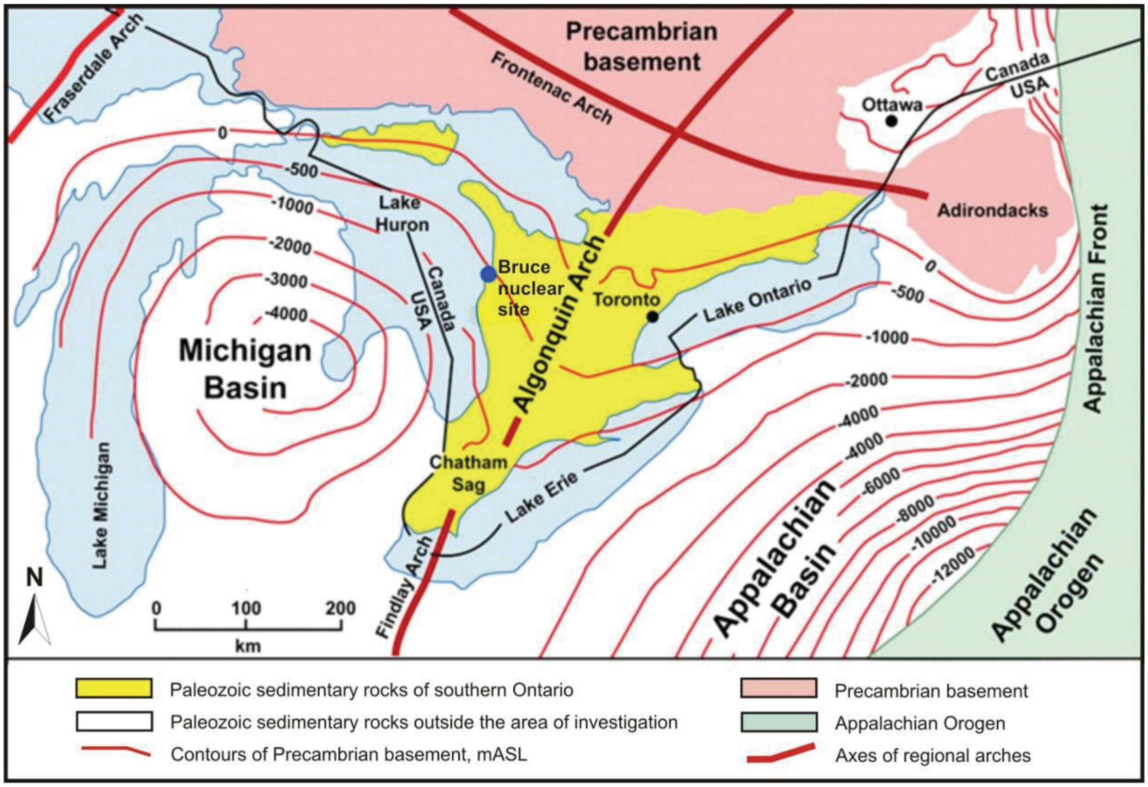
The preliminary design described above provides a reasonable shaft seal basis. However, it is recognized that it will be subject to further optimization based on knowledge gained during the 40 years of operation before seeking a decommissioning licence.

4.3 Geological Setting

4.3.1 Structural Geology

The proposed repository location is on the eastern edge of the Michigan Basin (Figure 4.10), a broadly circular intracratonic sedimentary basin. The Bruce nuclear site is located within the Huron Domain of the Precambrian basement Central Metasedimentary Belt (Figure 4.11). The structural stability of the basement is reflected in the structural simplicity of the Paleozoic rocks. The stratigraphy encountered in the DGR series of boreholes drilled at the Bruce nuclear site is consistent with regional data and predictions from regional geological modelling. Present and historical earthquake distribution data support the interpretation that the basement beneath the site is currently tectonically quiescent.

Investigations at the Bruce nuclear site have shown that the Paleozoic sediments are undeformed; dipping very gently (0.23° to 1.0°) to the southwest towards the basin depositional centre. A high degree of stratigraphic predictability and lateral facies consistency is observed between the DGR boreholes, and the DGR borehole stratigraphic data are consistent with expectations from interpolation of regional data to the site.



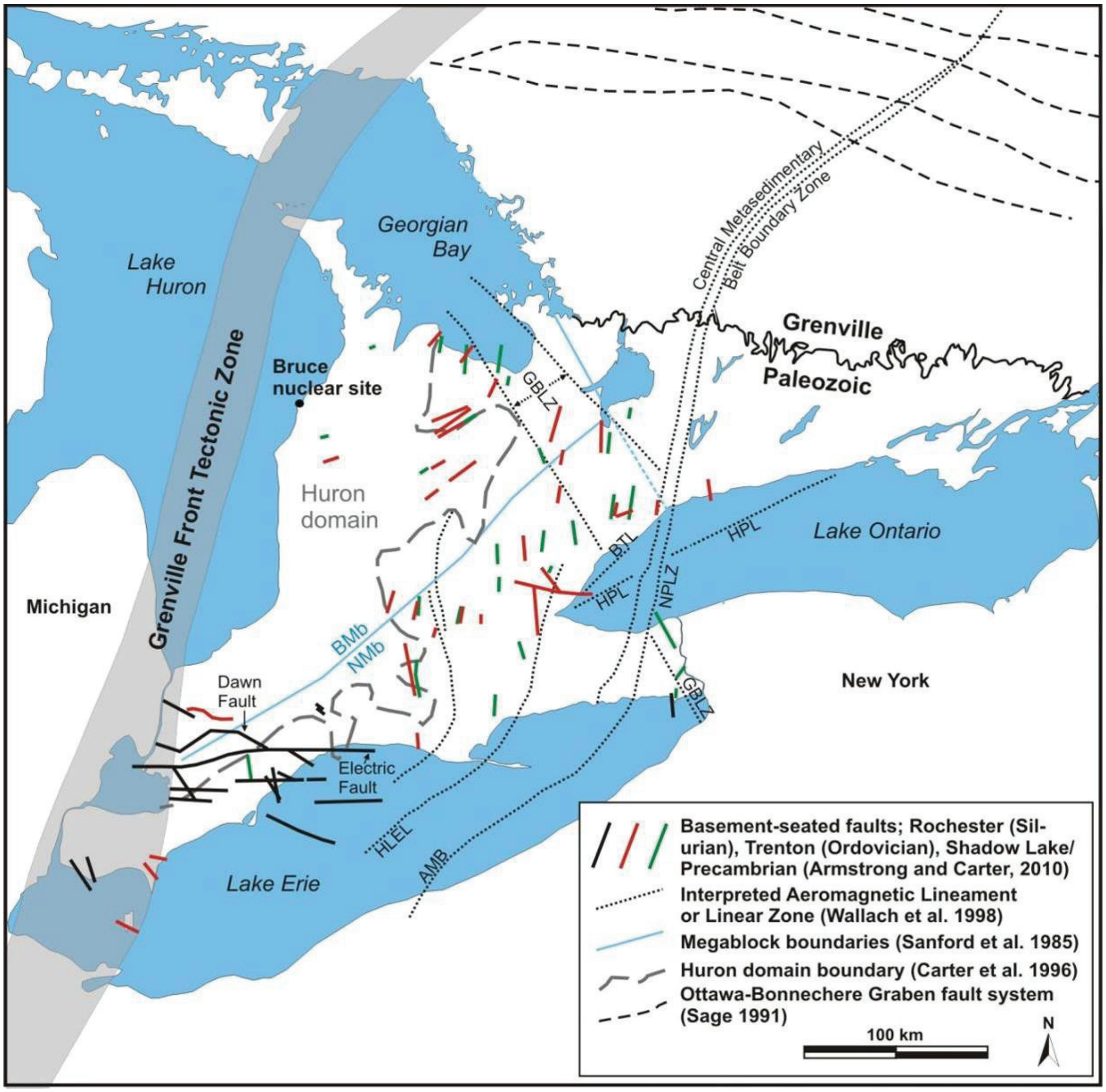
Note: Figure 2.2 in NWMO (2011a).

Figure 4.10: Large-scale Tectonic Elements in Southern Ontario

This indicates that there is a lack of significant faulting in the vicinity of the DGR boreholes. This is further supported by evidence from the angled deep boreholes DGR-5 and DGR-6 - the rock core obtained from these boreholes did not reveal the presence of vertical structure. Measured hydraulic conductivities in DGR-5 and DGR-6 were consistent with low values observed in vertical boreholes DGR-2/3/4.

Further evidence for the absence of sub-vertical/vertical fractures or fracture zones includes:

- Anomalous hydraulic heads through the Ordovician sequences, confirmed at deep boreholes DGR2/3/4, strongly suggest that transmissive sub-vertical/vertical discontinuities do not exist;
- Petrophysics studies within the Ordovician carbonates do not reveal the presence of enhanced permeability, porosity or dolomitization; all potentially associated with hydrothermal dolomitization of fracture zones in the Black River and Trenton groups;
- Micro seismicity monitoring has not revealed seismogenic features in the vicinity of the site that could indicate the presence of sub-vertical/vertical structure in the sedimentary sequence;
- Neotectonic studies conducted within 50 km of the Bruce nuclear site have not revealed evidence of liquefaction structures, offset beach terraces or the like within glacial drift that could be indicative of Holocene earthquakes and associated fault activity; and
- The closest interpreted fault structure is more than 25 km away from the site (Section 2.2.6.2 of the Geosynthesis report, NWMO 2011a).



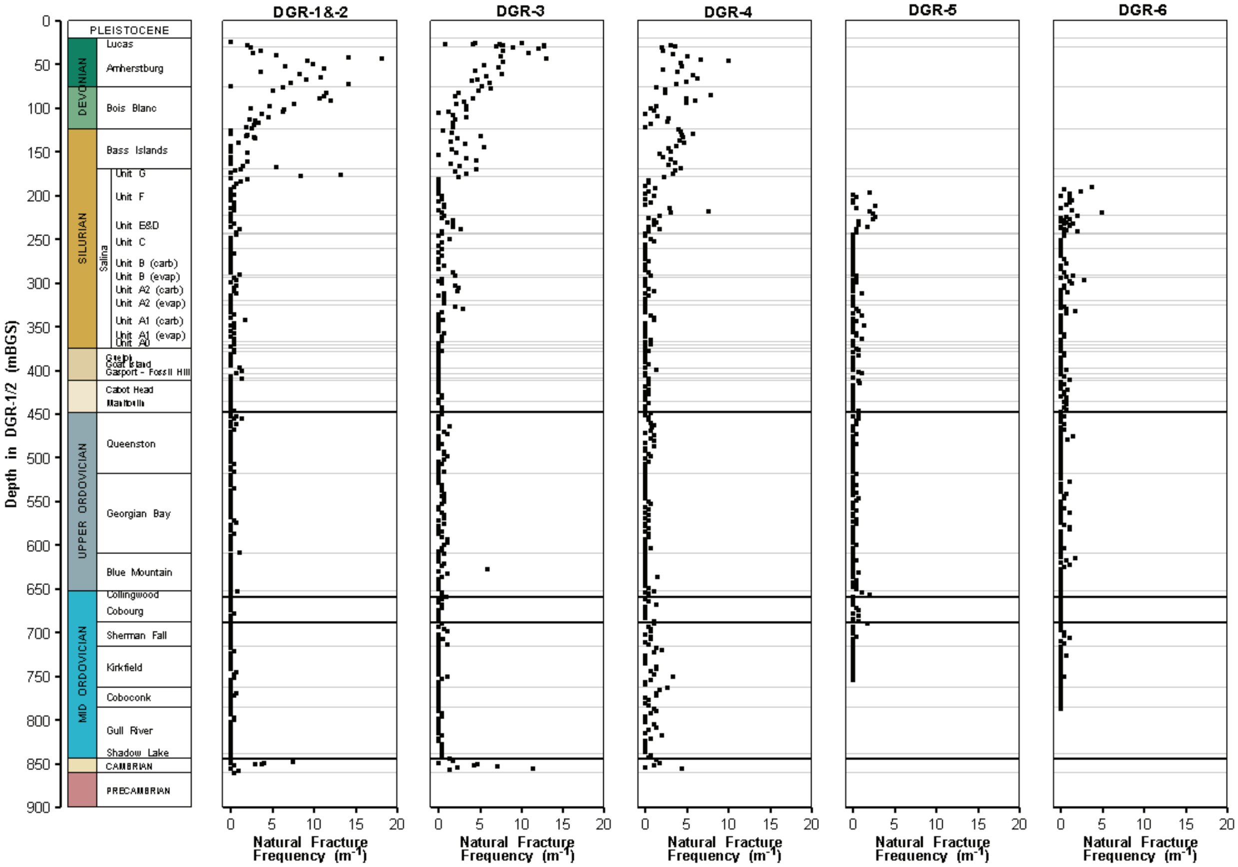
Notes:

AMB: Akron Magnetic Boundary; NPLZ: Niagara–Pickering Linear Zone; HLEL: Hamilton–Lake Erie Lineament; BTL: Burlington–Toronto Lineament; PL: Hamilton–Presqu'ile Lineament; GBLZ: Georgian Bay Linear Zone; EF: Electric fault; DF: Dawn fault; BMb – Bruce Megablock; NMb – Niagara Megablock.

Figure 2.5 in NWMO (2011a) and references therein.

Figure 4.11: Tectonic Boundary and Fault Contacts in Southern Ontario

Figure 4.12 shows the fracture frequency observed in cores from the DGR boreholes. The fracture frequency decreases with increasing depth, and is low below approximately 180 mBGS. This is to be expected because increasing overburden weight with increasing depth will tend to resist stress relief fracturing and tend to keep fractures closed. The majority of the joints observed within the Ordovician rocks are in the shales, with a joint spacing of >1.5 m.



Note: Figure 3.4 in INTERA (2011).

Figure 4.12: Profiles of Core Natural Fracture Frequency

4.3.2 Stratigraphy and Resources

The Paleozoic bedrock sequence overlying the Precambrian granitic basement has been measured to be approximately 845 m thick in the DGR site investigation boreholes. It comprises (from top to bottom) (Figure 4.13) approximately:

- 105 m of Devonian dolostones (dolomitic limestones);
- 325 m of Silurian dolostones and shales;
- 400 m of Ordovician shales and argillaceous to shaley limestone; and
- 15 m of Cambrian sandstone overlying Precambrian granitic gneiss.

Unconsolidated ('overburden') sediments overlie this bedrock sequence. These sediments are comprised of a comparatively complex sequence of Quaternary surface sands and gravels from former beach deposits (associated with Lake Huron) overlying clayey-silt to sandy silt till of glacial origin with interbedded lenses and layers of sand of variable thickness and lateral extent. The total thickness of this overburden varies from less than 1 m along the shore of Lake Huron to a maximum of about 20 m above the DGR site.

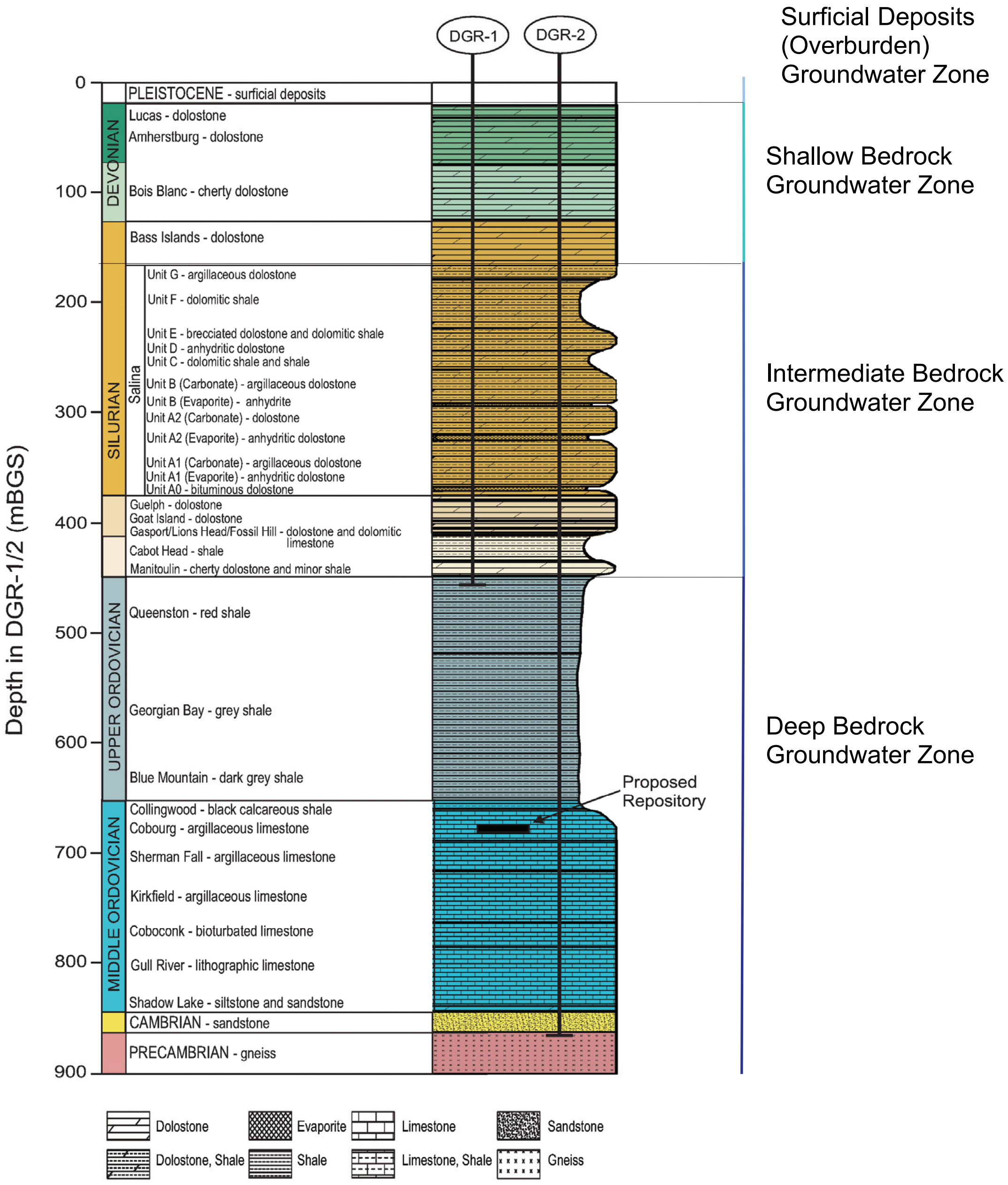


Figure 4.13: Reference Stratigraphic Column Showing Groundwater Zones

Exploration boreholes in the regional study area have shown that there are only minor oil and gas resources. These findings have been confirmed during logging of the DGR site investigation boreholes drilled at the Bruce nuclear site, which show that, although hydrocarbons have been detected, the quantities are small and are in discrete show zones that do not possess the permeability, source material or thermochronology to be considered commercially viable.

No evidence of commercial base metal mineralization has been observed in the core retrieved from the DGR site investigation boreholes. The boreholes have shown that there are minor amounts of salt and evaporates present as thin layers within the Paleozoic sequence at the Bruce nuclear site but these are not commercially viable: the formations are too thin and the salt/evaporate content too low for brine extraction to be viable, or for the formations to be used for gas storage.

The 20 m of overburden encountered at the site means that bedrock mining for uses such as aggregate, landscaping and for brick manufacture is not economic. However, the overburden does contain sand and gravel resources and there is some limited extraction. Four disused quarries exist in the controlled development zone around the Bruce nuclear site.

4.3.3 Hydrogeology

Four groundwater zones have been identified with differing lithological, hydrological and geochemical characteristics (Figure 4.13).

- **The Surficial Deposits (Overburden) Groundwater Zone:** the overburden sediments in which fresh water enters the groundwater system from precipitation through the recharge zone and flows vertically downwards into the underlying Shallow Bedrock Groundwater Zone. Layers of sand and gravel constitute local aquifers whereas the till layers are aquitards.

- **The Shallow Bedrock Groundwater Zone:** the Devonian and Upper Silurian dolostone sequence of the Lucas, Amherstburg, Bois Blanc and Bass Islands Formations. The direction of groundwater flow is westward to a point of near shore discharge in Lake Huron.

- **The Intermediate Bedrock Groundwater Zone:** includes the dolostone and shale sequence of the Salina, Guelph, Goat Island, Gasport, Lions Head, Fossil Hill, Cabot Head and Manitoulin Formations. The formations are dominantly of low permeability, movement of pore water is very slow and mass transport is considered to be diffusion dominated due to the very low permeability. The Guelph and Salina A1 Upper carbonate are relatively more permeable, although flow is limited by the low hydraulic gradients. Total dissolved solids (TDS) generally increase with depth down through the zone.

- **The Deep Bedrock Groundwater Zone:** is associated with the low permeability Ordovician shales and limestones and the underlying Cambrian sandstones and Precambrian granitic gneiss. Within the Ordovician sediments, movement of pore water is very slow and mass transport is considered to be diffusion dominated due to the very low permeability. Although the Cambrian is relatively more permeable, flow is limited by the low hydraulic gradient. The proposed repository is to be located in the Deep Bedrock Groundwater Zone at a depth of around 680 m within argillaceous limestone of the Cobourg Formation.

Figure 4.14 shows the hydraulic conductivity profile measured at the DGR site based on data from the in-situ straddle packer testing in the DGR site investigation boreholes.

Free gas is present in the rock pores in the Intermediate and Deep Bedrock Groundwater Zone. Measurements (Section 4.3.3 of the DGSM report, INTERA 2011) indicate free gas saturations of approximately 10 to 20%, and in certain cases up to 45% (Figure 4.15), although the values are uncertain due to the low rock porosity and other factors. The presence of this trapped free gas phase is a further indication of the low permeability of the zones. It is likely that most of this gas-filled porosity is not connected due to the low porosity and narrow pore sizes, and that the included gas is not mobile. Isotopic analysis indicates that the gas in the Middle Ordovician limestone is thermogenic in origin (i.e., formed by heating of organic matter deposited with the sediments at depth and, therefore, under high pressure, within the basin).

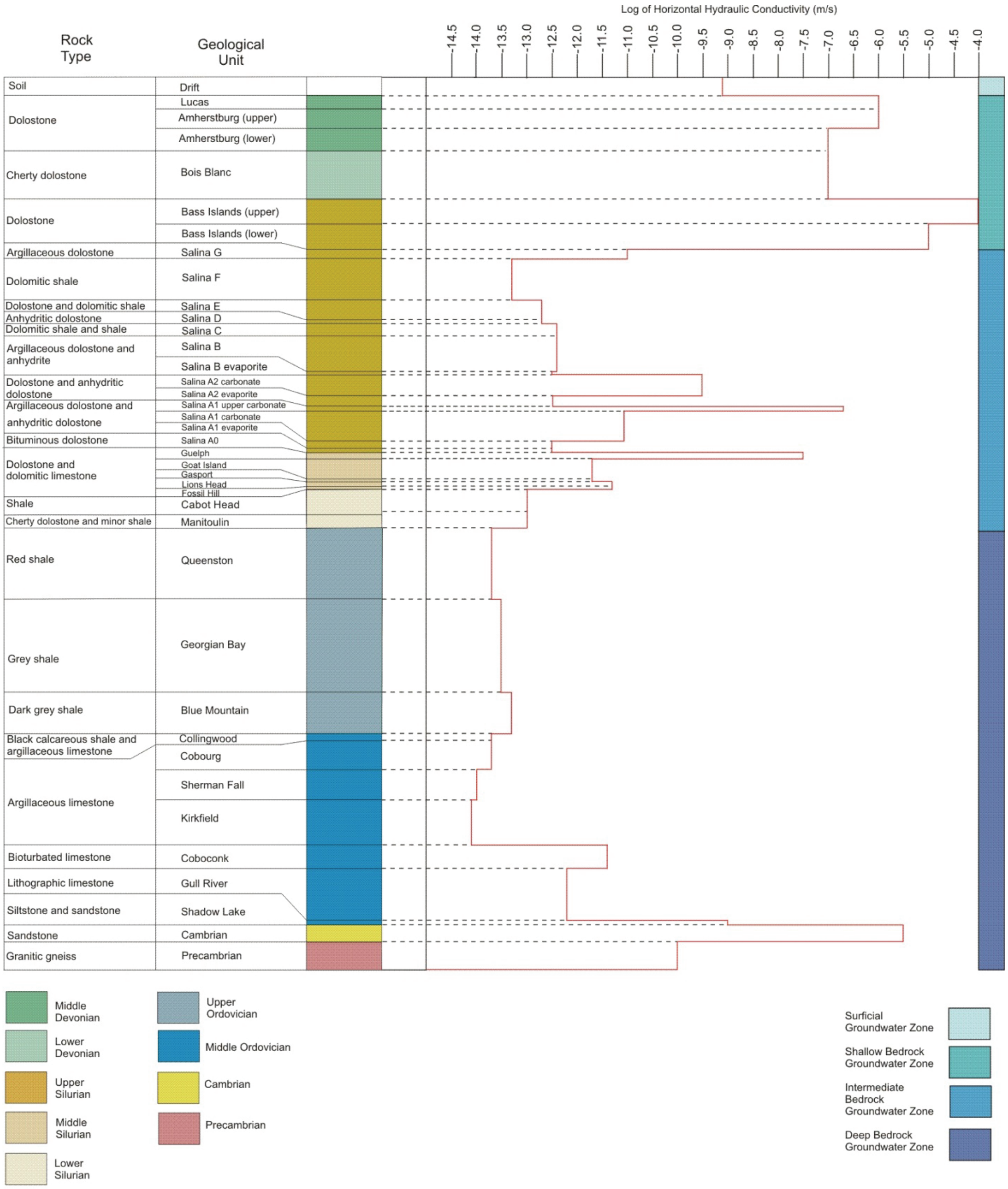
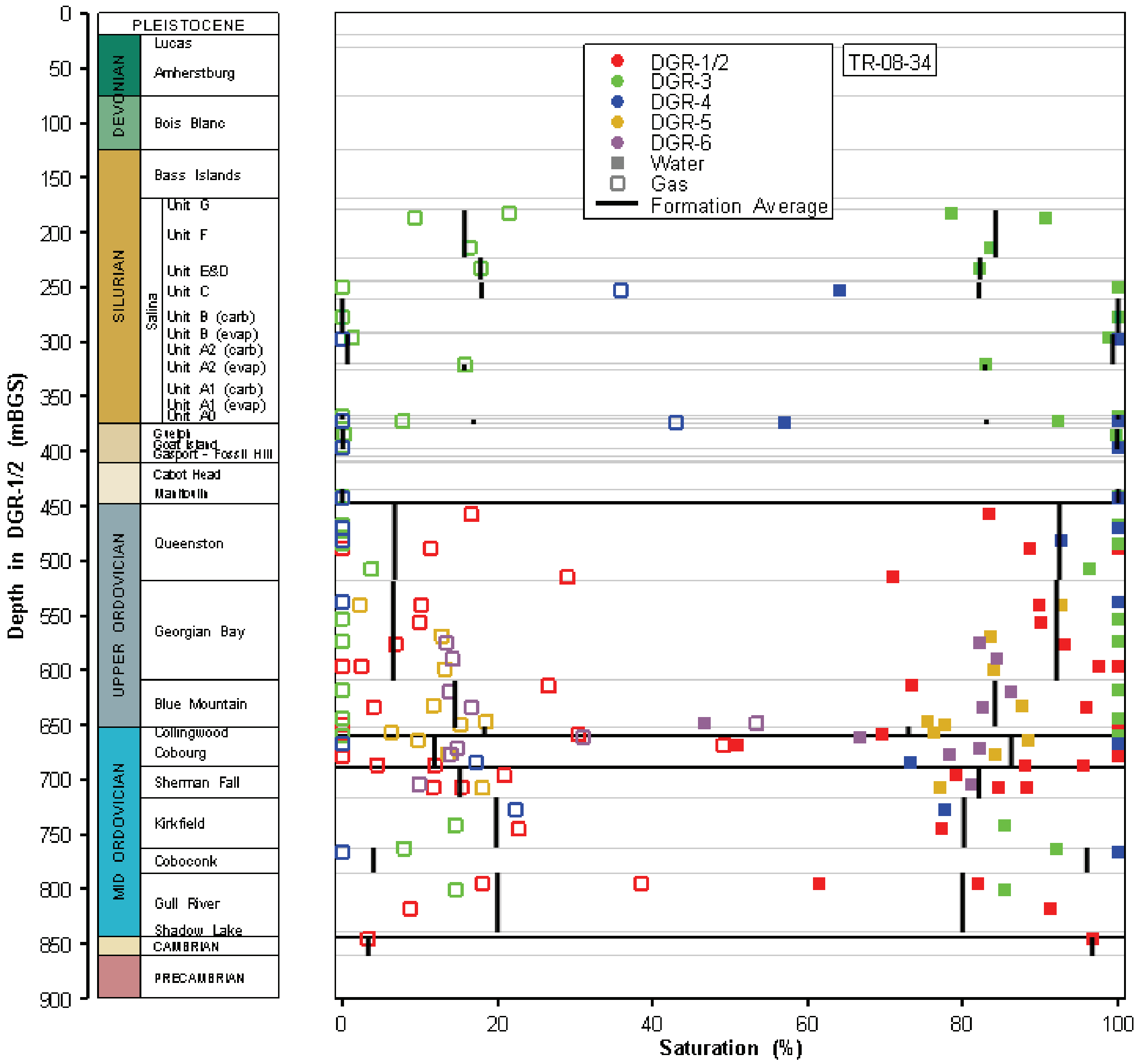


Figure 4.14: Hydraulic Conductivity Profile at the Bruce Nuclear Site



Note: Figure 4.8 in INTERA (2011).

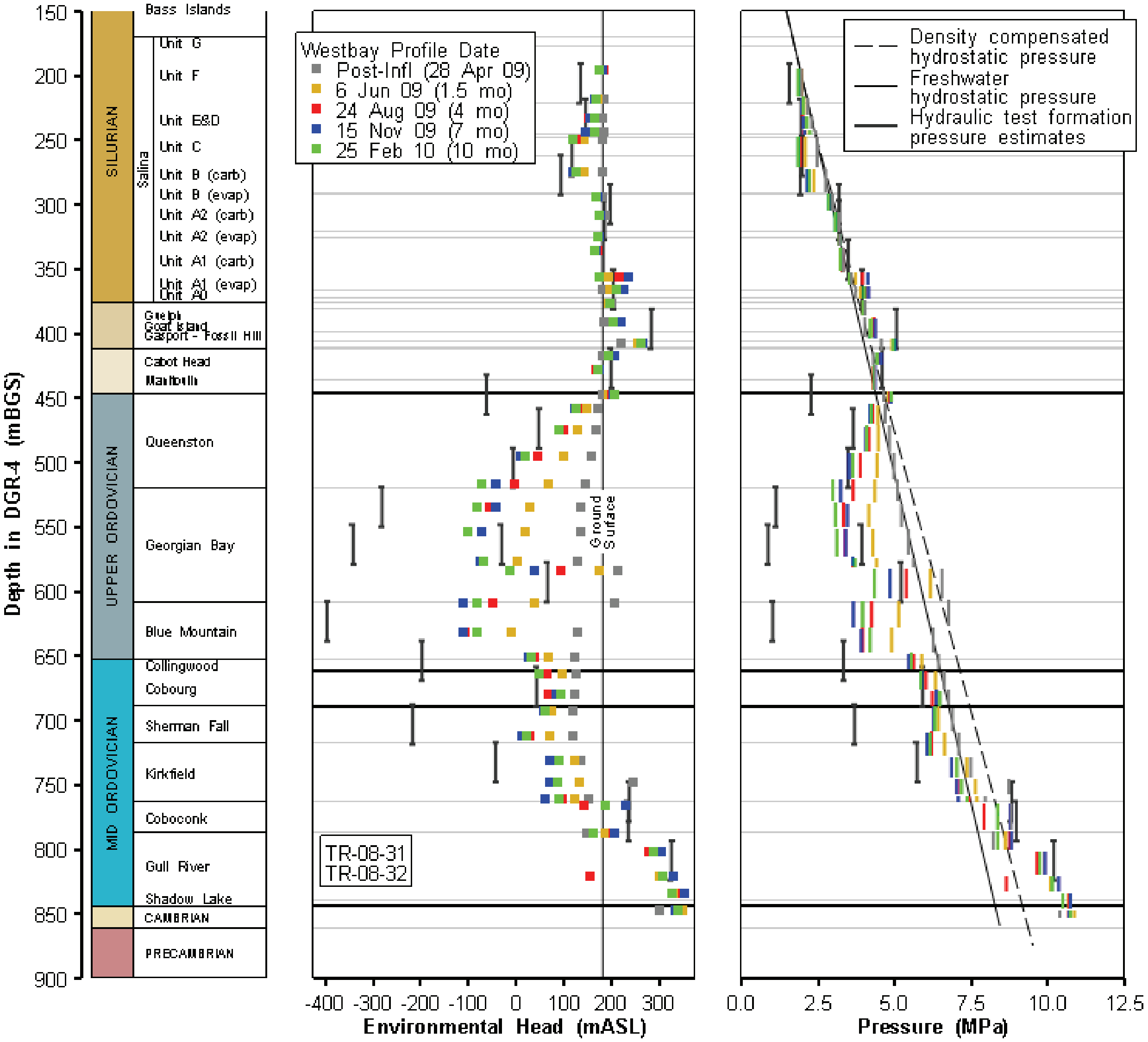
Figure 4.15: Saturation Profile in DGR Cores

Pressure data from the DGR boreholes indicate that the Cambrian sandstone and the Middle and Upper Silurian are overpressured relative to the ground surface, whereas the Ordovician limestone and shale are significantly underpressured. Measured head profiles for borehole DGR-4 are shown in Figure 4.16 and the associated density profile used to calculate environmental heads is shown in Figure 4.17.

Considerable work has been undertaken to understand the causes of these under and overpressures (Section 5.4.10 of the Geosynthesis report, NWMO 2011a). They may be related to glacial processes; however, paleoclimate models that considered various ice-sheet advance/retreat scenarios did not generate the required pressure anomalies. Osmosis is also not considered to be a viable mechanism. The overpressures observed in the Cambrian and

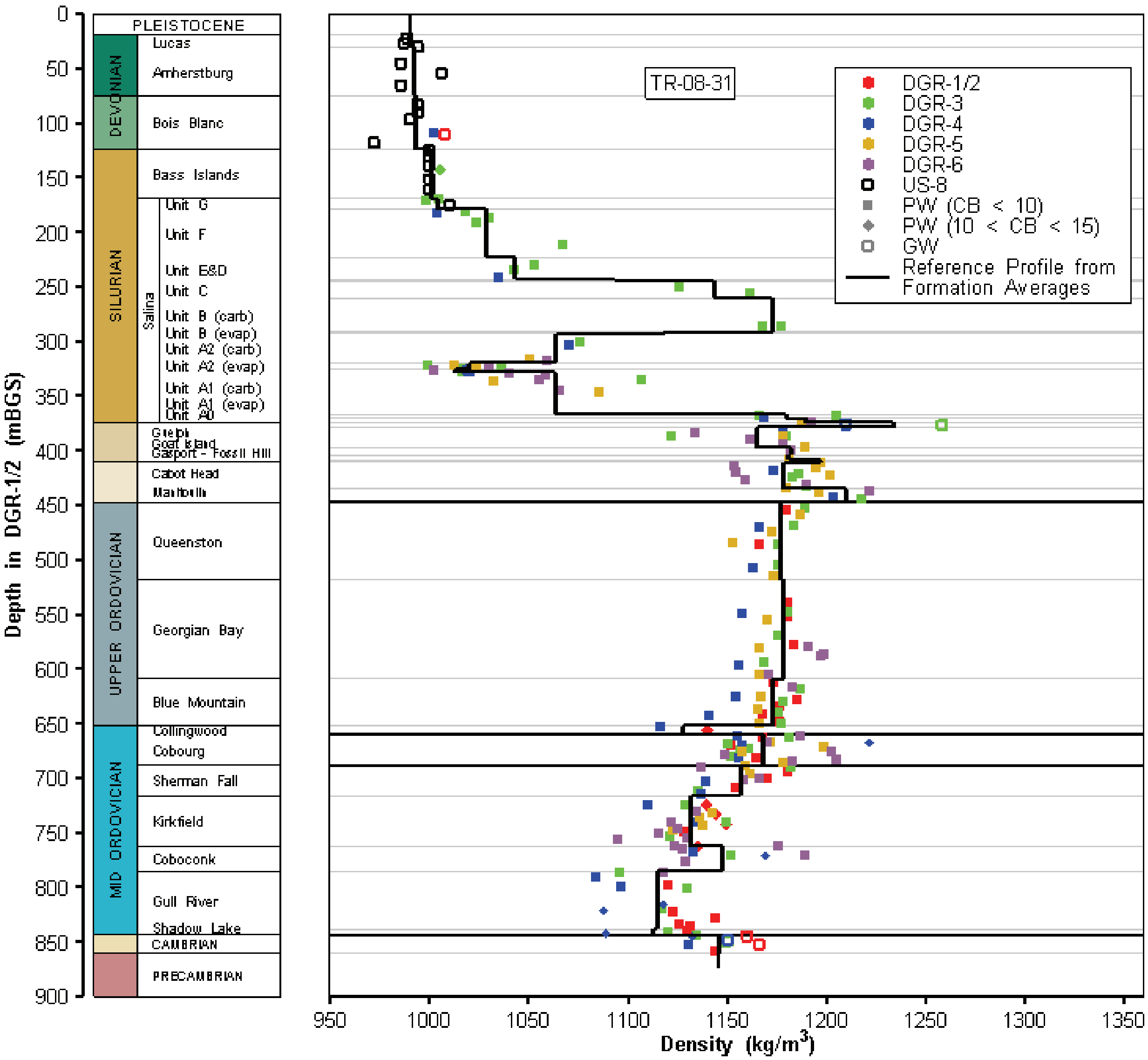
Middle and Upper Silurian are consistent with the density-dependent saturated flow analyses of the Michigan Basin cross-section. The observed underpressures in the Ordovician can be reproduced by assuming the presence of a non-wetting immiscible gas phase in the rock.

Regardless of their origin, these large and sustained anomalous pressure gradients indicate that the permeability is very low and that there is no transmissive vertical fracture network present within or near the DGR borehole footprint beneath the Bruce nuclear site.



Note: Figure 4.102 in INTERA (2011).
Based on data from the DGR-4 site investigation borehole.

Figure 4.16: Groundwater Vertical Head Profile at the Bruce Nuclear Site



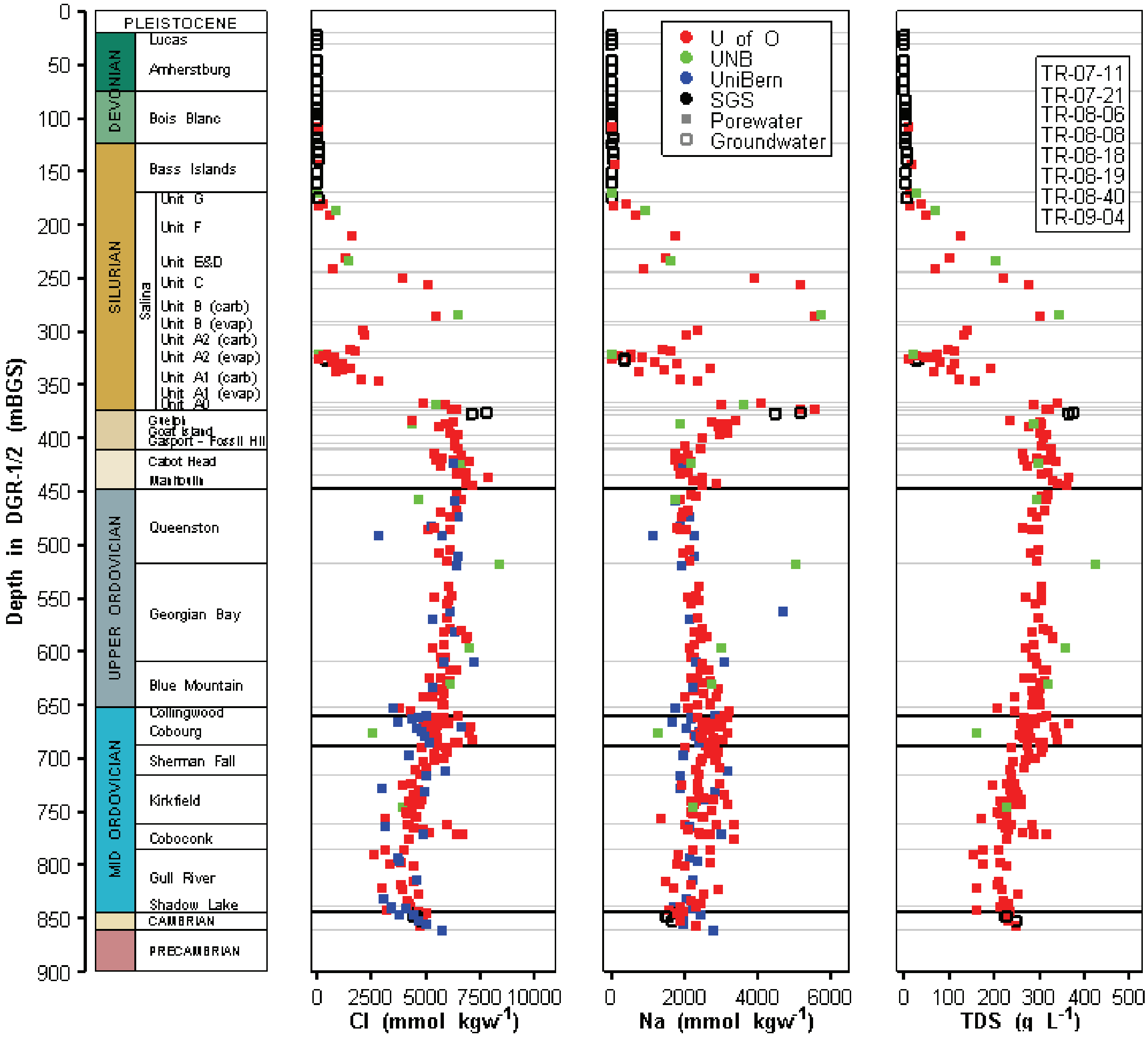
Note: Figure 4.81 in INTERA (2011).

Figure 4.17: Groundwater Density (Salinity) Profile at the Bruce Nuclear Site

4.3.4 Geochemistry

4.3.4.1 Water Chemistry

Figure 4.18 shows the major ion composition and total dissolved solids (TDS) of the groundwater/porewater at the Bruce nuclear site. The Shallow Bedrock Groundwater Zone contains relatively fresh water, consistent with this being the relatively permeable, actively flowing part of the system. Major anion concentrations increase through the deeper zones; the water is dense and saline.



Note: Figure 4.107 in INTERA (2011).

Figure 4.18: Major Ion Groundwater/Porewater Concentrations

The data indicates that porewaters in the Deep Bedrock Groundwater Zone have not mixed with, or been displaced by, surface waters, including glacial meltwaters. Coupled hydro-mechanical paleoclimatic groundwater flow models (Section 5.4.6 of the Geosynthesis report, NWMO 2011a) support this geochemical interpretation.

Regional geochemical evidence (Section 4.3.2 of the Geosynthesis report, NWMO 2011a) indicates that glacial or younger recharge is most often identified in shallow environments. Data from the DGR boreholes (Section 4.4 of the Geosynthesis report, NWMO 2011a) indicates that glacial meltwater has not penetrated below the base of the Shallow Bedrock Groundwater Zone, i.e., not below 180 m, except in the relatively permeable Salina A1 upper carbonate in the Intermediate Bedrock Groundwater Zone. The presence of waters with a glacial isotopic signature within this formation suggests injection of glacial meltwaters from outcrop/subcrop rather than via the overlying formations.

Geochemical evidence presented in Chapter 4 of the Geosynthesis report (NWMO 2011a) indicates that the brines in the Intermediate and Deep Bedrock Groundwater Zones are ancient (more than 250 million years old). This implies that the hydraulic conductivity must be very low, which is consistent with data from the Bruce nuclear site (Figure 4.14) and is reflected in the entrapment of hydrocarbons for more than 200 million years by equivalent formations elsewhere in the Michigan Basin.

4.3.4.2 Rock Chemistry

Mineralogical information is available from testing of DGR borehole core samples (Section 3.7 of the DGSM report, INTERA 2011). The whole rock mineralogy data are shown in Figure 4.19 to Figure 4.21. Points to note relating to the proposed host rock for the DGR (the Cobourg Formation) and surrounding formations are:

- Calcite and dolomite are significant constituents (>80%);
- Silicates are a minor constituent (<10%); and
- Evaporite minerals also occur in minor amounts (<10%).

Although the abundances of pyrite are small (<<1%), the fact that pyrite is present is strong evidence that in-situ conditions are reducing.

4.3.5 Seismicity

Southwestern Ontario and the Bruce region lie within the tectonically stable interior of the North American continent, which is characterized by low rates of seismicity. There are historical records since the late 1800s. Figure 4.22 shows the monitoring results since 1985 from the seismograph stations around the Bruce nuclear site. It shows that the Bruce region experiences sparse seismic activity, with no apparent concentrations of activity that might delineate regional active faults or other seismogenic features. Most recorded events have a Nuttli magnitude[13] less than **M**3, with rare occurrences of larger events up to **M**4.3 within a 150 km radius from the Bruce nuclear site.

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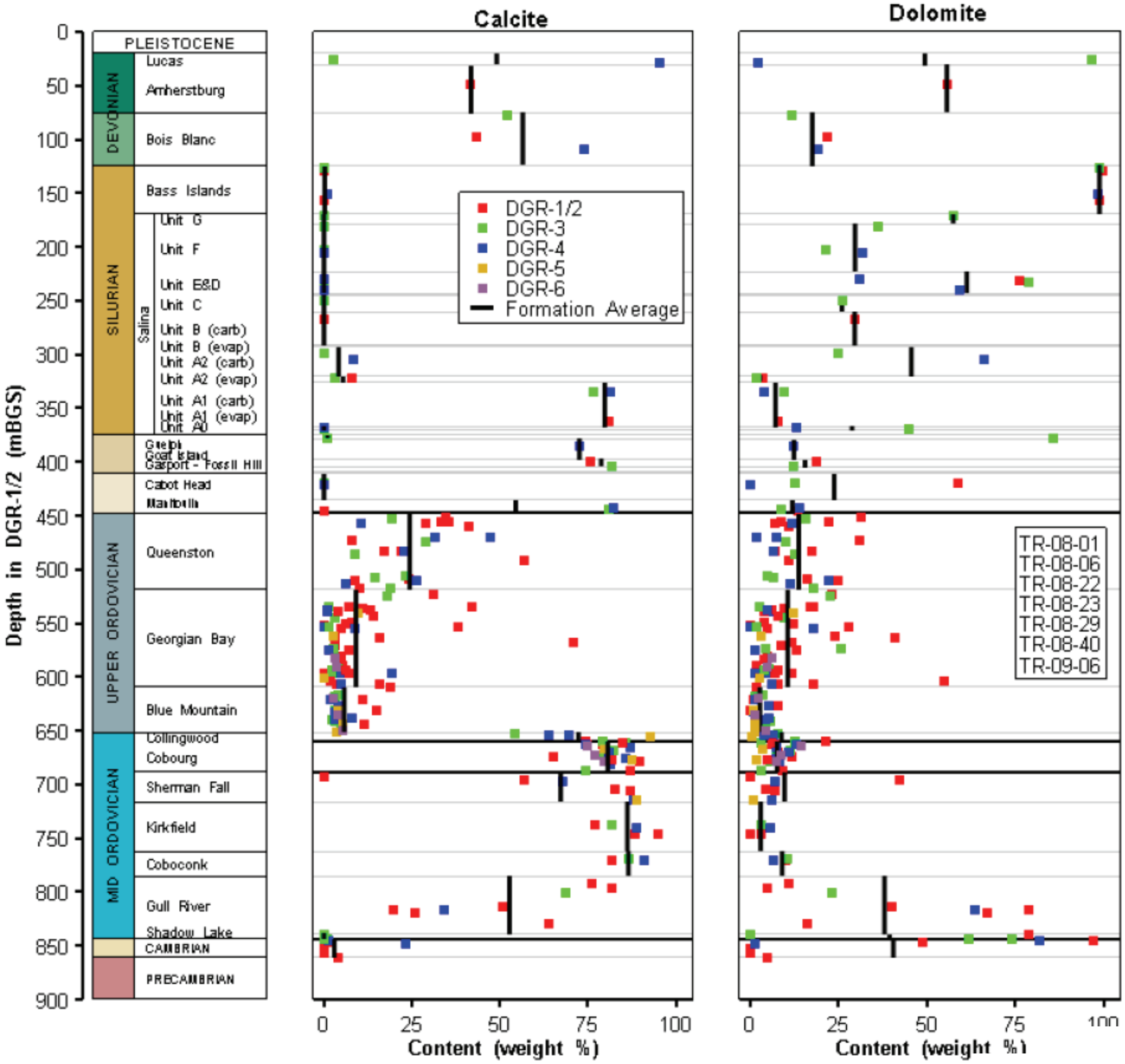
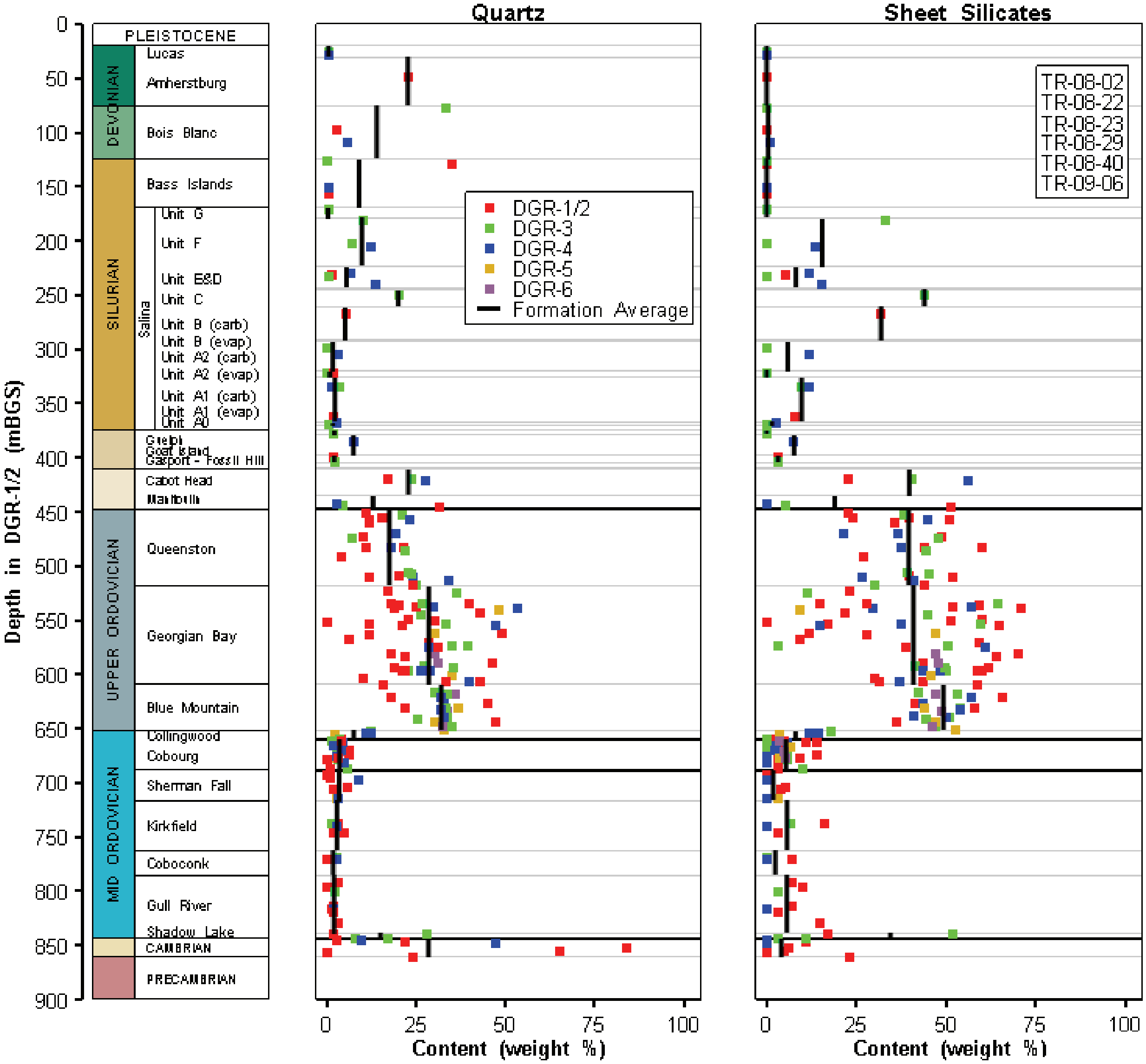
[13] Nuttli Magnitude (**M**) is the local magnitude scale used in the Bruce monitoring network. It can be related to the moment magnitude (Mm) scale by the empirical relationship Mm = 0.98M-0.39 for 4<M<6 (Sonley and Atkinson 2005). The moment magnitude scale was calibrated such that moment magnitude equals Richter magnitude in most cases (Hanks and Kanamori 1979), but it provides a more direct indication of earthquake fault size.



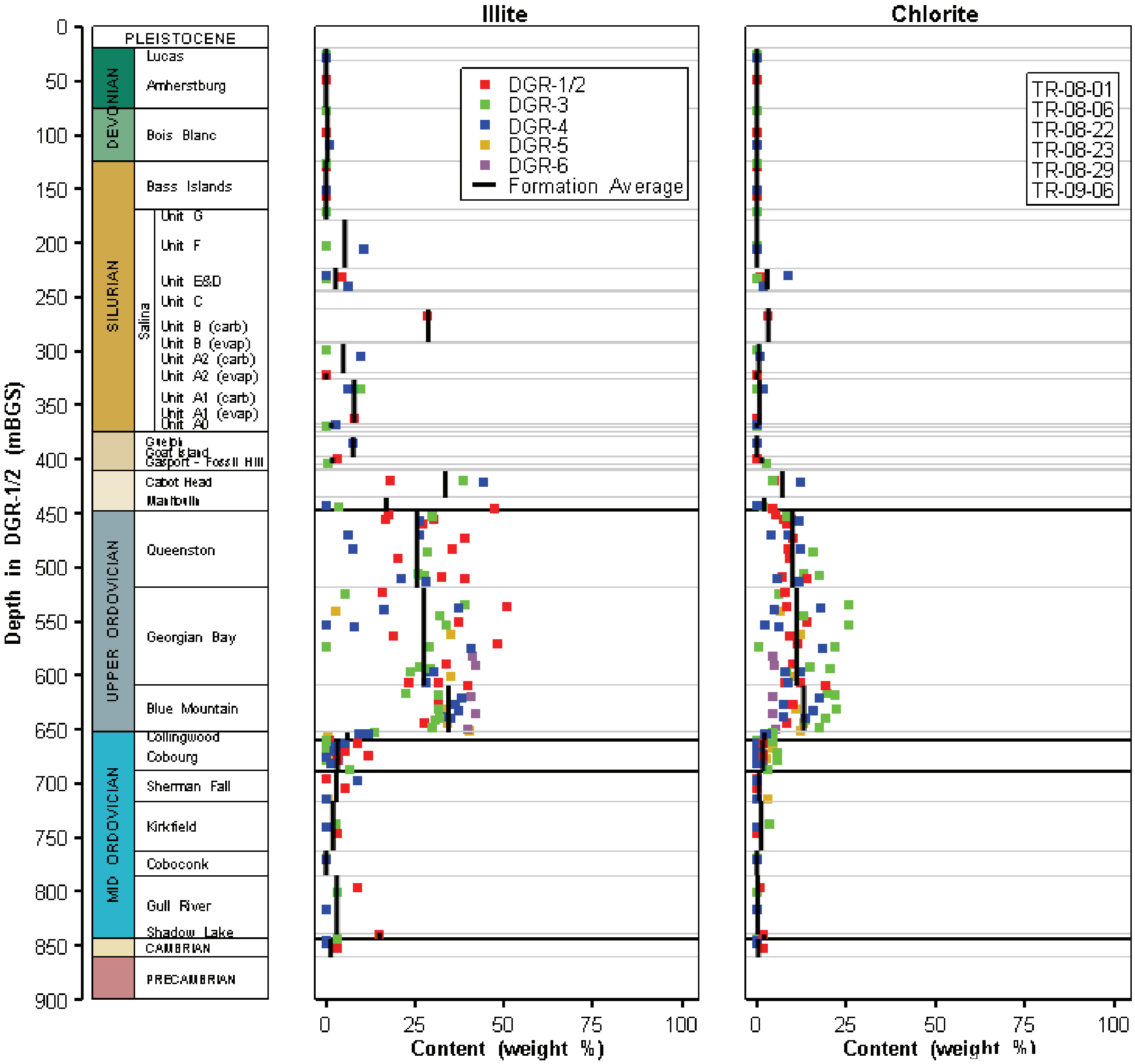
Note: Figure 3.5 in INTERA (2011).

Figure 4.19: Profiles of Calcite and Dolomite in DGR Cores



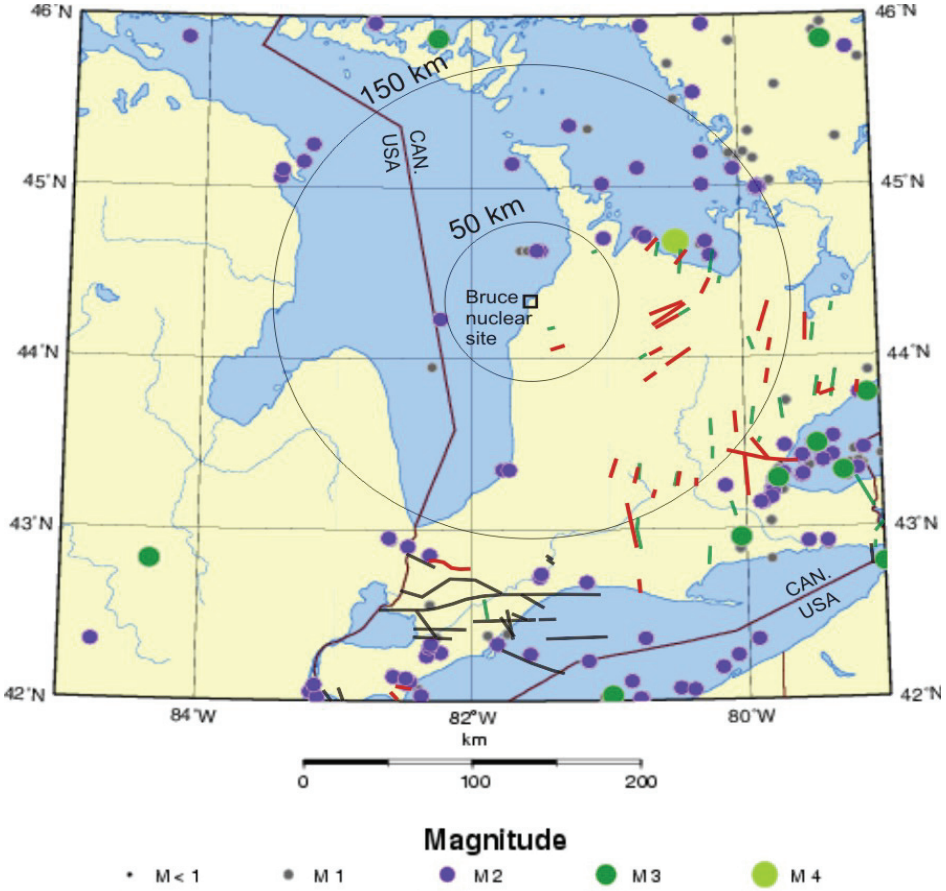
Note: Figure 3.6 in INTERA (2011).

Figure 4.20: Profiles of Quartz and Total Sheet Silicates in DGR Cores



Note: Figure 3.7 in INTERA (2011).

Figure 4.21: Profiles of Illite and Chlorite Clay Mineral Content in DGR Cores



Note: Figure 2.14 in NWMO (2011a).

Figure 4.22: Seismicity in the Bruce Region from 1985 to 2010 Overlain with Mapped Faults in Southern Ontario

These findings provide a sense of the seismic recurrence rate of the Bruce region. With no seismic events of **M** > 4.3 recorded in the past 100+ years, the likelihood of a large event in the Bruce region is very low, exhibiting a seismicity rate comparable to that of a cratonic region. The rate could potentially be affected if there was a future episode of glaciation; as such events lead to in-situ stress changes that may temporarily increase seismicity rates (Adams 1989). However, a recently completed remote-sensing and field-based study looked at landforms within 50 km of the Bruce nuclear site and found no evidence for neotectonic activity associated with the most recent glacial cycle within the area (Section 2.2.6.5 of NWMO 2011a).

A Probabilistic Seismic Hazard Assessment was performed for the Bruce nuclear site. The frequency of **M** ≥ 6 earthquakes within 200 km of the site was estimated at 10^{-4} per annum (Chapter 6, AMEC GEOMATRIX 2011). This is approximately equivalent to an annual frequency of an **M** ≥ 6 event of 10^{-6} within a 20-km radius of the site, assuming roughly uniform probability across the area. The peak ground accelerations obtained from the seismic hazard assessment are 0.18g for events with probability of exceedance of 10^{-5}/a, and 0.6g for events with probability of exceedance of 10^{-6}/a (Chapter 6 of AMEC GEOMATRIX 2011, Section 6.2.2.1 of NWMO 2011a).

The intensity of ground shaking due to an offsite earthquake normally decreases with depth. Therefore, for a given event, the potential for damage of the DGR and shaft seals in the Deep and Intermediate Bedrock Groundwater Zones is lower than the potential for damage to surface features. Dynamic mechanical modelling (Section 6.4 of the Geosynthesis report, NWMO 2011a) indicates that the DGR and its shaft will not be damaged by a one in a million year event. These results are consistent with case histories that show earthquake damage to underground structures is rare, particularly below 500 m (Pratt et al. 1979; Backblom and Munier 2002).

4.3.6 Safety Relevant Features

The following postclosure safety features and associated functions can be identified relating to the geosphere.

- The **low permeability and geomechanically stable rocks** act as the main natural barrier. They limit the ingress of water into the DGR and act as a physical and chemical barrier to migration of contaminants from the DGR. They are predictable with a large lateral extent.
- The **current Ordovician underpressures** result in any groundwater flow being towards (rather than away from) the Ordovician host rocks. They also provide evidence of a lack of local transmissive faulting and significant groundwater flow.
- The **tectonic and seismic stability** of the site and the **absence of large-scale faults/fractures** results in there being an absence of high permeability pathways from the repository level to higher horizons.
- The **thickness of the rocks** above the repository limits the nature and likelihood of human intrusion into the DGR and the impact of ice-sheets on the DGR and the deep geosphere.
- The **absence of economically viable mineral resources** limits the nature and likelihood of human intrusion. Shallow groundwater resources are isolated from saline intermediate and deep groundwaters.
- The relatively permeable **Guelph and Salina A1 upper carbonate formations** can divert gas or solutes migrating upwards from the repository via the geosphere and shafts.

4.3.7 Uncertainties

The geosphere has been extensively characterized at the site (NWMO 2011a and INTERA 2011), and work is continuing. The safety related features identified in Section 4.3.6 are well established. Nevertheless, the following areas of uncertainty that relate to the current status of the site and are relevant to its long-term safety are recognized:

- The extent and transport properties of the excavation damaged zone in the rock are uncertain. The information currently used in the assessment is based on modelling and international experience (see Sections 6.3 and 6.4 of the Geosynthesis report, NWMO 2011a). It will ultimately be verified by site-specific information as the shafts are excavated.
- The extent of the free gas phase in the Ordovician rocks and the rock gas transport parameters (in particular capillary pressure and relative permeability) are uncertain. However, it is nonetheless apparent that the ability for gas movement in the host rocks is very limited.

- The causes of the over and underpressures observed within the rocks at the site are not certain. However, there are plausible explanations for these (see Section 4.3.3), and in any event they are clearly currently present at the site.

4.4 Surface Environment

4.4.1 Topography

The Bruce nuclear site lies on the eastern shore of Lake Huron on the Douglas Point promontory (Figure 1.1). The topography around the site is relatively low-lying, varying between 176 m above sea level (mASL) (the level of Lake Huron) up to approximately 195 mASL (associated with the Nipissing Bluff). Elevations increase to approximately 230 mASL further inland to the east, associated with another bluff line, the Algonquin Bluff. Each of these bluffs represents remnants of post-glacial shorelines developed during the Holocene.

4.4.2 Atmosphere

The annual mean temperature is 8.2 °C in the vicinity of the site. Minimum and maximum from 2005 to 2009 were -21°C and 32°C, respectively (Section 5.3.2, GOLDER 2011c).

There is a relatively even distribution of meteoric precipitation between winter and summer seasons (combining rainfall and snowfall), typically totalling about 1.1 m annually. About 30% of this meteoric precipitation falls as snow (Section 5.3.3, GOLDER 2011c).

The average wind speed is 3.3 m/s with the prevailing winds being from the southwest (Section 5.3.4, GOLDER 2011c).

4.4.3 Surface Water Bodies

The Bruce nuclear site is located adjacent to the Lake Huron shoreline. The lake contains about 3,700 km^3 of water, covering an area of approximately 60,000 km^2. There are two small east-to-west drainage courses entering the lake adjacent to the site (Figure 4.23): Underwood Creek and Stream “C” empty into Baie du Doré to the north and the Little Sauble River, which forms the southern boundary of Inverhuron Provincial Park, discharges into Inverhuron Bay to the south. Stream “C” is characterized as a slow-flowing stream with a mean width of 3.0 m with maximum water depths ranging from 0.15 m to 0.8 m. To the east of the WWMF is a small wetland (4 ha). A ditch, known as the Railway Ditch, flows to the north of the WWMF around the edge of the wetland and continues into Stream “C” beyond the wetland. The Railway Ditch is approximately 3 m wide with a mean water depth of 0.15 m.

Note: Figure 5.4.3-1 in GOLDER (2011e).

Figure 4.23: Local Watersheds

4.4.4 Water Supply

Most of the rural population in the region obtains its water from private or communal wells, while the lake provides water for larger communities. In the Kincardine Municipality there are approximately 1000 wells (GOLDER 2003), five of which are within the Local Study Area. Water is drawn principally from the Shallow Bedrock Groundwater Zone from depths of between 30 and 100 m.

4.4.5 Soil

The overburden underlying the site is composed of a comparatively complex sequence of surface sand and gravel from former beach deposits overlying clayey to sandy silt glacial till with interbedded lenses of sand of variable thickness. Near the shoreline, thin deposits of sand, gravel and boulders overlie the bedrock and bedrock locally outcrops. In general, there is a shallow layer of topsoil with both sandy and loamy/clayey soils present.

4.4.6 Land Use

Current land uses on the Bruce nuclear site are restricted to those associated with the nuclear operations and support activities. The region around the site is mainly used for agriculture, recreation (e.g., Inverhuron Provincial Park) and some residential development (e.g., Inverhuron and Zepf's Pine Acres). Farmland accounts for around 62% of the land use in Bruce County, with cattle, sheep and pigs being reared, and crops such as oats, canola, barley and hay being produced. About 63% of Bruce County farms are family owned and operated. Local people also hunt wild animals including deer and waterfowl. The lake is used for water supply, recreational and commercial fishing, and boating.

The nearest population centre is Inverhuron (population of around 800) about 4 km to the southwest of the site. Larger towns are Port Elgin (population of over 7000) about 20 km to the northeast, and Kincardine (population of around 9300), 15 km to the southwest.

The traditional territory of the Ojibway in the Saugeen region covers the watersheds bounded by the Maitland River and the Nottawasaga River east of Collingwood, an area that includes the Bruce Peninsula and Grey and Bruce Counties. The Chippewas of Saugeen reserve is approximately 38 km^2 situated on Lake Huron, at the base of the Bruce Peninsula about 3 km northeast of Southampton. The Chippewas of Nawash reserve occupies 72 km^2 on the eastern shore of the Bruce Peninsula on Georgian Bay.

4.4.7 Biota

Although Bruce County contains a number of large forested areas and wetlands, providing core habitat for a variety of wildlife species, much of the region around the Bruce nuclear site consists of agricultural land. Details of terrestrial and aquatic biota at the site and in the region are provided in the Terrestrial Environment and Aquatic Environment technical support documents (GOLDER 2011g and 2011b).

The valued ecosystem components (VECs[14]) identified in the EA for the DGR include the following biota (GOLDER 2011a-g):

- Terrestrial plants – common cattail, eastern white cedar, heal-all;
- Aquatic plants – sago pondweed, variable leaf pondweed;
- Terrestrial mammals – meadow vole, white-tail deer;
- Aquatic mammals – muskrat;

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[14] VECs are features of the environment selected to be a focus of the environmental assessment because of their ecological, social, or economic value, and their potential vulnerability to the effects of the DGR project.

- Amphibians and reptiles – midland painted turtle, northern leopard frog, northern water snake;
- Terrestrial birds – bald eagle, great horned owl, red-eyed vireo, wild turkey, yellow warbler;
- Aquatic birds – double-crested cormorant, mallard;
- Benthic invertebrates – burrowing crayfish;
- Benthic fish – bluntnose minnow, creek chub, deepwater sculpin, lake whitefish, redbelly dace; and
- Pelagic fish – brook trout, smallmouth bass, spottail shiner.

4.4.8 Safety Relevant Features

The biosphere is evaluated as pathways that can lead to exposure or impacts. It is not assigned any safety relevant features. The large volume of Lake Huron is important in the pathway analysis due to its high dilution potential. However, this feature is not relied on for safety. Specifically, the site resident critical group is assumed to be living on the repository site and using a well that pumps water from the Shallow Bedrock Groundwater Zone (Section 6.2.1.3).

4.4.9 Uncertainties

The present-day surface environment in the vicinity of the Bruce nuclear site has been well characterized for input to the Environmental Impact Statement for the DGR (GOLDER 2011a-g, AMEC NSS 2011).

There is limited information on the surface water flow parameters (e.g., recharge and flow rates in the Railway Ditch and Stream C) at the site. However, these parameters are certain to change significantly over the time frame of this study, so exact values are not important. The parameters adopted for the purposes of the assessment are considered appropriate for the stylized representation of the surface environment that reflects the present-day conditions.

5. SCENARIO IDENTIFICATION AND DESCRIPTION

The postclosure safety of the DGR is assessed through consideration of a range of potential future scenarios. The guidance on assessing the long-term safety of radioactive waste management (CNSC 2006) defines scenarios as “a postulated or assumed set of conditions or events. They are most commonly used in analysis or assessment to represent possible future conditions or events to be modelled, such as the possible future evolution of a repository and its surroundings” (CNSC 2006). The purpose of scenario identification and development is not to predict the future; rather, it is to develop a sufficiently comprehensive range of possible future evolutions of the DGR against which the performance of the system can be assessed.

The guidelines for the preparation of the EIS for the DGR (CEAA and CNSC 2009) and the guidance on assessing the long-term safety of radioactive waste management (CNSC 2006) identify the need for the postclosure safety assessment to include a scenario of the normal (or expected) evolution of the site and facility with time based on reasonable extrapolations of present-day site features and receptors’ lifestyles (the Normal Evolution Scenario), and including its expected degradation (loss of barrier functions) with time. In accordance with G-320 (CNSC 2006), additional scenarios are considered to examine the impacts of unlikely disruptive events that lead to possible penetration of barriers and abnormal degradation and loss of containment (Disruptive Scenarios). As G-320 notes, occurrence of such events cannot be predicted accurately even in cases where they can be associated with an annual probability of occurrence or a return period. As such, the Disruptive Scenarios consider unlikely “what if” cases that are designed to test the robustness of the DGR system to scenarios that result in the breaching or extreme degradation of geosphere and/or engineered barriers.

In order to identify and define the scenarios of interest, the analysis considers the various external, internal and contaminant factors that could affect the DGR system and its evolution (Figure 5.1). These factors may be further categorized as features, events or processes (FEPs). For example, an earthquake is an external event, carbon steel waste package is an internal feature, and sorption is a contaminant process.

The internal and contaminant factors (Internal FEPs) occur within the spatial and temporal boundaries of the DGR system, whereas the external factors (External FEPs) originate outside these boundaries. The External FEPs provide the system with its boundary conditions and, in particular, include factors originating outside the DGR system that might cause change in the system. Included in this group are decisions related to repository design, operation and closure since these are outside the temporal boundary of the postclosure behaviour of the DGR system. If these External FEPs can significantly affect the evolution of the system and/or its safety functions (i.e., isolation and containment) within the assessment timescale (1,000,000 years), they can be considered to be scenario-generating FEPs (IAEA 2004) in the sense that whether they occur or not (or the extent to which they occur) could define a particular future scenario that should be considered within the postclosure safety assessment.

A list of potential External and Internal FEPs relevant to the DGR system has been developed (QUINTESSA et al. 2011). This FEPs list is based on lists developed in other programs, such as the international FEPs database developed by the OECD Nuclear Energy Agency (NEA 1999b), the IAEA’s ISAM FEPs list (IAEA 2004), and the FEPs list used in OPG’s Third Case Study (Garisto et al. 2004). The list identifies 53 External FEPs and almost 200 Internal FEPs.

The External (scenario-generating) FEPs are listed in Table 5.1. Those that are likely to affect the DGR system and its evolution are identified and discussed in Section 5.1 (the associated status of Internal FEPs for the Normal Evolution Scenario is discussed in the FEPs report, QUINTESSA et al. 2011). The effects of less likely External FEPs and certain Internal FEPs that might lead to abnormal degradation and loss of containment (Disruptive Scenarios) are considered in Section 5.2.

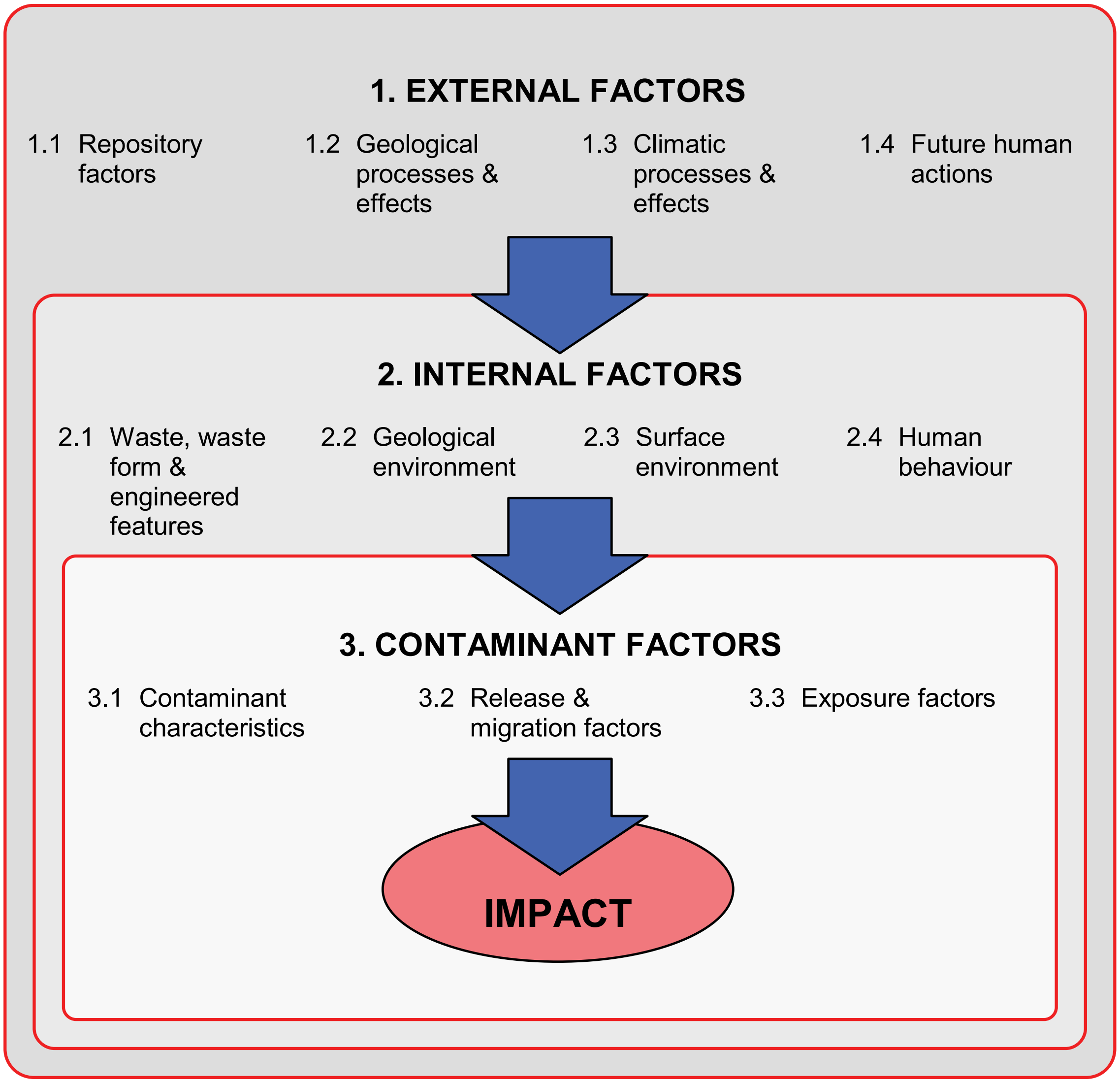

Figure 5.1: External, Internal and Contaminant Factors/FEPs

5.1 The Normal Evolution Scenario

5.1.1 External FEPs

The External FEPs in Table 5.1 have been reviewed, in light of information from the assessment context (documented in Section 3) and the system description and its supporting documents (Section 4), to identify those that should be included or excluded from consideration when addressing the expected evolution of the DGR system over the timescale of interest (1,000,000 years). The resulting list of included/excluded External FEPs considered for the DGR is given in Table 5.2, together with a brief justification for their inclusion/exclusion in the assessment. Further details of the External FEPs and the justification for their inclusion/exclusion are provided in the FEPs report (QUINTESSA et al. 2011).

From the analysis of the External FEPs presented in Table 5.2, it can be seen that the repository itself is largely unaffected by External FEPs primarily due to its depth (around 680 m below the ground surface) and the site's geological characteristics (described in Section 4.3).

Although the effects of glacial cycling are likely to cause major changes in the surface and near-surface environment, the DGR itself is intentionally isolated from the main consequences of climate change. A range of geoscientific observations can be used to provide evidence that the formations at these depths have been isolated from surface changes through the nine glacial cycles that have affected the Bruce nuclear site in the last one million years. For example, geochemical data indicate that: brines in the Deep and Intermediate Bedrock Groundwater Zones are ancient (more than 250 million years old); glacial meltwaters have not generally penetrated below the base of the Shallow Bedrock Groundwater Zone; and transport in the deep groundwater domain has been diffusion-dominated (Section 4.3.4.1).

In addition, results of transient paleoclimate groundwater flow simulations undertaken for the Laurentide glacial episode (~120,000 a to 10,000 a BP) showed that heads in the Ordovician and Cambrian formations were little affected by Laurentide ice-sheet loading and unloading, and solute transport in the deep groundwater domain has remained diffusion dominated (Section 5.4.10 of the Geosynthesis report, NWMO 2011a). Geomechanical modelling studies have also been undertaken to examine the impact of glacial cycling on the long-term emplacement room stability and shaft integrity (Chapter 6 of NWMO 2011a). While emplacement rooms would eventually collapse and fill with repeated glacial cycles, the ice-sheets do not affect the long-term barrier integrity of the overlying Ordovician shales or the EDZ within the shafts.

Table 5.1: External FEPs Considered

1.1	**Repository Factors**	
	1.1.01	Site investigations
	1.1.02	Design of repository
	1.1.03	Schedule and planning
	1.1.04	Construction
	1.1.05	Operation
	1.1.06	Waste allocation

	1.1.07	Repository closure
	1.1.08	Quality assurance
	1.1.09	Repository administrative control
	1.1.10	Accidents and unplanned events
	1.1.11	Retrieval
	1.1.12	Repository records and markers
	1.1.13	Monitoring
1.2	**Geological Processes and Effects**	
	1.2.01	Tectonic movement
	1.2.02	Orogeny
	1.2.03	Seismicity
	1.2.04	Volcanic and magmatic activity
	1.2.05	Metamorphism
	1.2.06	Hydrothermal activity
	1.2.07	Denudation and deposition (large-scale)
	1.2.08	Diagenesis
	1.2.09	Pedogenesis
	1.2.10	Salt diapirism and dissolution
	1.2.11	Hydrological response to geological changes
	1.2.12	Geomorphologic response to geological changes
	1.2.13	Deformation (elastic, plastic or brittle)
1.3	**Climate Processes and Effects**	
	1.3.01	Global climate change
	1.3.02	Regional and local climate change
	1.3.03	Sea-level change
	1.3.04	Periglacial effects
	1.3.05	Local glacial and ice-sheet effects
	1.3.06	Warm climate effects (tropical and desert)
	1.3.07	Hydrological response to climate changes
	1.3.08	Ecological response to climate changes
	1.3.09	Human behavioural response to climate changes
	1.3.10	Geomorphologic response to climate changes

1.4	**Future Human Actions**	
	1.4.01	Human influences on climate
	1.4.02	Social and institutional developments
	1.4.03	Knowledge and motivational issues (repository)
	1.4.04	Drilling activities
	1.4.05	Mining and other underground activities
	1.4.06	Un-intrusive site investigations
	1.4.07	Surface excavations
	1.4.08	Site development
	1.4.09	Archaeology
	1.4.10	Water management (groundwater and surface water)
	1.4.11	Explosions and crashes
	1.4.12	Pollution
	1.4.13	Remedial actions
	1.4.14	Technological developments
	1.4.15	Deliberate human intrusion
1.5	**Other External Factors**	
	1.5.01	Impact of meteorites and human space debris
	1.5.02	Evolution of biota

Note: Table is from QUINTESSA et al. (2011).

The analysis of the External FEPs shows that the DGR system might be impacted by a number of External FEPs:

- The effects of global climate change leading to glacial/interglacial cycling (FEPs 1.3.01, 1.3.02, 1.3.04, 1.3.05, 1.3.07, 1.3.08, 1.3.09, 1.3.10, 1.2.07,1.2.09 and 1.2.13);
- The occurrence of earthquakes (FEP 1.2.03);
- Human influence on global climate (FEP 1.4.01) resulting in global warming; and
- Social and institutional developments leading to changes of land use at the Bruce nuclear site (FEP 1.4.02), and associated drilling, site development and water management (FEPs 1.4.04, 1.4.08 and 1.4.10).

Table 5.2: Status of External FEPs for the Expected Evolution of the DGR System

External FEP			Status*	Comment
1.1	Repository Factors			
	1.1.01	Site investigations	Included	Available data from site characterization are included (INTERA 2011). All site investigation boreholes are appropriately sealed. No undetected geological features and no identified commercially viable mineral resources.
	1.1.02	Design of repository	Included	The DGR is built consistent with the design basis, as summarized in Section 4.2.
	1.1.03	Schedule and Planning	Included	DGR is operated from 2018 to 2053 and finally closed in 2062 (Section 3.8). Account taken for decay of radioactivity prior to start of postclosure period (i.e., prior to 2062).
	1.1.04	Construction	Included	DGR is constructed as described in Section 4.2.1.
	1.1.05	Operation	Included	DGR is operated as described in Section 4.2.2.
	1.1.06	Waste allocation	Included	LLW and ILW wastes are generally placed in separate emplacement rooms (Table 4.7) that are laid out in the configuration describe in Section 4.2.1.
	1.1.07	Repository closure	Included	Closure of the DGR is undertaken under OPG's/NWMO's quality assurance program and is consistent with the description provided in Section 4.2.3.
	1.1.08	Quality Assurance	Included	Construction, operation, monitoring and closure of the DGR are all undertaken under OPG's/NWMO's quality assurance program.
	1.1.09	Repository administrative control	Included	Controls remain effective for 300 years following DGR closure (Section 3.8).
	1.1.10	Accidents and unplanned events	Excluded	Accidents and unplanned pre-closure events that could impact the long-term safety of the repository are unlikely due to the application of preventative measures. If they were to occur, then they would be mitigated before the repository was closed.

External FEP			Status*	Comment
	1.1.11	Retrieval	Excluded	The DGR design has features that improve retrievability, notably the absence of backfill in the repository rooms and tunnels, and the extended monitoring period with active ventilation of rooms before their closure. However, it is assumed that there is no retrieval of waste after repository closure.
	1.1.12	Repository records and markers	Included	Any repository records and markers are effectively maintained for 300 years following DGR closure (Section 3.8).
	1.1.13	Monitoring	Excluded	Monitoring during waste emplacement and after repository closure to confirm that the DGR is performing as expected is carried out in a manner to ensure that it has no consequences for the long-term safety of the DGR.
1.2	Geological Processes and Effects			
	1.2.01	Tectonic movement	Excluded	Site is in a tectonically stable region away from plate margins with no tectonic activity over the timescale of interest, 1,000,000 years (Section 4.3.1).
	1.2.02	Orogeny	Excluded	No orogenic activity over the timescale of interest (1,000,000 years) due to the site’s location (Section 4.3.1).
	1.2.03	Seismicity	Included	Earthquakes will occur over the timescale of interest (1,000,000 years). However, as the area is not a seismically active region, the likely magnitude, frequency and distance of earthquakes would limit their impact at the repository location (Section 4.3.5). Nevertheless, larger earthquakes could occur in particular during retreat of ice-sheets.
	1.2.04	Volcanic and magmatic activity	Excluded	No volcanic or magmatic activity over the timescale of interest (1,000,000 years) due to the site’s location (Section 4.3.1).
	1.2.05	Metamorphism	Excluded	No processes occur over the timescale of interest (1,000,000 years) that will cause metamorphism (Section 4.3.1).
	1.2.06	Hydrothermal activity	Excluded	Site is geologically stable, there are no signs of historic hydrothermal activity at the site and no drivers of hydrothermal activity are present over the timescale of interest (1,000,000 years) (Section 4.3.1).

External FEP			Status*	Comment
	1.2.07	Denudation and deposition (large-scale)	Included	The area is topographically flat and not high above sea level so there is limited potential for large-scale denudation. However over the past 1,000,000 years, ice-sheet erosion and deposition has shaped the topography and could continue to do so in the future.
	1.2.08	Diagenesis	Excluded	Would have negligible effect on repository safety over the timescale of interest (1,000,000 years).
	1.2.09	Pedogenesis	Included	Glacial/interglacial cycling will result in removal and formation of soils over the timescale of interest (1,000,000 years). The removal and development of soils will impact the nature of plants in the area, and therefore potentially human behaviour (e.g., feasibility of farming).
	1.2.10	Salt diapirism and dissolution	Excluded	No significant salt deposits are located in the vicinity of the site (Section 4.3.2). Historically, there were salt deposits but these have already been dissolved over a long period in the distant past.
	1.2.11	Hydrological response to geological changes	Included	The observed pattern of over- and underpressures in the groundwater and porewater hydraulic head data represent a state of disequilibrium due to previous geological events and related processes (Section 4.3.3)
	1.2.12	Geomorphologic response to geological changes	Excluded	Although geomorphologic changes will occur, these will be driven by climate change (see FEP 1.3.10) rather than geological change given the site’s geologically stable location and timescales of interest (Section 4.3.1).
	1.2.13	Deformation (elastic, plastic or brittle)	Included	Although deformation due to tectonic movement and orogeny is unlikely over the timescale of interest (1,000,000 years) due to the site’s tectonically stable location, deformation due to loading from ice-sheets is likely. Peltier (2011, Section 4.2.5) has estimated that the associated maximum crustal depressions might be in excess of 500 m over continental scale.

External FEP			Status*	Comment
1.3	Climate Processes and Effects			
	1.3.01	Global climate change	Included	After an initial period of global warming, it is likely that Quaternary glacial/interglacial cycling continues since the basic solar insolation variation driving this cycling will continue (Section 6.3 of the System and Its Evolution report, QUINTESSA 2011b).
	1.3.02	Regional and local climate change	Included	Regional/local climate will respond to global climate change (Section 6.3 of the System and Its Evolution report, QUINTESSA 2011b).
	1.3.03	Sea-level change	Excluded	Changes in sea level do not affect the site due to its elevated continental location.
	1.3.04	Periglacial effects	Included	These will occur during colder climate states experienced during the glacial/interglacial cycling that is likely to occur at the site over a one million year timeframe. In particular, this would include permafrost development (Section 6.3 of the System and Its Evolution report, QUINTESSA 2011b).
	1.3.05	Local glacial and ice-sheet effects	Included	Ice-sheets are likely to cause a range of local effects. These include crustal deflection, change in rock stress (and possible earthquake initiation), changes in surface and near-surface hydrology (see FEP 1.3.07), ecosystems (see FEP 1.3.08), human behaviour (see FEP 1.3.09), and surface topography (see FEP 1.3.10).
	1.3.06	Warm climate effects (tropical and desert)	Excluded	Climate change does not result in development of tropical or hot desert conditions at the site due to its northerly latitude. There is no evidence of tropical or hot desert conditions having been present at the site during the Quaternary. An initial period of human-induced global warming will not result in extreme temperature rise resulting in tropical or desert conditions in this region.

External FEP			Status*	Comment
	1.3.07	Hydrological response to climate changes	Included	Glacial/interglacial cycling impacts primarily on the hydrological conditions in the Surficial and Shallow Bedrock Groundwater Zones. Previous glaciations have had no impact on the groundwater flow in the Deep Bedrock Groundwater Zone (Section 4.3.4.1). Key responses are: permafrost formation; meltwater events primarily affecting the Surficial and Shallow Bedrock Groundwater Zone; and the formation of a major proglacial lake over the site during ice-sheet retreat (Section 6.3 of the System and Its Evolution report, QUINTESSA 2011b).
	1.3.08	Ecological response to climate changes	Included	Flora and fauna at the site change in response to glacial/interglacial cycling (Section 6.3 of the System and Its Evolution report, QUINTESSA 2011b).
	1.3.09	Human behavioural response to climate changes	Included	Human behaviour changes in response to glacial/interglacial cycling (Section 6.3 of the System and Its Evolution report, QUINTESSA 2011b).
	1.3.10	Geomorphologic response to climate changes	Included	Glaciation results in significant changes to the present-day landforms found at the site (Section 6.3 of the System and Its Evolution report, QUINTESSA 2011b).
1.4	Future Human Actions			
	1.4.01	Human influences on climate	Included	Human-induced global warming is likely to delay the onset of the next ice-sheet advance that affects the site (Section 6.3 of the System and Its Evolution report, QUINTESSA 2011b).
	1.4.02	Social and institutional developments	Included	Controls on the development of the site are effective for 300 years following DGR closure (Section 3.8). Once controls are no longer effective, land use change at the site is likely (see also FEP 1.4.08).
	1.4.03	Knowledge and motivational issues (repository)	Excluded	No knowledge of the repository is assumed once controls are no longer effective. No human intrusion into the DGR due to its depth (around 680 m below ground surface – Section 4.2) and the lack of commercially viable natural resources at depth (Section 4.3.2).

External FEP			Status*	Comment
	1.4.04	Drilling activities	Included	Once controls are no longer effective, the drilling of shallow water wells in the area is included since such wells currently exist in the region around the site (Section 4.4.4). However, the drilling of deep exploration boreholes at the site that penetrate to the repository is excluded from the expected evolution due to its depth (around 680 m), the relatively small panel footprint (~0.25 km^2), and the lack of commercially viable natural resources at depth in the area of the site (Section 4.3.2).
	1.4.05	Mining and other underground activities	Excluded	No mining since no commercially viable mineral resources have been identified at the site (Section 4.3.2). Other underground activities are unlikely at the site because the geology is uniform across a large area and so there is nothing unique at the site (Section 4.3). These activities would likely be preceded by exploratory drilling – see FEP 1.4.04.
	1.4.06	Un-intrusive site investigation	Excluded	No direct impact on repository safety.
	1.4.07	Surface excavations	Excluded	No direct impact on repository safety due to depth of repository (around 680 m).
	1.4.08	Site development	Included	Site land use changes are likely once controls are no longer effective (see also FEP 1.4.02). Land uses in the previously controlled area are likely to become consistent with the land uses currently found in the area surrounding the Bruce nuclear site (i.e., predominantly agriculture and recreation – Section 4.4.6).
	1.4.09	Archaeology	Excluded	No direct impact on repository safety due to depth of repository (around 680 m).
	1.4.10	Water management (groundwater and surface water)	Included	The drilling of shallow water wells in the area is considered once controls are no longer effective (see FEP 1.4.04). Wells in the deeper groundwater zones are excluded since the groundwater in these zones is not potable (Section 4.3.4.1). There is present-day abstraction of groundwater in the area from the Shallow Bedrock Groundwater Zone for domestic and agricultural purposes (Sections 4.4.4 and 4.4.6). Lake Huron could also be used as a source of water.

External FEP			Status*	Comment
	1.4.11	Explosions and crashes	Excluded	Surface explosions and crashes would have no direct impact on repository safety due to the depth of the repository (around 680 m). Postclosure explosions in the repository are unlikely due to absence of an ignition source and oxygen.
	1.4.12	Pollution	Excluded	Impact of surface contaminants on the wastes placed in the DGR is likely to be insignificant because of the repository depth (around 680 m) and buffering capacity of the rocks above the repository (Section 4.3.2).
	1.4.13	Remedial actions	Excluded	Remedial actions are unlikely following closure of repository, and if they occurred then the effects on the repository would need to be assessed at that time based on the specific remediation.
	1.4.14	Technological developments	Excluded	Consistent with the recommendations of ICRP (2000), Section 7.5.4 of CNSC (2006) states that human habits and characteristics should be based on current lifestyles. Therefore technological developments are not considered.
	1.4.15	Deliberate human intrusion	Excluded	Excluded since it is expected that the intruders would take appropriate precaution.
1.5	Other External Factors			
	1.5.01	Impact of meteorites and human space debris	Excluded	Excluded due to low probability (due to relatively small panel footprint of ~0.25 km^2) and low consequence (due to depth of repository - around 680 m). See FEP 1.5.01 of QUINTESSA et al. 2011 for further details.
	1.5.02	Evolution of biota	Excluded	No evolution of humans assumed, consistent with ICRP's recommendation to apply the concept of (present-day) Reference Man to the disposal of long-lived solid radioactive waste (ICRP 2000). Similarly, no evolution of non-human biota assumed. General characteristics of biota are assumed to remain similar to current biota.

Notes: * Status – *Included* means that this factor is considered in the Normal Evolution Scenario. *Excluded* means that this factor is not considered in the Normal Evolution Scenario. Further discussion of the rationale for including/excluding FEPs is provided in the FEPs report (QUINTESSA et al. 2011).

5.1.2 Description

From consideration of the above External FEPs and the Internal FEPs discussed in the System and Its Evolution and the FEPs reports (QUINTESSA 2011b, QUINTESSA et al. 2011), the following high-level narrative of the expected evolution of the DGR system can be developed. This narrative can be used to inform both the subsequent development of the conceptual model for assessment in Section 6.2.1, and the variations to this model considered in alternative calculation cases in Section 6.3.

The heat generated by radioactive decay within the repository is small – about 2 kW at the time of closure and decaying. This is low relative to the steady natural geothermal flux through the DGR's panel footprint of 10 kW. The repository will remain near its natural ambient temperature of around 20 °C.

During the years following closure, there is corrosion of the carbon steel containers and degradation of organic materials in the wastes. The atmosphere in the repository becomes anaerobic as oxygen is consumed by corrosion. Subsequent slow anaerobic degradation of the wastes and packaging materials in the DGR generates various decomposition products, in particular gases (predominantly CO_2 and CH_4 from the microbial decomposition of organics, and H_2 from the corrosion of metals). The gas pressure rises to a level determined by the gas generation rate in the repository, the natural gas and water pressure in the surrounding host rock, and the water level in the repository.

The DGR's shafts resaturate more rapidly than the DGR's rooms and tunnels because they are: backfilled (smaller volume to be resaturated); are exposed to more permeable rock formations; tend to pull water in (bentonite); and are not a gas generation source. The low permeability of the shaft seals and the host rock, plus the gas pressure in the rooms and tunnels and the water consumption by corrosion reactions, all limit the resaturation of the rooms and tunnels. It might take many hundreds of thousands or even millions of years to resaturate.

Most of the waste packaging is not long-lived, and allows water to contact the wastes as the repository resaturates (the higher activity ILW containers are more robust and are likely to take longer to degrade). All packages eventually fail. Even then, the failed packages may continue to provide some physical limitation (e.g., diffusion) or local chemistry control (e.g., alkalinity in concrete containers) that inhibits the release of contaminants, especially in the case of the ILW retube and resin waste containers.

Contaminants are released from the waste by dissolution into repository water and, especially for H-3 and C-14, the formation of radio-labelled gases. The rate of release varies with the type of wastes, with contaminants in the Zircaloy pressure tubes (containing most of the long-lived Zr-93) being released as the waste form corrodes, resulting in a slower release than for other waste categories. Once released into the water or gas in the repository, the migration of contaminants from the repository is limited by the low-permeability shaft seals and very low permeability host rock. The excavation of the repository results in a damaged zone developing around the shaft, emplacement rooms and tunnels, with higher porosity and permeability. This is also a potential pathway for contaminant transport.

The host rock has good rock mechanical quality, and together with the emplacement room design (i.e., alignment with principal stresses, low excavation volume), results in a mechanically stable configuration. However, as the rooms and tunnels are not backfilled (the wastes occupy about 50% of the volume), it is expected that rockfall from the roofs and walls of the rooms and tunnels will occur due to eventual degradation of engineered rock support and, in the longer term, due to seismic and/or glacial events. This process will continue intermittently over a period of a few hundred thousand years, until the collapsed rock fills the available space and is able to support the roof and prevent further failure.

The regional area around the Bruce nuclear site is tectonically stable and is characterized by low rates of seismicity. Large earthquakes are very unlikely in general, but are more likely around the time of ice-sheet retreat at the end of a glacial cycle. The host rock is strong, and small earthquakes will have little effect. The primary effect of large earthquakes will be rockfall as noted above until the rooms and tunnels fill and stabilize. Rockfall also damages the containers.

Most radionuclides decay within the repository and the surrounding rock. However, slow migration of some dissolved or gaseous contaminants occurs into the geosphere surrounding the repository and into the repository shafts. Some contaminants may eventually discharge to the Shallow Groundwater Bedrock Zone, and then to the biosphere. Potential impacts on humans are estimated based on assuming a critical group of a self-sufficient family farm located on the repository site and using groundwater from a well.

The surface environment will change significantly over these time frames. Initially there could be changes due to global warming, but regionally the area is expected to retain a temperate climate and ecosystem during this initial warming period.

Currently, the Earth is in a configuration where periodic ice ages occur, with nine major cycles in the past million years. Key factors contributing to these cycles – variations in solar insolation to the northern hemisphere and the arrangement of the continents – will not change appreciably over the next million years. Although global warming and a weak solar insolation variation are likely to delay the onset of the next ice-sheet advance for at least 60,000 years, it is prudent to assume that glacial cycles will resume in the long term and, therefore, to consider the potential effects on the DGR system.

It is expected that ice-sheets will advance and retreat over the site over a glacial/interglacial cycle with a periodicity of approximately 100,000 years (Peltier 2011, BIOCLIM 2004) A stylized climate sequence for the Normal Evolution Scenario has been identified in Chapter 6 of the System and Its Evolution report (QUINTESSA 2011b), based on the results of the University of Toronto Glacial Systems Model (Peltier 2011), and is reproduced in Figure 5.2 and Figure 5.3.

As climatic conditions cool in the long term, the ecosystem around the site changes from temperate to tundra. Agriculture and forestry become less viable. As the climate grows progressively cooler and drier, arctic conditions are established with permanent human habitation in the vicinity of the site becoming increasingly less likely (assuming present-day demographic/climatic relations), and the site is eventually covered by an advancing ice-sheet. The subsequent warming of the climate and the resulting ice-sheet retreat are followed by re-establishment of tundra and potentially temperate ecosystems and the eventual re-population of the site. Each glacial/interglacial cycle also causes biosphere change due to glacial and periglacial processes (e.g., the development of proglacial lakes, the erosion and deposition of surface deposits, the formation of soils, and the change in shoreline location).

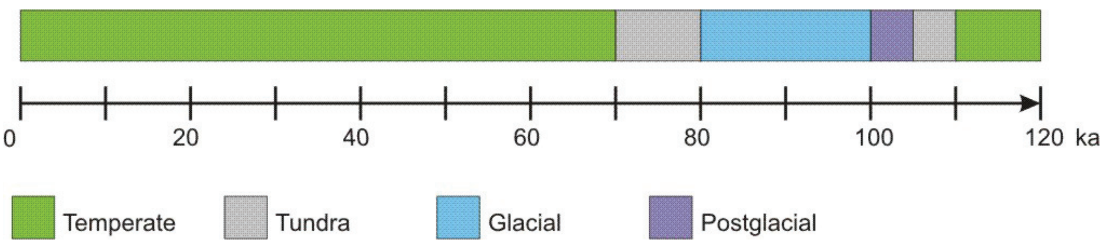

Figure 5.2: Sequence of Climate States for the Next 120,000 Years for the Normal Evolution Scenario

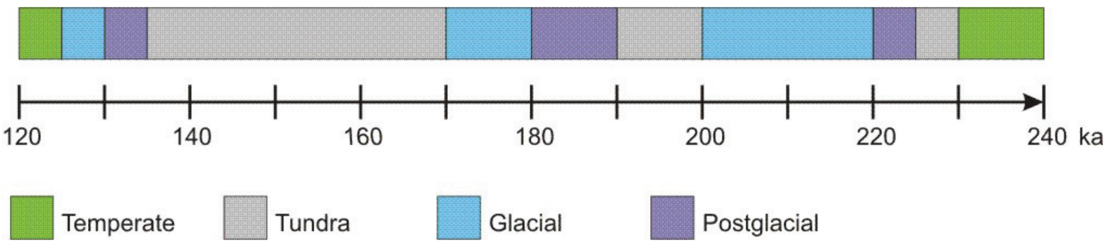

Figure 5.3: Sequence of Climate States from 120,000 Years to 240,000 Years for the Normal Evolution Scenario (Sequence Assumed to Repeat Indefinitely)

The ice-sheet causes major changes in the Surficial and Shallow Bedrock Groundwater Zones, in terms of permafrost, hydraulic pressures and flow rates, and in the penetration of glacial recharge waters. Based on continental scale modelling of the last ice-sheet, the repository site is expected to see shallow discontinuous permafrost. It is also likely to experience multiple cycles of glacial advance and retreat, as well as creation and loss of proglacial lakes, due to its proximity to the southern extent of the ice-sheet.

However, the impacts of glacial cycles on the Deep Bedrock Groundwater Zone are expected to be primarily changes in the stress and hydraulic pressure regime resulting from ice-sheet loading and unloading. This is supported by evidence from the site itself, where the deep groundwaters do not show signs of impact from past glaciations, as well as from modelling of the behaviour of the groundwater and geomechanical environment around the repository. The overall rock is expected to remain intact and solute transport remains diffusion-dominated, as in previous glacial cycles (Section 5.4 and Chapter 8 of NWMO 2011a).

In the long term, the underground repository is likely to develop into an assemblage of mostly limestone rock containing magnetite, siderite and other mineral products of the wastes and their packaging, with little change in the surrounding rock beyond the vicinity of the repository. The porosity in the rock will contain a mixture of brine and methane gas.

5.2 Disruptive Scenarios

5.2.1 Identification of Disruptive Scenarios

A set of Disruptive Scenarios has been identified through evaluating the potential for the External FEPs identified in Table 5.1 to compromise the isolation and containment safety functions of the DGR system. These high-level safety functions are in turn defined in terms of several safety arguments. The various External FEPs that might compromise these safety arguments are listed and screened in Table 5.3 to identify those that need to be considered further.

As a further check, the potential for the Internal FEPs (summarized in Table 5.4) to compromise the long-term safety arguments is also considered (Table 5.5). Note that the FEPs considered under the "Contaminant Factors" category in Table 5.4 are not capable, on their own, of modifying the DGR system to an extent that results in a fundamentally different evolution of the system to that considered in the Normal Evolution Scenario. Therefore, they are not scenario generating. Rather, they modify the rate at which contaminants are released and migrate from the DGR and the magnitude and timing of any impacts. Their effects can, therefore, be evaluated through considering different calculation cases for the Normal Evolution Scenario rather than through the development of Disruptive Scenarios. The failure mechanisms identified in Table 5.3 and Table 5.5 can be grouped into four Disruptive Scenarios as discussed below and summarized in Table 5.6. As the long-term safety of the DGR is based on the strength of the geosphere barrier and the shaft seals, the Disruptive Scenarios considered focus on scenarios in which these can be bypassed.

There are no known commercially viable natural resources at or below repository level, and the DGR's panels have a small footprint (~0.25 km^2) and the repository is at a depth of around 680 m. These factors limit the range of human activities that could directly impact the closed repository to a borehole unintentionally drilled into the repository as part of a future geological exploration program[15]. Even this situation has a low probability of occurrence. Nevertheless, it is recognized that once controls on the use of the site are no longer effective, the possibility of inadvertent human intrusion by this method cannot be ruled out over long timescales[16]. Such a borehole could provide an enhanced permeability pathway to the surface environment and potential for direct exposure to waste. This scenario is referred to as the **Human Intrusion Scenario**.

A second scenario by which the geosphere barrier can be bypassed is via the main and ventilation shafts. These are 9.2 m and 7.5 m diameter holes that penetrate through the geosphere, but are placed away from the waste panels and carefully sealed in the preliminary design. The Normal Evolution Scenario takes account of the role of engineered barriers and assumes their performance meets design specifications; it includes an expected degree of degradation of the seals with time. The **Severe Shaft Seal Failure Scenario** considers the possibility that the seals are not fabricated or installed appropriately, or that the long-term performance of the seals and shaft/repository EDZs is poor due to unexpected physical, chemical and/or biological processes. Either situation could result in an enhanced permeability pathway to the surface. It is difficult to assign a probability to the scenario; however, it would be expected to be very unlikely due to the quality control measures that will be applied to the DGR shaft seal closure, and multiple durable material layers in the shaft.

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[15] The assessment excludes deliberate human intrusion since it is expected that the intruders would take appropriate precaution.

[16] The repository might appear as an anomaly in any surface/air-borne survey of the area, and this could encourage drilling at the site. However, the uniformity of the sediments and general lack of interesting minerals or geologic features in the area would argue against deliberate surveys of the area. Furthermore, a cautious approach to drilling might be used if such unexpected anomalies were identified that would minimize the consequences of any intrusion into the DGR.

Table 5.3: External FEPs Potentially Compromising Arguments Relating to the Long-term Safety of the DGR

Long-term Safety Argument	Potentially Compromised by	Need to Consider as Failure Mechanism
1. The DGR is isolated from the biosphere by its depth	Near-surface design adopted (FEP 1.1.02).	**No**, only deep design being considered for the DGR (Section 4.2.1).
	Meteorite impact (FEP 1.5.01).	**No**, due to low probability of meteor impact capable of compromising safety due to relatively small panel footprint, ~0.25 km^2) and depth of repository, (~680 m). (See FEP 1.5.01 discussion in QUINTESSA et al., 2011)
	Exploration borehole penetrates into repository providing enhanced permeability pathway to surface environment and potential for direct exposure to waste (FEP 1.4.03 and 1.4.04).	**Yes**, although the depth (~680 m) and relatively small panel footprint (~0.25 km^2) of the DGR will mean that the annual probability of such a borehole intruding into the DGR will be very low.
	Mining and other underground activities resulting in excavation in the vicinity of the repository (FEP 1.4.05).	**No**, due to absence of proven commercially viable mineral resources at or below repository level (Section 4.3.2). Other underground activities are unlikely at site because the geology is uniform across a large area and so there is nothing unique at the site other than the repository (i.e. deliberate intrusion) (Section 4.3). Also, such activities would likely be preceded by exploration boreholes, as addressed above.
	Deliberate human intrusion into repository (FEP 1.4.15).	**No**, exclude deliberate human intrusion since it is expected that the intruders would take appropriate precaution.

Long-term Safety Argument	**Potentially Compromised by**	**Need to Consider as Failure Mechanism**
	Could discover resources that were not identified during site investigations (FEP 1.1.01) or exploit existing rocks that have become a commercially viable resource. These new resources are exploited by drilling or mining at or below repository level (FEP 1.4.04 and 1.4.05).	**No**. The host rocks are laterally extensive and uniform in properties. The lack of resources seen at the site is consistent with regional information. Even if the existing rocks became commercially viable, the DGR site is unlikely to be the mine site because of the large lateral extent of the host rocks, which extend to shallower depths elsewhere. Impact of drilling is already considered under exploration borehole (FEP 1.4.04).
	Ice-sheet erosion resulting from climate change removes a significant thickness of rock above repository (FEP 1.2.07, 1.3.01, 1.3.02, 1.3.05).	**No**. Extrapolating the past rate of erosion implies that of the order of 100 m of bedrock may be eroded over 1,000,000 years (Section 2.2.7.2 of NWMO 2011a). This would not significantly reduce the geosphere barrier at the Bruce nuclear site given the depth of the DGR (~680 m).
2. Multiple barriers provide containment[17]	An enhanced permeability pathway is introduced through the sequence of rocks by human-induced processes (e.g., drilling activities – FEP 1.4.04).	**Yes**, see discussion of drilling activities under Argument 1.
	Site investigations do not identify a relatively high permeability fracture zone or fault that provides a connection between the DGR horizon and higher horizons (FEP 1.1.01).	**Yes**. Although very unlikely (given the strong geological, hydrogeological, and geochemical evidence to the contrary, Section 4.3.1), such a feature cannot be categorically ruled out and so is considered in a “what if” scenario.

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[17] Multiple barriers include the various distinct physical features and processes that isolate and contain the contaminants. See also the safety-relevant features in Section 4.1.5, Section 4.2.4, and Section 4.3.6.

Long-term Safety Argument	Potentially Compromised by	Need to Consider as Failure Mechanism
	Ice-sheet erosion resulting from climate change removes a significant thickness of rock above the repository (FEP 1.2.07, 1.3.01, 1.3.02, 1.3.05).	**No**, see discussion of ice-sheet erosion under Argument 1.
	Poor construction techniques impact on the performance of the repository and shaft EDZs providing an enhanced permeability pathway to the surface environment (FEP 1.1.04).	**Yes**, although application of OPG's quality control will ensure that poor construction is very unlikely.
	Repository and shafts not properly sealed at time of closure providing an enhanced permeability pathway to the surface environment (FEP 1.1.07).	**Yes**, although application of OPG's quality control will ensure that poor sealing is very unlikely.
	Site investigation/monitoring borehole not properly sealed at time of closure providing an enhanced permeability pathway to the surface environment (FEP 1.1.01 and 1.1.13).	**Yes**, although application of OPG's quality control will ensure that poor sealing is very unlikely.
	High magnitude seismic event results in reactivation of undetected existing structural discontinuity and/or failure of shaft seals which provides an enhanced permeability pathway to higher horizons (FEP 1.2.03).	**Yes**, the assessment timescales are such that a significant event with a magnitude of $M \geq 6$ may occur, even though its annual probability of occurrence within a 20 km radius of the Bruce nuclear site is around 10^{-6} (Section 4.3.5). Even then, the probability that the earthquake could actually reactivate a nearby fracture or fail the shaft seals is very small since it would take a significant amount of energy and since there is no evidence for faults near the DGR site.
	Other external geological processes disrupt the DGR system, i.e., tectonic movement (FEP 1.2.01), orogeny (FEP 1.2.02), volcanic and magmatic activity (FEP 1.2.04), metamorphism (FEP 1.2.05), hydrothermal activity (FEP 1.2.06), diagenesis (FEP 1.2.08) and salt diapirism and dissolution (FEP 1.2.10).	**No**, since precluded by site's location and assessment timescales (see Table 5.2 and also related discussion in Geosynthesis, NWMO 2011a).

Long-term Safety Argument	Potentially Compromised by	Need to Consider as Failure Mechanism
3. Mass transport is diffusion-dominated at the repository depth	Ice-sheet meltwater penetrates into the Deep Bedrock Groundwater Zone and affects flow in this zone (FEP 1.3.07).	**No**. No evidence from site investigation of meltwater from previous glaciations penetrating the Deep Bedrock Groundwater Zone due to its low permeability and the relatively high permeability of the Shallow Bedrock Groundwater Zone (Section 4.4 of Geosynthesis, NWMO 2011a).
	Ice-sheet erosion resulting from climate change removes a significant thickness of rock above the repository resulting in the establishment of an advection dominated system surrounding the DGR (FEP 1.2.07, 1.3.01, 1.3.02, 1.3.05).	**No**, see discussion of ice-sheet erosion under Argument 1.
4. Hydrological and chemical conditions limit contaminant mobility at the repository depth	Ice-sheet meltwater penetrates into the Deep Bedrock Groundwater Zone and modifies hydrogeochemical conditions in this zone (FEP 1.3.07).	**No**, see discussion of ice-sheet meltwater under Argument 3.
	Ice-sheet erosion resulting from climate change removes a significant thickness of rock above the repository and modifies hydrogeochemical conditions around the DGR (FEP 1.2.07, 1.3.01, 1.3.02, 1.3.05).	**No**, see discussion of ice-sheet erosion under Argument 1.
5. The groundwater at the repository depth is resilient to natural external perturbations	Ice-sheet meltwater penetrates into the Deep Bedrock Groundwater Zone and affects transport in this zone through the introduction of fresh aerobic water (FEP 1.3.07).	**No**, see discussion of ice-sheet meltwater under Argument 3.
	Ice-sheet loading/unloading results in reactivation of a fault and/or failure of shaft seals which provides an enhanced permeability pathway from the repository to higher horizons (FEP 1.2.11 and 1.2.13).	**No**, geomechanical modelling has shown that the consequences of ice-sheet loading/unloading are limited (Chapter 6 of Geosynthesis, NWMO 2011a).

Long-term Safety Argument	Potentially Compromised by	Need to Consider as Failure Mechanism
	Ice-sheet erosion resulting from climate change removes a significant thickness of rock above the repository (FEP 1.2.07, 1.3.01, 1.3.02, 1.3.05).	**No**, see discussion of ice-sheet erosion under Argument 1.
6. Resaturation of the repository with groundwater will be very slow	Rapid resaturation of repository occurs due to an enhanced permeability pathway from the repository to the surface environment, i.e., poorly constructed shafts (FEP 1.1.04), poorly sealed shafts (FEP 1.1.07), or future exploration borehole (FEP 1.4.04).	**Yes**, although application of OPG's quality control will ensure that poor construction and sealing is very unlikely and the depth and relatively small panel footprint will mean that the annual probability of a future exploration borehole intruding into the DGR will be very low.
	Rapid resaturation of repository occurs due to an enhanced permeability pathway from the repository to the surface environment via a DGR site investigation borehole (FEP 1.1.01) or monitoring borehole (FEP 1.1.13)	**No**, since it is a requirement that there is a separation between any part of the repository and an existing or planned deep borehole (NWMO 2010d). Currently the closest borehole (DGR-2) is around 100 m from the DGR (Figure 4.3).
7. Institutional Controls will limit the potential for human encounter with the DGR system in the near-term after closure	Institutional controls on the development of the site are ineffective (FEP 1.4.02) and knowledge of the site is lost (FEP 1.4.03) in the near-term. This allows development of the site (1.4.08) and human intrusion into the repository to occur by drilling (FEP 1.4.04) and/or mining (FEP 1.4.05)	**No**. Measures will be taken in the near-term to ensure that information regarding the purpose, location, design and contents of the repository is preserved so that future generations are made aware of the consequences of any actions they may choose to take. With these institutional measures as well as general societal memory, and with the absence of commercially viable natural resources at depth, inadvertent intrusion in the near-term after closure is not considered. However, Human Intrusion is considered in the long-term.

Table 5.4: Summary of Internal FEPs from the DGR FEPs List

2. INTERNAL FACTORS		
2.1	Waste, Waste Form & Engineered Components	
	2.1.01*	Waste inventory
	2.1.02*	Waste-form characteristics
	2.1.03*	Waste-packaging characteristics
	2.1.04*	Emplacement room, access, tunnel and shaft & services area characteristics
	2.1.05*	Shaft characteristics
	2.1.06*	Mechanical processes and conditions (in wastes, emplacement rooms, tunnels and shafts)
	2.1.07*	Hydraulic/hydrogeological processes and conditions (in wastes, emplacement rooms, tunnels and shafts)
	2.1.08*	Chemical/geochemical processes and conditions (in wastes, emplacement rooms, tunnels and shafts)
	2.1.09*	Biological/biochemical processes and conditions (in wastes, emplacement rooms, tunnels and shafts)
	2.1.10*	Thermal processes and conditions (in wastes, emplacement rooms, tunnels and shafts)
	2.1.11*	Gas sources (in wastes, emplacement rooms, tunnels and shafts)
	2.1.12	Radiation effects (in wastes, emplacement rooms, tunnels and shafts)
	2.1.13	Effects of extraneous materials
	2.1.14	Nuclear criticality
2.2	Geological Environment	
	2.2.01	Stratigraphy
	2.2.02	Host rock lithology
	2.2.03*	Disturbed zone (in geosphere)
	2.2.04*	Large-scale discontinuities (in geosphere)
	2.2.05*	Mechanical processes and conditions (in geosphere)
	2.2.06*	Hydraulic/hydrogeological processes and conditions (in geosphere)
	2.2.07*	Chemical/geochemical processes and conditions (in geosphere)
	2.2.08	Biological/biochemical processes and conditions (in geosphere)
	2.2.09*	Thermal processes and conditions (in geosphere)
	2.2.10*	Gas processes and effects (in geosphere)
	2.2.11	Geological resources (in geosphere)
	2.2.12	Undetected features (in geosphere)

2.3	Surface Environment	
	2.3.01	Topography and morphology
	2.3.02	Biomes
	2.3.03*	Soil and sediment
	2.3.04	Near-surface aquifers and water-bearing features
	2.3.05*	Terrestrial surface-water bodies
	2.3.06	Coastal features
	2.3.07	Marine features
	2.3.08	Atmosphere
	2.3.09	Vegetation
	2.3.10	Animal populations
	2.3.11	Climate and weather
	2.3.12	Hydrological regime and water balance (near-surface)
	2.3.13	Erosion and deposition
	2.3.14	Ecological/biological/microbial systems
	2.3.15	Biotic intrusion
2.4	Human Behaviour	
	2.4.01	Human characteristics (physiology, metabolism)
	2.4.02	Age, gender and ethnicity
	2.4.03*	Diet and liquid intake
	2.4.04	Habits (non-diet-related behaviour)
	2.4.05*	Community characteristics
	2.4.06	Food preparation and water processing
	2.4.07	Dwellings
	2.4.08	Natural/semi-natural land and water use
	2.4.09	Rural and agricultural land and water use
	2.4.10	Urban and industrial land and water use
	2.4.11	Leisure and other uses of environment
3. CONTAMINANT FACTORS		
3.1	Contaminant Characteristics	
	3.1.01	Radioactive decay and in-growth
	3.1.02	Organics and potential for organic forms
	3.1.03	Chemical/organic toxin stability
	3.1.04	Inorganic solids/solutes
	3.1.05	Volatiles and potential for volatility

	3.1.06	Noble gases
3.2	Contaminant Release and Migration Factors	
	3.2.01	Contaminant release pathways
	3.2.02*	Water-mediated migration of contaminants
	3.2.03	Solid-mediated migration of contaminants
	3.2.04	Gas-mediated migration of contaminants
	3.2.05	Atmospheric migration of contaminants
	3.2.06	Microbially/biologically-mediated processes, effects on contaminant release and migration
	3.2.07	Animal-, plant- and microbe-mediated migration of contaminants
	3.2.08	Human-action-mediated migration of contaminants
	3.2.09	Colloid-mediated migration of contaminants
	3.2.10*	Dissolution, precipitation and mineralization
	3.2.11*	Speciation and solubility (contaminant)
	3.2.12*	Sorption and desorption (contaminant)
	3.2.13*	Complexing agent effects (contaminant)
	3.2.14	Food chains and uptake of contaminants
3.3	Exposure Factors	
	3.3.01	Contaminant concentrations in drinking water, foodstuffs and drugs
	3.3.02	Contaminant concentrations in non-food products
	3.3.03	Contaminant concentrations in other environmental media
	3.3.04*	Exposure modes
	3.3.05*	Dosimetry and biokinetics
	3.3.06*	Radiological toxicity/effects
	3.3.07*	Chemical toxicity/effects
	3.3.08	Radon and radon daughter exposure

Notes: * These FEPs are sub-divided further in the FEPs Report (QUINTESSA et al. 2011).

Table 5.5: Internal FEPs Potentially Compromising Arguments Relating to the Long-term Safety of the DGR

Long-term Safety Argument	Potentially Compromised by	Need to Consider as Failure Mechanism
1. The DGR is isolated from the biosphere by its depth	No Internal FEP could result in a significant change in the depth of the repository. Note that FEP 2.3.13 relates to the erosion of surficial deposits and not bedrock.	-
2. Multiple barriers provide containment	An undetected feature (e.g., a fracture zone or fault) in the geosphere provides a relatively high permeability connection between the DGR horizon and higher horizons (FEPs 2.2.04 and 2.2.12)	**Yes**. Although very unlikely (given the strong geological, hydrogeological, and geochemical evidence to the contrary, Section 4.3.1), such a feature cannot be categorically ruled out and so is considered in a "what if" scenario.
	Karst features provide a relatively high permeability connection between the DGR horizon and higher horizons (FEP 2.2.04)	**No**. Section 2.3.8 of the Geosynthesis report (NWMO 2011a) notes that conditions are unsuitable for karst development in the Intermediate and Deep Bedrock Groundwater Zones. Paleokarst horizons do exist but hydraulic conductivity does not appear to be significantly elevated and the horizons are not interconnected.
	Gas pressure in the repository could exceed lithostatic pressure and cause fracturing of geosphere (FEPs 2.1.11 and 2.2.10).	**No**. Repository pressures expected to be significantly less than the lithostatic pressure of about 17 MPa, and regional horizontal stresses of 20 - 30 MPa (see Section 8.1 of the Gas Modelling report, GEOFIRMA and QUINTESSA 2011). Any fractures would be horizontal from repository rather than vertical due to the local rock stress conditions.
	Various repository FEPs (e.g., FEPs 2.1.06 to 2.1.11) and geosphere FEPs (e.g., FEPs 2.2.05 to 2.2.10) can affect the rate at which contaminants are released from the DGR and migrate through the shafts and geosphere.	**Yes**. Although geological, hydrogeological, and geochemical evidence (Section 4.3) indicates that the geosphere will be robust to uncertainties in internal repository and geosphere FEPs, the possibility of such FEPs resulting in repository and shaft seal/EDZ degradation deviating from that expected cannot be categorically ruled out and so are considered in a "what if" scenario.

Long-term Safety Argument	Potentially Compromised by	Need to Consider as Failure Mechanism
3. Mass transport is diffusion-dominated at the repository depth	An undetected feature (e.g., a fracture zone or fault) in the geosphere provides a relatively high permeability connection between the DGR horizon and higher horizons (FEPs 2.2.04 and 2.2.12)	**Yes**, see discussion of undetected feature under Argument 2.
	Gas pressure in the repository could exceed lithostatic pressure and cause fracturing of geosphere (FEPs 2.1.11 and 2.2.10).	**No**, see discussion of gas fracturing under Argument 2.
4. Hydrological and chemical conditions limit contaminant mobility at the repository depth	Various repository FEPs (e.g., FEPs 2.1.06 to 2.1.11) have the potential to modify the hydrological and chemical conditions at the repository depth.	**No**. The effects are likely to be localized to the immediate vicinity of the DGR and these FEPs can be evaluated through considering different calculation cases for the Normal Evolution Scenario rather than through the development of alternative Disruptive Scenarios.
5. The groundwater at the repository depth is resilient to natural external perturbations	Relates to External FEPs only (see Table 5.3). The impact of Internal FEPs is considered under Argument 4 above.	-
6. Resaturation of the repository with groundwater will be very slow	The rate of resaturation will be affected by repository FEPs 2.1.07 to 2.1.11, and geosphere FEPs 2.2.06 and 2.2.10.	**No**. The effect of earlier resaturation can be addressed through calculation cases for the Normal Evolution Scenario that consider a range of resaturation times, rather than through the development of alternative Disruptive Scenarios.
7. Institutional Controls will limit the potential for human encounter with the DGR system in the near-term after closure	Affected by External FEPs relating to Future Human Actions (see Table 5.3) rather than the Internal FEPs relating to human behaviour that responds to the Future Human Actions.	-

Table 5.6: Potential Failure Mechanisms and Associated Scenarios

Failure Mechanism	Associated Scenario
Exploration borehole penetrates into repository providing an enhanced permeability pathway to the surface environment and potential for direct exposure to waste	Human Intrusion
Poor construction techniques impact on the performance of the repository and shaft EDZs providing an enhanced permeability pathway to the surface environment	Severe Shaft Seal Failure
Repository and shafts are not properly sealed at the time of closure, providing an enhanced permeability pathway to the surface environment	Severe Shaft Seal Failure
Long-term performance of shaft seals and EDZs deviates from that expected, due to some unexpected internal processes, resulting in an enhanced permeability pathway to the surface environment	Severe Shaft Seal Failure
Site investigation/monitoring borehole is poorly sealed at time of closure providing an enhanced permeability pathway to the surface environment	Poorly Sealed Borehole
Long-term performance of site investigation/monitoring borehole seal deviates from that expected, due to some unexpected internal processes, resulting in an enhanced permeability pathway to the surface environment	Poorly Sealed Borehole
Site investigations do not identify a relatively high permeability fracture zone or fault that provides a connection between the DGR horizon and higher horizons	Vertical Fault
Seismic event results in reactivation of an existing structural discontinuity and/or failure of shaft seals that provides an enhanced permeability pathway to higher horizons	Bounded by Vertical Fault and Severe Shaft Seal Failure
Rapid resaturation of the repository occurs due to an enhanced permeability pathway from the repository to higher horizons	Included in Human Intrusion and Severe Shaft Seal Failure

Another way in which the geosphere barrier can be bypassed is through the site characterization/monitoring boreholes. These boreholes occur in the vicinity of the DGR down to and beyond the depth of the DGR. In all cases, the boreholes are located at least 100 m from the repository. Furthermore, they will be appropriately sealed on completion of site investigation/monitoring activities and consequently they will have no effect on the repository performance. However, if a deep borehole were not properly sealed or were to extensively degrade, then it could provide a small but relatively permeable pathway for the migration of contaminants from the repository horizon. The scenario is termed the **Poorly Sealed Borehole Scenario**. Like the Severe Shaft Seal Failure Scenario, such a situation is very unlikely due to the adoption of good engineering practice and quality control.

There is strong geological, hydrogeological, and geochemical evidence that transmissive vertical faults/fracture zones which could provide an enhanced permeability pathway from the repository horizon to an overlying aquifer do not exist within the footprint or vicinity of the DGR (Section 4.3.1). This evidence has been gathered through a deep drilling/coring program, a 2-D seismic reflection survey, petrophysics, in-situ borehole testing and micro-seismic monitoring. Despite this evidence, a “what if” scenario is considered to investigate the safety implications of a hypothetical transmissive vertical fault, either undetected or representing the displacement of an existing structural discontinuity. Regionally, any such discontinuities are often associated with hydrothermal dolomitized carbonate and are found to originate in the Precambrian or Cambrian and extend up to the Ordovician shales where they terminate (Armstrong and Carter 2010). The hypothetical fault is assumed to be in close proximity to the DGR and is assumed to extend beyond the Ordovician shales and into the permeable Guelph formation. The scenario is termed the **Vertical Fault Scenario**.

Other potential Disruptive Scenarios were considered, but ruled out on various grounds as described in QUINTESSA (2011b) and QUINTESSA et al. (2011). For example, no volcanic activity is anticipated in the area over the next one million years, and the probability of being hit by a large meteor capable of damaging the repository is remote. Seismic activity is possible, and likely earthquakes are included in the Normal Evolution Scenario, where their main effect is rockfall within the repository (Section 5.1.2). Large earthquakes are unlikely, and their main effects on the repository are bounded by the Severe Shaft Seal Failure and Vertical Fault Scenarios, so there is no need to consider an additional earthquake scenario. Similarly, repository gas pressures are expected to be significantly less than the lithostatic pressure of about 17 MPa and the regional horizontal stresses of 20-30 MPa (see Section 8.1 of the Gas Modelling report, GEOFIRMA and QUINTESSA 2011). Therefore, they do not cause fracturing of the rock and this scenario is not evaluated. Glaciation could affect the site; it is considered within the Normal Evolution Scenario.

In order to build confidence that an appropriate set of Disruptive Scenarios has been identified using the safety function and argument approach described above, a complementary approach was also used. The approach involved reviewing each of the External FEPs identified in Table 5.1 to see whether, given the assessment context (specified in Chapter 3) and the system description (given in Chapter 2 of the System and Its Evolution report, QUINTESSA 2011b), it was possible for the External FEP to have one or more alternative states to the state considered in the Normal Evolution Scenario. The same set of four additional scenarios, identified using the safety argument approach, was identified (see Table 8-5 in QUINTESSA 2011b).

Further confidence that an appropriate set of Disruptive Scenarios has been identified can be built by comparing the scenarios (additional to the "reference/base/normal evolution" scenario) considered in the postclosure safety assessments of other deep repositories. A review of the scenarios considered in assessments of deep repositories in other countries was undertaken. The results are summarized in Table 5.7[18]. It can be seen that, consistent with the DGR assessment, most assessments have identified a limited number of additional scenarios that consider the degradation/failure of engineered and natural barriers by natural processes (e.g., earthquakes, climate change) and human actions (e.g., drilling, poor quality control). Although there are some scenarios identified in Table 5.7 that are not considered in the DGR Disruptive Scenarios, these are either not relevant to the Bruce nuclear site (e.g., volcanic activity, sea-level rise, mining of resources) or have been included in the DGR's Normal Evolution Scenario (e.g., climate change, canister failure, gas generation).

The selected Disruptive Scenarios are described in Section 5.2.2 below. Figure 5.4 shows their locations assumed for the safety assessment. Human intrusion occurs into Panel 1, which has the highest amount of ILW. The poorly sealed borehole is the closest existing borehole at repository depth. Two locations for the vertical fault are considered – one just outside the well-characterized site area at a 500 m distance, and one within the area at 100 m from the waste panels.

The Disruptive Scenarios are evaluated separately rather than in combination, since the individual scenarios have low probability and independent causes, and so their probabilities of occurring together are even lower.

5.2.2 Description of Disruptive Scenarios

5.2.2.1 Human Intrusion Scenario

The Human Intrusion Scenario considers the same evolution of the DGR system as for the Normal Evolution Scenario with the only difference being the occurrence of human intrusion into the repository at some time after institutional control of the site is no longer effective.

In this scenario, an exploration borehole is drilled down through the geosphere. Upon encountering the repository, the drilling crew would register a loss of drill fluid to the repository void if the repository pressure is less than the drill fluid pressure, or a surge of gas from the repository up the borehole if the repository pressure is greater than the drill fluid pressure. No significant amount of water is expected to be expelled, as the saturation of the repository is projected to be very low (less than 1% for the Normal Evolution Scenario's Reference Case, Section 5.1.1.2, Gas Modelling report, GEOFIRMA and QUINTESSA 2011). Current technology necessary to drill to 680 m depth would enable the drillers to ascertain the nature of the void

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[18] Assessments often sub-divide a given scenario down into a number of "sub-scenarios" or variant/alternative cases. For example, the exploration drilling scenario considered in SAFIR 2 has three variants: examination of the drill core; contamination of soil by drill cuttings; and preferential pathway for groundwater flow (ONDRAF/NIRAS 2001). In NAGRA (2002), alternative conceptualizations of the Reference Scenario address phenomena in the near field and the geosphere where uncertainty exists about their importance for the reference radionuclide release pathway. Given that the purpose of the review was to compare the top-level scenarios, any division of a scenario into sub-scenarios or variant/alternative cases is not included in Table 5.7.

that had been encountered, and to limit upflow from the repository (e.g., this is standard practice in sedimentary rocks where one may encounter natural gas).

Table 5.7: Additional Scenarios Considered in Other Safety Assessments

Assessment	Reference	Additional Scenarios Considered
SAFIR 2 (Belgium)	ONDRAF/NIRAS (2001)	• Exploitation drilling (water well) • Exploratory drilling • Greenhouse effect • Poor sealing of repository • Fault activation • Severe glacial period • Failure of engineered barriers • Gas-driven transport
Olkiluoto (Finland)	POSIVA (2010)	• Defective canister (early and delayed penetration) • Earthquake/rock shear • Disrupted buffer • Release affected by gas • Exploitation drilling (water well) • Exploratory drilling
Dossier Argile (France)	ANDRA (2005)	• Seal failure and defective plug • Defective waste and spent fuel containers • Borehole penetrating repository • Functioning of repository greatly degraded
H12 (Japan)(1)	JNC (2000)	• Climate and sea-level change • Exploitation drilling (water well) • Engineering defects
SRCan (Sweden)	SKB (2006)	• Extended greenhouse effects • Disrupted buffer (e.g., due to advection, freezing) • Canister failure (e.g., due to load, shear or corrosion) • Exploitation drilling (water well) • Exploratory drilling • Rock excavation • Poorly sealed repository
Opalinus (Switzerland)	NAGRA (2002)	• Gas pathways • Exploitation drilling (water well) • Exploratory drilling • Poorly sealed repository
GPA (UK)	NIREX (2003)	• Exploratory drilling
WIPP (USA)	USDoE (2004)	• Mining • Exploratory drilling
Yucca Mountain (USA)(2)	USDoE (2002)	• Exploratory drilling • Seismicity • Volcanic event

Notes:

1. Isolation Failure Scenarios that involve penetration of the repository (including magma intrusion, human intrusion and meteorite impact) were also considered but screened out on the grounds that they are extremely unlikely to occur. Some 'what if' calculations were carried out instead.
2. The term 'scenario' is used in a way that differs from the other assessments reviewed. Three Thermal Load Scenarios are discussed that are design variants, while two No-action Scenarios refer to futures in which the Yucca Mountain facility does not go ahead.

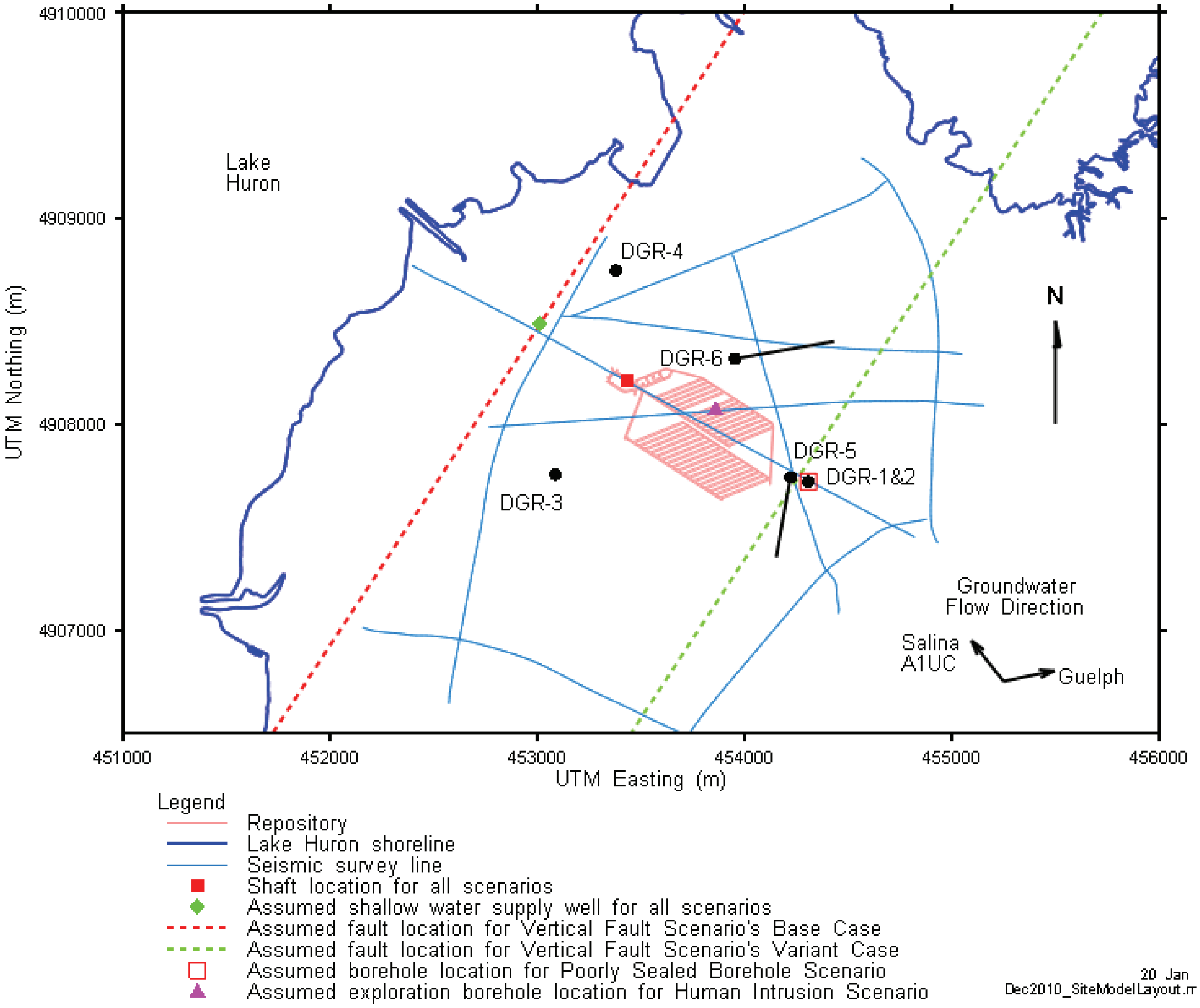


Figure 5.4: Location of Disruptive Scenarios Evaluated in the Safety Assessment

In an exploration borehole, the investigators would most likely collect samples or conduct measurements at the repository level, which would readily identify if there were still significant residual radioactivity (e.g., gamma logging is a standard borehole measurement). In this case, the investigators would likely initiate appropriate precautions to prevent further exposure, including ensuring any surface-released materials were appropriately disposed and sealing the borehole. Therefore, under normal drilling, there would be little impact.

Nevertheless, the Human Intrusion Scenario considers “what if” the intrusion is inadvertent and:

- It is not recognized that the drill has intercepted a waste repository so no safety restrictions are imposed; <u>and</u>
- The borehole and drill site are not managed and closed to current standards; and material from the borehole is released on surface around the drill site.

Further, the scenario also considers the long-term consequences of:

- The borehole being poorly sealed, resulting in the creation of a pathway for contaminants into permeable geosphere horizons above the repository; and
- As a very unlikely variant case, "what if" the borehole were continued down into the pressurized Cambrian Formation, and again not properly sealed.

For this scenario, therefore, contaminants can be released, and humans and non-human biota exposed, via:

- Direct release to the surface of pressurized contaminated gas prior to sealing of the borehole;
- Retrieval and uncontrolled dispersal of contaminated drill core on the site;
- Retrieval and examination of drill core contaminated with waste; and
- The long-term release of contaminated water from the repository into permeable geosphere horizons via the exploration borehole, if the borehole was continued down into the pressurized Cambrian and subsequently poorly sealed.

These releases could result in the exposure of the drill crew or other people at the time of intrusion, and people who might occupy the site subsequent to the intrusion event.

5.2.2.2 Severe Shaft Seal Failure Scenario

The shafts represent a potentially important pathway for contaminant release and, therefore, the repository design includes specific measures to provide good shaft seals, taking into account the characteristics of the geosphere. The Normal Evolution Scenario considers the likely behaviour of the shaft seals and the repository/shaft EDZs; it includes some expected degree of degradation of the seals with time. The Shaft Seal Failure Scenario considers the same evolution of the DGR system and the same exposure pathways as the Normal Evolution Scenario, the difference being that there is rapid and extensive shaft seal degradation and the repository/shaft EDZs have significantly degraded properties. Like the other Disruptive Scenarios, the scenario is a bounding “what if” scenario that is designed to investigate the robustness of the DGR system.

5.2.2.3 Poorly Sealed Borehole Scenario

Several site investigation/monitoring boreholes have been drilled in the vicinity of the DGR down to and beyond the depth of the repository during the site investigation phase. The Poorly Sealed Borehole Scenario considers the consequences of one of the boreholes not being properly sealed or having a seal that extensively degrades. The evolution of the system is similar to the Normal Evolution Scenario with the key difference being that the poorly sealed borehole provides an enhanced permeability connection between the level of the repository, the overlying groundwater zones and the biosphere, thereby bypassing some of the natural geological barriers to contaminant migration from the DGR. The subsequent exposure pathways are the same as those considered in the Normal Evolution Scenario.

5.2.2.4 Vertical Fault Scenario

The Vertical Fault Scenario considers the hypothetical case of “what if” a transmissive vertical fault, either undetected or representing the displacement of an existing structural discontinuity, which propagates from the Precambrian into the Guelph Formation in the Intermediate Bedrock

Groundwater Zone, in close proximity to the repository. Such a fault could provide an enhanced permeability pathway that bypasses the Deep Bedrock Groundwater Zone, one of the natural barriers to contaminant migration from the DGR. Groundwater flow in the Guelph is assumed to be horizontal and to discharge to the lake. Consideration is given to exposure of two critical groups: one that obtains its water and fish from the lake’s near shore; and one that farms above the repository and has the same characteristics as that considered in the Normal Evolution Scenario.

6. ASSESSMENT MODELS

6.1 Model Development Approach

The approach used for the development of conceptual and mathematical models and their implementation in the software tool used for assessment impacts is illustrated in Figure 6.1 and described below. It is consistent with model formulation and implementation processes described in IAEA (2004).

First, a conceptual model is developed for each scenario in the assessment (Chapter 5) using input from the assessment context (Chapter 3), the system description (Chapter 4), and the DGR FEPs list (QUINTESSA et al. 2011). The aim is to provide, for each scenario considered, a description of the release, migration and fate of contaminants from the repository through the identification of key features, events and processes. The conceptual model provides the set of qualitative and quantitative assumptions used to describe the DGR system for the purposes of the postclosure safety assessment. These assumptions concern the geometry and dimensionality of the system, its temporal and spatial boundary conditions, and the nature of the relevant physical and chemical processes. The associated features, events and processes are audited against the DGR FEPs list to ensure that important issues have not been neglected in the conceptual models (for example the audited FEPs list for the Normal Evolution Scenario is provided in Appendix C, QUINTESSA 2011a).

Once each conceptual model has been developed, there is a need to consider the various sources of uncertainties associated with the model. This, together with consideration of future and data uncertainty, allows various calculation cases to be identified. Each scenario can have several associated calculation cases due to the range of associated conceptual model and data uncertainties identified.

The conceptual model for each calculation case is then used as a prescription for the mathematical models that are required. The calculation cases and mathematical models determine the parameters for which data are required. The mathematical models and associated data are then implemented in a software tool to generate a computer model that is used to simulate the migration of contaminants from the repository via the various pathways and calculate the resulting endpoints.

Consistent with the IAEA safety guide on the safety case and safety assessment for radioactive waste disposal (IAEA 2010), learning from the analysis of the initial results of the computer model may cause refinements to understanding regarding the formulation of the conceptual model. In particular, the results of detailed gas and groundwater modelling (i.e., modelling undertaken using 2-D and 3-D finite-element/finite-difference codes) can be used to inform the development of the conceptual model used in the assessment-level modelling (i.e., modelling using a simplified model to represent the entire DGR system). Therefore, there is a process of feedback to the conceptual models, once the detailed mathematical models have been implemented and analyzed. The final conceptual model is a result of this iteration and feedback.

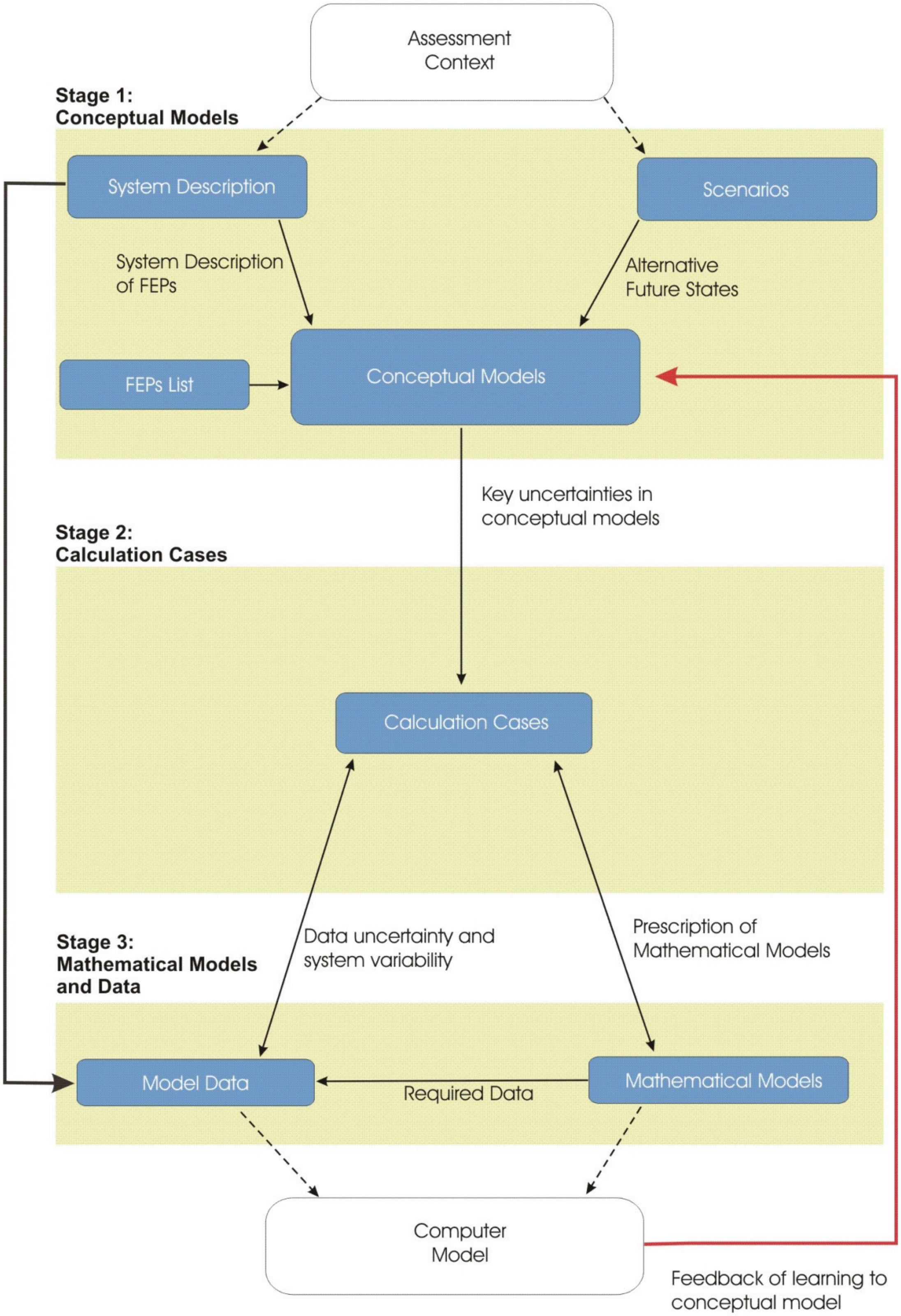


Figure 6.1: Model Development Approach

6.2 Conceptual Models

6.2.1 Normal Evolution Scenario

The main aspects of the conceptual model for the Normal Evolution Scenario are summarized in Figure 6.2 to Figure 6.4 and in Box 1; a more detailed summary is given below based on the detailed description given in Section 2.3 of the Analysis of the Normal Evolution Scenario report (QUINTESSA 2011a).

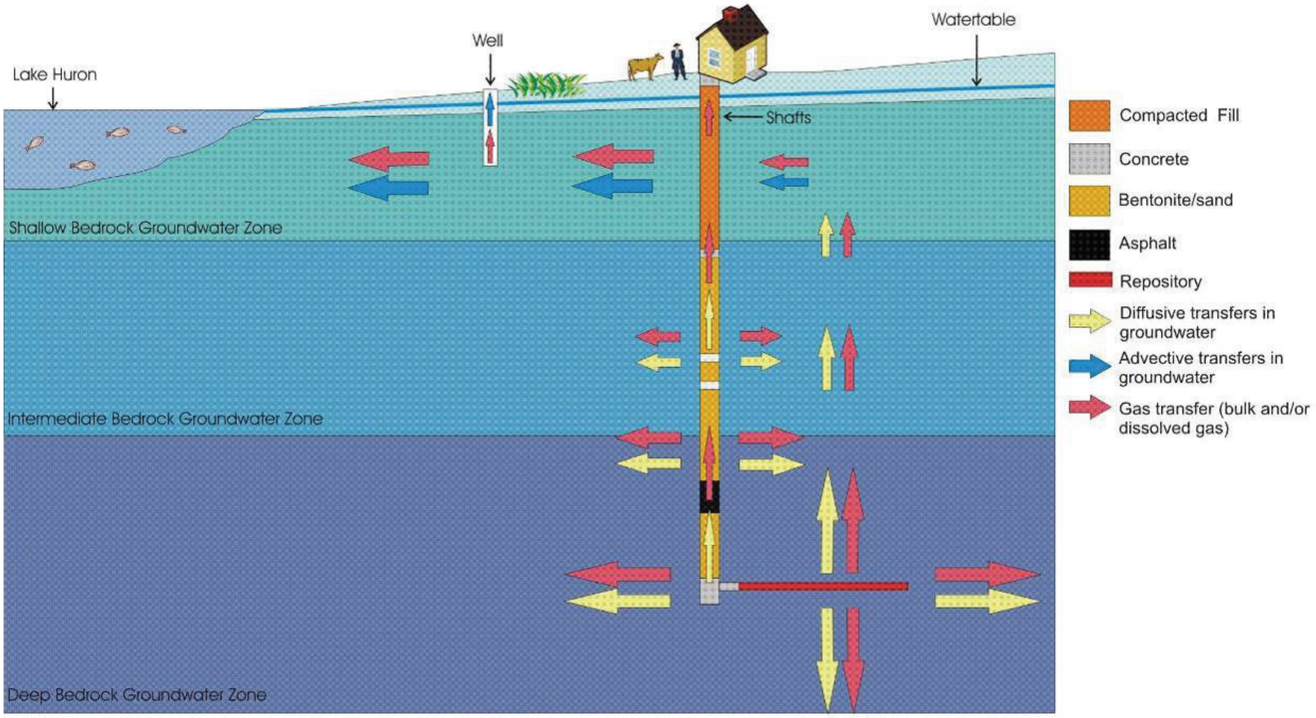
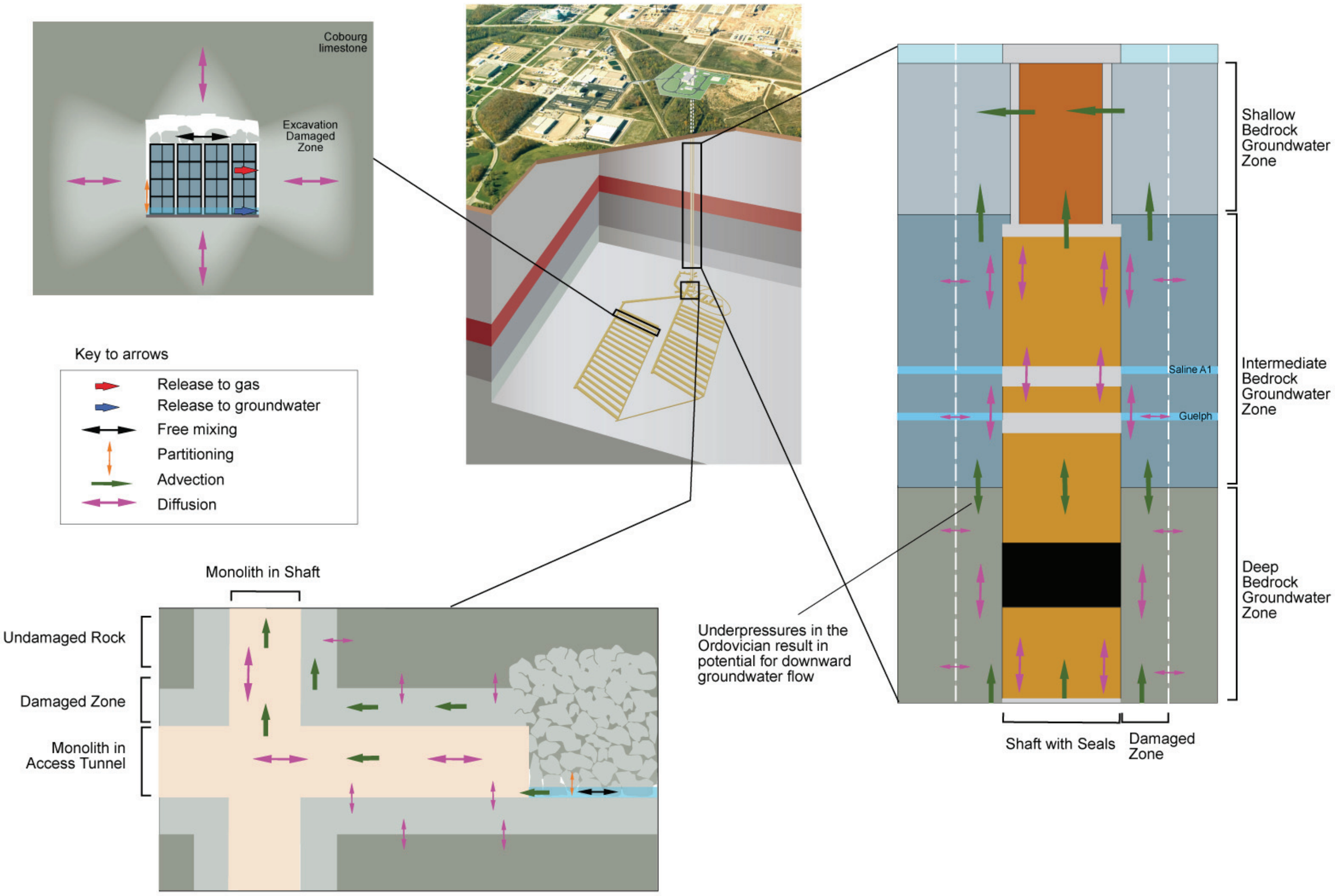


Figure 6.2: Schematic Representation of Potential Transport Pathways for the Normal Evolution Scenario



Note: See Figure 4.9 for shaft seal materials.

Figure 6.3: Detailed Representation of Potential Transport Pathways in the Repository and Geosphere for the Normal Evolution Scenario

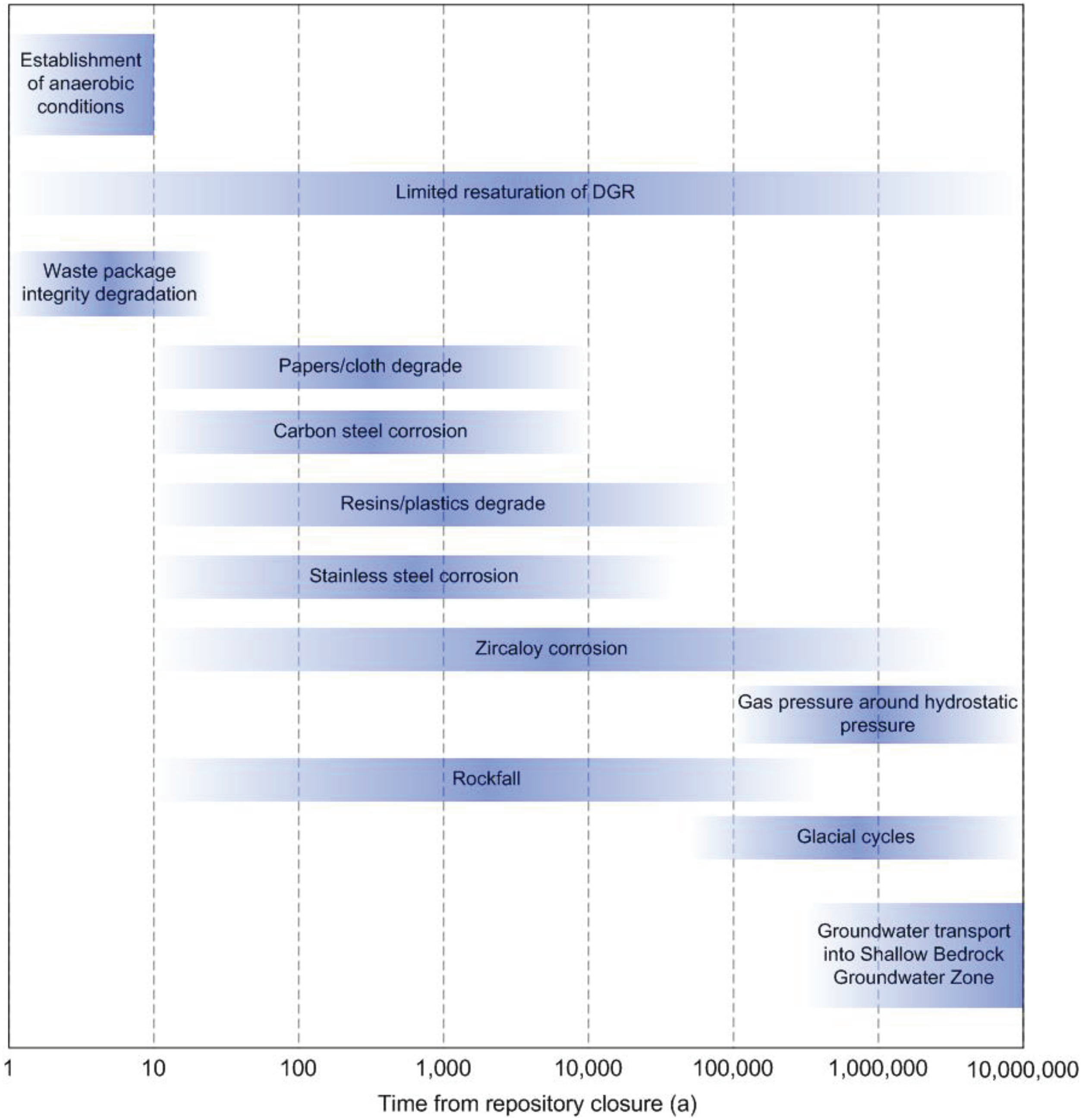


Figure 6.4: Timeframes for Key Processes Considered in the Normal Evolution Scenario

Box 1: Key Aspects of the Conceptual Model for the Normal Evolution Scenario

Waste and Repository:

- Reference waste inventory of about 200,000 m^3 (emplaced volume) and 16,000 TBq (Table 4.3 and Table 4.4).
- Reference repository design with no backfill, except concrete monolith at shaft base (Section 4.2).
- Rockfall occurs from closure, reaching a stable equilibrium (see Section 6.2.1.1).
- Metals degrade anaerobically to release H_2; organics degrade microbially to release CH_4 and CO_2.
- Resaturation of repository is determined by water inflow/outflow, gas generation, gas inflow/outflow and gas pressure (see Section 6.2.1.1).
- Contaminants are released into water via instantaneous and congruent release processes (Table 6-1); no credit is given to waste packaging as a chemical or physical barrier.
- H-3 and C-14 are also released as gas as a result of waste degradation (see Section 6.2.1.1).
- Once released from waste, H-3, C-14, Cl-36, Se-79, and I-129 partition between water and gas in the repository (see Section 6.2.1.1).
- No sorption of contaminants and solubility limitation only for C (see Section 6.2.1.1).
- Contaminants may migrate into the host rock and shafts by diffusion and/or advection[19].

Geosphere and Shafts:

- Very low permeability host rock with no significant fracturing or joints, some anisotropy in diffusion and permeability along versus across bedding planes[19].
- Underpressures in the Ordovician rocks are present initially but may equilibrate over time.
- Overpressure in the Cambrian sandstone remains constant over assessment timeframe.
- Ordovician rocks are partially unsaturated, with some methane gas.
- No significant groundwater flow in flow within Guelph or Salina A1 upper carbonate formations.
- Excavation damaged zones (EDZs) exist around all excavations, including the shafts; no self-sealing due to creep or precipitation processes (see Section 6.2.1.2).
- Relative permeability of gas phase is described by van Genuchten models for capillary pressure (see Section 4.2.1 of the Gas report, GEOFIRMA and QUINTESSA 2011).
- Some degradation of concrete structures, but no further significant change in bulk properties of shaft seal materials or EDZ occurs over assessment timescale (see Section 6.2.1.2).
- Contaminants may migrate through the host rock by diffusion[19].
- Contaminants may migrate up the shafts by diffusion and/or advection in groundwater and in gas through the shaft seals and/or excavation damaged zones (EDZs)[19].
- Zr, Nb, Cd, Pb, U, Np and Pu may sorb in the shafts and geosphere (Appendix D of the Data report, QUINTESSA and GEOFIRMA 2011a).

Biosphere:

- Constant temperate climate conditions (see Section 6.2.1.3).
- Horizontal flow in the Shallow Bedrock Groundwater Zone discharges into the near shore lake bed (see Section 6.2.1.3).
- Potable groundwater is pumped from a well in the Shallow Bedrock Groundwater Zone for domestic and farming use, including irrigation (see Section 6.2.1.3).
- Surface media may become contaminated following release of contaminants via the well and via groundwater discharge to the lake (see Section 6.2.1.3).
- Potential impacts are estimated based on assuming a self-sufficient family farm located on the repository site and using groundwater from well (see Section 6.2.1.3).

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[19] Based on findings presented in the Groundwater Modelling report (Section 5.2, GEOFIRMA 2011) and the Gas Modelling report (Section 5.1, GEOFIRMA and QUINTESSA 2011).

6.2.1.1 Waste and Repository

<u>Evolution of Repository Conditions</u>

Around 160,000 m^3 of LLW and 40,000 m^3 of ILW are emplaced in 31 rooms over the operational lifetime of the DGR (approximately 40 years). For the purposes of the safety assessment, it is assumed that during the operational lifetime there is no loss of contaminants from the packages except by decay.

On closure, each waste emplacement room is expected to be dry, with little or no standing water, but a relative humidity of around 100% (Section 5.1.1.7, Gas Modelling report, GEOFIRMA and QUINTESSA 2011). The rate of water inflow, and hence resaturation, is slow due to the very low permeability of the host rock (see below). Both the wastes and their packaging degrade under the humid conditions. Initially conditons in the DGR will be aerobic, but corrosion and microbial degradation[20] consume oxygen with the formation predominantly of rust on steel packaging and generation of CO_2 from organic wastes. The chemical conditions in the repository rapidly become anaerobic - initially in localized areas within packages, and then across the entire repository.

Under anaerobic conditions, metallic wastes and packaging corrode, generating H_2 gas as a by-product (Figure 6.5). The radioactivity in the waste may locally enhance corrosion in some packages, but overall it is too low to generate appreciable radiolytic gases. Organic materials are subject to microbial degradation, generating a variety of intermediate products (mostly CH_4 and CO_2) depending on the microbe and other factors (Section 4.2, QUINTESSA and GEOFIRMA 2011b), but ultimately converting the organics into predominantly CH_4 (Figure 6.5). CO_2 formed from the degradation of organics is microbially metabolized to CH_4 by reaction with H_2 gas. Some CO_2 also reacts with water and iron to form siderite ($FeCO_3$) and H_2 gas. Consequently, in the long term, the repository will contain mostly methane gas, consistent with natural gas reservoirs in sedimentary rocks.

The end stage reaction, which degrades most of the organic wastes into methane gas, depends upon the availability of methanogens. These are a widely distributed group of microbes, including in deep rock locations where they can be a significant source of natural gas. However, they are sensitive to environmental conditions, and may be inhibited by the highly saline waters[21] or by metals that would be present in any water within the repository. Over long times, it is expected that they will be present in the repository and able to utilize the energy present in the organic wastes; however, variant cases are also presented where they are assumed to be inhibited.

These corrosion/degradation reactions usually require water. There is a small amount of water initially present in the wastes, but continued corrosion/degradation will depend on water seeping

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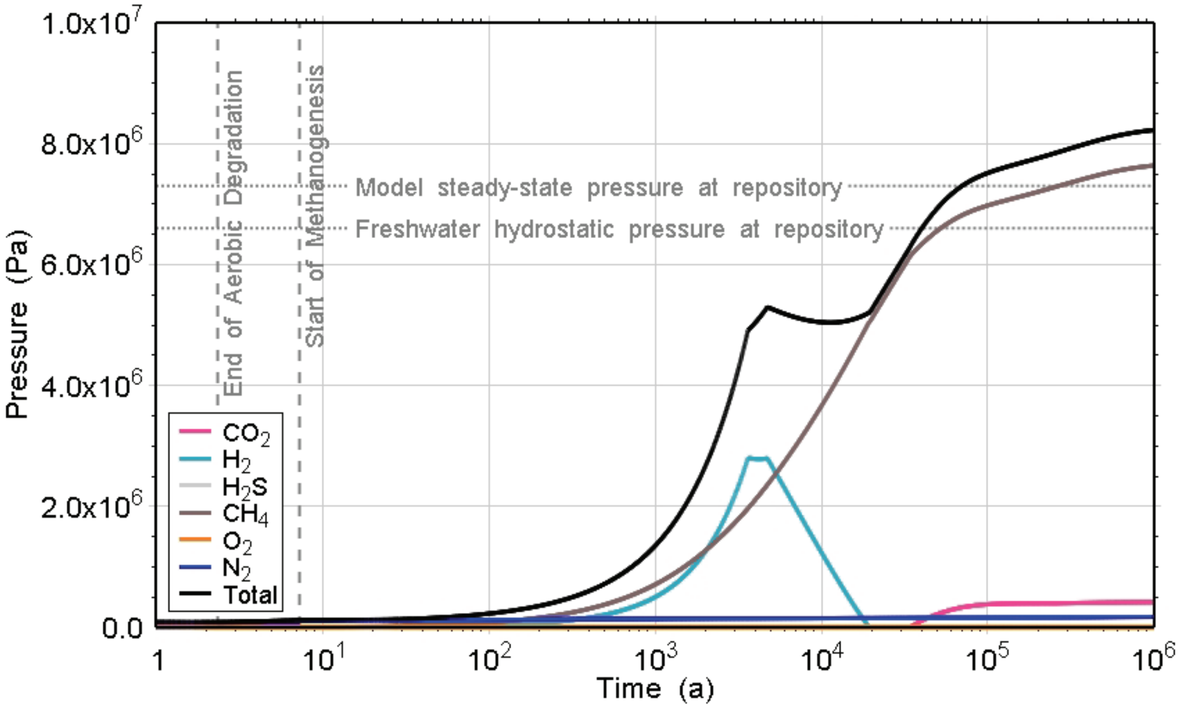
[20] The degradation of the organics (but not the corrosion of steel) requires the presence of an active anaerobic microbial community. However, the rock porewater around the repository is highly saline and not favourable for microbes, and tests of the host rock formations do not exhibit appreciable microbial activity. Furthermore, locally the presence of concrete could lead to high values of pH which are not favourable to microbial development. Nevertheless, the safety assessment assumes that microbial waste degradation occurs.

[21] Preliminary tests of the host rock did not exhibit appreciable microbial activity.

into the DGR from the host rock and/or shafts. Since the surrounding host rock and the shaft seals have low permeability, the rate of water supply may limit the corrosion /degradation rate.

As the wastes and packaging corrode and degrade, the gas pressure inside the repository begins to rise (Figure 6.5), with the rate of increase dependent on:

- The rate of gas generation through the degradation of wastes and packaging;
- The inflow/outflow of gas between the repository and the host rock; and
- The available gas headspace in the repository (depending on the water level in the repository).



Note: Figure 5.7 in GEOFIRMA and QUINTESSA (2011).

Figure 6.5: Repository Gas Pressures and Composition for the Normal Evolution Scenario's Reference Case

The free gas pressure is important, because it affects both the repository resaturation time (and hence the water level in the repository) and the potential for migration of gaseous radionuclides from the repository. Due to the very low permeability of the host rock, most of the gases are retained within the repository void space and hence the gas pressure in the repository can rise to levels of around 8 MPa at around a million years for the reference conditions (Figure 6.5). This peak pressure is about 0.8 MPa above the steady-state hydraulic pressure in the host rock and reflects the presence of a higher pressure free formation gas phase in the geosphere, which flows from the host rock into the lower pressure repository at long times. This pressure is well below the 17 MPa rock lithostatic pressure and the 20-30 MPa horizontal rock stresses. Geomechanical modelling of the DGR with peak gas pressures of 7 MPa shows no fracturing.

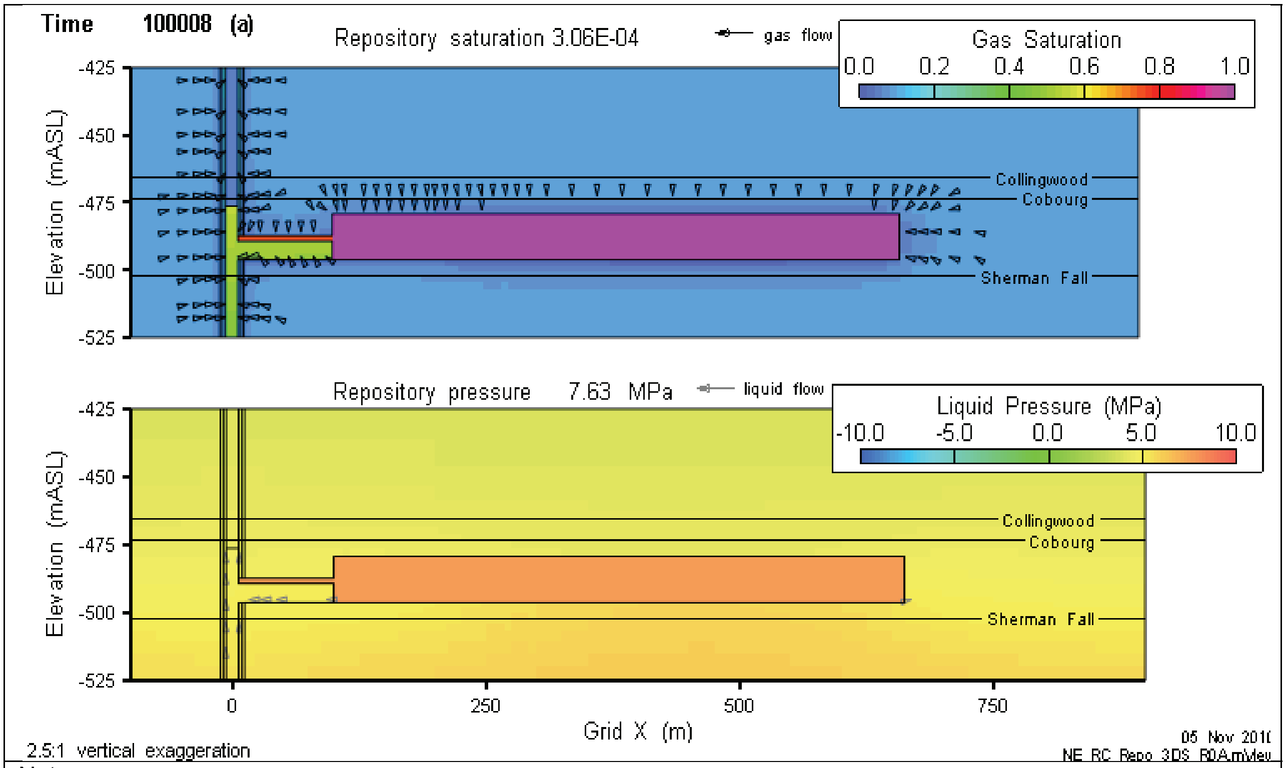
Even if gas pressures were to reach 15 MPa, there would only be formation of several metres long horizontal fractures (Chapter 6 of the Geosynthesis report, NWMO 2011a).

The gas pressure influences the saturation profile of the repository by affecting the rate of inflow/outflow of water into/from the repository via the shafts and the geosphere surrounding the DGR. The repository saturation profile is also affected by the characteristics of the host rock, and to a lesser degree, water generation/loss resulting from the corrosion/degradation of repository and waste materials. Calculations for the Reference Case show repository saturation remains extremely low, peaking at 0.7% after about 3000 a before falling to essentially zero and remaining at this low level (see Figure 5.3 of the Gas Modelling report, GEOFIRMA and QUINTESSA 2011).

Figure 6.6 shows the saturation profile and pressures in the repository and adjacent rock at about 100,000 years after most of the gas generation has occurred (Section 5.1.2.2 of GEOFIRMA and QUINTESSA 2011). At this time the repository is virtually 100% gas, while the shaft and surrounding rock are at around 10% gas saturation (within the rock porosity of 1-10%), the initial estimated gas content of these rocks. The concrete monolith at the shaft base and a small region of rock above the monolith are largely unsaturated. There is slow gas movement from the surrounding rock into the repository and eventually through the monolith area and into the shaft.

The quantities of cementitious materials present in the repository are relatively small (around 15% of the total volume) and are not expected to have a large effect on the average pH conditions within the DGR, which are expected to be around pH 6 to 8 (see discussion of chemical and biological evolution of the DGR in Section 4.5 of the System and Its Evolution report, QUINTESSA 2011b). However, these materials might locally affect the pH of repository water significantly (e.g., in the vicinity of cementitious waste packages). Any conditioning of repository water pH by cement will be greatest during the initial period, when pore fluids having pH >13 are likely to be present within the cementitious materials. However, in general, it is expected that the high solute concentrations in the water entering the repository limit significant chemical changes due to the strong buffering reactions associated with the high carbonate concentrations in the water which will balance the tendency to high pH from the cement and the tendency to low pH from CO_2 gas. Calculations indicate that only a small amount of carbonate rock will dissolve under these conditions (Appendix G, QUINTESSA 2011b). Within the porewater in the surrounding rocks, it is likely that SO_4 is the dominant S species, and Fe(II) is the dominant aqueous Fe-species (Section 4.5.1, QUINTESSA 2011b).

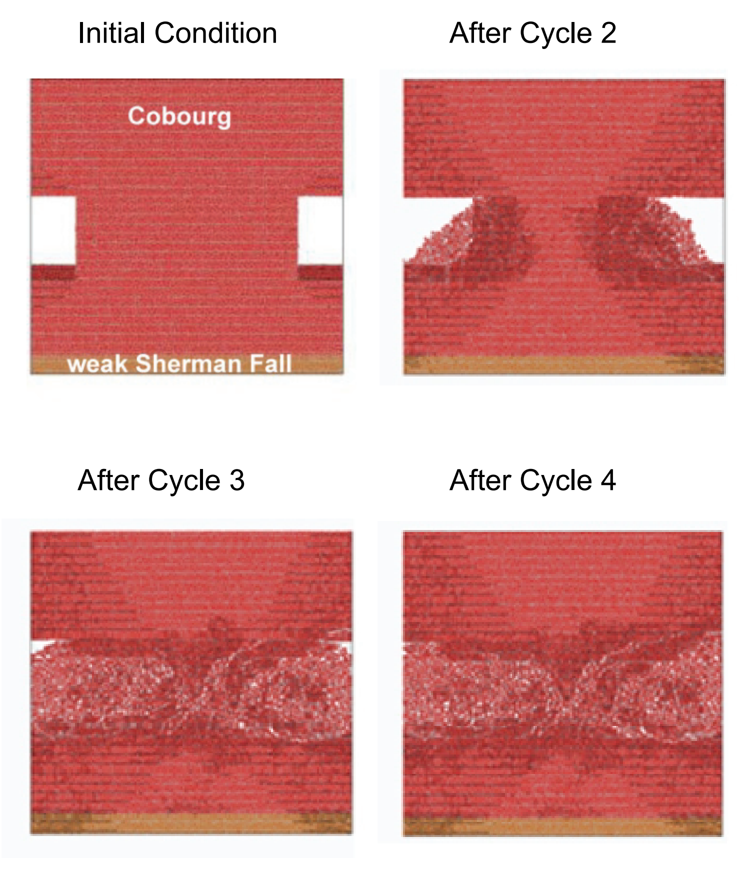
Some localized thermal gradients exist initially due to cement curing (e.g., the concrete monoliths at the base of the shafts) and radiogenic heat from some ILW wastes, but they are not spatially or temporally extensive. Corrosion of waste metals, and decomposition or degradation of organic materials will not emit significant heat. Overall, no significant thermal effects are expected given the limited heating power of the repository (maximum 2 kW at closure) relative to the 10 kW natural geothermal flux through the DGR panels footprint (see Section 4.2 of the System and Its Evolution report, QUINTESSA 2011b).



Notes:
The host rock has an initial hydraulic pressure of about 5 MPa and 10% gas saturation. The repository is represented as a porous volume that includes the maximum extent of rockfall.
Figure 5.32 in GEOFIRMA and QUINTESSA (2011).

Figure 6.6: Saturation, Flows and Pressures around the Repository for the Normal Evolution Reference Case after about 100,000 Years

Over the assessment timescale, it is expected that, in addition to the release of rock stresses resulting from the excavation of DGR rooms and tunnels, external events such as earthquakes and ice-sheet advances and retreats could induce loads on the rock. These events could lead to rockfall in the DGR rooms and tunnels. Geomechanical modelling shows that after three to four cycles of ice-sheet loading and unloading the excavations will become mechanically stable as rock that falls from the roof and room pillars fills the open space and becomes self-supporting (Section 6.4 of the Geosynthesis report, NWMO 2011a) (Figure 6.7). The modelling shows that the rockfall zone would propagate about 10 m into the repository roof before it stabilizes, and therefore would not affect the overlying geological formations. For the purposes of the safety assessment, the full rockfall is assumed to occur quickly after closure, and is assumed to affect all tunnels and rooms (i.e., it is not “patchy”).



Note: Adapted from Section 6.4 in NWMO (2011a).

Figure 6.7: Rockfall within and around the Emplacement Rooms after Four Glacial Cycles

Figure 6.8 provides a general illustration of a partially resaturated repository with the lower waste packages standing in water. Contaminants are released from wastes into water or gas, depending on the fraction of wastes that are saturated, and the nature and form of each contaminant. As the waste packages degrade over time, there is some collapse of the stacked packages into the void space that originally existed between and around the containers. The collapse is conservatively taken to occur at closure, minimizing the stack height and maximizing the amount of waste in contact with the water. This is consistent with the assumption of full rockfall at closure, which would damage the containers and promote collapse.

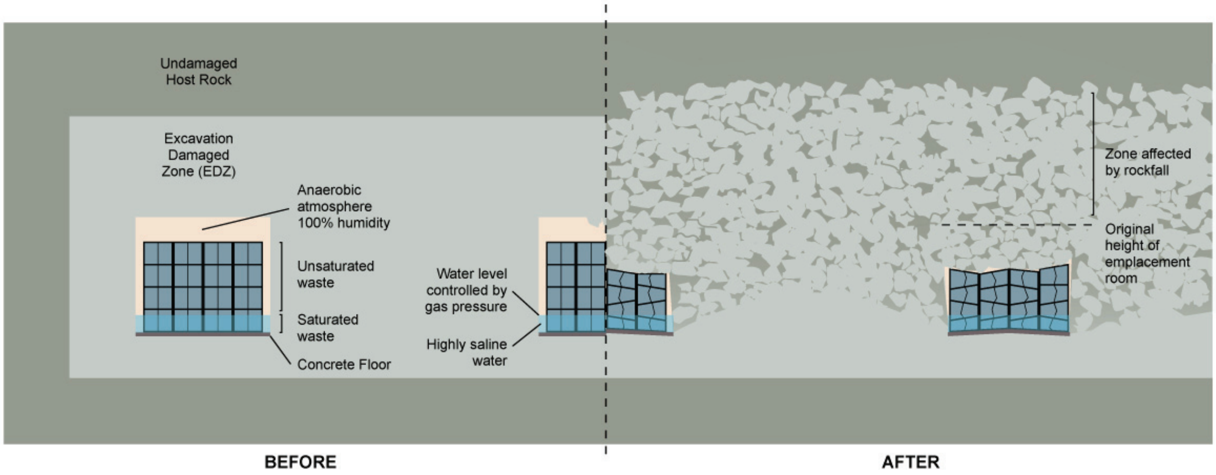


Figure 6.8: General Illustration of Repository Conceptual Model before and after Rockfall

Contaminant Releases to Repository Water

Each waste category is modelled with respect to its contaminant content and its release processes. Releases to water occur only once water in the repository contacts the waste, and then only from that part of the waste which is saturated. Thus, the releases are consistent with the resaturation and package failure history presented above. If the repository partially resaturates and then subsequently largely desaturates, contaminants from the wetted waste are still considered to be able to diffuse through the floor of the repository.

The two processes considered for releases to water are instant release and congruent release (see Appendix D.3.1 of the Analysis of the Normal Evolution Scenario report, QUINTESSA 2011a). Table 6.1 indicates the release processes to water that are considered for each waste category.

The majority of the contaminants associated with LLW are expected to be released quickly on contact with water. This is because the wastes are in ‘light’ packaging that is likely to degrade relatively rapidly postclosure, for example, through corrosion of the carbon steel drums. Also the contamination is generally present on the surfaces of the wastes, such that, once it comes in contact with repository water, it is rapidly transferred into the water.

Many of the ILW wastes are packaged more heavily for operational reasons (i.e., with additional containment and shielding), including the use of steel and concrete packaging (see Table 4.2). For these wastes, the packaging could form a barrier to water-waste interaction and contaminant release to repository water. However, the potential effect of ILW packaging is conservatively ignored for the assessment modelling.

Table 6.1: Contaminant Release Models from Waste to Repository Water

Waste Classification	Waste Categories	Release Model
LLW	Bottom Ash	Instant
	Baghouse Ash	Instant
	Compacted wastes - Boxes	Instant
	Compacted wastes - Bales	Instant
	Non-Processible - Drums	Instant
	Non-Processible - Boxes	Instant
	Non-Processible - Other	Instant
	LL/ALW Resins	Instant
	Steam Generators	Instant
	ALW Sludges	Instant
ILW	CANDECON Resins	Instant
	Moderator Resins	Instant
	PHT Resins	Instant
	Miscellaneous Resins	Instant
	Irradiated Core Components	Congruent
	Filters and Filter Elements	Instant
	IX columns	Instant
	Retube Wastes - Pressure Tubes	Congruent
	Retube Wastes - End Fittings	Congruent
	Retube Wastes - Calandria Tubes	Congruent
	Retube Wastes - Calandria Tube Inserts	Congruent

For some of the ILW wastes, the contamination is present in the matrix of the materials in the form of neutron activation products. For these wastes, contaminants only become available for release as the waste itself corrodes/degrades. Such a process is represented with a congruent release model and is relevant to irradiated core components and retube wastes.

Aqueous contaminant concentrations may be solubility limited. However, it is difficult to estimate solubility limits with confidence for water in the DGR rooms due to the large number of materials present in the waste, containers and DGR construction materials, and the different rates and durations of degradation processes. Therefore, solubility limits have not been applied to contaminant releases, except for C-14 where carbonate equilibria control can be assumed due to the surrounding limestone rock (see Appendix C of the Data report, QUINTESSA and GEOFIRMA 2011a).

Gaseous Contaminant Releases

Radioactive trace gases are also generated in the form of:

- C-14 labelled CH_4 and CO_2;
- H-3 released as tritiated water vapour and tritiated hydrogen gas;
- Rn-222 produced by radioactive decay of actinides in the wastes; and
- I-129, Cl-36 and Se-79 which may be volatilized.

Releases of radioactive trace gases from waste packages into the repository can occur under saturated and unsaturated conditions. The containers are not considered to be a barrier to gas release. This is consistent with the assumption that the containers fail immediately post-closure, that LLW is 'lightly' packaged, and that many of the more robust ILW packages have gas vents. It is conservative for ILW retube wastes that are in robust packaging that is expected to be gas tight. Therefore, gaseous releases can occur immediately on repository closure, and any losses of gaseous radionuclides during storage or waste emplacement operations are conservatively neglected.

H-3 is present as different species in different wastes, although it is likely mostly as HTO in LLW. Conservatively, the entire H-3 inventory is assumed to be released from the wastes immediately at closure. Under anaerobic repository conditions HTO may be reduced to HT, due to anaerobic metal corrosion reactions. H-3 is, therefore, likely to be present as HTO and HT. Some HT gas will dissolve in water in the DGR, in accordance with Henry's law. Some of the tritium associated with hydrogen gas and water might subsequently be microbially incorporated in methane. However, this is expected to be a secondary process and is not included in the model.

C-14 is present as surface contamination on wastes particularly as C-14 labelled carbonate/bicarbonate ions on exchange sites on ILW resins, and as an activation product in the matrix of irradiated metals. ILW resins are the major source of C-14 in the wastes. C-14 present as surface contamination is released from unsaturated wastes as radiolabelled CO_2 gas. The release rates used in the assessment are the measured rates for ILW resins in storage (Chapter 7 of OPG 2011b). C-14 labelled CH_4 and CO_2 gases are also generated from C-14 present as carbides in metal wastes, with release congruently controlled through corrosion of both saturated and unsaturated metals.

C-14 released as radiolabelled CO_2 gas is expected to be subsequently microbially metabolized to CH_4 by reaction with H_2 gas. C-14 will be redistributed by the CO_2 processes. These include reaction of CO_2 with metals, resulting in some C-14 trapped in siderite precipitates. It includes CH_4 and CO_2 gas dissolved in water in the repository in accordance with Henry's law, precipitation or exchange with carbonate minerals and cement, and incorporation into microbial biomass. A specific activity model is used in the assessment calculations to describe the partitioning of C-14 between aqueous and gaseous phases. This model assumes that the partitioning of C-14 mirrors the behaviour of bulk stable carbon (i.e., C-12) and uses the results of the detailed T2GGM model to determine C-14 mass flows out of the repository. It does not consider precipitation as calcite or exchange with carbonate rocks.

Cl-36, Se-79 and I-129 can be microbially metabolized, forming methylated species that are volatile. These radionuclides are included as gases in the current assessment, based on a partition coefficient between water and gas phases (Appendix G of the Data report, QUINTESSA and GEOFIRMA 2011a).

Rn-222 is ingrown in the repository through radioactive decay of Ra-226 and can be released to the gas phase from both the saturated and unsaturated wastes. However, the gas pathway travel time is so long (see Section 8.2 of the Gas Modelling report, GEOFIRMA and QUINTESSA 2011) that Rn-222 will decay before reaching the surface. Therefore, Rn-222 released from the repository is not of interest for the Normal Evolution Scenario and is not modelled.

Migration of Contaminants

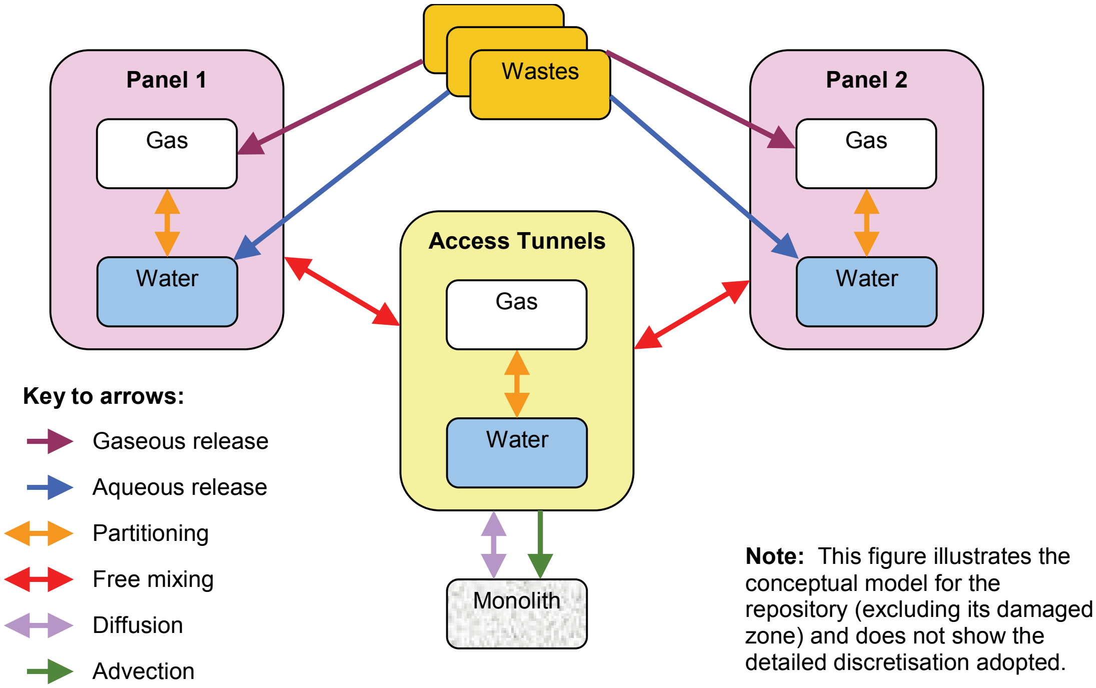
The preliminary design has two waste panels joined by connecting access tunnels. **Water** within the DGR is assumed to equilibrate to a common (time-dependent) depth, and contaminants within the water can mix freely through diffusion. No credit is taken for the role of any walls at the ends of the emplacement rooms or closure walls in the access tunnels in limiting water movement since they are not designed to be long-term barriers for groundwater flow and transport. Rockfall in the emplacement rooms and tunnels does not limit the diffusion of contaminants around the repository as there remains sufficient porosity; therefore, the freewater diffusivity is adopted for repository water.

Once contaminants have been released from the waste into repository water, they can migrate from the emplacement rooms through diffusion into the surrounding damaged zone and geosphere, and via advection/diffusion through the concrete monolith and its associated damaged zone at the base of the shafts (Figure 6.9). When the repository is partially saturated, diffusion of contaminants in the water into the geosphere can only occur from the base and part of the sides of the repository. During periods of desaturation of the repository due to increasing gas pressure, contaminants in water will be forced from the repository by the enhanced gas pressure.

Contaminants dissolved in the water may be retained by sorption and precipitation within the repository. However, the current assessment conservatively neglects sorption in the repository for all elements. It is assumed that no precipitation of elements occurs once they have been released from the waste packages into repository water.

The majority of the **gas** contaminants are retained in the repository due to the low permeability of the host rock. However, some can be released from the repository through dissolution into repository water or porewater within the adjacent host rock and by subsequent migration away from the repository through the host rock or along the access tunnel to the shaft.

The processes discussed above are illustrated in Figure 6.9, which shows how they apply to and between specific waste and repository components.



Note: This figure illustrates the conceptual model for the repository (excluding its damaged zone) and does not show the detailed discretisation adopted.

Figure 6.9: Conceptual Model for the Repository - Contaminant Release and Migration Processes

6.2.1.2 Geosphere and Shafts

Evolution of Geosphere and Shaft Conditions

During construction of the repository and its shafts, the host rock around the excavation will change due to mechanical disturbance and stress relaxation of the rock into the excavations. The extent of change will decrease with distance from the excavation, and can be conceptually divided into a thin highly damaged zone (HDZ), an Excavation Damaged Zone (EDZ), and then an excavation disturbed zone with no property changes. The hydraulic conductivity within the HDZ and EDZ is likely to be significantly enhanced relative to host rock (see Section 5.4.2 of the Data report, QUINTESSA and GEOFIRMA 2011a). Any HDZ is normally reinforced during operations for worker safety through rock supports (e.g., rock bolts, meshing, and shotcrete).

On closure, the HDZ is removed from around the shafts from the repository to the top of the Salina F as part of the shaft sealing (Section 4.2.3.2), but is left in place around the access tunnels. The EDZs are always present and, for greater accuracy in the modelling, are divided into inner and outer regions, with the extent of damage being greater in the inner region.

The shafts are backfilled using a combination of sealing materials, some of which intersect the inner EDZs (Figure 4.9). The hydraulic conductivities of these sealing materials are low to restrict the migration of contaminants up the shafts (see Section 4.5 of the Data report, QUINTESSA and GEOFIRMA 2011a). The concrete monolith and bulkheads are affected by some degradation due to chemical reactions (such as carbonation and sulphate attack) and stresses (see Section 4.5.3 of the System and Its Evolution report, QUINTESSA 2011b), which is conservatively taken to occur from closure, and the bulkheads are conservatively taken not to be keyed into the EDZ around the shafts.

In light of system-specific calculations presented in Appendix E of the System and Its Evolution report (QUINTESSA 2011b), it is concluded that limited alteration/degradation of the bentonite-sand and asphalt seals will occur over the timescales of interest and this has been incorporated into the parameterization of the seal properties (Section 4.5 of the Data report, QUINTESSA and GEOFIRMA 2011a). The effect of ice-sheet loading and unloading on the shaft EDZ was assessed and found to be a small additional effect (Section 6.4, NWMO 2011a), and incorporated into its parameterization (Section 5.2.1 of the Data report, QUINTESSA and GEOFIRMA 2011a).

The DGR's shafts will resaturate with groundwater more rapidly than the DGR's rooms and tunnels, in part because they are backfilled (i.e., a smaller volume). Results from detailed gas modelling (Section 5.1.2.1, GEOFIRMA and QUINTESSA 2011) show that the resaturation process will have mostly been completed by around 1000 to 10,000 a for the Reference Case.

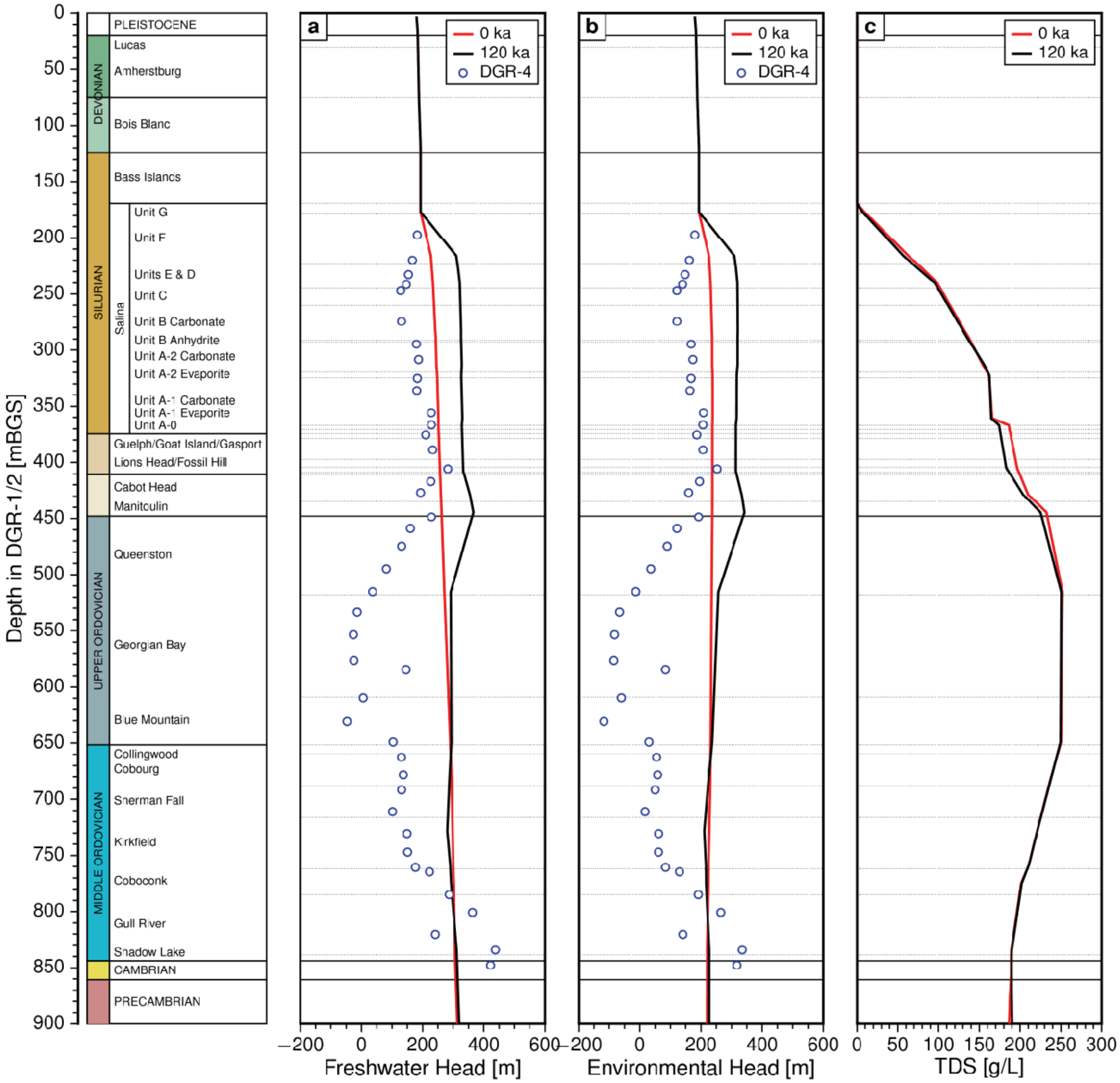
The primary impacts of glacial cycles on the Deep and Intermediate Bedrock Groundwater Zones are changes in the hydraulic heads and the stress regime resulting from ice-sheet loading and unloading (see Chapter 5 of the System and Its Evolution report, QUINTESSA 2011b). Based on evidence from site characterization and regional groundwater modelling (Sections 5.4.6 and 6.2 of NWMO 2011a) and a study of glacial erosion (Hallet 2011), these changes will not significantly affect the overall integrity and low-permeability of the host rock materials. For example, Figure 6.10 shows the effect of a full glacial cycle on hydraulic head and groundwater concentrations. The results show very little effect in the Deep Bedrock Groundwater Zone. In contrast, significant changes are likely to occur in the Shallow Bedrock Groundwater Zone (e.g., changes in recharge, development of permafrost, and changes in groundwater chemistry).

The geosphere hydraulic heads measured in the DGR site investigation boreholes show significant overpressures and underpressures in the deep rock formations (Section 4.3.3). These underpressures and overpressures provide the basis for the Reference Case calculation, consistent with the detailed groundwater modelling (GEOFIRMA 2011). The causes of these over- and underpressures are not certain, although there are plausible explanations. They are represented in two ways in the conceptual model.

In the Reference Case, the existing measured conditions are adopted as initial conditions. The overpressure in the Cambrian is conservatively assumed to remain constant (i.e., it does not dissipate) over the assessment timeframe. However, the underpressure is allowed to naturally dissipate. The resulting head profile calculated from detailed groundwater modelling is shown in Figure 6.11, which shows that significant underpressures still exist in the Ordovician rocks even after a million years. The results of the detailed groundwater modelling (see Figure 6.12) for the Reference Case indicate very low advective groundwater flow in the shafts above the DGR (around 0.1 mm/a) towards the Blue Mountain formation (i.e., groundwater flow in the shafts at the top of the Ordovician is downwards because of the underpressure).

In the alternative Simplified Base Case, the steady Cambrian overpressure is again assumed, but the underpressures are assumed to be of recent origin, and to dissipate relatively quickly so are not important for long-term safety. A steady hydraulic gradient vertically upwards exists in this case.

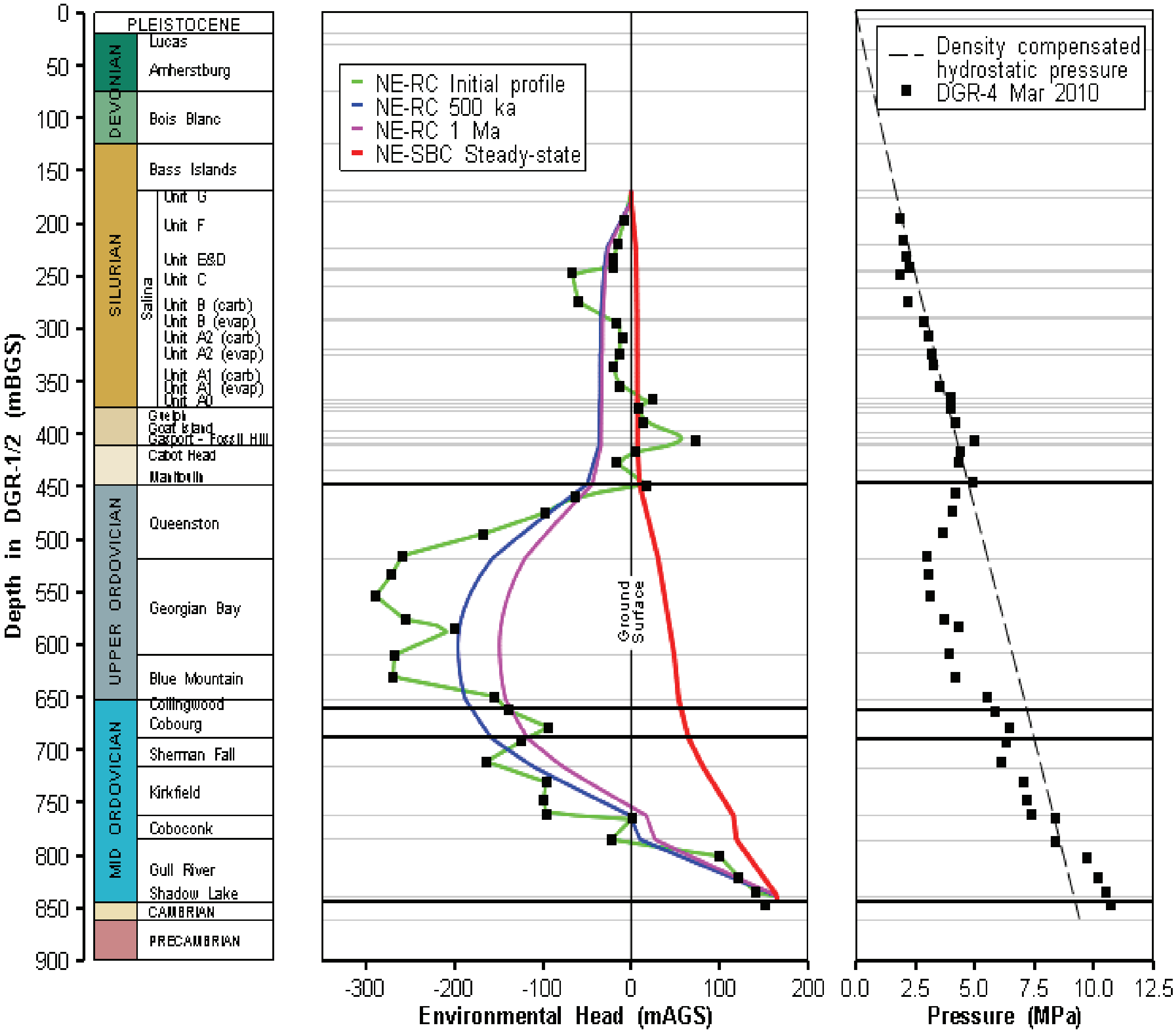
Further details describing the thermal, hydraulic, mechanical, chemical and biological evolution of the geosphere are provided in Chapter 5 of the System and Its Evolution report (QUINTESSA 2011b).



Notes:

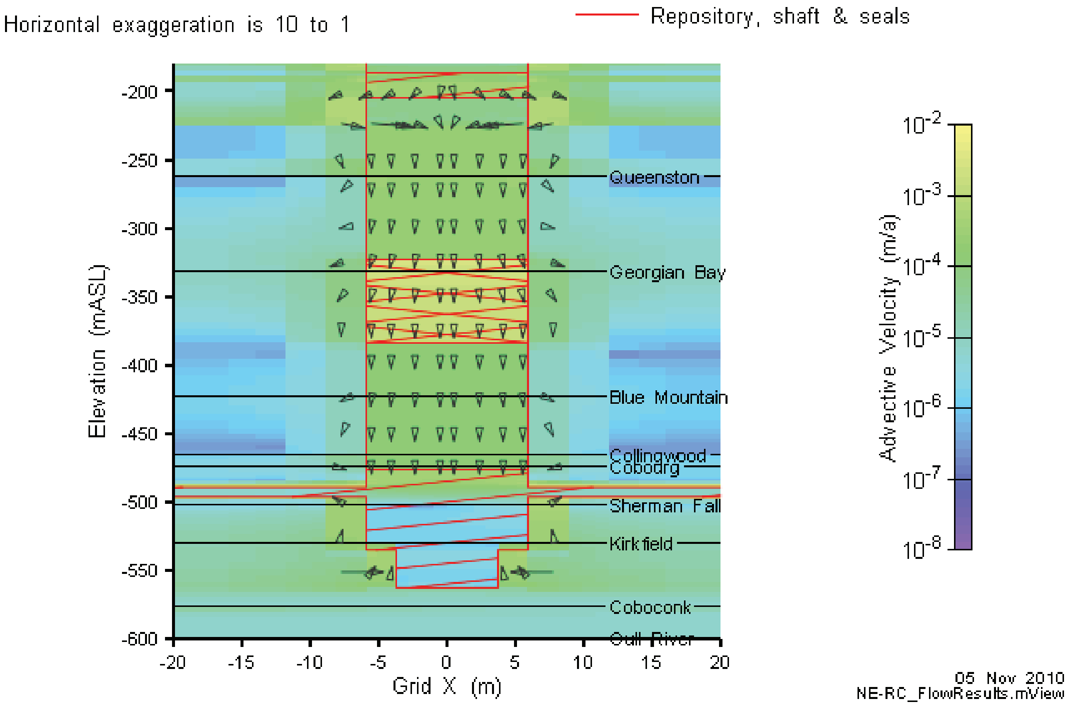
a) freshwater head, (b) environmental head, and (c) total dissolved solids concentration at beginning (0 a) and end (120,000 a) of paleoclimate simulation. Freshwater and environmental heads for site characterization borehole DGR-4 are shown. Figure adapted from Figures 5.30 and 5.32 in NWMO (2011a), fr-base-paleo.

Figure 6.10: Effect of One Glacial Cycle on Hydraulic Heads and Salinity Profile



Note: Figure adapted from Figure 5.3 in GEOFIRMA (2011). Detailed groundwater and gas models focussed on the low-permeability intermediate and deep geosphere as shown (Salina Unit G and below).

Figure 6.11: Hydraulic Head and Pressure Profiles for the Reference Case (NE RC-F3) and Simplified Base Case (NE-SBC-F3) from Detailed Groundwater Modelling



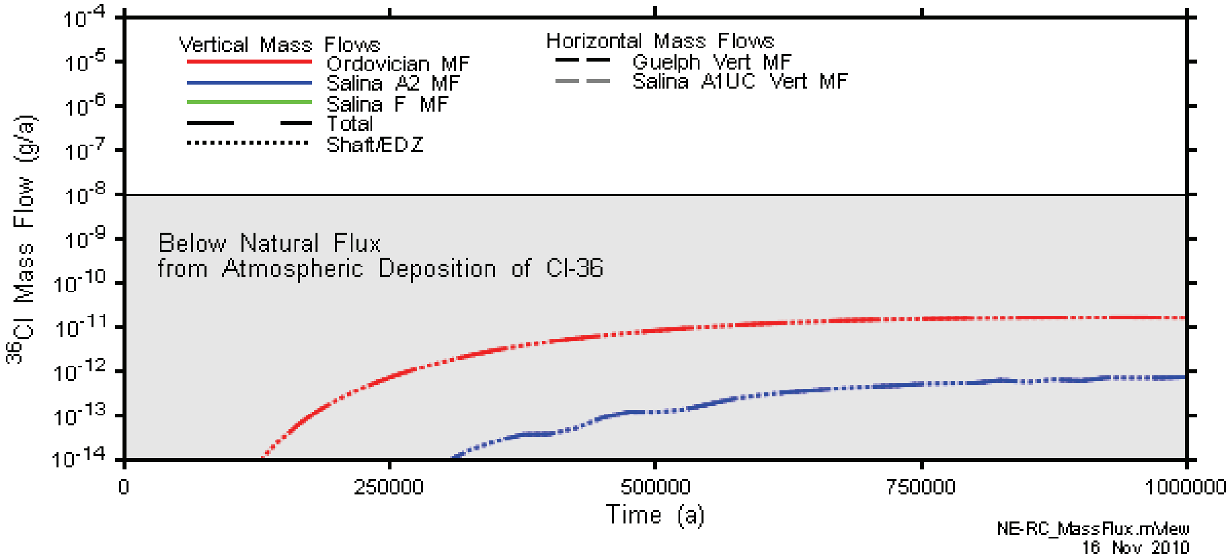
Note: Figure 5.7 in GEOFIRMA (2011). Also, note horizontal exaggeration.

Figure 6.12: Advective Velocities in the Lower Shaft for the Reference Case (NE-RC-F3) at 1,000,000 Years from Detailed Groundwater Modelling

Migration of Contaminants

Detailed groundwater modelling for the Reference Case (Section 5.2, GEOFIRMA 2011) has shown that transport for contaminants in **groundwater** in the host rock is dominated by diffusion in the Deep and Intermediate Bedrock Groundwater Zones. Contaminant transport in the shafts and their associated EDZs is also diffusion dominated, with transport towards the Shallow Bedrock Groundwater Zone being against the very low advective groundwater velocities in the shafts at the top of the Ordovician. The primary pathway for any contamination reaching the shallow system is via the shafts and their EDZs rather than the geosphere, although the amounts are very low (Figure 6.13). Furthermore, certain elements will be retarded by sorption in the geosphere and shafts (see Appendix D of the Data report, QUINTESSA and GEOFIRMA 2011a). Transport of any contaminants reaching the Shallow Bedrock Groundwater Zone is advective towards Lake Huron with discharge to the biosphere in the near-shore region (Figure 6.2).

Colloids are not expected to be significant in the transport of contaminants through the geosphere for a number of reasons including: the high salinity conditions are expected to make colloids unstable and susceptible to agglomeration and dissolution; the small pore size and low permeability of the rocks and shaft seals is expected to prevent migration of colloids by filtering; and the transport of any colloids is expected to be a diffusion process which will occur at a slower rate than the diffusion of dissolved contaminants due to greater interaction with the shaft seals and rocks (see screening analysis for FEP 3.2.09 (Colloid-mediated migration of contaminants) in the FEPs report, QUINTESSA et al. 2011). Also, conservative values are adopted in this assessment for solubilities and sorption coefficients.



Note: Figure adapted from Figure 5.13 in GEOFIRMA (2011). MF = Mass Flux.[22]

Figure 6.13: Mass Transport Results for Cl-36 for the Reference Case Plus Instant Resaturation and Release (NE-RC-F3) from Detailed Groundwater Modelling

The Guelph and Salina A1 upper carbonate formations are more permeable than the surrounding formations in the Intermediate Bedrock Groundwater Zone (Section 2.3.6.2 of QUINTESSA 2011b). Some topographically driven flow occurs within these formations, but it is limited by the low hydraulic gradients under normal conditions. Under glacial conditions, there may be movement in these formations, although only the Salina A1 upper carbonate shows signs of glacial meltwater penetration at the DGR site.

However, any groundwater flow in these formations would divert contaminant transport from the shafts/EDZs laterally and reduce the amount of contamination migrating to the Shallow Bedrock Groundwater Zone above the repository. These horizontal flows would further provide dispersion, dilution and time for decay of contaminants. Therefore, horizontal groundwater flow in the Guelph and Salina A1 upper carbonate is ignored in the Reference Case. Even without flow, these formations provide a more porous and permeable path into which some of the contaminants that reach this level can diffuse (horizontally), especially free gas. (An alternative case with horizontal gradients is also evaluated.)

The low hydraulic gradient in the Cambrian will also limit migration of any contaminants that might have diffused down from the repository (Section 2.3.6.2 of QUINTESSA 2011b). Migration in the Cambrian will be further limited by the long distance to outcrop discharge points (in excess of 100 km).

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[22] The FRAC3DVS-OPG model assumes instantaneous resaturation of the repository and release of Cl-36 at closure. The time profiles should be seen as illustrative since the conceptual model for the assessment calculations assumes different resaturation and release profiles (see Sections 6.2.1.1 and 6.2.1.2, respectively). No line on chart indicates that the result is below 10^{-14} g/a throughout. See Figure 4.13 for geologic stratigraphy.

Certain contaminants (i.e., H-3, C-14, Cl-36, Se-79 and I-129) will be present in the **gas** phase in the repository and have the potential to migrate from the DGR via gas permeation in addition to dissolution into repository water (and subsequent transport in groundwater). Free gas tends to migrate vertically upwards from the repository, while dissolved gas migration follows the groundwater flow pathways for both advection and diffusion. The rate of gas permeation through the rock and shaft materials is a function of the gas pressure, the seal or rock threshold capillary pressure, and the permeability of the media under two-phase flow conditions. At the DGR site, the gas movement is impeded by the very low permeability limestone and shale horizons, the low-permeability shaft seals, and the Ordovician underpressures. Gas that permeates past these may then be diverted laterally into the more permeable Guelph or Salina A1 upper carbonate formations.

Results presented in Section 8.2 of the Gas Modelling report (GEOFIRMA and QUINTESSA 2011) indicate that free gas does not reach the Shallow Groundwater Bedrock Zone via the shafts and geosphere for any of the Normal Evolution Scenario calculation cases considered. The results also indicate that no dissolved gas reaches the Shallow Groundwater Bedrock Zone for the majority of cases (including the Reference Case). However, there are some variant cases for which dissolved gas, including that dissolved from free gas in the shafts, does reach the zone (Section 8.2, GEOFIRMA and QUINTESSA 2011). Depending on the case, gas reaching the shallow system dissolved in groundwater may be released as free gas due to the lower pressures in the shallow system; correspondingly, free gas reaching upper formations may dissolve into groundwater, and some may be swept up and dissolved into the flowing groundwater in the upper aquifer.

Under glacial conditions, the site characterization and regional modelling evidence indicates that transport in the deep geosphere remains diffusion controlled, as noted above. The main effect of the ice-sheet is to transiently increase and decrease the hydraulic pressures across the vertical cross-section at the DGR site. Therefore, for the postclosure safety assessment, the effects of ice-sheets on contaminant transport within the deep geosphere are expected to be small and are not explicitly modelled[23].

The effects of ice-sheet on contaminant transport within the shallow geosphere will be significant; however, there is very little contaminant release to this system. Since no continuous extended permafrost is anticipated at the DGR site (Section 5.2.3, System and Its Evolution report, QUINTESSA 2011b), the main effect of ice-sheets will be to increase or decrease the shallow geosphere flow rates, but in any event these are represented in the conceptual model (which uses current flow rates) as leading to rapid release to the nearby lake.

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[23] Also, since reversion towards glacial conditions is not likely for at least 60,000 a, most of the C-14 will have decayed. Since C-14 is the primary radionuclide in the gas phase, any effects on glaciation on gas movement will be less important as a release pathway.

6.2.1.3 Biosphere

Evolution of Biosphere Conditions

Climate change can have a major impact on the biosphere system through the modification of temperature, precipitation, biota, water bodies, sediment/soil, and human activities. As discussed in Section 5.1.2, a stylized climate sequence has been developed and is represented in Figure 5.2 and Figure 5.3. Rather than explicitly representing the sequence of climate states identified in Figure 5.2 and Figure 5.3, the conceptual model considers stylized, constant-climate conditions which are comparable with those found at present in the area surrounding the site (i.e., primarily agricultural and recreational).

In particular, it is assumed that the site is occupied by a self-sufficient farming family living directly above the repository and extracting well water for drinking, domestic water usage, and irrigation. This provides a useful indicator of potential impact even on long timescales, as this system is readily understandable because (1) it aligns with current conditions, (2) it allows agriculture, which tends to increase potential exposure, and (3) glacial cycles return periodically to temperate conditions. However, the potential impact of a tundra climate is also considered to illustrate the impact of a different climate condition and associated different human receptors and exposure pathways. Detailed modelling of the potential impacts of glaciation in a Canadian Shield setting indicate that assuming this type of conservative, stylized constant-climate receptor is a reasonable indicator for the effects of glacial cycles, considering the transient changes in lifestyles, water conditions and geosphere release rates in that hypothetical case study (Garisto et al. 2010).

Migration of Contaminants

The biosphere features into which contaminants may be released are (Figure 6.2):

- Soils irrigated by well water (pumped from the Shallow Bedrock Groundwater Zone) and used to grow crops and raise animals; and
- Lake water (contaminated by natural groundwater discharge from the Shallow Bedrock Groundwater Zone) which is used as a source of fish.

For any potential free gas releases, the biosphere features into which contaminants may be released are:

- A house conservatively assumed to be located above the main shaft; and
- Soil above the ventilation shaft and its EDZs, which is used to grow crops and raise animals.

Subsequent migration of any contaminants in the biosphere results in the contamination of additional media (Figure 6.14).

Humans are exposed due to the potential release of contaminants into the biosphere and their subsequent migration. Human exposure to the features in Figure 6.14 occurs by a variety of pathways, as illustrated in Figure 6.15. Contaminants in soil, water and the atmosphere are assimilated by plants and animals (that may in turn be ingested by humans) and expose humans by external irradiation. Inhalation exposure and external air irradiation occur if contaminants are volatilized and released from soil and water or if there is release of contaminated free gas to the atmosphere. The pathways modelled are consistent with recommendations of CSA N288.1 for biosphere modelling (CSA 2008b).

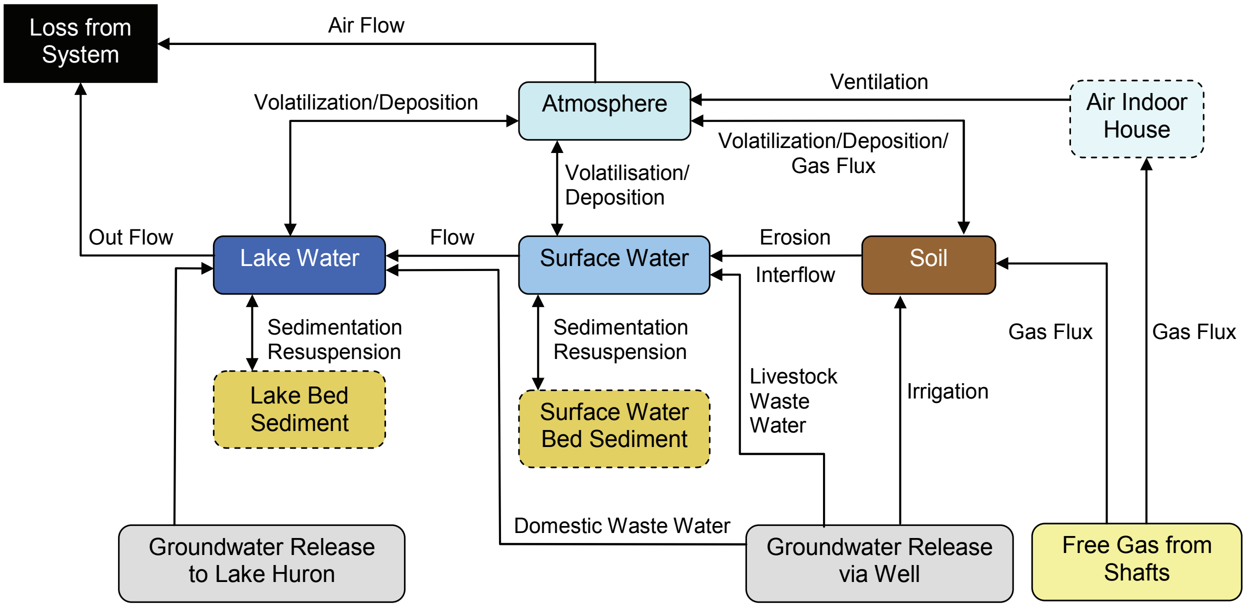

Figure 6.14: Conceptual Model for the Biosphere – Contaminant Migration Processes (Dotted Borders Indicate Equilibrium Compartments)

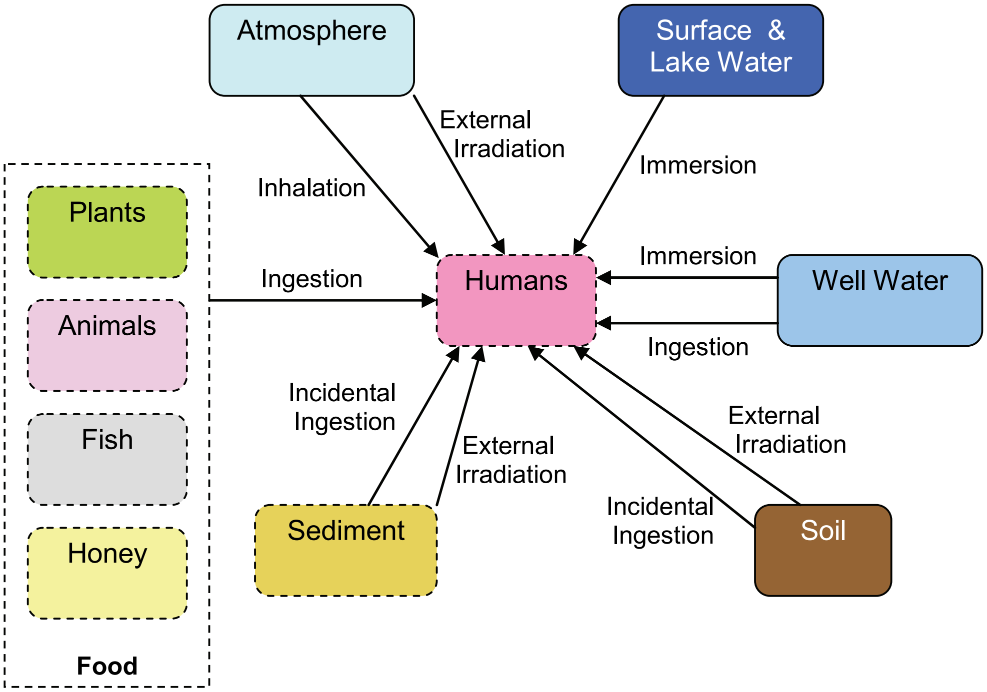

Figure 6.15: Conceptual Model for the Biosphere – Human Exposure Pathways (Dotted Borders Indicate Equilibrium Compartments)

In order to assess potential impacts, a hypothetical critical group (the “Site Resident” Group) is defined that is exposed, via the potential exposure pathways illustrated in Figure 6.15, to any repository-derived contaminants released from the geosphere. This conservatively-defined hypothetical family lives a self-sufficient lifestyle on a farm on the repository site. Their house is over the main shaft. They grow their own grain, fruit and vegetables from fields that are located above the repository, and in particular on the ventilation shaft. They pump water from a well drilled into the Shallow Bedrock Groundwater Zone at a location that maximizes capture of any contaminants released from the shafts, for drinking, domestic use, watering animals, and irrigating garden and feed crops. The family comprises two adults, a child and an infant. The livestock comprise dairy and beef cattle, pigs, lambs, goats and chickens. They hunt locally for deer and rabbits, catch fish from the stream and from Lake Huron, and consume local honey. They swim recreationally in the lake.

6.2.2 Human Intrusion Scenario

Table 6.2, Table 6.3, Figure 6.16, Figure 6.17 and Box 2 summarize the main aspects of the conceptual model for the Human Intrusion Scenario; a more detailed summary is given below based on the description given in the Disruptive Scenarios report (QUINTESSA and SENES 2011).

6.2.2.1 Borehole Characteristics

It is most likely that any borehole drilled at the site would be associated with oil and gas exploration, since similar sedimentary rocks hold oil and gas in other parts of southern Ontario, whereas these rocks do not contain minerals at depth in the region (see Section 2.3.5 of the System and Its Evolution report, QUINTESSA 2011b). It is also noted that an oil and gas borehole would have a larger diameter borehole than a mineral exploration borehole.

It is assumed that a borehole of 20.3 cm (8 inch) diameter penetrates the upper and intermediate formations (Shallow Bedrock Groundwater Zone and Intermediate Bedrock Groundwater Zone). It would be cased in the Shallow Bedrock Groundwater Zone (to protect the potable groundwater). Through the Ordovician shales and limestones (collectively termed the Deep Bedrock Groundwater Zone), a narrower diameter borehole is drilled (15.24 cm or 6 inch), consistent with typical drilling practice of reducing borehole diameter with depth.

Drilling would be expected to cease once the repository had been encountered, as the void would be registered by change in drill pressure. This anomaly would be investigated, the presence of the wastes likely realized, and the borehole then appropriately sealed. However, during the initial period, there could be some exposure of the drill crew or local residents. This is the Base Case for the Human Intrusion Scenario. However, it is possible, although unlikely, that the borehole could be continued to greater depth, reaching the Cambrian. If this was to occur and the borehole was then poorly sealed, there would be potential for groundwater flow upwards through the repository due to the high pressure in the Cambrian. This variant case is, therefore, also examined in the assessment.

Table 6.2: Exposure Situations for the Human Intrusion Scenario

Critical Group	Direct Release to Surface		Release to Shallow Bedrock Groundwater Zone
	Release Mechanism:		Release Mechanism:
	Gas	Drill Core	Groundwater
Drill crew at wellhead	✓		
Resident near to drill site	✓		
Laboratory technician		✓	
Future resident using contaminated soil		✓	
Future site resident using contaminated groundwater			✓

Table 6.3: Human Intrusion Scenario: Exposure Mechanisms and Key Characteristics

Critical Group				
Drill Crew	**Nearby Resident**	**Laboratory Technician**	**Future Resident Using Contaminated Soil**	**Future Site Resident Using Contaminated Groundwater**
• Incidental ingestion of soil • Inhalation of dust and gas • External irradiation from soil	• Inhalation of gas	• Incidental ingestion of surface contamination on core samples • Inhalation of dust • External irradiation from core samples	• Ingestion of plants, animal products, and soil • Inhalation of dust and volatilized contaminants • External irradiation from soil and dust	• Ingestion of water, plants, animal products, fish, honey, sediment, and soil • Inhalation of dust and volatilized contaminants • External irradiation from water, soil, sediment, and dust

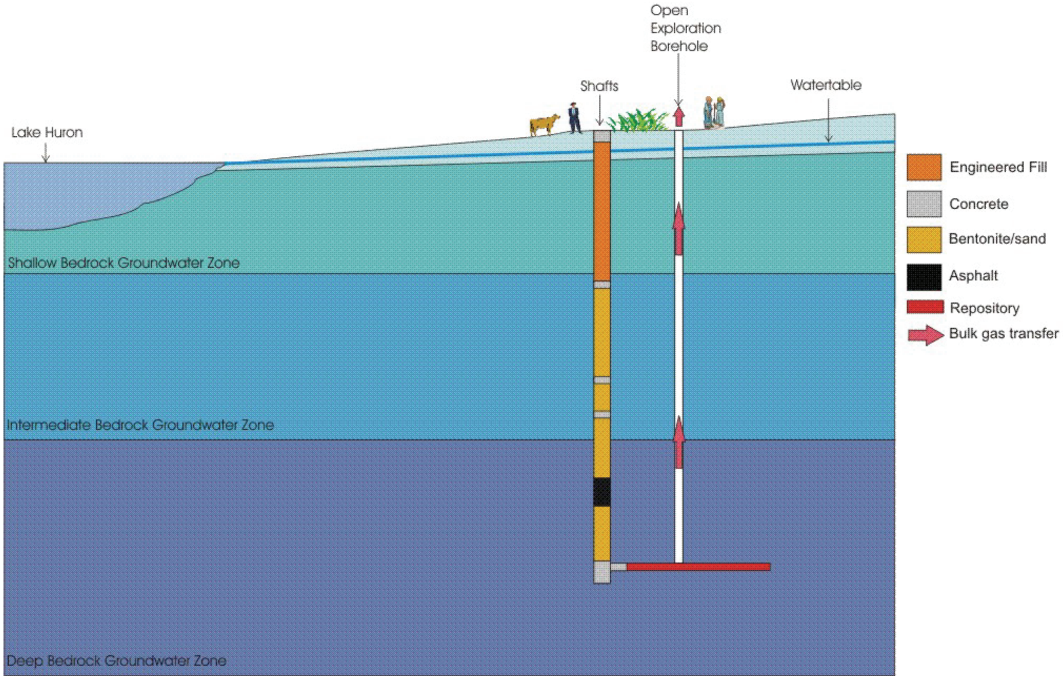

Figure 6.16: Human Intrusion Scenario: Schematic Representation of Short-term Gas Release

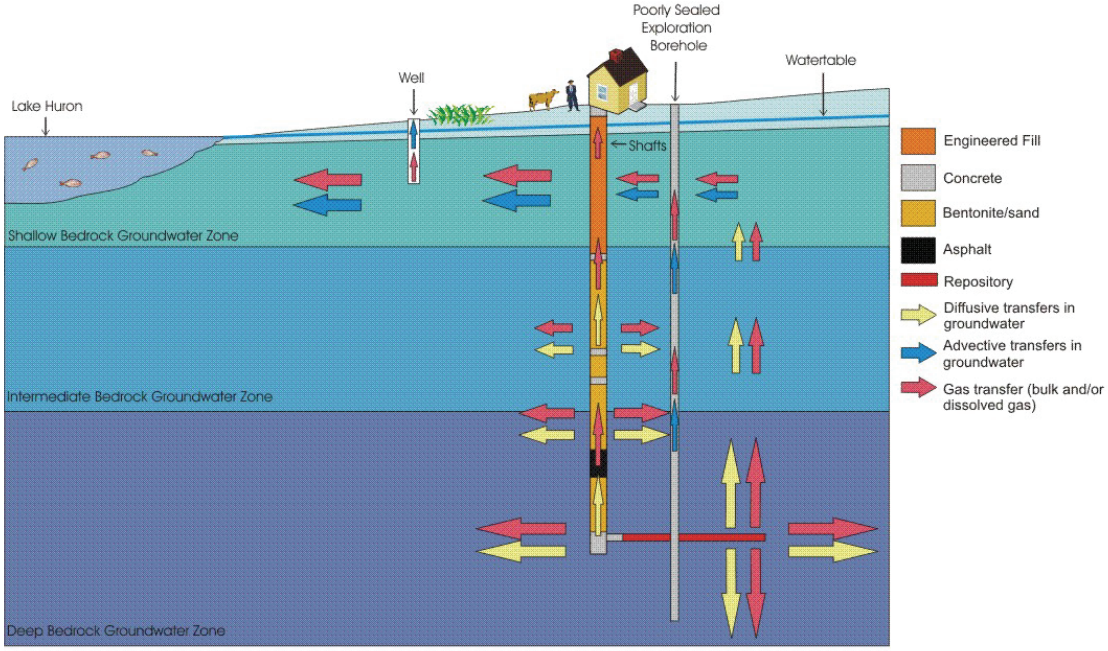

Figure 6.17: Human Intrusion Scenario: Schematic Representation of Long-term Groundwater Release

Box 2: Key Aspects of the Conceptual Model for the Human Intrusion Scenario

Gas Release:

- Intrusion via exploration borehole directly into an emplacement room in Panel 1 at some time after controls are no longer effective (i.e., after 300 years – Section 3.8).
- Resaturation profile prior to borehole intrusion consistent with the Normal Evolution Scenario (Section 6.2.1.1).
- Contaminants (H-3, C-14, Cl-36, Se-79, I-129 and Rn-222) released via borehole from repository into surface environment as gas (Section 6.2.2.2).
- Gas release via the borehole is limited by blowout preventers, as per normal practice in sedimentary rocks, but depressurization is allowed to occur (Section 6.2.2.2).
- Atmospheric dispersion of released gas (Section 6.2.2.4).
- Direct impacts on drill crew and nearby resident (100 m) considered (Section 6.2.2.4).

Drill Core Release:

- Intrusion via exploration borehole into an emplacement room in Panel 1 at some time after controls are no longer effective (i.e., after 300 years – Section 3.8).
- Retrieval of waste in drill core debris (Section 6.2.2.2) and subsequent spreading over the surface soil resulting in direct impacts on drill crew and future resident using the soil (see Section 6.2.2.4).
- Retrieval of a sample of waste in drill core (Section 6.2.2.2) and subsequent direct impacts on laboratory technician examining core (see Section 6.2.2.4).

Groundwater Release:

Consistent with the Normal Evolution Scenario (Box 1 and Section 6.2.1.1). In addition consider:

- Intrusion via exploration borehole into an emplacement room in Panel 1 at some time after controls are no longer effective (i.e., after 300 years – Section 3.8).
- Resaturation profile prior to borehole intrusion consistent with the Normal Evolution Scenario.
- The borehole is poorly sealed (seal has the properties of engineered fill) and the casing degrades allowing relatively rapid resaturation of the repository following borehole intrusion.
- If the repository pressurizes (i.e., the borehole penetrates down into the pressurized Cambrian Formation) (Section 6.2.2.3), then there will be a gradient causing contaminated groundwater flow from the repository via the borehole. The rate of release of groundwater into the Shallow Bedrock Groundwater Zone is based on detailed groundwater modelling[24].
- Impacts calculated for site resident group assumed living directly on site and pumping groundwater for domestic use and irrigation.

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[24] See Section 6.2 of the Groundwater Modelling Report (GEOFIRMA 2011).

6.2.2.2 Sources

The borehole could in principle penetrate any part of the repository with equal likelihood. For this analysis, calculations are made on the basis of the average concentrations of contaminants in gas, water and waste in Panel 1, which has the largest proportion of ILW (8 out of the 12 ILW emplacement rooms, see Table 4.7).

Concentrations of the contaminants in the repository will vary with time, as they will be dependent on radioactive decay, the rate of release of contaminants from the wastes, and the rate of migration of contaminants into rock and the shafts. For potentially gaseous contaminants, it will also depend on the partitioning of the element between water and gas.

The borehole provides a pathway for the release of any pressurized **gas** from the repository. Standard drilling techniques involve the use of blowout preventers during drilling, and, if at pressure, the combustible repository gases are assumed to be flared. Once the pressure between the repository and the surface had equilibrated, releases of gas would effectively cease (any ongoing gas generation would be at a very low rate). Various contaminants could be present in the gas released from the repository:

- H-3 gas can be liberated from tritiated water in waste and in H_2 generated during corrosion reactions;
- C-14 as CH_4 - detailed calculations show that more than 90% of C-14 is present in gas in this form (see Figure 5.12 of the Gas Modelling report, GEOFIRMA and QUINTESSA 2011);
- Cl-36, Se-79 and I-129 from methylation and volatilization; and
- Rn-222 ingrown from Ra-226.

Calculations for the Normal Evolution Scenario indicate that the repository will be almost completely unsaturated over the modelled period, reaching a peak of less than 1% for the Reference Case (Section 5.1.1.2 of the Gas Modelling report, GEOFIRMA and QUINTESSA 2011). Therefore, there would be no **water** released through the borehole. However, if a borehole was to penetrate down into the Cambrian and was not properly sealed on closure, then, in the long term, pressurized water from the Cambrian could continue to flow through the borehole, into the repository, and then up the borehole to the permeable formations in the Intermediate and Shallow Bedrock Groundwater Zones (see Section 6.2.1 of the Groundwater Modelling report, GEOFIRMA 2011).

Waste may be brought to the surface as **drill core** samples if the borehole accidentally cores through a waste package. It is expected that the drill core from the repository would be considered unusual, and sent to laboratory for analysis. Also, contaminated drill core and drilling mud could be brought to surface; it is assumed that this material is not properly disposed and just spread around the drill site. As the borehole could strike any part of the repository, the average concentration of contaminants in waste in Panel 1 is assumed to be present in the retrieved contaminated materials. In addition, consideration is given to intercepting specific waste categories.

6.2.2.3 Release Pathways

The borehole itself can be considered to be a “fast” pathway through the geosphere; that is, contaminants would be transported rapidly up the borehole in comparison with the timescales associated with other processes.

Two main points of release are assessed:

- Immediate release at the surface upon intrusion and shortly afterwards; and
- A variant case that considers the long-term slow release to the Shallow Bedrock Groundwater Zone.

For the surface release, the pathway can be represented as a transfer of gas and drill core directly from the repository to the surface environment where it may expose people, as well as entering the atmosphere, soil and food chain. This is referred to as the **Surface Release Pathway**. It has a relatively short duration, occurs at the time of intrusion, and is driven by the gas pressure in the repository.

In the longer term, if the borehole is conservatively taken to be poorly sealed, it provides an enhanced permeability pathway for release into the geosphere, conducting contaminants at a rate determined by the pressure difference between the point of release and the repository, and the effectiveness of the borehole sealing. Groundwater flow modelling (Section 6.1 and 6.2 of GEOFIRMA 2011) indicates that this would only occur if the borehole is continued down into the Cambrian. In this case, overpressured fluid from the Cambrian could flow up the borehole at a steady long-term rate limited by the borehole permeability.

The calculations show that contaminants would be released into the Salina A1 upper carbonate and Guelph formations, as well as the Shallow Bedrock Groundwater Zone. The assessment adopts conservative assumptions that (a) there is no dilution of contaminated water during its transit up the borehole, and (b) all the contaminated water is released into the Shallow Bedrock Groundwater Zone (closest to the surface).

The subsequent transport of contaminants in the Shallow Bedrock Groundwater Zone is by advection and dispersion in the relevant formations. A portion may be intercepted by a well, the remainder ultimately entering Lake Huron. This is referred to as the **Shallow Bedrock Groundwater Zone Release Pathway**. The conceptual model for this element of the transport pathway is consistent with the conceptual model used for the Shallow Bedrock Groundwater Zone for the Normal Evolution Scenario (Section 6.2.1.2).

6.2.2.4 Receptors for the Surface Release Pathway

In determining the relevant receptors for the Surface Release Pathway, it is necessary to consider the potential for different routes of exposure associated with the release of contaminants in gas and drill core.

Gas

The conceptual model for exposure following a gas release is shown in Figure 6.18. Two potential critical groups are assessed:

- Those directly exposed to gases close to the point of release (i.e., the drill crew); and
- Those exposed for a longer duration to the gas plume (e.g., a resident living nearby).

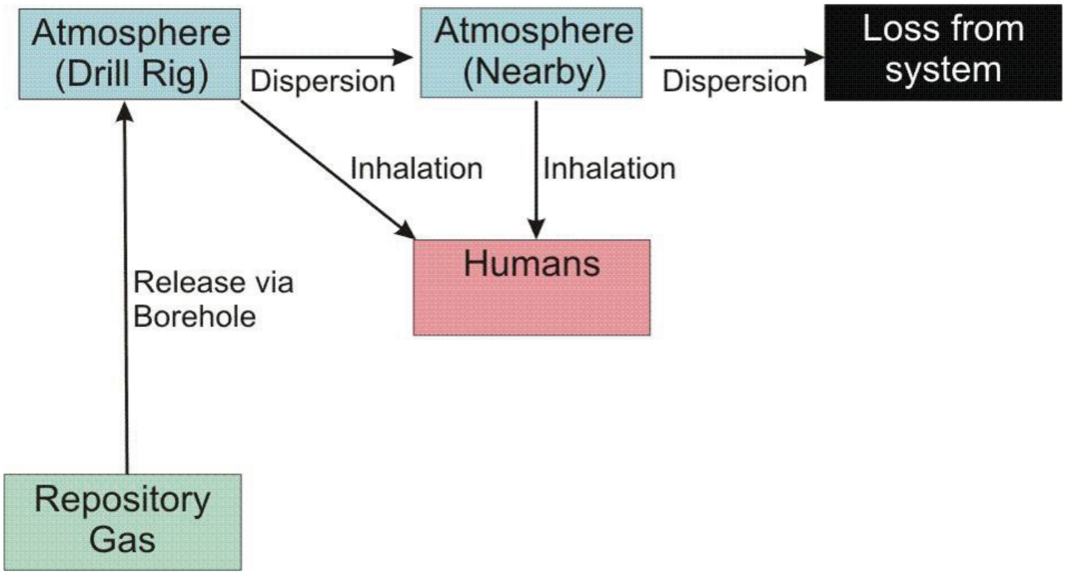

Figure 6.18: Human Intrusion Scenario: Conceptual Model for Gas Release

No precautions against inhalation of the gas when the borehole strikes the repository are included in the assessment of the **drill crew**, although borehole blowout controls are effective and limit the flux of gas. Typical working patterns are used to define the exposure duration and exposure conditions.

A **nearby resident** could also be exposed, but would live further from the borehole (as the drilling site would not permit dwellings). Potential exposure pathways associated with the uptake of contaminated gas by plants, and inhalation by animals, are expected to be of limited significance compared with the direct exposure of people by gas inhalation, and so are not assessed.

Drill Core Sample

While it is unlikely that an intact sample of waste could be retrieved via a borehole, a solid sample of some quality and integrity might be retrieved. In this context, the most relevant potential receptor is a **laboratory technician** due to the duration and proximity of the exposure resulting from examining a core sample containing waste. Irradiation from a small (several kg) sample of waste could occur when it is analyzed in the laboratory. Inadvertent ingestion (by contamination of the skin during handling) and inhalation (of dust generated when cutting the core into samples) may also expose the technician to the contaminants in the sample. The conceptual model is illustrated in Figure 6.19. Note that exposure via dermal absorption is expected to be minor for relevant radionuclides (only important for tritium, which will have decayed) and so excluded from the model.

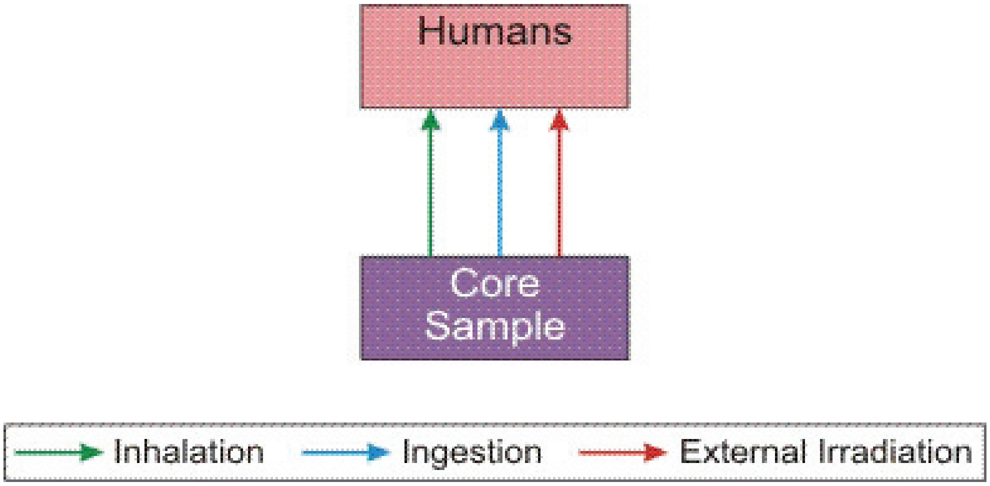

Figure 6.19: Human Intrusion Scenario: Conceptual Model for Exposure of the Laboratory Technician to Contaminated Drill Core Sample

Drill Core Debris Left on Site

Drill core debris extracted from the borehole would be collected and disposed of with other drilling wastes under current requirements. It is conservatively assumed, however, that this waste is spread over the surface at the drill site, resulting in the potential exposure of a drill crew (Figure 6.20) and a future resident (Figure 6.21).

Direct exposure of the **drill crew** can result from external irradiation, inhalation and inadvertent ingestion of contamination directly from the drill core debris. The crew could also be exposed by soil contaminated by the core material spread over the drill site. For the soil, relevant modes of exposure include external irradiation, inadvertent ingestion, and inhalation of suspended dust. Volatilization of contaminants is not expected to be a significant pathway for the drill crew, as the amount of volatiles will be small and exposure time is relatively short and so is not considered. Exposure via dermal absorption is also considered to be minor (mostly relevant for tritium, which would have decayed) and so is excluded from the model.

A **future resident** could use the contaminated drill site for farming after the borehole has been abandoned. The characteristics of the future resident are the same as defined for the Site Resident Group in the Normal Evolution Scenario (Section 6.2.1.3) but, due to the limited volume of extracted wastes and so the limited area of contamination, only the growing of fruit and vegetables on the site is considered (see Section 2.4.3.3 of the Analysis of Human Intrusion and Disruptive Events report, QUINTESSA and SENES 2011).

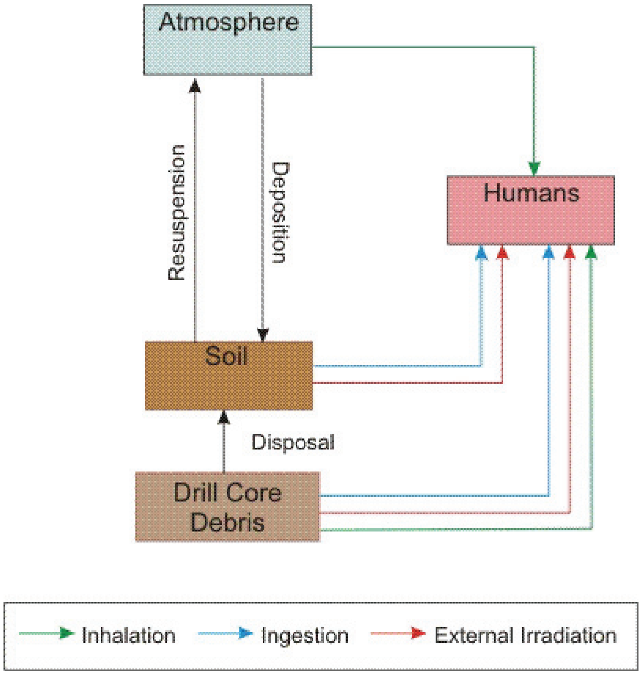

Figure 6.20: Human Intrusion Scenario: Conceptual Model for Exposure of the Drill Crew from Contaminated Drill Core Debris

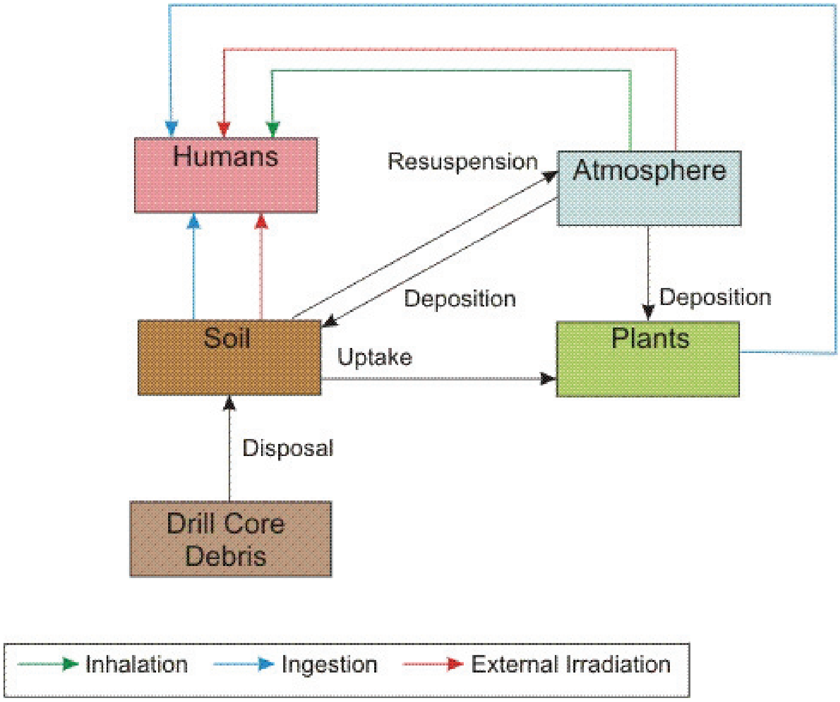

Figure 6.21: Human Intrusion Scenario: Conceptual Model for Exposure of the Future Resident to Soil Contaminated from Contaminated Drill Core Debris

6.2.2.5 Receptors for the Shallow Bedrock Groundwater Zone Release Pathway

Releases to the Shallow Bedrock Groundwater Zone would occur only if the borehole were continued down into the pressurized Cambrian Formation and was also poorly sealed. This case has conservatively been considered as a “what if” variant calculation.

The model assesses the effects of the release of contaminated groundwater from the borehole into the Shallow Bedrock Groundwater Zone, by considering exposure via a shallow well, and also to Lake Huron. It is, therefore, reasonable to adopt for this case the conceptual model of the biosphere and associated critical group as considered for the groundwater release in the Normal Evolution Scenario (Section 6.2.1.3).

6.2.3 Severe Shaft Seal Failure Scenario

The conceptual model is the same as for the Normal Evolution Scenario (Section 6.2.1), since the changes to the FEPs can be represented using modifications to parameter values. These changes are used to represent the significantly degraded physical and chemical characteristics of the concrete monoliths and shaft seals, and the increased permeability of the repository/shaft EDZs.

These differences result in increased flow of water down the shaft into the repository initially, and, later, contaminated water and gas up the shafts from the repository (see discussion in Section 3.2.2 of the Disruptive Scenarios report (QUINTESSA and SENES 2011).

The key transport pathways for releases from the repository are summarized in Figure 6.22.

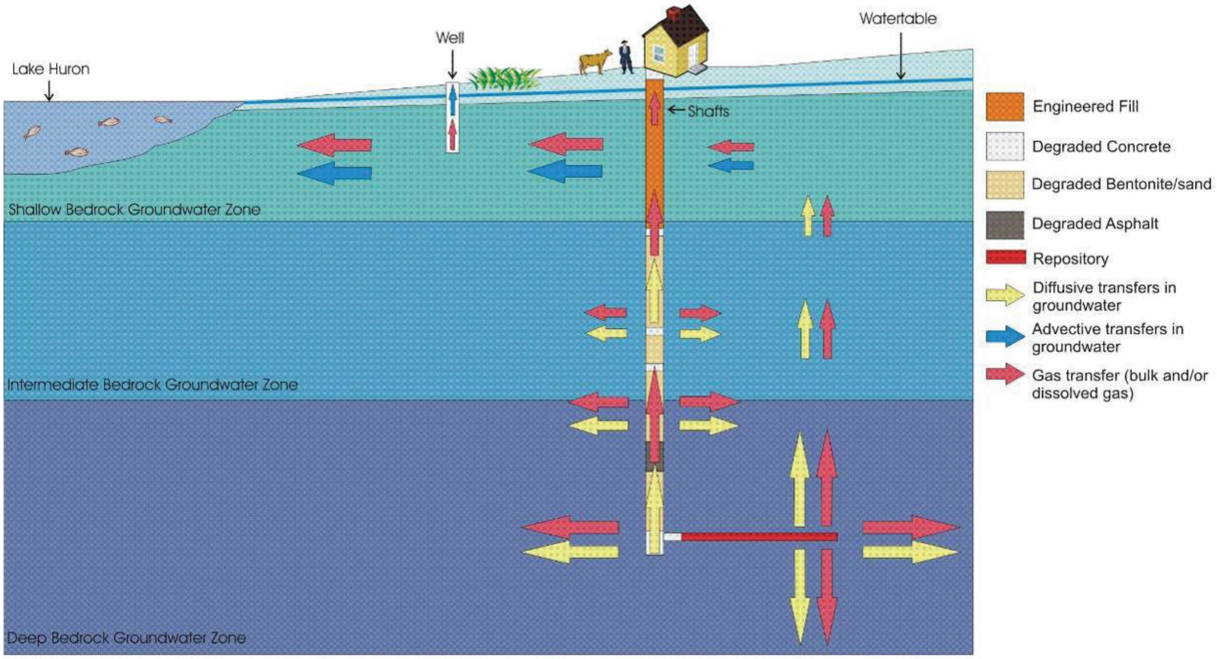

Figure 6.22: Schematic Representation of Potential Transport Pathways for the Severe Shaft Seal Failure Scenario

6.2.4 Poorly Sealed Borehole Scenario

The conceptual model is the same as for the Normal Evolution Scenario (Section 6.2.1) since the FEPs are broadly the same. The only difference is that, due to the poor sealing of the site investigation/monitoring borehole, there is an additional pathway for contaminants to migrate from the repository to the Shallow Bedrock Groundwater Zone - via the borehole. For quantitative estimate of potential impact, the DGR-2 borehole location is used, at 100 m east of Panel 2, as this is the closest borehole (Figure 5.4).

Groundwater flow modelling (Section 6.5.1, GEOFIRMA 2011) shows that the presence of the borehole does not perturb the regime in the vicinity of the repository to any notable degree. Flow rates from the repository horizontally towards the borehole are comparable to diffusion rates, and contaminants transported by the borehole have diffused through the rock prior to intercepting the conductive pathway. The conceptual model for contaminant transport, therefore, only considers a diffusive flux of contaminants from repository to the borehole.

The key transport pathways for releases from the repository are summarized in Figure 6.23.

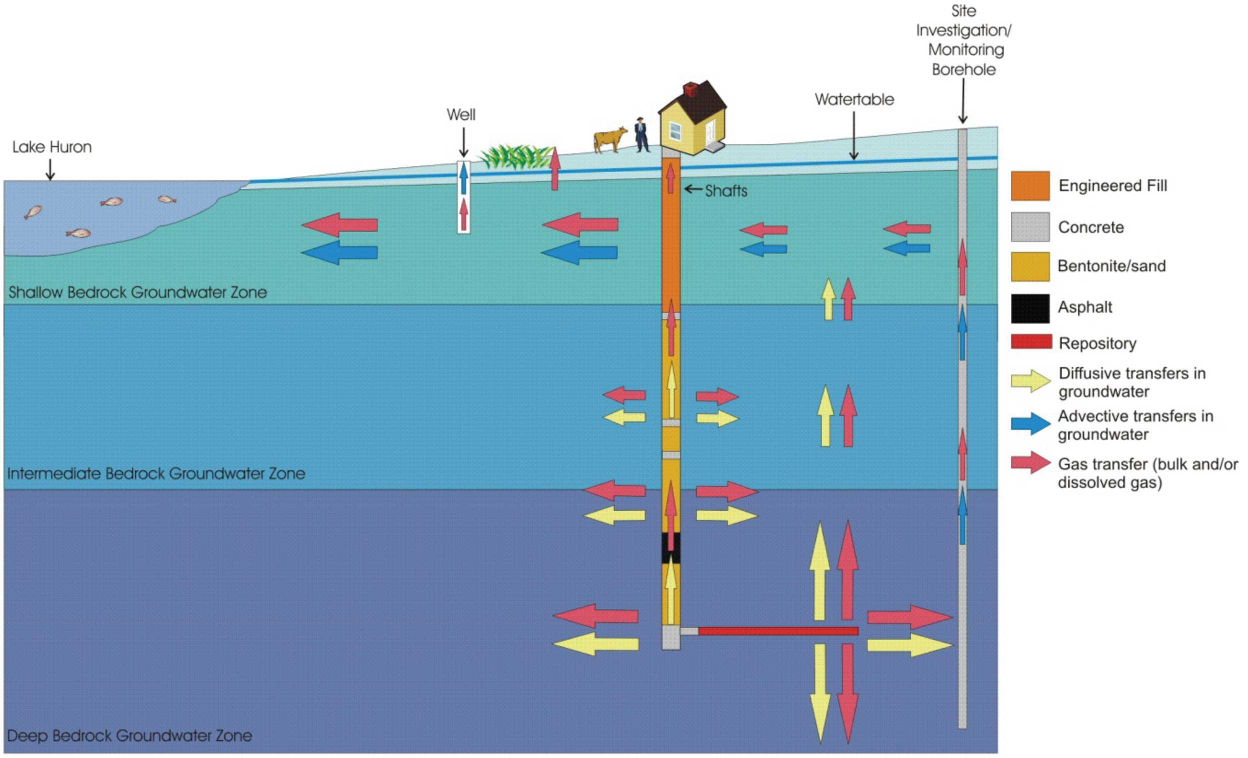

Figure 6.23: Schematic Representation of Potential Transport Pathways for the Poorly Sealed Borehole Scenario

6.2.5 Vertical Fault Scenario

The conceptual model is largely the same as for the Normal Evolution Scenario (Section 6.2.1), since the FEPs are broadly the same. The only difference is that there is a transmissive vertical fault connecting the Precambrian and Guelph formations and there is horizontal groundwater flow in the Cambrian, the Guelph and Salina A1 upper carbonate formations. The fault provides an additional pathway for contaminants to migrate vertically from the repository horizon into the overlying Guelph Formation. In this case, since losses to the Guelph formation may be important, the formation is conservatively assumed to connect to the near-shore lake bottom. The fault is taken to be 500 m to the northwest of the repository, i.e., beyond the area considered in the site investigation program (Figure 5.4). A transmissive vertical fault is also considered at 100 m southeast from the repository, i.e., within the site investigation program footprint (Figure 5.4). This is a variant case.

The fault extends from the Precambrian basement to the Guelph formation, but not into the Shallow Bedrock Groundwater Zone, consistent with the lack of site and regional evidence for such faults. Regionally, any such discontinuities are found to originate in the Precambrian or Cambrian and extend up to the Ordovician shales where they terminate (Armstrong and Carter 2010).

The key transport pathways for releases from the repository are summarized in Figure 6.24. In the conceptual model, the overpressurized Cambrian is assumed to be unaffected, despite being connected by a permeable path to the lower head and permeable Guelph Formation.

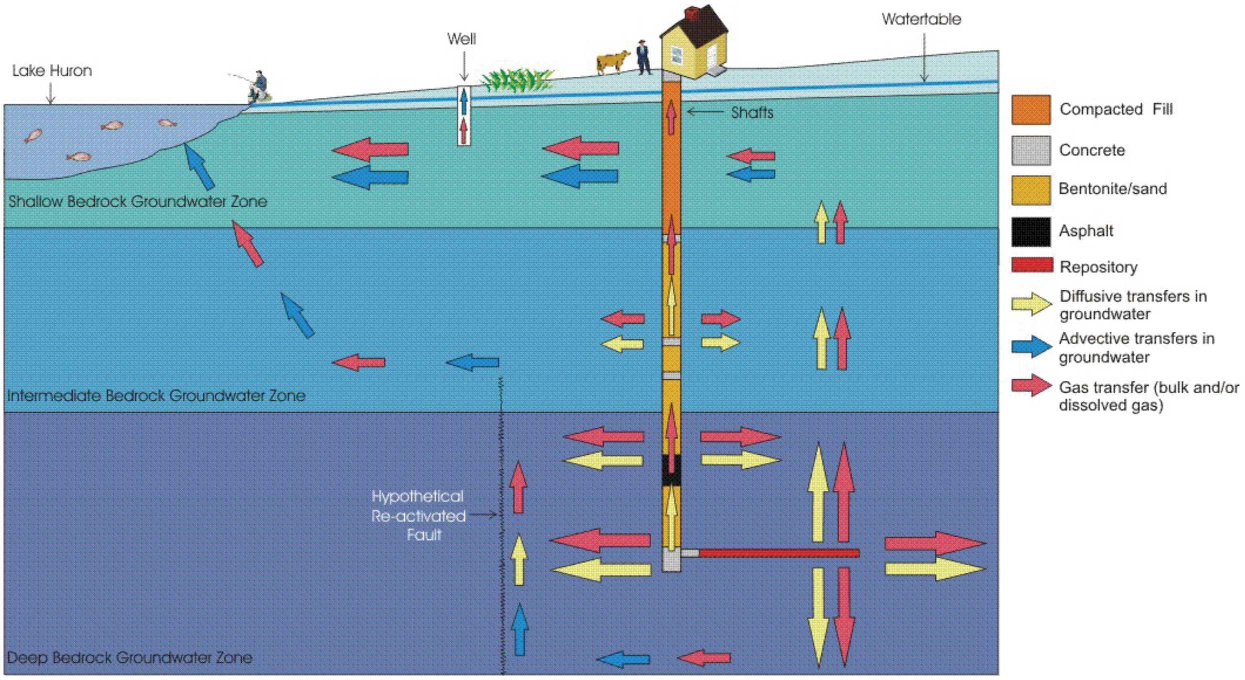

Figure 6.24: Schematic Representation of Potential Transport Pathways for the Vertical Fault Scenario

6.3 Calculation Cases

The treatment of uncertainties is central to any assessment of the safety of a radioactive waste repository. Uncertainties can be accounted for using various strategies (Section 3.6) including the evaluation of an appropriate range of calculation cases with the aim of demonstrating that the DGR system is robust to the uncertainties and that the range of cases bounds the uncertainties. In this section, each of the key uncertainties associated with the current assessment is summarized and the calculation cases that have been used to evaluate the impacts of the uncertainties are presented. As noted in Section 3.6, three broad uncertainties categories can be used to help structure the analysis and presentation of uncertainties, i.e., scenario, model, and data uncertainty.

The uncertainty associated with the future evolution of the system (**scenario uncertainty**) is addressed through considering a range of scenarios (Chapter 5). So in addition to the Normal Evolution Scenario, the impacts of four disruptive scenarios are assessed:

- Human Intrusion - inadvertent intrusion into the DGR via an exploration borehole;
- Severe Shaft Seal Failure - poorly constructed or substantially degraded shaft seals;
- Poorly Sealed Borehole - poorly sealed site investigation/monitoring borehole in close proximity to the DGR; and
- Vertical Fault - transmissive vertical fault in close proximity to the DGR.

For each scenario, there is a calculation case which acts as a benchmark against which relevant acceptance criteria can be compared and against which the variant calculation cases undertaken to investigate model and data uncertainties can be compared (Table 6.4). For the Normal Evolution Scenario, the benchmark case is termed the “Reference Case”; for each Disruptive Scenario the benchmark case is termed the “Base Case” (to avoid ambiguity with the Normal Evolution Scenario Reference Case).

Table 6.4: Reference/Base Cases for the Scenarios Evaluated

Scenario	Description*
Normal Evolution	Reference Case (**NE-RC** for radionuclides and **NE-NR** for non-radioactive elements and chemical species) parameters based on inventory, design and site characterization data summarized in Chapter 4. Assume steady-state Cambrian overpressure (+165m), 10 m rockfall from closure, initial Ordovician underpressures allowed to equilibrate, no salinity gradient, no surface erosion, and no horizontal gradients applied to any formations. Gas modelling case based on gradual repository (including shaft) resaturation, gas generation and partial gas saturations of 10% in Ordovician. Groundwater modelling case based on instant repository (including shaft) resaturation, and no gas generation or gas flow to minimize potential impact of groundwater pathway.
Human Intrusion	Based on Normal Evolution Reference Case but with an exploration borehole drilled down into the unsaturated repository (**HI-BC** for radionuclides **and HI-NR** for non-radioactive elements and chemical species).
Severe Shaft Seal Failure	Based on Normal Evolution Reference Case but with hydraulic properties of all shaft seals and repository/shaft EDZs set to significantly degraded values from repository closure (e.g., hydraulic conductivity of 10^{-9} m/s for the seals – an order of magnitude higher than the maximum value given in NWMO 2010d) (**SF-BC** for radionuclides and **SF-NR** for non-radioactive elements and chemical species).

Poorly Sealed Borehole	Based on Normal Evolution Reference Case but with a poorly sealed site investigation/monitoring borehole extending from the surface to the Precambrian and located 100 m to the south east of Panel 2 (i.e., DGR-2) (**BH-BC** for radionuclides and **BH-NR** for non-radioactive elements and chemical species).
Vertical Fault	Based on Normal Evolution Reference Case but with single 1 m wide, transmissive vertical fault located 500 m northwest of the repository, connecting the Precambrian and Guelph (**VF-BC** for radionuclides and **VF-NR** for non-radioactive elements and chemical species).

Notes: * See Table 7.1 for explanation of the ID scheme used for the calculation cases.

Model uncertainty encompasses uncertainties in the conceptual, mathematical and computer models used to simulate the behaviour of the repository system. The uncertainties in the conceptual models summarized in Section 6.2 are identified and discussed in the reports describing the analysis of the Normal Evolution Scenario (QUINTESSA 2011a) and the Disruptive Scenarios (QUINTESSA and SENES 2011). These uncertainties, together with the variant calculation case used to investigate their impact on the safety of the DGR, are summarized in Table 6.5. In addition, a number of variant calculation cases have been developed specifically to evaluate uncertainties arising from simplifications introduced into the mathematical and computer models used in the assessment (Table 6.6).

There are uncertainties associated with the parameter values selected for use in the computer models used to evaluate the safety of the DGR. Key areas of **data uncertainty** highlighted in the Normal Evolution and Disruptive Scenarios reports (QUINTESSA 2011a; QUINTESSA and SENES 2011) and the Data report (QUINTESSA and GEOFIRMA 2011a) are summarized in Table 6.7 and their associated variant calculation cases identified. The parameter values used for the variant calculations are documented and justified in the associated modelling reports (QUINTESSA 2011a, QUINTESSA and SENES 2011, GEOFIRMA 2011, and GEOFIRMA and QUINTESSA 2011).

Most of the uncertainties are addressed through deterministic calculations. This provides very clear information on the influence of the varied process or parameter. The disadvantage is that these are not able to provide a complete coverage of the parameter space. Some probabilistic modelling is, therefore, included, but it is focussed on contaminant transport parameters around the NE-RC reference case. Cases with significantly different groundwater flow or gas flow are only considered within the deterministic set.

Table 6.5: Conceptual Model Uncertainties

Source of Uncertainty	**Brief Description**	**Variant Calculation Cases***
Waste		
Contaminant release rate	While broad assumptions concerning contaminant release can be derived consistent with the resaturation profile and chemical and physcial conditions in the DGR, there remain uncertainties with DGR conditions (see below) and with the nature of the release mechanisms themselves (Section 6.2.1.1). In the Reference Case, a conservative instant release model for releases to water is applied for the majority of waste categories; although a congruent release model is used for certain categories (Table 6.1).	Variant case with instant resaturation of repository and instant release of contaminants to water for all waste categories under transient (**NE-RT1**) and steady-state groundwater flow conditions (**NE-RT2**).
Repository		
Repository design	The repository design described in Chapter 6 of the PSR (OPG 2011b) is considered in the current assessment (Section 4.2). The design will be subject to further review and optimization before the detailed design is prepared and the DGR constructed.	Variant cases with alternative design features, i.e., backfilling of room and tunnels (**NE-BF**), keying of seals into damaged zone (**NE-EDZ2**), and no asphalt in shaft seals (**NE-GT4, NE-GT5**).
Availability of water	Corrosion and degradation reactions are dependent on the availability of water in the repository (see Chapter 4, T2GGM software documentation, QUINTESSA and GEOFIRMA 2011b). There is uncertainty relating to the availability of water in the repository. The Reference Case conservatively assumes that water is not consumed within repository by corrosion and degradation reactions, which increases the amount of water available.	Alternative water-limited (**WL**) cases are considered in which the full water mass balance is included, including loss through corrosion and degradation reactions.
Repository resaturation	The rate of repository resaturation is influenced by the evolution of repository gas pressure and porewater conditions which in turn are subject to uncertainties. The resaturation profile for the Reference Case is informed by coupled gas and groundwater modelling (Section 6.2.1.1).	Variant case with instant repository resaturation at closure and no gas generation (**NE-RS** for Normal Evolution Scenario). Additional cases consider repository resaturation with no gas generation under transient (**NE-NG1**) and steady-state (**NE-NG2**) pressure conditions.

Source of Uncertainty	Brief Description	Variant Calculation Cases*
Repository chemistry	Chemical conditions evolve with time as materials degrade and interact with the local saline porewater. While the main processes of interest are evaluated (Section 6.2.1.1), uncertainties remain relating to the detailed evolution of chemical conditions.	Variant case with instant release of contaminants from DGR (i.e., no attenuation of contaminants in repository) (**NE-RT1, NE-RT2**) and no methane-generating microbial activity (**NE-NM**). Also, cases with higher (**NE-GG1**) and lower organic degradation rates (**NE-GG2**).
Rockfall	Geomechanical modelling indicates that, after three to four cycles of ice-sheet loading and unloading, a rockfall zone would propagate about 10 m into the repository roof (Section 6.2.1.1). However, there are uncertainties over the timing, extent and impact of rockfall in the repository.	In all calculation cases rockfall is assumed to occur at closure, affect all tunnels and rooms, damage waste packages and remove 10 m of geosphere barrier.
	Geosphere	
Over and underpressures	The over- and underpressure in the Cambrian and Ordovician affects the rates of repository resaturation and gas generation. The reference model is that these over- and underpressures are ancient, are not of ice-sheet origin and will equilibrate gradually (Section 4.3.3 and 6.2.1.2). The Reference Case includes transient evolution of the underpressures, but fixed Cambrian overpressure.	Variant case with Cambrian overpressure maintained indefinitely and Ordovician underpressure immediately dissipated (**NE-SBC**).
Gradients in Guelph & Salina A1 upper carbonate	The permeable Guelph and Salina A1 upper carbonate formations might act as preferential horizontal pathways for contaminant transport in groundwater resulting in reduced contaminant releases to the biosphere (Section 6.2.1.2). The reference model conservatively assumes no gradient in these formations and so maximizes vertical transport into the local biosphere above the DGR.	Variant case with horizontal groundwater flow in Guelph & Salina A1 upper carbonate resulting in discharge to the near-shore region of Lake Huron (**NE-HG**).
	Biosphere	
Glaciation	Glacial cycles are assumed to eventually occur, although not for at least 60,000 a. These would have a profound effect on the biosphere and human lifestyles. (Section 6.2.1.2). However, the Reference Case assumes that current temperate climate conditions continue (Section 6.2.1.3). This stylized approach provides a measure of impacts that can be easily compared with what would be currently acceptable.	Variant cases with different biosphere state (i.e., tundra rather than temperate) (**NE-CC**) and removal of 100 m of geosphere due to surface erosion (**NE-ER**).

Source of Uncertainty	Brief Description	Variant Calculation Cases*
Geosphere-biosphere interface	The Reference Case considers the pumping of groundwater from the Shallow Bedrock Groundwater Zone via a well and the discharge of groundwater from the Shallow Bedrock Groundwater Zone into the near shore of the lake (Section 6.2.1.3).	Variant case with discharge of groundwater from the Shallow Bedrock Groundwater Zone into a stream rather than into the lake (**NE-CC**)
Critical group	The Reference Case considers a self-sufficient farming family living in the vicinity of the DGR (Section 6.2.1.3).	Variant case with a Site Shore Resident Group and a Downstream Resident Group exposed via consumption of lake fish and water from the near shore and South Basin of Lake Huron, respectively (**NE-CG**).
Human actions	The potential impact of future human actions on the DGR is evaluated in the Human Intrusion Scenario. The Base Case assumes an exploration borehole is drilled down into the repository and subsequently sealed (Section 6.2.2.1).	Variant cases with borehole poorly sealed (**HI-GR1**) and borehole penetrating down to overpressurized Cambrian and being poorly sealed (**HI-GR2**).

Notes: * See Table 7.1 for explanation of the ID scheme used for the calculation cases.

Table 6.6: Mathematical and Computer Model Uncertainties

Source of Uncertainty	Brief Description	Variant Calculation Cases*
Representation of salinity profiles	Most cases ignore the salinity profiles at the Bruce nuclear site since it simplifies the modelling approach (e.g., it allows use of steady-state models) and in general is conservative. The effect of salinity gradients is partially included in transient calculation cases as initial head profiles are based on environmental heads which are compensated for fluid density.	Variant case with explicit representation of saline fluid density effects (**NE-SE**).
Gas characteristics	All cases assume a single gas as the bulk gas transported through the geosphere. Most cases assumed CH_4 since gas generation modelling indicated that this is the dominant gas (Figure 6.5).	Variant cases with air (**NE-MG**) and H_2 (**NE-NM**).

Notes: * See Table 7.1 for explanation of the ID scheme used for the calculation cases.

Table 6.7: Data Uncertainties

Source of Uncertainty	Brief Description	Variant Calculation Cases*
Waste		
Contaminant concentrations in wastes	As noted in Section 4.1.6, concentrations of contaminants are subject to a degree of uncertainty as they are based on waste-type-specific sampling and scaling factors, rather than direct measurement of each waste package. The Reference Case adopts an inventory derived from the Reference L&ILW Inventory report (OPG 2010) (Table 4.4).	Variant case with radionuclide inventory increased by an order of magnitude (**NE-IV**).
Waste package characteristics	As noted in Section 4.1.2, OPG's waste packages are mostly well defined and reference assumptions based on information in the Reference L&ILW Inventory report (OPG 2010) have been adopted.	Variant case with increased use of overpacks resulting in an approximate 25% increase in the inventory of metals (**NE-GG1**).
Waste corrosion & degradation rates	Metal corrosion and organic degradation rates are affected by the hydraulic, chemical, physical and biological evolution of the repository and the characteristics of the waste packages. There is uncertainty associated with these rates (see Section 3.6.5.1 and 3.6.6.1 of the Data report, QUINTESSA and GEOFIRMA 2011a).	Variant cases with up to an order of magnitude increase in corrosion and degradation rates (**NE-GG1**), and up to an order of magnitude reduction in degradation rates (**NE-GG2**) (i.e., maximum and minimum values given in the Data report, QUINTESSA and GEOFIRMA 2011a). The variant case with instant contaminant release to water for all waste categories (**NE-RT1** and **NE-RT2**) acts as a bounding case.
Repository		
Shaft seal performance	The shaft seals are made from durable materials. Some degradation of the seals is expected and has been incorporated into the Normal Evolution Scenario (Section 4.5 of the System and Its Evolution report, QUINTESSA 2011b). The reference hydraulic conductivity values have been taken from the upper end of the ranges derived from the literature cited in Section 4.5 of the Data report (QUINTESSA and GEOFIRMA 2011a)	Significant/extreme degradation resulting in two or more orders of magnitude increase in the Reference Case hydraulic conductivities is addressed in the Severe Shaft Seal Failure Scenario (**SF-BC** and **SF-ED** for radionuclides, and **SF-NR** for non-radioactive elements and chemical species). Also consider an order of magnitude increase in bentonite-sand hydraulic conductivity and the replacement of the asphalt seal with bentonite-sand (**NE-GT5**).

Source of Uncertainty	Brief Description	Variant Calculation Cases*
Geosphere		
Damaged zone properties	The reference EDZ properties used in the current assessment are based on literature review and geomechanical modelling (Sections 3.4, 6.3, and 6.4 of the Geosynthesis report, NWMO 2011a). The EDZ extends a full shaft-radius thickness around each shaft. No credit is taken for self-sealing over time.	Variant case with increased hydraulic conductivity for shaft and repository damaged zones by up to three orders of magnitude (**NE-EDZ1**) (i.e., maximum values given in the Data report, QUINTESSA and GEOFIRMA 2011a).
Free gas phase in rock	Site characterization data suggest that there is some gas in the rock mass in the Ordovician. However, quantification of gas saturations is uncertain, as the permeability and porosity of the rock mass are at the threshold at which measurements can be made. A reference value of 10% initial gas saturations is adopted.	Variant cases with different amounts of initial gas within the rock. 5% is used for **NE-RC1** and formation specific values taken from GEOFIRMA (2011) for **NE-RC2**.
Gas transport parameters	As noted in Sections 4.7 and 5.6 of the Data report (QUINTESSA and GEOFIRMA 2011a), the gas transport parameters in the shaft seals and rock (in particular capillary pressure and relative permeability) are uncertain. A reference set of values has been adopted (see Section 4.2 of the Gas Modelling report, GEOFIRMA and QUINTESSA 2011).	Variant cases with different shaft seal gas transport parameters (**NE-GT4** and **NE-GT5**) and different rock gas transport parameters (**NE-GT1**, **NE-GT2** and **NE-GT3**)
Retardation of contaminants	There are no sorption data measured specifically for rock, shaft seal and groundwater conditions at the Bruce nuclear site. Conservative (i.e., lower than likely) sorption values have been specified for certain elements in light of a literature review (Appendix D of the Data report, QUINTESSA and GEOFIRMA 2011a).	Variant cases with no retardation of contaminants in the geosphere and shafts (**NE-RT1** and **NE-RT2**).
Anisotropies	Vertical hydraulic conductivity and effective diffusion coefficients have not been measured but are inferred from horizontal measurements. Reference values (typically 10:1 and 2:1, horizontal:vertical) are adopted for hydraulic conductivity and effective diffusion coefficients, respectively.	Variant cases with reduced anisotropies for hydraulic conductivity (typically 2:1) (**NE-AN1**) and increased anisotropies for effective diffusion coefficients (typically 10:1) (**NE-AN2**).
Hypothetical fault location	To demonstrate the robustness of the DGR, it is useful to consider an alternative location for the hypothetical fault to the one considered in the Vertical Fault Scenario's Base Case.	Variant case with fault 100 m to the southeast of the DGR (**VF-AL**)

Source of Uncertainty	Brief Description	Variant Calculation Cases*
Waste, Repository, Geosphere and Biosphere		
Various	Reference Case and variant cases are deterministic. Uncertainties can be further investigated through probabilistic calculations (Section 3.6.1).	Probabilistic case with sampling of key parameters identified through deterministic calculations (**NE-PC**)

Notes: * See Table 7.1 for explanation of the ID scheme used for the calculation cases.

6.4 Mathematical Models and Software Implementation

The mathematical modelling approach used in the assessment is based on the use of an assessment-level (system) model incorporating all key processes relevant to contaminant release, transport and impact, supported by detailed models for the groundwater flow and transport, and gas generation and transport processes (see Figure 6.25). The development of the mathematical models and their implementation has been undertaken under the project's quality plan (QUINTESSA 2010) and Quintessa's quality management system, which has been certified against the requirement of ISO 9001:2008.

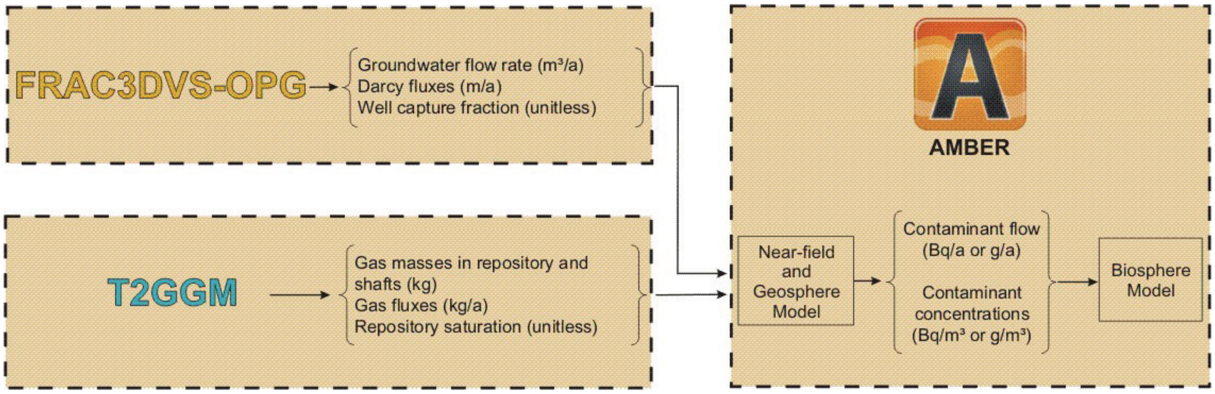

Figure 6.25: Information Flow between the Detailed Groundwater (FRAC3DVS-OPG) and Gas (T2GGM) Codes and the Assessment Model (AMBER)

The assessment-level model is implemented in AMBER 5.3 (QUINTESSA 2009a). This computer code represents contaminant transport within a compartment model approach. AMBER has been used in postclosure safety assessments of deep geologic repositories for radioactive waste in a 'total systems' manner, including the previous safety assessment calculations (QUINTESSA et al. 2009). A brief overview of AMBER, including its quality assurance status, is provided in Appendix A.1.

The specific mathematical formulae used to represent the various release, migration and exposure mechanisms identified in the conceptual models are documented in the Normal Evolution and Disruptive Scenarios reports (QUINTESSA 2011a, QUINTESSA and SENES 2011). These have been implemented in four AMBER cases (which have been audited against the specified mathematical model and data):

- A case file for the repository, shafts and geosphere model – AMBER_V2_NF&GEOv1.cse;
- A case file for the biosphere model – AMBER_V2_BIOv1.cse; and
- Variants of these two case files (AMBER_V2_NF&GEO_NRv1.cse and AMBER_V2_BIO_NRv1.cse) in which the radionuclides are replaced with non-radioactive contaminants.

The AMBER case files have been developed to represent contaminant movement. AMBER does not readily allow the use of the many small compartments that are needed for detailed water or gas flow modelling. This limitation has been overcome through the use of supporting detailed codes that explicitly solve such problems, with the results then being incorporated as input to the AMBER case files. Two such detailed codes have been used in the current assessment – FRAC3DVS-OPG and T2GGM. The incorporation of their results into AMBER is described in the Appendix J of the Analysis of the Normal Evolution Scenario report (QUINTESSA 2011a).

FRAC3DVS-OPG is a three-dimensional (3-D) finite-element/finite-difference groundwater flow and contaminant transport code. FRAC3DVS-OPG can support both equivalent-porous-medium and dual-porosity representations of geologic media. The code has been used extensively on behalf of OPG and NWMO for regional groundwater flow studies, and for near-field and far-field modelling in support of the Third Case Study for a hypothetical deep geologic repository for spent fuel. A brief overview of FRAC3DVS-OPG, including its quality assurance status, is provided in Appendix A.2 and its application to the current assessment and the associated calculation cases are described in the Groundwater Modelling report (GEOFIRMA 2011). A simplified 3-D (3DS) model of the Deep and Intermediate Bedrock Groundwater Zones has been implemented in FRAC3DVS-OPG to evaluate groundwater flow and transport. A separate three-dimensional model of the Shallow Bedrock Groundwater Zone has also been implemented (the 3DSU model) to evaluate flow and transport from the shafts to the well and lake (see Section 4.2 of GEOFIRMA 2011).

T2GGM is a code that couples the Gas Generation Model (GGM) and TOUGH2 (QUINTESSA and GEOFIRMA 2011b). GGM, a project-specific code, models the detailed generation of gas within the DGR due to corrosion and microbial degradation of the metals and organics present, and TOUGH2 models the subsequent two-phase transport of the gas through the repository and geosphere. The coupling of GGM and TOUGH2 allows the interactions between gas generation/pressure and water saturation in the repository to be represented explicitly. A brief overview of T2GGM, including its quality assurance status, is provided in Appendix A.3 and its application to the current assessment and the associated calculation cases are described in the Gas Modelling report (GEOFIRMA and QUINTESSA 2011). Four different but complimentary models of the DGR system have been implemented (see Section 4.3 of GEOFIRMA and QUINTESSA 2011).

- A detailed three dimensional geometry of the repository, the shafts and the surrounding geosphere (the 3DD model).
- A simplified three-dimensional representation of the repository and the surrounding geosphere that includes the shafts and associated EDZ (the 3DSRS model).
- A simplified three-dimensional representation of the repository and the surrounding geosphere that does not include the shafts (the 3DSR model).
- A two-dimensional vertical and radial representation of the shaft systems that connect the repository to the Shallow Bedrock Groundwater Zone (the 2DRS model).

The use of these different modelling codes allows the uncertainties associated with the use of mathematical and computer models to represent the repository system to be evaluated.

6.5 Data

The data used for the Reference Case are summarized in Table 6.8[25]. Further data are provided in the Data report (QUINTESSA and GEOFIRMA 2011a), together with details of the derivation of the data.

The host rock hydraulic conductivity is very low, as demonstrated by various analyses in Section 4.3.3. The EDZ around the shaft is modelled as one-shaft-radius-thick, based on the maximum extent calculated in geomechanical modelling at a particular rock formation (Section 6.4 of the Geosynthesis report, NWMO 2011a), but conservatively assumed to apply to the entire shaft. The properties will vary across this thickness; they are modelled as an inner and outer EDZ region. In the reference case, the effective vertical hydraulic conductivity of the inner EDZ is set to 100 times the host rock hydraulic conductivity across the shaft height, and the outer EDZ is set to 10 times the host rock hydraulic conductivity. This is based on experience with EDZ in underground laboratories in other sedimentary rocks, and considering the rock properties, horizontal bedding plane direction and stress conditions at the DGR site (Section 6.4 of Geosynthesis report, NWMO 2011a). (The uncertainty is considered in a variant case where higher values are adopted.)

The reference shaft seal concept is based on a combination of low-permeable bentonite/sand, concrete and asphalt (Section 4.2.3.2). The primary seal is a 70/30 wt% bentonite/sand mixture. For compacted in-situ material, a reasonable target is a dry density of 1600 kg/m^3, which corresponds to an Equivalent Montmorillonite Dry Density (EMDD) of around 1215 kg/m^3 (Section 4.3.2 of the Data report, QUINTESSA and GEOFIRMA 2011a). At groundwater salinities of 100 and 350 g/L, which bracket the range of conditions around the shaft, the hydraulic conductivity of bentonite/sand ranges from 4×10^{-12} and 1×10^{-11} m/s (Figure 6.26). Similarly swelling pressures of 0.4 to 1 MPa would be expected (Figure 6.27). Additional characteristics and experience with bentonite/sand seals is summarized in Box 3.

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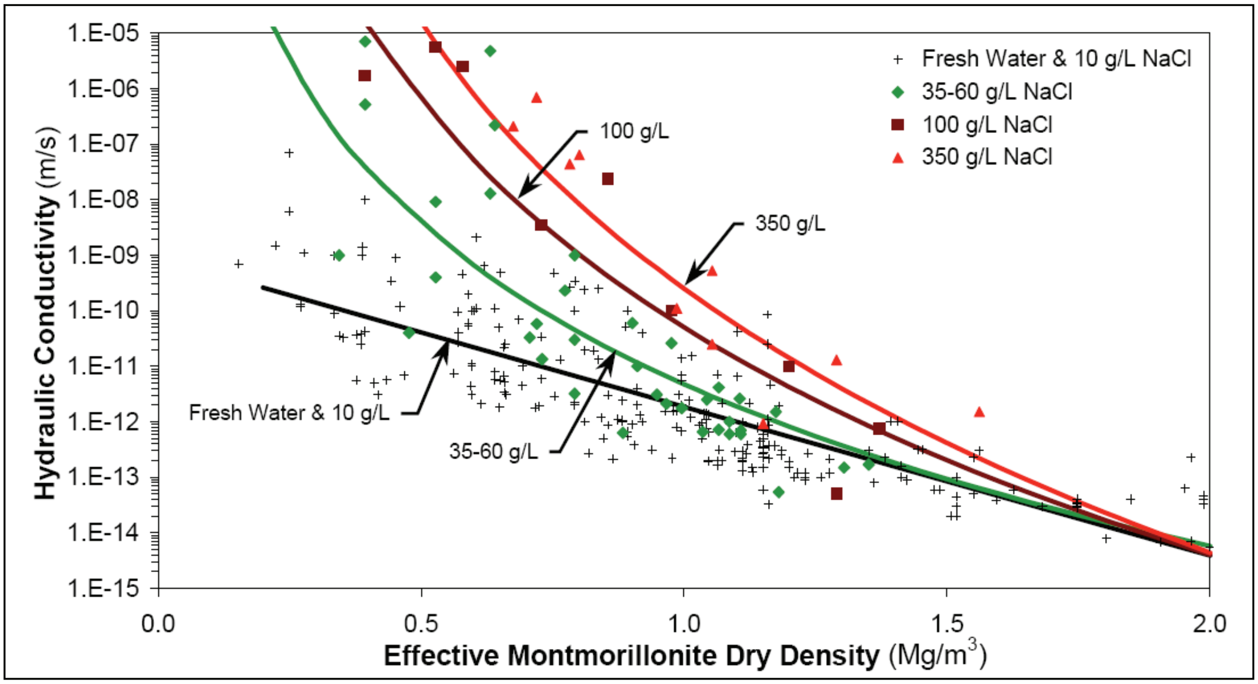
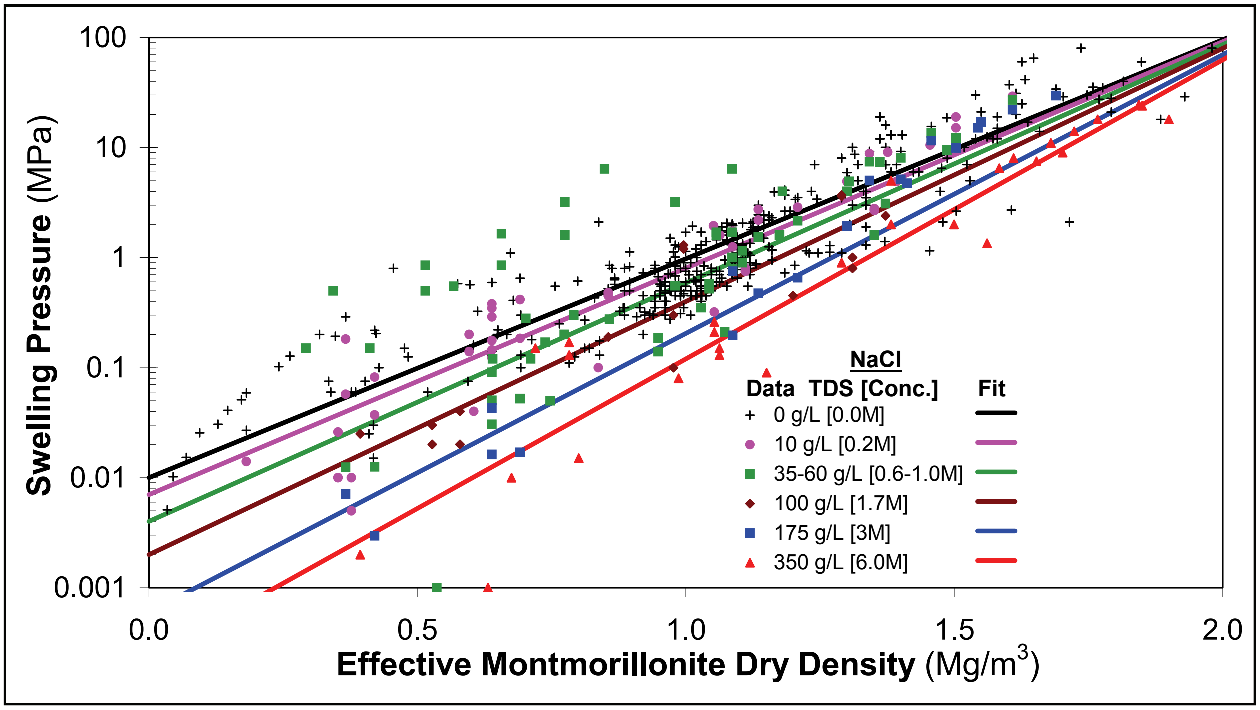
[25] Note that there is a degree of simplification between the detailed description provided in the Data report (QUINTESSA and GEOFIRMA 2011a) and the representation of that system in AMBER. This is described in Appendices H and J of the Analysis of the Normal Evolution Scenario report (QUINTESSA 2011a).



Note: Figure 3 in Baumgartner 2006.

Figure 6.26: Hydraulic Conductivity as a Function of EMDD and Total Dissolved Solids



Note: Figure 4 from Baumgartner 2006.

Figure 6.27: Swelling Pressure of as a Function of EMDD and Total Dissolved Solids

Box 3: Bentonite/Sand Seals

- The reference bentonite/sand mixture is primarily clay. The 70/30 wt% bentonite/sand ratio was selected since it retains a clay-dominated composition, while being easier to handle than 100% clay and having improved mechanical properties. The density was chosen so that it would swell with water under the DGR saline conditions.

- There is experience in Canada with using bentonite-sand mixtures as repository seals, including the AECL URL BCE Test (50:50), ITT Test (50:50), Tunnel Sealing Experiment (70:30) and the Enhanced Seal Project (ESP) (60:40 and 70:30) (Dixon et al. 2002; Martino et al. 2007).

- Achieving the desired properties of the seal requires appropriate quality control during the emplacement process. This includes the use of a graded grain size distribution for the sand component, as well as water control during placement. The seal is expected to be placed in layers and compacted in-situ.

- Bentonite is known to be a durable material, with natural deposits that are many millions of years old that still contain montmorillonite (Laine and Karttunen 2010).

- Higher temperatures (>100°C) and alkaline conditions encourage mineralogical transformations, but the DGR shaft will be at low temperatures (<25°C), with only localized alkaline conditions near the concrete monolith and bulkheads.

- The effects of water salinity and groundwater chemical species are more complex. There is some evidence of reduced stability under certain high salinity conditions (e.g., Herbert et al. 2004), but also evidence that only cation exchange is likely to occur (Kaufhold and Dohrmann 2009). Although there is no direct data on bentonite stability under the highly saline Na-Ca-Cl site groundwater conditions at the DGR site, there are some natural analogs, notably some Spanish bentonites, that have been exposed to saline Na-Cl (sea) water over millions of years, and show no significant mineral alteration (Laine and Karttunen 2010; Savage 2005).

- Simple estimates indicate that the bentonite degradation processes such as illitization will be slow at the DGR (Appendix E.3, QUINTESSA 2011b). There will be a reaction zone adjacent to concrete surfaces, and against the shaft wall, but these are expected to be limited in extent. They will be limited in part due to the low temperatures, which limits the rate of reaction, and due to the low permeabilities of the shaft seal and rock, which limits the rate of supply of reacting species. Also, the groundwater at the DGR site is near neutral pH, and the concrete bulkheads will be fabricated from low-pH cement.

The primary references used for the safety assessment are:

- The Reference L&ILW Inventory Report (OPG 2010) for the waste and waste packaging;
- The Chapter 6 (Facility Description) of the Preliminary Safety Report (OPG 2011b) for the repository design;
- The Geosynthesis Report (NWMO 2011a) and Descriptive Geosphere Site Model (DGSM) Report (INTERA 2011) for the geological setting; and
- The Technical Support Documents (TSDs) supporting the Environmental Assessment (EA) for the DGR (GOLDER 2011a-g, AMEC NSS 2011) and the EA Study Report for the WWMF (OPG 2005) for the surface environment.

Thus most of the data are specific to the DGR system and have been taken from its waste and site characterization programs. The overall DGR program has been structured such that the safety assessment has been produced in multiple iterations, with data freezes in synchronization with the inventory, design and geoscience programs. Datasets required for safety assessment outside of referenceable documents have been released for use within the DGR project using a data clearance process. Approved data have been documented using a data clearance form that records the persons providing and approving the dataset, together with the purpose and nature of the dataset, its status/history, and any limitations/restrictions on its use/application.

In addition, literature reviews have been undertaken to derive values for certain parameters such as solubility limits, sorption coefficients, metal corrosion rates and organic degradation rates suitable for the expected conditions in the DGR (see Appendices C, D, E and F of the Data report, QUINTESSA and GEOFIRMA 2011a).

Alternative/additional data that are used for certain calculation cases for the Normal Evolution Scenario and the calculation cases for the Disruptive Scenarios are documented, together with their derivation, in the associated Normal Evolution and Disruptive Scenario reports (Sections 4.3 and 4.4, QUINTESSA 2011a; Sections 2.4.3, 3.4.3, 4.4.3 and 5.4.3 of QUINTESSA and SENES 2011).

Some parameter values used are model-specific (e.g., compartment areas and volumes for AMBER) and are derived from information presented in the Data report (QUINTESSA and GEOFIRMA 2011a) rather than being explicitly given in the report. Such data are documented, together with their derivation, in the relevant report, i.e., QUINTESSA (2011a) for the assessment modelling for the Normal Evolution Scenario, QUINTESSA and SENES (2011) for the assessment modelling for the Disruptive Scenarios, GEOFIRMA (2011) for the detailed groundwater modelling, and GEOFIRMA and QUINTESSA (2011) for the detailed gas modelling.

The management of data for use in the postclosure safety assessment has been undertaken under the project's quality plan (QUINTESSA 2010) and Quintessa's quality management system, which has been certified against the requirement of ISO 9001:2008. It is consistent with NWMO's governance, NWMO-PROC-EN-0002 Technical Computer Software Procedure (NWMO 2010e) that is used for the procurement, development and maintenance of reference datasets.

Table 6.8: Reference Values for Key Parameters for the Normal Evolution Scenario

PARAMETER	VALUE(S)
Repository	
Repository depth	680 m
Number of emplacement rooms	Panel 1: 14; Panel 2: 17
Volume of emplacement rooms	Panel 1: 1.7×10^5 m^3; Panel 2: 2.5×10^5 m^3
Average width of emplacement rooms	Panel 1: 8.25 m; Panel 2: 8.5 m
Average repository height	7 m (used to represent the initial height throughout the repository)
Distance between Panel 1 access tunnel and Panel 2 emplacement rooms	20 m
Panel 1 access tunnels dimensions	L 537 m, W 5.4 m, H 7.0 m
Panel 2 access tunnels dimensions	L 787 m, W 5.9 m, H 7.0 m
Monolith dimensions (within repository)	L 85 m, W 11.8 m, H 7.0 m (only modelled from open access tunnels to base of a combined shaft)
Monolith dimensions (within shafts)	Radius 5.9 m; H 13 m (from repository ceiling level upwards)
Panel footprint	2.4×10^5 m^2
Excavated volume	Excavated: 5.3×10^5 m^3; Void: 4.2×10^5 m^3.
Waste volume (as emplaced)	Panel 1: 6.8×10^4 m^3 ; Panel 2, 1.3×10^5 m^3
Waste inventory	8.8×10^2 TBq LLW, 1.6×10^4 TBq ILW at 2062
Mass of organics (waste, packages & engineering)	2.2×10^7 kg
Mass of concrete (waste, packages & engineering)	2.1×10^8 kg (includes monolith)
Mass of metals (waste, packages & engineering)	6.6×10^7 kg
Backfilling of rooms and tunnels	None except monolith in immediate vicinity of shafts
Monolith properties	K_h and K_v 1×10^{-10} m/s; porosity 0.1; effective diffusion coefficient 1.25×10^{-10} m^2/s (degraded from closure)
Repository HDZ	K_h 1×10^{-6} m/s, $K_v = K_h$; porosity 4 x rock mass Emplacement rooms and tunnels: 0.5 m thick above/below and sides Supported tunnels: 2 m thick above/below, 0.5 m thick sides
Repository EDZ	K_h 10^3 x rock mass, $K_v = K_h$; porosity 2 x rock mass Emplacement rooms and tunnels: 8 m thick above/below and sides Supported tunnels: 3 m thick above/below and sides
Rockfall	Rockfall affects all rooms and tunnels, extending 10 m into ceiling immediately after closure
Resaturation profile	Variable – depends on calculation case
Corrosion rates	Un-passivated carbon steel and galvanized steel: 1×10^{-6} m/a (unsaturated), 2×10^{-6} m/a (saturated), Passivated carbon steel, stainless steel and Ni-alloys: 1×10^{-7} m/a Zr-alloys: 1×10^{-8} m/a
Degradation rates	Cellulose: 5×10^{-4} /a IX resins, plastics and rubber: 5×10^{-5} /a
Solubility and sorption in repository	Solubility limitation only considered for aqueous C releases (0.6 mol/m^3). No sorption considered
Shaft	
Internal diameter (lower section)	Main: 9.15 m; Ventilation: 7.45 m; Combined: 11.8 m (concrete lining and HDZ removed)
Length (lower section)	483.5 m (top of monolith to top of bulkhead at top of Intermediate Bedrock Groundwater Zone)
Internal diameter (upper section)	Main: 6.5 m; Ventilation: 5.0 m
Length (upper section)	178.6 m (top of upper bulkhead to ground surface)
Backfill and seals	Sequence of bentonite-sand, asphalt, LHHPC and engineered fill – see Figure 4.9. LHHPC bulkheads (degraded from closure) keyed across the inner EDZ
Vertical and horizontal hydraulic conductivity	Bentonite-sand: 1×10^{-11} m/s; Asphalt: 1×10^{-12} m/s; LHHPC: 1×10^{-10} m/s; Engineered fill: 1×10^{-4} m/s
Diffusion and transport porosity	Bentonite-sand: 0.3; Asphalt: 0.02; LHHPC: 0.1; Engineered fill: 0.3
Effective diffusion coefficient	Bentonite-sand: 3×10^{-10} m^2/s; Asphalt: 1×10^{-13} m^2/s; LHHPC: 1.25×10^{-10} m^2/s; Engineered fill: 2.5×10^{-10} m^2/s

PARAMETER	VALUE(S)
EDZ	Inner EDZ, 0.5 x shaft radius thick, K_v x 100 rock mass, K_h = K_v; porosity 2 x rock mass Outer EDZ, 0.5 x shaft radius thick, K_v x 10 rock mass, K_h = K_v; porosity = rock mass
Sorption in shaft and EDZ	Certain elements (Zr, Nb, Cd, Pb, U, Np and Pu) (see Tables 4.25 and 5.13 of the Data report, QUINTESSA and GEOFIRMA 2011)
Geosphere	
Host rock type	Low permeability argillaceous limestone (Cobourg Formation)
Temperature at repository depth	22 °C
Groundwater composition at depth	Na-Ca-Cl dominated brine; TDS: 131-375 g/l; pH: 6.5 to 7.3; Eh: reducing
Hydraulic heads	+165 m at top of the Cambrian sandstone Observed variable head profile with underpressures in the Ordovician (up to -290 m) 0 m at the top of the Lucas formation (top of the Shallow Bedrock Groundwater Zone)
Deep Bedrock Groundwater Zone:	
horizontal hydraulic conductivity	8×10^{-15} to 4×10^{-12} m/s (1×10^{-9} in the Shadow Lake and 3.0×10^{-6} in the Cambrian sandstone)
vertical hydraulic conductivity	10% of horizontal hydraulic conductivity for all, but Coboconk and Gull River (0.1%) and Cambrian which is isotropic
transport porosity	0.009 to 0.097
effective diffusion coefficient	2.2×10^{-13} to 2.4×10^{-11} m^2/s (some anisotropy – Section 5.5.1.4 of the Data report, QUINTESSA and GEOFIRMA 2011a)
horizontal hydraulic gradient	0
Intermediate Bedrock Groundwater Zone:	
horizontal hydraulic conductivity	5×10^{-14} to 2×10^{-7} m/s
vertical hydraulic conductivity	10% of horizontal hydraulic conductivity for all formations other than Guelph and Salina A1 upper carbonate which are isotropic
transport porosity	0.007 to 0.2
effective diffusion coefficient	3×10^{-14} to 6.4×10^{-11} m^2/s (some anisotropy – Section 5.5.1.4 of the Data report, QUINTESSA and GEOFIRMA 2011a)
horizontal hydraulic gradient	0
Shallow Bedrock Groundwater Zone:	
horizontal hydraulic conductivity	1×10^{-7} to 1×10^{-4} m/s
vertical hydraulic conductivity	10% of horizontal hydraulic conductivity for all formations
transport porosity	0.057 to 0.077
effective diffusion coefficient	6×10^{-12} to 2.6×10^{-11} m^2/s
horizontal hydraulic gradient	0.003
Sorption in geosphere	Certain elements (Zr, Nb, Cd, Pb, U, Np and Pu) (see Tables 5.13 of the Data report, QUINTESSA and GEOFIRMA 2011)
Biosphere	
Average annual surface temperature	8.2 ºC
Average total precipitation	1.07 m/a
Ecosystem	Temperate
Groundwater release paths	1) 80 m deep well located 500 m down gradient of combined shaft. Well demand of 6388 m^3/a for self-sufficient farm with crop irrigation (Section 6.2.3 of Data report, QUINTESSA and GEOFIRMA 2011a). 2) near shore lake bed (for discharge from Shallow Bedrock Groundwater Zone)
Gas release path	Soil and House located above repository
Sorption in biosphere	For all elements except for B, Li, Tl and W
Land use	Agriculture, recreation, forestry
Critical group	Site resident, living on repository site and farming. Habit data provided in Section 7.1 of the Data report, QUINTESSA and GEOFIRMA (2011a) based on CSA N288.1 (CSA 2008b)
Human dose coefficients	See Section 7.2 of the Data report, QUINTESSA and GEOFIRMA (2011a)

Abbreviations used in the table:

LLW: Low Level Waste
ILW: Intermediate Level Waste
IX: Ion exchange
K_v: vertical hydraulic conductivity
K_h: horizontal hydraulic conductivity
LHHPC: Low Heat High Performance Cement

TDS: Total Dissolved Solids
L: Length
W: Width
H: Height
HDZ: Highly Damaged Zone
EDZ: Excavation Damaged Zone

7. RESULTS AND DISCUSSION

This section presents safety assessment results that demonstrate how the DGR performs in respect of the acceptance criteria identified in Section 3.4. Results are presented for the Normal Evolution Scenario and the Disruptive Scenarios. A public dose constraint of 0.3 mSv/a has been defined for the normal evolution of the system, while a public dose criterion of 1 mSv/a is applied to low-probability scenarios involving natural disruptive events or human intrusion. For Disruptive Scenarios, the likelihood of occurrence is also taken into account.

Due to the good containment provided by the DGR system, some peak impacts may not occur within one million years. Calculated results may, therefore, be presented beyond one million years to show that these impacts are small. Over such long time periods the reliability of quantitative predictions diminishes with increasing timescale due to growing uncertainties, in part since FEPs that operate over timescales much longer than 1 Ma, such as tectonic movement, were not considered in the present analysis. Therefore, the results should be seen as indicative and not predictive; performance indicators (e.g., contaminant amounts and fluxes) are used as well as the safety indicators (i.e., radiation dose and environmental concentrations) (Section 3.5). Graphs showing results beyond 1 million years use a grey background for the period beyond 1 million years to emphasize the illustrative nature of the results over such timescales.

The results are presented in graphical and tabular format using a variety of approaches. In many cases, it is necessary to present very low calculated impacts to allow indicative comparison of different calculation case results. So some calculated concentrations presented are well below typical detection limits[26]. Similarly, some doses are presented that should be considered as being negligible and the magnitude of the values below this value should be seen as illustrative (i.e., calculated doses in the region of 10^{-6} mSv/a and lower).

As discussed in Section 6.3, a large number of calculation cases have been undertaken to investigate the uncertainties associated with the evolution of the DGR system and its associated models and data. Detailed results for all the cases are presented and analyzed in the supporting reports for the Normal Evolution Scenario (QUINTESSA 2011a), Disruptive Scenarios (QUINTESSA and SENES 2011), Groundwater Modelling (GEOFIRMA 2011), and Gas Modelling (GEOFIRMA and QUINTESSA 2011). A summary of the calculation cases considered in the assessment is illustrated in Figure 7.1 and Figure 7.2, and given in Table 7.1. Further details concerning these cases are provided in Appendix B. Particular emphasis has been placed on the evaluation of the Normal Evolution Scenario (47 of the 67 cases), since this scenario represents the expected long-term evolution of the repository and site following closure and there is need to understand its key processes and sensitivities.

The results for the Normal Evolution and Disruptive Scenarios are based on a simplified representation of the entire repository system. Key modelling assumptions are summarized in Table 7.2 for the Normal Evolution Scenario and Table 7.3 to Table 7.6 for each of the four Disruptive Scenarios.

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[26] For example, a typical detection limit for I-129 is around 10 Bq/m^3 (SELLAFIELD 2010).

Table 7.1: Calculation Cases for the Postclosure Safety Assessment

Calculation Case	Description	Code		
		FRAC3DVS-OPG	T2GGM	AMBER
Normal Evolution Scenario				
NE-RC	Reference case parameters based on inventory, original preliminary design and site characterization data summarized in Chapter 4 and Section 6.5. Assume steady-state Cambrian overpressure (+165m), transient Ordovician underpressures, 10 m rockfall from closure, no salinity gradient, no explicit representation of glacial cycling, and no horizontal gradients applied to Cambrian, Guelph and Salina A1 upper carbonate. T2GGM and AMBER cases based on gradual repository (including shaft) resaturation, gas generation and initial gas saturations of 10% in Ordovician. FRAC3DVS-OPG case based on instant repository (including shaft) resaturation, no gas generation and zero gas saturation.	F3	T2	A
NE-PD-RC	As NE-RC-A but adopting the final preliminary design	F3	T2	A
NE-SBC	As NE-RC but with no underpressures or initial gas saturations in Ordovician (all other parameters as for NE-RC)	F3	T2	A
NE-RS	As NE-RC but with immediate water resaturation of repository (including shaft) for assessment model and no gas generation in repository	-	-	A
NE-EDZ1	As NE-SBC but with increased hydraulic conductivity in shaft and repository EDZs	F3	T2	A
NE-EDZ2	As NE-EDZ1 but with seals keyed into repository HDZ/EDZ	F3	-	-
NE-HG	As NE-SBC but with horizontal gradient in Guelph and Salina A1 upper carbonate and discharge to lake	F3	-	A
NE-AN1	As NE-SBC but with reduced horizontal to vertical anisotropy of hydraulic conductivity	F3	-	-
NE-AN2	As NE-SBC but with increased horizontal to vertical anisotropy of effective diffusion coefficient	F3	-	-
NE-AN3	As NE-SBC but with increased vertical permeability resulting in no anisotropy in most formations	-	T2	-
NE-SE	As NE-RC but with explicit representation of saline fluid density effects on groundwater flow	F3	-	-
NE-NG1	As NE-RC but with no gas generation	-	T2	-

Calculation Case	Description	Code		
		FRAC3DVS-OPG	T2GGM	AMBER
NE-NG2	As NE-SBC but with no gas generation	-	T2	-
NE-MG	As NE-SBC but using air as gas rather than methane	-	T2	-
NE-RC1	As NE-RC but with initial gas saturations in Ordovician equal to residual gas saturation of 5%	-	T2	-
NE-RC2	As NE-RC but with initial gas saturations and two-phase flow parameters on a formation basis as given in INTERA (2011)	-	T2	-
NE-GT1	As NE-GG1 but with decreased van Genuchten air-entry pressure and less steep air entry curve	-	T2	-
NE-GT2	As NE-GG1 but with increased van Genuchten air-entry pressure and steeper air entry curve	-	T2	-
NE-GT3	As NE-GG1 but with relative permeability curve modified with residual liquid saturation and residual gas saturation set to zero	-	T2	-
NE-GT4	As NE-GG1 but with asphalt layer in shaft replaced by bentonite/sand seal	-	T2	-
NE-GT5	As NE-GT4 but with lower gas entry pressure for shaft seals	F3	T2	A
NE-PD-GT5	As NE-GT5 but adopting the final preliminary design	F3	T2	A
NE-BF	As NE-SBC but with repository backfilled with gravel	-	T2	A
NE-GG1	As NE-SBC but with increased gas generation amount and rates	-	T2	A
NE-GG2	As NE-SBC but with reduced organic degradation rates for organics resulting in reduced gas generation rates	-	T2	A
NE-NM	As NE-SBC but with no microbial reactions generating methane	-	T2	A
NE-RT1	As NE-RS but with instantaneous release, no solubility limits, and no sorption	-	-	A
NE-RT2	As NE-SBC but with instantaneous resaturation and release, no gas generation, and no sorption	-	-	A
NE-IV	As NE-RC but with increased inventory	-	-	A
NE-ER	As NE-RC but with surface erosion of 100 m over 1 Ma	-	-	A
NE-CC	As NE-RC but with tundra climate	-	-	A
NE-CG	As NE-HG but with alternative critical groups	-	-	A

Calculation Case	Description	Code		
		FRAC3DVS-OPG	T2GGM	AMBER
NE-PC	As NE-RC but represented by a probabilistic simulation case	-	-	A
NE-NR	As NE-RC but with non-radioactive contaminants	-	-	A
Human Intrusion Scenario				
HI-BC	As NE-RC but with surface release for unsaturated DGR via intruding exploration borehole	-	-	A
HI-GR1	As NE-RC but with instant resaturation of the repository and potential long-term release to Shallow Bedrock Groundwater Zone for exploration borehole terminated in DGR	F3	-	-
HI-GR2	As NE-GR1 but with exploration borehole drilled through DGR and terminated in Cambrian	F3	-	A
HI-NR	As HI-BC but with non-radioactive contaminants	-	-	A
Severe Shaft Seal Failure Scenario				
SF-BC	As NE-RC but with significantly degraded shaft seals (e.g., hydraulic conductivity of 10^{-9} m/s) and increased hydraulic conductivity in shafts' EDZs	F3	T2	A
SF-ED	As NE-RC but with extra degraded shaft seals (e.g., hydraulic conductivity of 10^{-7} m/s) increased hydraulic conductivity in shafts' EDZs	F3	T2	A
SF-NR	As SF-BC but with non-radioactive contaminants	-	-	A
Poorly Sealed Borehole Scenario				
BH-BC	As NE-RC for FRAC3DVS-OPG and NE-RS for AMBER but with poorly sealed investigation/monitoring borehole	F3	-	A
BH-NR	As BH-BC but with non-radioactive contaminants	-	-	A
Vertical Fault Scenario				
VF-BC	As NE-RC for FRAC3DVS-OPG and NE-RS for AMBER but with vertical fault 500 m northwest of DGR	F3	-	A
VF-AL	As VF-BC but with vertical fault 100 m southeast of DGR	F3	-	A
VF-NR	As VF-BC but with non-radioactive contaminants	-	-	A
Total		18	22	31

Calculation Case	Description	Code		
		FRAC3DVS-OPG	T2GGM	AMBER

Notes:

First two letters – indicate the scenario addressed by the calculation case:

NE – Normal Evolution Scenario
HI – Human Intrusion Scenario
SF – Severe Shaft Seal Failure Scenario
BH – Poorly Sealed Borehole Scenario
VF – Vertical Fault Scenario

Last letter (and number) – indicates the code used in the calculation case:

F3 – FRAC3DVS-OPG
T2 – T2GGM
A – AMBER

Other letters (and number) – indicate scope of case being considered:

RC – reference case
PD – final preliminary design
SBC – simplified base case variant
RS – repository resaturation variant
EDZ1&2 – excavation damaged zone variants
HG – horizontal gradient variant
AN1,2&3 –anisotropy variants
SE – saline fluid density effects variant
NG1&2 – no gas variants
MG – multiple gas (air) variant
RC1&2– no gas variant based on simplified base case
GT1,2,3,4&5 – gas transport variants
BF – repository backfill variant
GG1&2 – gas generation variants
NM – no methane variant
RT1&2 – radionuclide transport variants
IV – increased inventory variant
ER – surface erosion variant
CC – climate change variant
CG – critical group variant
PC – probabilistic case variant
NR – non-radioactive contaminants variant
BC – base case
GR1&2 – groundwater release variants (for Human Intrusion Scenario)
SR – surface release from saturated DGR variant (for Human Intrusion Scenario)
ED – extra degradation variant (for Severe Shaft Seal Failure Scenario)
AL – alternative location variant (for Vertical Fault Scenario)

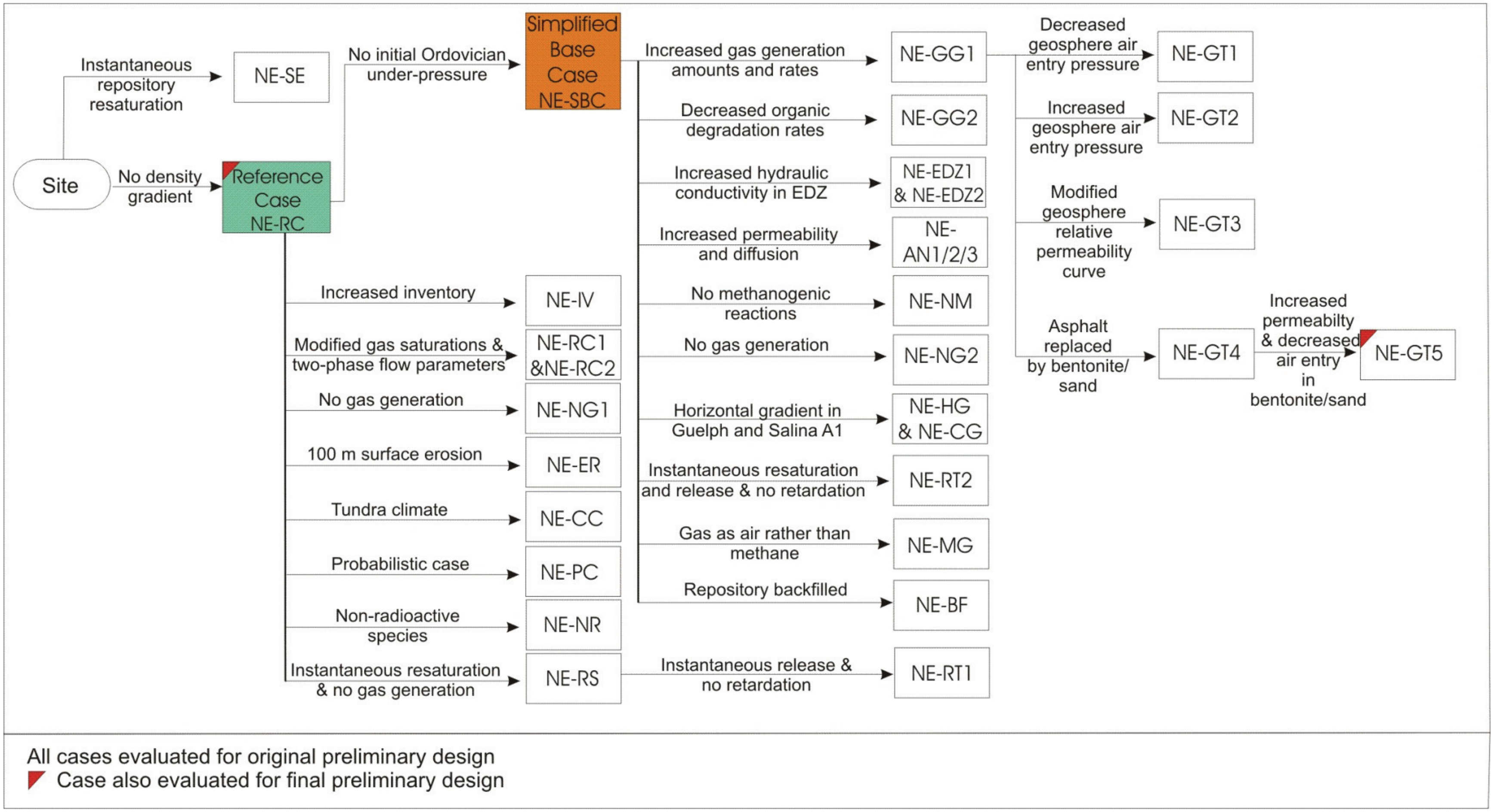


Figure 7.1: Normal Evolution Scenario: Summary of Calculation Cases

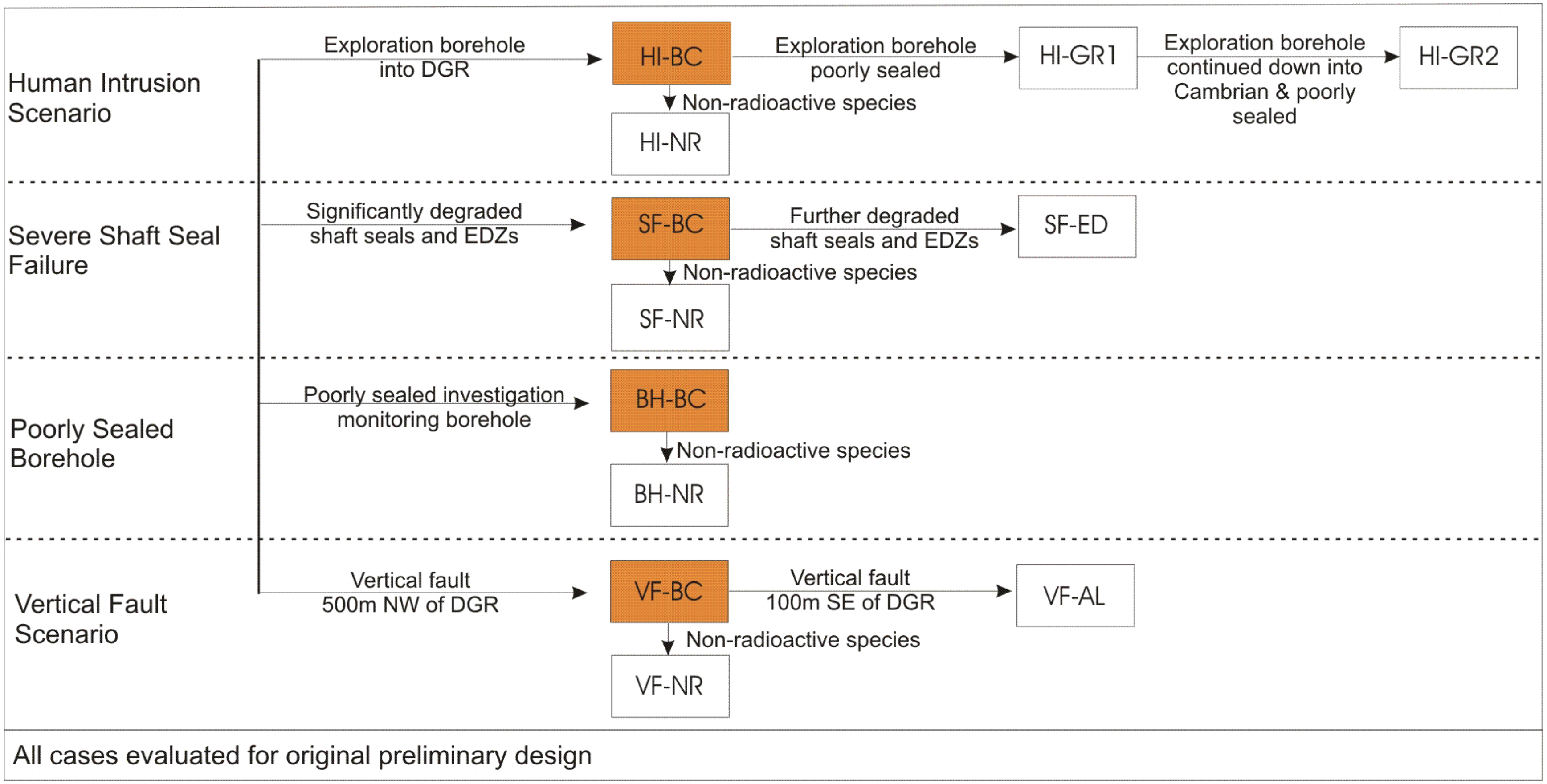


Figure 7.2: Disruptive Scenarios: Summary of Calculation Cases

Table 7.2: Summary of Key Modelling Assumptions for the Normal Evolution Scenario Reference Case and Simplified Base Case

Key Assumption	Motivation/Reason for Assumption	Impact of Assumption
Conceptual Model		
Microbial reactions occur in DGR if there are energy sources and moisture present	Water chemistry in repository could be unfavourable for microbes, but they tend to be ubiquitous when food and moisture are available.	Maximizes the generation of gases, which increases the pressure in the DGR. This delays resaturation but enhances the potential for gas migration to the surface. Variant cases explore different gas generation rates (NE-GG1, NE-GG2), no gas generation (NE-NG1, NE-NG2), no methane-generating microbial activity (NE-NM), and instant resaturation (NE-RC and NE-SBC for groundwater modelling, and NE-RS for assessment modelling).
“Non-water-limited” repository model	Conservatively allows for some unidentified water sources	Water consumed in anaerobic corrosion and gas generating reactions is not included in the repository water balance. This overstates the amount of water available to support repository reactions. The importance of this assumption is tested in “water-limited” WL cases.
Degradation reactions proceed to completion with respect to generation of gases	Conservative assumption to avoid the complexities of microbial reactions.	Maximizes the generation of gases, which increases the pressure in the DGR and also delays resaturation. See also variant cases described above.
Concrete monolith and bulkheads in the shafts are degraded from closure	Timing of degradation is uncertain. Simplifies representation in detailed gas and groundwater modelling codes.	Degraded concrete is more permeable than undegraded concrete by around two orders of magnitude, so this assumption maximizes the potential for contaminants to migrate from the DGR.
Bentonite/sand seal does not significantly degrade for relevant timescales	Bentonite and sand are durable natural materials. Degradation is expected to be slow under the low-flow, low-temperature DGR conditions.	Bentonite/sand seal properties consistent with exposure to brine are used as reference. There will likely be interaction zones at the interface between bentonite/sand and concrete bulkheads, but these will be localized. More permeable seals are considered; see NE-GT5 and SF-BC.

Key Assumption	Motivation/Reason for Assumption	Impact of Assumption
Asphalt seal does not significantly degrade for relevant timescales	The organic component of the asphalt seal is degradation-resistant bitumen. In the absence of UV radiation and conditions favourable to microbes, degradation is expected to be slow.	The case NE-GT4 shows that the asphalt could be replaced with bentonite/sand without significantly affecting the shaft performance. Asphalt provides a redundant seal material. If instead the asphalt were to degrade, the shaft seal would still be provided by the bentonite/sand seals.
Damaged rock zones around repository and shafts remain connected, and do not seal due to creep or precipitation processes	Shales contain clay and some self-sealing would be possible, but the long-term behaviour of damaged zones in these rocks has not been studied.	Provides a more permeable pathway from the repository than the geosphere, and so represents a conservative assumption that maximizes the potential for contaminants to migrate from the DGR via the shafts.
The Reference Case represents transient development of the observed hydraulic pressure gradients, while the Simplified Base Case assumes that the gradients have reached a steady-state equilibrium from closure	Addresses uncertainty associated with the future development of hydrogeological pressure gradients.	The Reference Case includes the initial underpressures observed in Ordovician formations, which results in the potential for downward groundwater flow in the shafts. The Simplified Base Case represents a constant steady-state gradient upward from the DGR to the Shallow Bedrock Groundwater Zone and, therefore, has potential for constant upward groundwater flow from the DGR. The Simplified Base Case is, therefore, **conservative** and maximizes potential contaminant transport from the DGR to the shallow system.
There is no significant effect of glacial cycles on contaminant transport in the Deep Bedrock Groundwater Zones	Consistent with site evidence, regional hydrogeological modelling, and shaft geomechanical modelling (see Section 5.2.3 and 5.3.3 of the System and Its Evolution report, QUINTESSA 2011b).	Impacts on stress may result in rockfall in the repository, which is represented but assumed to occur at closure. Ice-sheet loading and unloading will cause changes in the vertical groundwater pressure gradients (initially increasing the downward gradient, and then reversing to an upward gradient). These could potentially affect contaminant transport. However, the impacts on groundwater pressure gradients are not sufficient to change the deep geosphere from diffusion dominated transport.

Key Assumption	Motivation/Reason for Assumption	Impact of Assumption
Horizontal groundwater flow in the Guelph and Salina A1 upper carbonate is not represented	Flow is very slow, and discharge point is not certain but likely distant. In long-term, flow and discharge point are likely to change with the passage of ice-sheets.	Horizontal groundwater flow in the Guelph and Salina A1 upper carbonate would divert contaminant transport away from the Shallow Bedrock Groundwater Zone. The formations would provide longer transport pathways to the biosphere, with associated greater dispersion and decay. Ignoring these pathways therefore maximizes contaminant transport to the local biosphere above the repository. The impact of this assumption is explored via the NE-HG case that includes horizontal groundwater flow in the Guelph and Salina A1 upper carbonate.
Groundwater well in the Shallow Bedrock Groundwater Zone intercepts the highest concentrations in the plume at the depth of potable water	Future location and depth of a groundwater well is uncertain.	The well is placed a short distance downstream from the repository in the plume path to capture contaminants from the repository.
Constant present-day temperate biosphere	Provides a readily understandable estimate of potential impact on humans. Use of a constant biosphere provides clarity on changes due to repository/geosphere evolution. Simplifies modelling.	The range of biosphere conditions relevant to the DGR site cover temperate, tundra, glacial and post-glacial conditions (see Section 5.1.2). Human uses of the site will be more limited under tundra, glacial and post-glacial conditions due to their associated colder climates. Representing contaminant releases to a constant temperate biosphere state is, therefore, a useful indicator of potential exposures to humans as it maximizes the range of exposure pathways and the use of local resources. The NE-CC case considers release to a tundra biosphere system.
Potential critical group is a self-sufficient farming family that maximizes its use of local resources and lives in a house located on top of the main shaft	Addresses uncertainty surrounding future human behaviour.	Maximizing use of local resources and living in a house located on top of the main shaft are **conservative** assumptions in respect of potential exposures to humans. Alternative potential critical groups who are exposed via high consumption of lake fish and water from the near shore or from the South Basin of Lake Huron are considered in the NE-CG calculation case.

Key Assumption	Motivation/Reason for Assumption	Impact of Assumption
Mathematical Model		
Single combined shaft and access tunnel pathway	Simplifies the representation of the DGR system in the models.	The properties and key geometric aspects of these features are preserved. In particular, the cross-sectional areas of the shaft and shaft EDZ are the same as for the two shafts.
Instantaneous collapse of waste package stacks at closure	Addresses uncertainty concerning the timing of collapse of waste stacks.	Minimizing the height of waste in the DGR maximizes the amount of waste that can come into contact with groundwater in a partially resaturated repository. This maximizes potential contaminant releases to groundwater and is therefore **conservative** for this pathway.
Packaging does not limit access of water to the wastes or releases in liquid or gaseous phases	The packages are not designed for long-term containment. Duration of their integrity is uncertain.	The exclusion of the packaging from the contaminant release models is **conservative,** as it allows earlier release. (Note that the amount of metal and concrete packaging is taken into account in determining the associated gas generation, non-radioactive element and chemical species, and repository chemical evolution.)
Limited solubility and sorption in repository and geosphere	Limited data available to support the solubilities and sorption of elements under repository conditions, notably the high salinity.	Conservative assumption that is unlikely to underestimate impacts. The limiting case of no solubility limitation and no sorption of any elements is assessed by a case that considers instant resaturation of DGR and no solubility limitation or sorption in the DGR or geosphere (NE-RT1 and NE-RT2).
Instantaneous rockfall at closure	Rockfall is likely to be gradual over thousands of years, but exact timing is uncertain. Simplifies the representation of the process in the detailed gas and groundwater modelling codes.	Maximizes the extent of damage to the host rock and to waste packages from DGR closure. This reduces the thickness of low permeability rock above the repository and maximizes the interface area between the repository and the rock around the concrete monolith close to the shafts, and is, therefore, **conservative** for potential contaminant migration.
Salinity gradient in geosphere not represented	Simplifies the representation of the DGR system in the detailed gas and groundwater models.	Ignoring the salinity gradient is generally **conservative** since it is expected to limit contaminant migration due to density effects. The effect of salinity gradients is partially included in transient calculation cases, as initial head profiles are based on environmental heads which are compensated for fluid density. The NE-SE case explicitly represents saline fluid density effects.

Key Assumption	Motivation/Reason for Assumption	Impact of Assumption
The bulk gas transported through the geosphere as a single gas	Simplifies the representation of the DGR system in the detailed gas model.	A gas mixture could interact differently with the shaft and host rock than a single gas. However, generally methane is the likely dominant gas in the host rock and in repository. No differentiation is made between uncontaminated and contaminated gas. Variant cases consider air (NE-MG) and H_2 (NE-NM).

Table 7.3: Summary of Key Modelling Assumptions for the Human Intrusion Scenario

Assumption	Motivation/Reason for Assumption	Impact of Assumption
Surface Release Pathway (Gas)		
Gas is vented from a blowout preventer	Blowout preventers are standard practice in drilling in deep sedimentary rocks. But gas is assumed to be vented and not capped.	A release rate of 1 m^3/s (atmospheric) is assumed for the period that a drill crew is on site (Section 2.4.3.1, QUINTESSA and SENES 2011). The calculated air concentration is directly proportional to the release rate that is assumed.
Both the drill crew and a nearby resident are exposed	Considers potential impacts on both intruder and inadvertent public.	A drill crew would be exposed if the repository were intercepted. An offsite resident is less likely to be present but has been **conservatively** assumed to be living 100 m from the drill site.
Surface Release Pathway (Drill Core)		
Waste is retrieved in drill core	The assumption is made to examine the possible consequences of direct exposure to waste by a laboratory technician.	The calculated dose to a laboratory technician is directly proportional to the activity concentration in the waste. The reference calculations consider the average concentration in Panel 1.
Core is examined in a laboratory, without precautions	The assumption is made to examine the possible consequences of direct exposure to waste.	The assumptions concerning exposure in the laboratory determine the dose and are **conservative.** However, the contaminated core may not be examined at all, or may rapidly be identified as requiring careful handling.
Drill crew do not wear personal projective equipment	Conservative assumption on future human behaviour, ingestion and inhalation pathways are relevant.	In practice, external irradiation dominates the calculated exposures; therefore, this is not a key assumption.
Drill core debris is not disposed of properly	Conservative assumption on future human behaviour.	Normal practice involves the collection of drill core and associated debris for storage/disposal under controlled conditions; therefore, the assumed fate of the drill core debris in the model (dispersed in the soil used to grow food) would not occur. The calculated doses for a future resident of the drill site are directly proportional to the drill core concentration in soil.

Assumption	Motivation/Reason for Assumption	Impact of Assumption
Drill core debris is mixed with soil and not leached before being used for farming	Conservative assumption on future human behaviour.	Leaching of soil will reduce the concentrations of contaminants in soil that is farmed, therefore the assumption is **conservative**. The assumption that the soil is used by a farmer soon after the completion of drilling, is also **conservative**.
Groundwater Release Pathway		
Intrusion borehole occurs after 300 years	This is the earliest credible time that all institutional control and memory might not be effective in preventing intrusion.	The impacts could be higher if the intrusion is early due to less radioactive decay.
Borehole extends to the Cambrian	Necessary for groundwater flow to occur up the borehole.	If the borehole were terminated at the repository, there would be no release of contaminants in water via the borehole as the repository would pressurize only very slowly; the increased pressure of the Cambrian is necessary to drive flows up to the Shallow Bedrock Groundwater Zone. It is, however, unlikely that a borehole would be continued after the repository had been encountered.
Borehole is poorly sealed	Necessary for flows to occur up the borehole.	The borehole would be expected to be sealed. The model assumes that this is not the case and the borehole has a hydraulic conductivity of 10^{-4} m/s. The hydraulic conductivity determines the rate of release of contaminants via the borehole.
No sorption occurs in the borehole	Conservatively permits the maximum rate of release of contaminants to the Shallow Bedrock Groundwater Zone.	Contaminants will sorb to the material filling the borehole, reducing the concentrations released to the Shallow Bedrock Groundwater Zone. The assumption that there is no sorption is **conservative** and maximizes the rate at which contaminants are released.

Notes: * The Human Intrusion Scenario utilizes the same models for the near-field (surface release pathway), geosphere and biosphere (groundwater release pathway) as the Normal Evolution Scenario's Reference Case, and the key associated assumptions referred to in Table 7.2, therefore, also apply.

Table 7.4: Summary of Key Modelling Assumptions for the Severe Shaft Seal Failure Scenario

Assumption	Motivation/Reason for Assumption	Impact of Assumption
Instantaneous physical degradation of all shaft seals	One potential cause of broad degradation of shaft seals is poor installation practice, which would be effective from the time of closure.	Allows earlier ingress of water into repository through the shaft, which enhances contaminant release rates from the wastes. Also conservatively allows for earlier release from repository, before there is significant decay.
Reduced sorption in the shaft seals	There is no specific likely cause, although in principle a major change in the geochemical conditions could affect sorption.	Reduced capacity of shaft materials to retard radionuclides. In practice, the sorption assumptions do not have a significant effect on calculated releases, which are dominated by C-14 released through the shaft as free gas.
Extra degradation of shaft/repository EDZs	The same failure mechanism that affects the shaft seals, affects the damaged zones around the shafts and repository.	Maximizes the flux of contaminants from the emplacement rooms to the base of the shafts and then up through the shafts. In practice, the shaft EDZs are not a significant pathway in this scenario due to the larger volume of degraded shaft seal material.

Notes: * The Severe Shaft Seal Failure Scenario utilizes the same models for the near-field, geosphere and biosphere as the Normal Evolution Scenario's Reference Case, and the key associated assumptions referred to in Table 7.2, therefore, also apply.

Table 7.5: Summary of Key Modelling Assumptions for the Poorly Sealed Borehole Scenario

Assumption	Motivation/Reason for Assumption	Impact of Assumption
Borehole is not properly sealed	Necessary to investigate the possibility of an enhanced permeability pathway to the surface environment.	Established practice would ensure that the boreholes are sealed so as to prevent any residual flows through them, once they were no longer used. The assumption that the borehole is not sealed is, therefore, very **conservative**. The borehole is conservatively assumed to have a fill similar to compacted sand. These conditions are necessary to permit a flow to occur upwards to the Shallow Bedrock Groundwater Zone.
Repository resaturates at closure	Maximizes the potential release of contaminants from the repository that could subsequently be captured by the poorly sealed borehole.	Under the likely unsaturated conditions in the repository, there would be no significant release of contaminants in groundwater and, therefore, the poorly sealed borehole would not provide a pathway for contaminant migration. Therefore, a **conservative** assumption is made that the repository rapidly resaturates and contaminants begin to be released in groundwater soon after closure.
No sorption occurs in the borehole	No specific seal material is identified.	The assumption that there is no sorption is **conservative** and maximizes the rate at which contaminants can migrate through the borehole.

Notes: * The Poorly Sealed Borehole Scenario utilizes the same models for the near-field, geosphere and biosphere as the Normal Evolution Scenario's Reference Case, and the key associated assumptions referred to in Table 7.2, therefore, also apply.

Table 7.6: Summary of Key Modelling Assumptions for the Vertical Fault Scenario

Assumption	Motivation/Reason for Assumption	Impact of Assumption
Vertical fault is present close to the repository	A vertical fault could provide a natural pathway connecting the repository horizon to overlying permeable rocks.	There is no evidence of the presence of transmissive vertical faults in the vicinity of the repository, although the presence of such a fault would likely have been noticed in the site characterization program. It is **conservatively** assumed to be located in one of two locations; one just outside the detailed site characterization area and one within the area.
Fault extends from Precambrian to Guelph formation	Consistent with regional fault structures, in which faults originate in basement structures and extend into the Ordovician sediments.	This provides a pathway to bypass the low permeability deep geosphere. It is **conservatively** assumed that the fault extends into the Guelph formation in the Silurian. Regional evidence shows that faults do not normally extend even this far vertically, and they extend into the Ordovician (rather than the Silurian). Faults extending to surface are not credible since existing faults would likely have been visible, and creation of new faults to surface would require huge energy releases.
Repository resaturates at closure	Maximizes the potential release of contaminants from the repository that could subsequently move via groundwater to the vertical fault.	Assuming rapid resaturation of the repository maximizes the flux of contaminants through the hypothetical vertical fault.
No sorption occurs in the vertical fault	Mineral and other materials within the fault are not known.	The assumption that there is no sorption maximizes the rate at which contaminants can migrate through the fault.
Groundwater flow in Guelph and Salina A1 upper carbonate discharges to near-shore lake over approximately 1 km pathlength	Discharge location is not known for certain.	This is a **conservative** assumption, since site evidence suggests that any flow from the Guelph and Salina A1 upper carbonate into the biosphere is likely to be over a significantly longer pathlength than approximately 1 km. Discharge into the near shore minimizes dilution of any contaminants released into the lake.

Notes: * The Vertical Fault Scenario utilizes the same models for the near-field, geosphere and biosphere as the Normal Evolution Scenario’s Reference Case, and the key associated assumptions referred to in Table 7.2, therefore, also apply.

Results for the Reference and Simplified Base Cases of the Normal Evolution Scenario are presented in Section 7.1, and results for the Disruptive Scenarios are presented in Section 7.2. Section 7.3 summarizes the assessment of uncertainties, while Section 7.4 summarizes the measures that have been adopted to build confidence in the assessment and its results. The results and the associated commentary presented in this chapter are, of necessity, a summary of the more detailed results and commentary presented in the supporting reports. More detailed analyses of the results are provided in relevant supporting reports (QUINTESSA 2011a, QUINTESSA and SENES 2011, GEOFIRMA 2011, and GEOFIRMA and QUINTESSA 2011).

7.1 Normal Evolution Scenario: Reference Case and Simplified Base Case

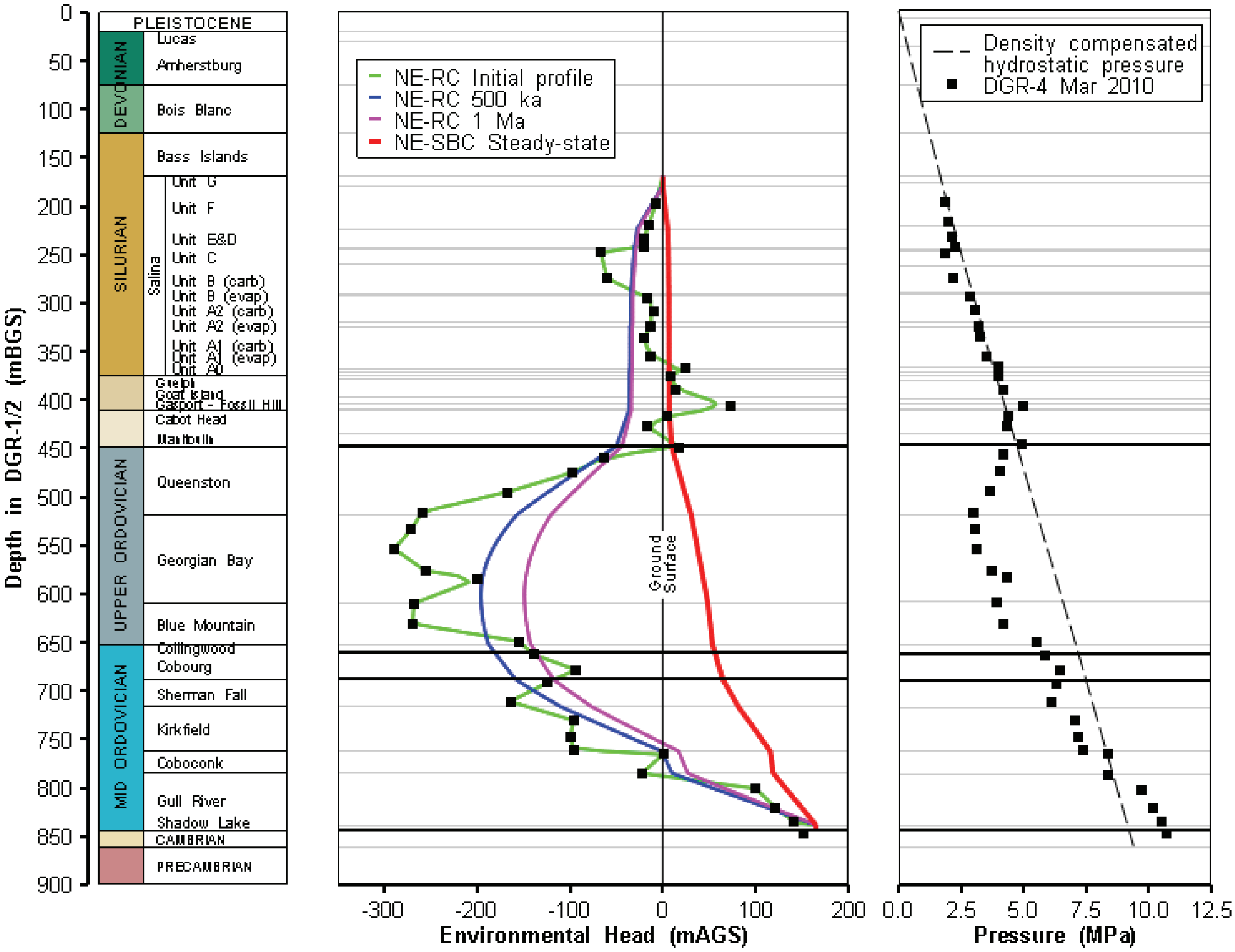
The Reference Case (NE-RC) model is based upon transient groundwater flow starting with the underpressures observed in the Ordovician sediments and overpressures observed in the Cambrian sandstone. The Reference Case builds directly on the results of the geosphere characterization program (INTERA 2011) and the associated geosynthesis study (NWMO 2011a). The NE-RC case is based on the original preliminary design (Section 4.2). In addition, a case (NE-PD-RC) based on the final preliminary design has also been evaluated.

A more conservative, Simplified Base Case (NE-SBC), is also represented based on the original preliminary design, in which steady-state conditions are established from the start of the assessment, with overpressure within the repository as a consequence of the overpressured Cambrian. The overpressure is dissipated across the Deep and Intermediate Bedrock Groundwater Zones, such that a constant vertical head gradient is maintained towards the Shallow Bedrock Groundwater Zone (Figure 7.3).

The following subsections present the results of the NE-RC and NE-SBC cases by exploring the outputs for the repository (Section 7.1.1), then describing the calculated fluxes via the host rock and shafts to the surface environment (Section 7.1.2) and finally presenting the resulting potential impacts in the biosphere (Section 7.1.3). The Reference Case results based on the final preliminary design (NE-PD-RC) are presented in Section 7.1.4.

7.1.1 Containment of Contaminants in the Repository

Radionuclides are initially present in the wastes within the waste packages. It is assumed in the safety assessment that all waste packages fail at closure. Radionuclides may be released either as gas (mainly C-14 and H-3) or after contact of the wastes with repository water. The release to repository water is either instant on contact with water, or determined by the corrosion/degradation rate of the associated wasteform.

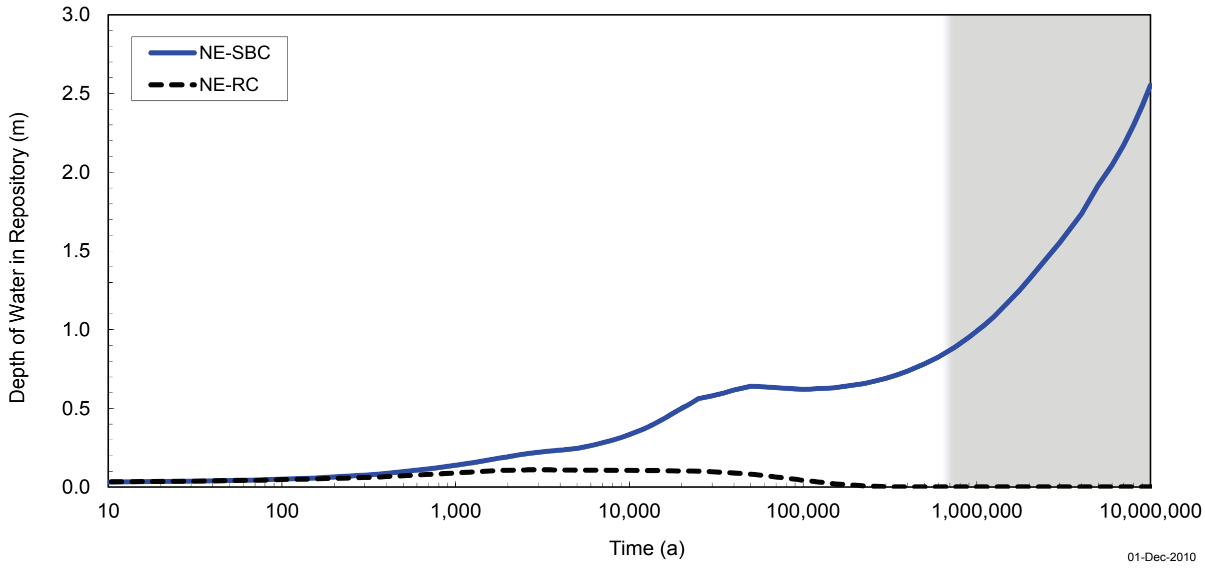


Note: Figure adapted from Figure 5.3 in GEOFIRMA (2011). Detailed groundwater and gas models focussed on the low-permeability intermediate and deep geosphere as shown (Salina Unit G and below).

Figure 7.3: Hydraulic Head and Pressure Profiles for the Reference Case (NE-RC) and Simplified Base Case (NE-SBC)

The water level in the DGR determines the degree to which the wastes are contacted by water and, therefore, their potential to release radionuclides into the repository water. Figure 7.4 shows the calculated level of water in the DGR for the Reference and Simplified Base Cases, drawing directly on the results of the detailed T2GGM calculations. The results show that the DGR remains almost completely unsaturated (the emplacement rooms are 7 m high plus assumed 10 m of rockfall) due to the slow in-seepage of water from the surrounding rock and the slow degradation of waste and containers leading to the build-up of gas pressure (Figure 6.5).

In neither case does the water level fully saturate the collapsed wastes, which range in height up to 6.5 m. Indeed, in the Reference Case, the water level never rises above 0.1 m; in the Simplified Base Case, the water level reaches the height of about 0.7 m at about 300,000 years. This low saturation is due in part to the low-permeability of the host rock, and in part due to the anaerobic generation of gases within the repository which further reduces water entry.

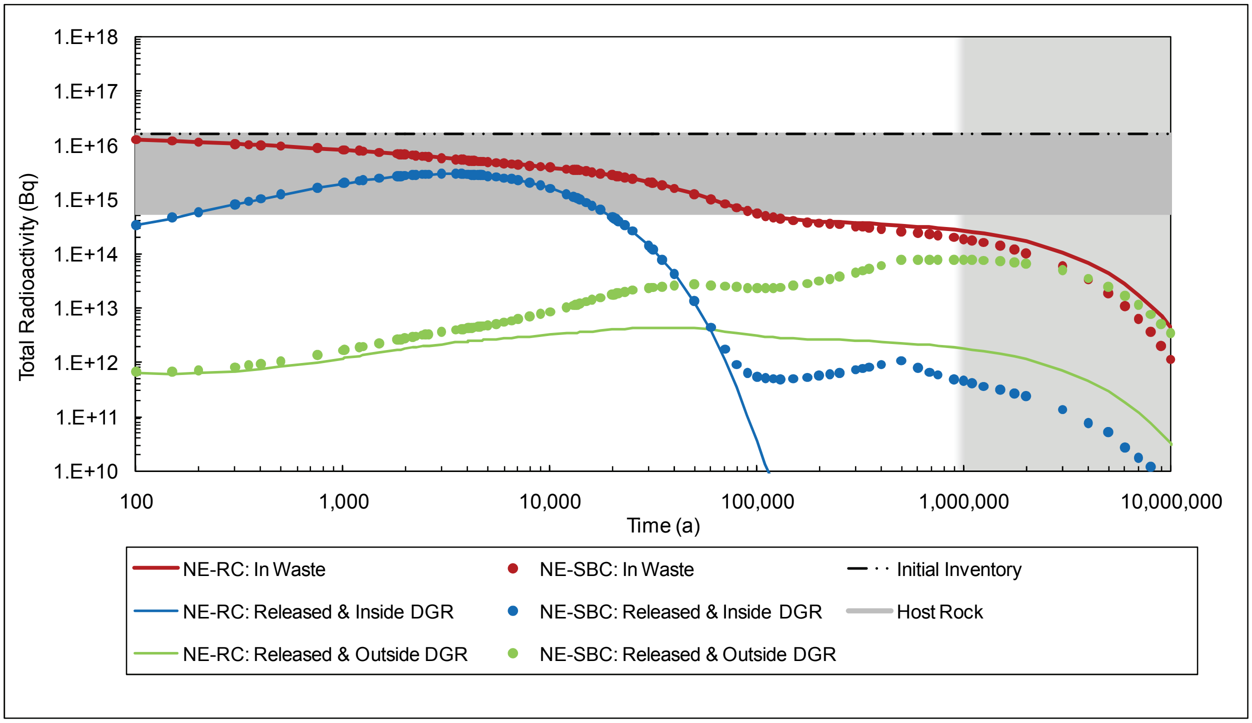


Note: Figure 6.1 in QUINTESSA (2011a).

Figure 7.4: Depth of Water in the Repository for the Reference Case (NE-RC) and Simplified Base Case (NE-SBC)

H-3 is assumed released instantly to the gas phase in the DGR and C-14 is released relatively rapidly to the gas phase. However, the small degree of repository resaturation means that other radionuclides remain within the wastes as they are only released on contact with water. Most of the total radioactivity decays without being released. This is illustrated in Figure 7.5, which shows the amount of radioactivity that is released from the waste but remaining within the DGR, and that released from the DGR to the host rock and shafts. The figure shows that the higher saturation in the Simplified Base Case results in a greater release from the wastes at long times in comparison to the Reference Case. For comparison, the figure also shows the natural radioactivity in the rocks above the repository as a horizontal grey band. The upper part of this band corresponds to the Bruce nuclear site; the lower part of this band corresponds to the DGR footprint.

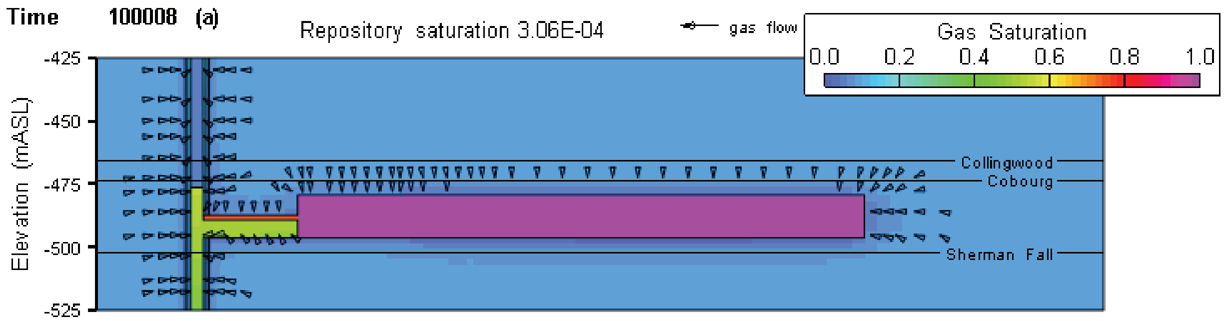
Figure 7.5 also shows that the amount of radioactivity outside the waste reaches a maximum of 18% of the initial inventory in both cases. This is due to the release of C-14 (from resins) as gas within the DGR. The amount of radioactivity outside the DGR reaches a maximum of 0.03% of the initial inventory for the Reference Case and 0.5% for the Simplified Base Case.



Note: Horizontal grey band is the range of natural rock radioactivity above the repository. Lower level corresponds to rock over repository footprint area and upper level to the Bruce nuclear site area.

Figure 7.5: Total Radioactivity in Reference Case (NE-RC) and Simplified Base Case (NE-SBC)

Radionuclides in the DGR water can be released to the host rock via diffusion from the repository floor, and can be released to the shafts (and their EDZs) via diffusion and flow through the concrete monolith and its associated damaged zones. The detailed T2GGM modelling shows that free gas is not released from the DGR for either the Reference Case or Simplified Base Case (see Sections 5.1.2, 5.2.2, 7.1.2, and 7.2.2 of GEOFIRMA and QUINTESSA 2011). Figure 7.6 shows the calculated gas saturations and flow rates in and around the repository after about 100,000 years for the Reference Case and illustrates that there is no free gas pathway via the shafts; this is representative of the results through to the end of the T2GGM calculations. In this case, there is still inflow of gas from the rock formation into the repository.



Note: Figure 5.32 in GEOFIRMA and QUINTESSA (2011).

Figure 7.6: Repository Gas Saturation and Flows at around 100,000 Years for the Reference Case from the 3DD T2GGM Model

Figure 7.7 provides a summary of the transfer fluxes from the DGR and shows that diffusion into the host rock dominates over contaminant migration to the shafts by more than three orders of magnitude in both cases due to the relatively large interface with the host rock[27] compared to the small interface with the shafts via the monolith and its damaged zones[28] together with low rates of groundwater advection. The perturbations in the radionuclide transfer flux from the repository to the monolith reflect fluctuations in groundwater flow rates.

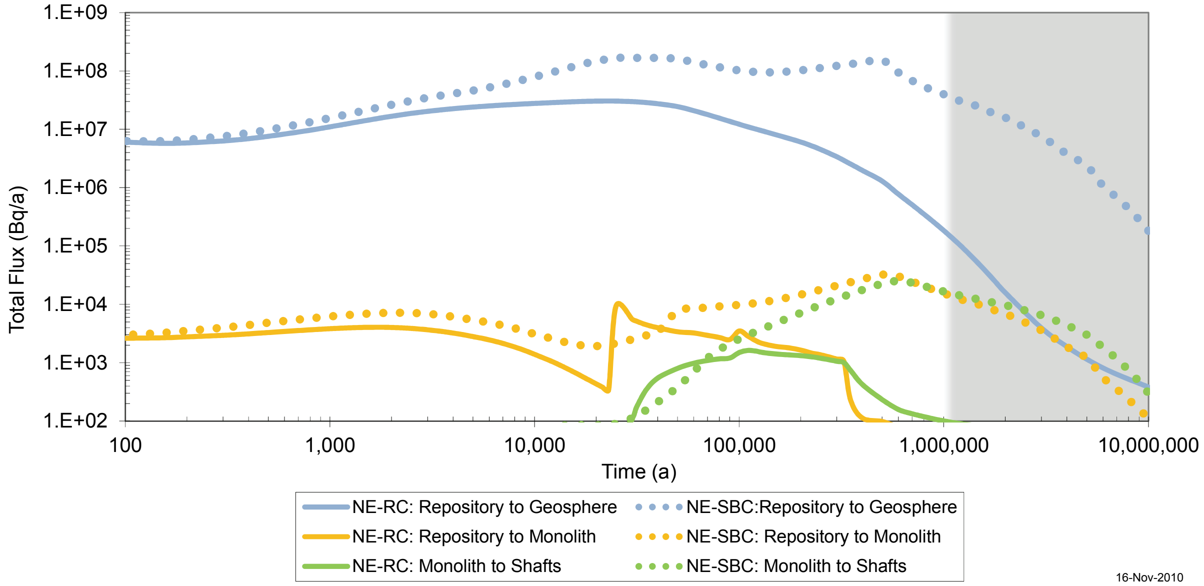


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Figure 7.7: Radionuclide Transfer Fluxes from the DGR

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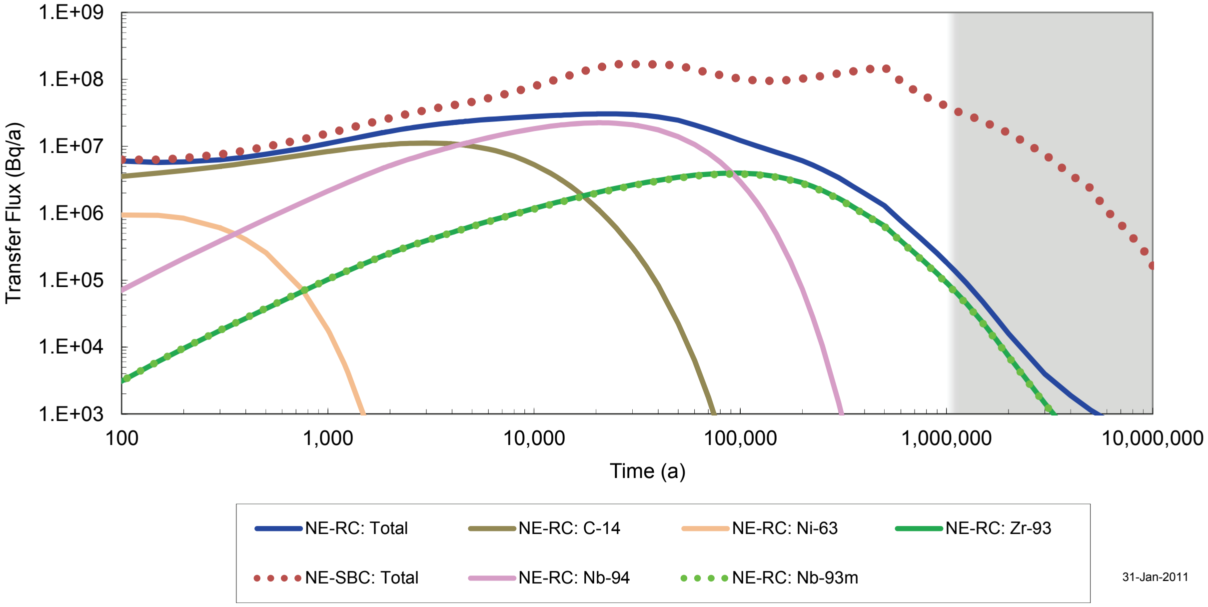
[27] Note that a very small depth of water in the DGR allows diffusion into the host rock via the repository floor.

[28] Note that the fluxes to the monolith and shafts include fluxes to their EDZs in Figure 7.7.

Radionuclide transfer fluxes increase when groundwater flow away from the repository commences in each case (after 25,000 years for the Reference Case and 50,000 years for the Simplified Base Case), indicating that groundwater advection dominates over diffusion as a process for contaminant migration to the shafts (see Figure 7.7).

The radionuclide transfer flux from the DGR into the host rock is shown in Figure 7.8 by radionuclide for the Reference Case and the total for the Simplified Base Case (for which the key radionuclides are the same). The figure shows the diffusive flux via groundwater into the repository HDZ and is indicative of the radionuclides present in the repository water. The figure shows that, consistent with the total radioactivity chart given in Figure 4.1, C-14, Nb-94 and Zr-93 are the key radionuclides beyond a few hundred years. H-3, Cs-137 and Ni-63 are important at earlier times but their relatively short half-lives (12.3 years, 30.2 years and 100 years, respectively) mean that they do not persist.



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Note: Figure adapted from Figures 5.7 and 6.2 in QUINTESSA (2011a).

Figure 7.8: Radionuclide Transfer Flux from the DGR to the Host Rock Due to Diffusion in Groundwater for the NE-RC and NE-SBC Cases

As for the radionuclides, the very low degree of repository saturation means that only a very small fraction (3%) of the non-radioactive inventory is released from the repository. Figure 7.9 shows the calculated flux of non-radioactive contaminants from the monolith to the shaft, which peaks at less than 0.1 g/a after about 100,000 years and is dominated by Ni and Cr (over 50% of which comes from non-waste sources such as steel waste containers) and Cu (which is dominated by non-processible LLW).

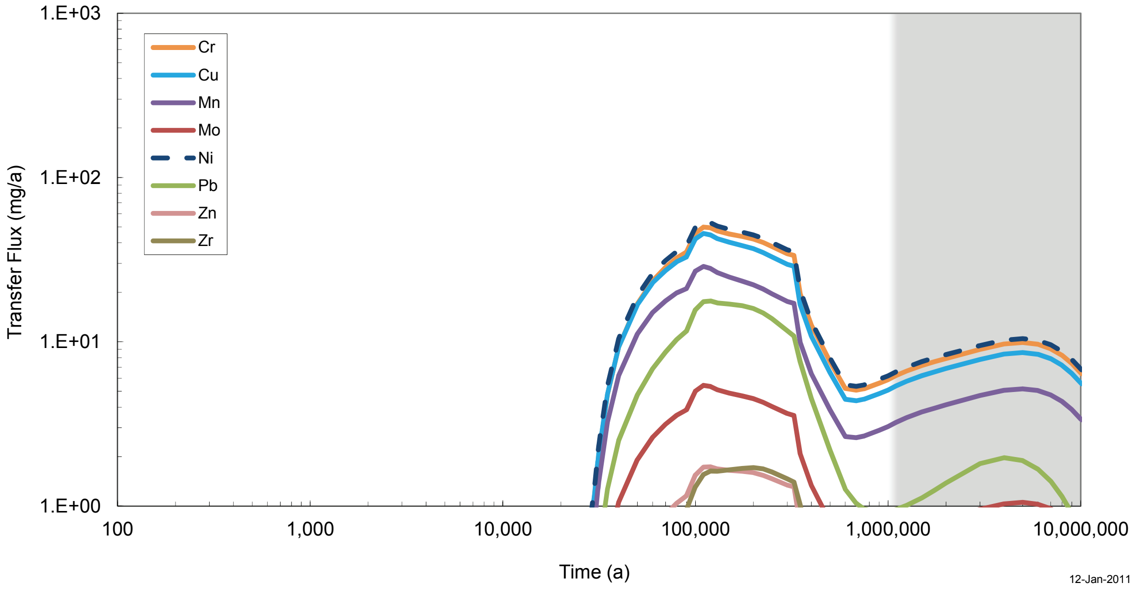


Figure 7.9: Non-radioactive Contaminant Transfer Flux from the Monolith to the Shafts for the NE-NR Case

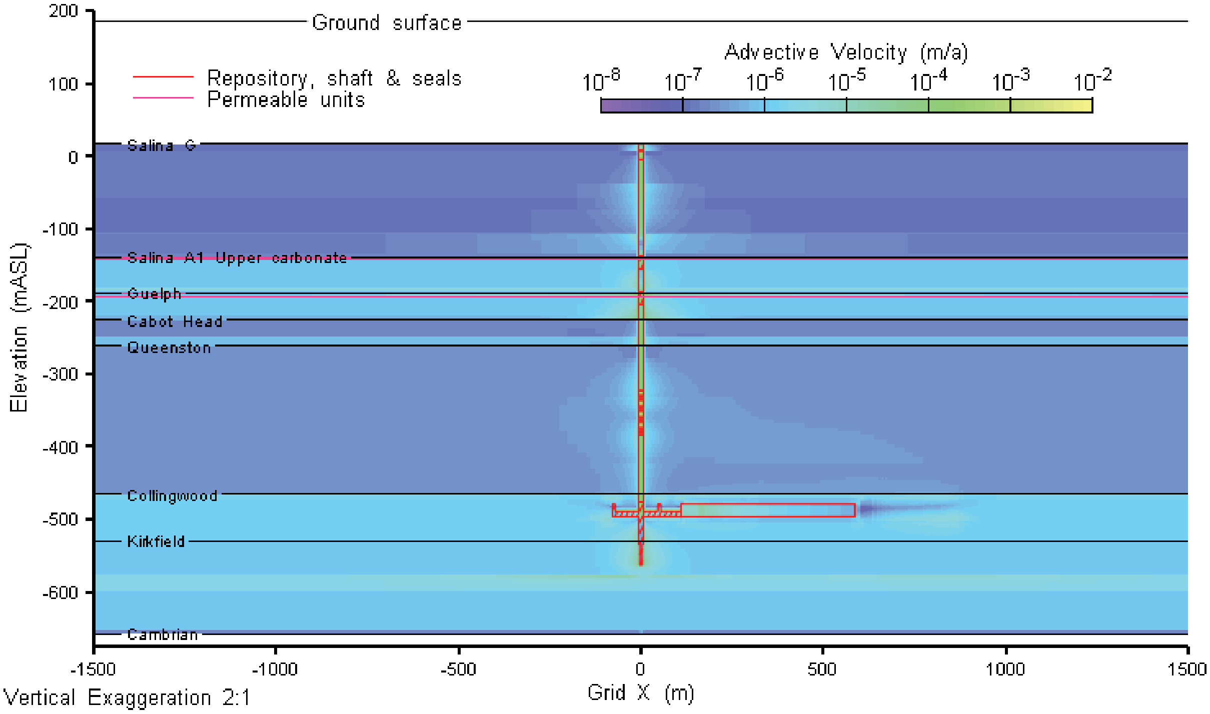
In summary, the low level of repository saturation in the Reference Case and Simplified Base Case mean that most of the radionuclides in the wastes decay without being released. This, coupled with the impermeability of the host rock and shaft seals to gas, means that less than 0.5% of the initial radioactive inventory is outside the DGR at any time (see Table 7.7). For non-radioactive contaminants, the maximum fraction of the initial inventory that is released from the DGR is 3% for the Reference Case in 1 Ma.

Table 7.7: Maximum Amount Released Compared to the Initial Inventory

Calculation Case	Released & Outside the Waste	Released & Outside the DGR	Basis
NE-RC: Reference Case	18.3%	0.027%	Radioactive inventory
NE-SBC: Simplified Base Case	18.4%	0.48%	
NE-NR: Reference Non-Radioactive Case	3.0%	3.0%	Non-radioactive inventory

7.1.2 Containment of Contaminants in the Geosphere and Shafts

The host rock surrounding the DGR has very low permeability, such that transport of contaminants away from the repository is diffusion dominated. Figure 7.10 shows the advective groundwater velocities calculated by FRAC3DVS-OPG for the Simplified Base Case; which is conservative in relation to the Reference Case with regards to groundwater flow. The figure shows that calculated groundwater velocities are effectively zero at about 0.001 mm/a. This is consistent with a diffusion-dominated groundwater regime.



Note: Figure 5.22 in GEOFIRMA (2011). Detailed groundwater model focussed on the low-permeability intermediate and deep geosphere. Permeable formations above Salina G were modelled separately.

Figure 7.10: Advective Groundwater Velocities for the Steady-State Simplified Base Case FRAC3DVS-OPG Model

Figure 7.11 shows the total calculated concentrations in host rock above the DGR for both the Reference Case and Simplified Base Case. The figure shows that calculated concentrations build up in sequence with increasing distance from the DGR. Nb-94 and Zr-93 (and its decay product Nb-93m), which are sorbed onto shales (including the Collingwood and Blue Mountain formations) but not on limestones (like the Cobourg), dominate the releases from the DGR beyond about 4,000 years. Their greater retention on the shales means that concentrations in the Collingwood formation exceed those in the Cobourg formation, which is closer to the DGR, after about 100,000 years. Diffusion of contaminants down into the Cambrian results in a peak concentration of around 3300 Bq/m^3 in the Cambrian for the Reference Case after about 1.5 million years[29].

The shales in the vicinity of the DGR contain about 3 x 10^6 Bq/m^3 of natural radioactivity (mostly K-40 and U-238). This is illustrated in Figure 7.11, which shows that the calculated concentrations in the Blue Mountain formation, arising from radionuclides released from the DGR, do not exceed the natural background concentration for the Reference Case and only exceed background concentrations by with a factor of three close to the repository for the Simplified Base Case.

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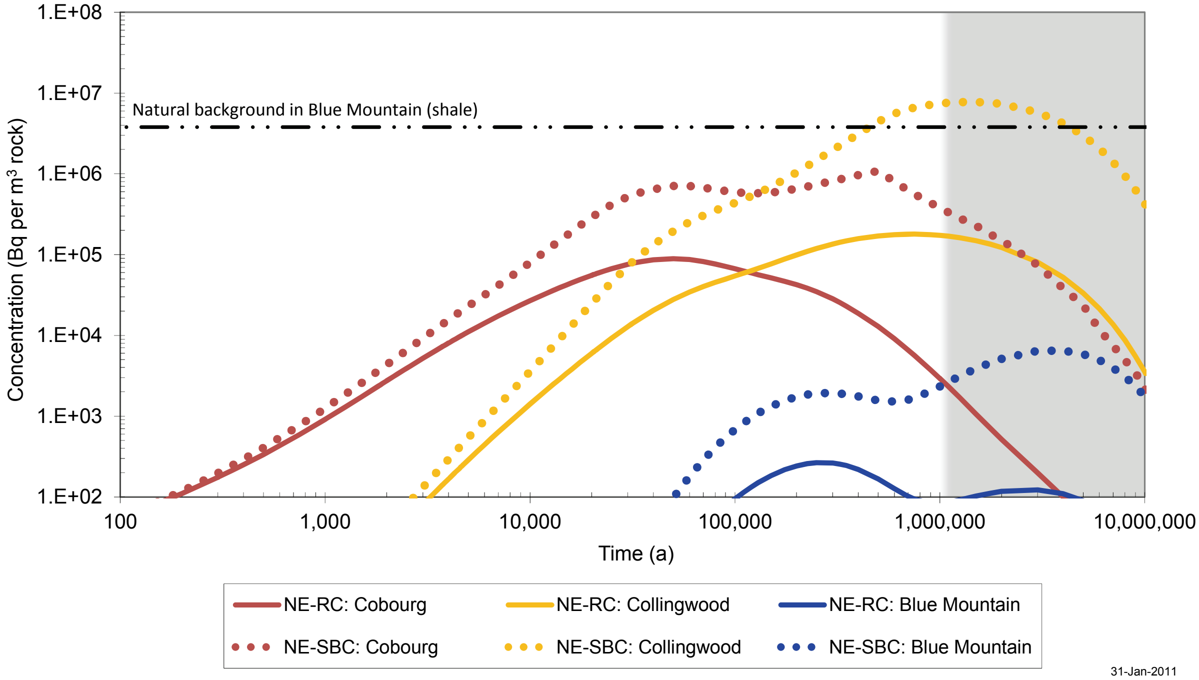
[29] Consumption of water with this concentration would result in a dose of around 0.002 mSv/a if it were assumed that water was pumped directly from the Cambrian and used without any treatment. This is not possible since the salinity of Cambrian water is around 200 g/L, a factor of 7 times higher than seawater.

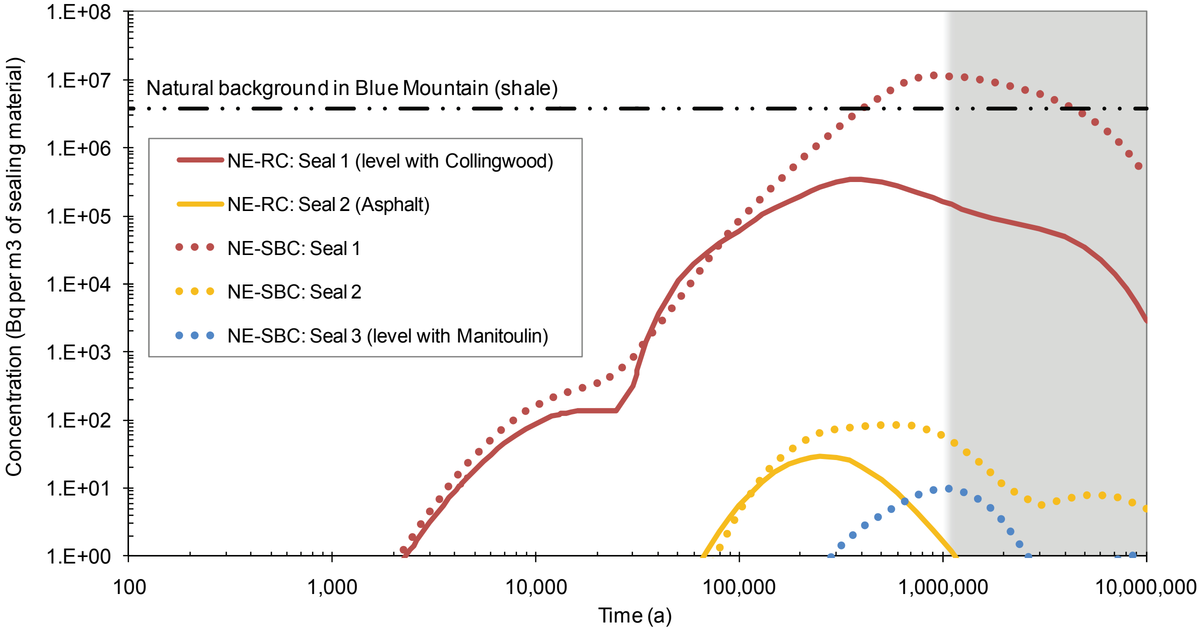


Note: Figure adapted from Figure 5.8 in QUINTESSA (2011a).

Figure 7.11: Radionuclide Concentration in the Deep Bedrock Groundwater Zone above the DGR

The decline in concentrations with increasing distance from the DGR means that calculated concentrations in the host rock are comparable to the natural background radioactivity in the Cobourg and Collingwood, and do not exceed 1 Bq/m^3 of rock beyond the Queenston formation at the top of the Deep Bedrock Groundwater Zone in either the Reference Case or Simplified Base Case. This indicates that the host rock does not provide a pathway for contaminants to migrate to the fresh groundwater that is present in the Shallow Bedrock Groundwater Zone.

The shafts are also not a pathway for contaminants. Figure 7.7 indicates that a relatively small amount of radionuclides (up to 3 x 10^4 Bq/a) reaches the base of the shafts. Figure 7.12 shows the calculated concentrations in the shaft sealing materials and demonstrates their effectiveness at minimizing contaminant transport. The figure shows that concentrations are reduced to very small levels as the distance from the DGR increases. No concentrations greater than 1 Bq/m^3 are calculated above the top of the seal in the Manitoulin formation for the Reference Case. No concentrations greater than 1 Bq/m^3 are calculated above the seal in the Salina A1 upper carbonate for the Simplified Base Case. Figure 7.12 also shows that calculated concentrations in the shaft remain below natural background concentrations at the points shown for the Reference Case and only exceed background concentrations by less than a factor of five for the Simplified Base Case close to the DGR.



Note: Figures 5.9 and 6.3 in QUINTESSA (2011a).

Figure 7.12: Radionuclide Concentration in Shaft

Using the example of nickel, Figure 7.13 shows how the shaft seals effectively limit the migration of non-radioactive contaminants from the DGR, with very small concentrations that decrease with distance from the repository.

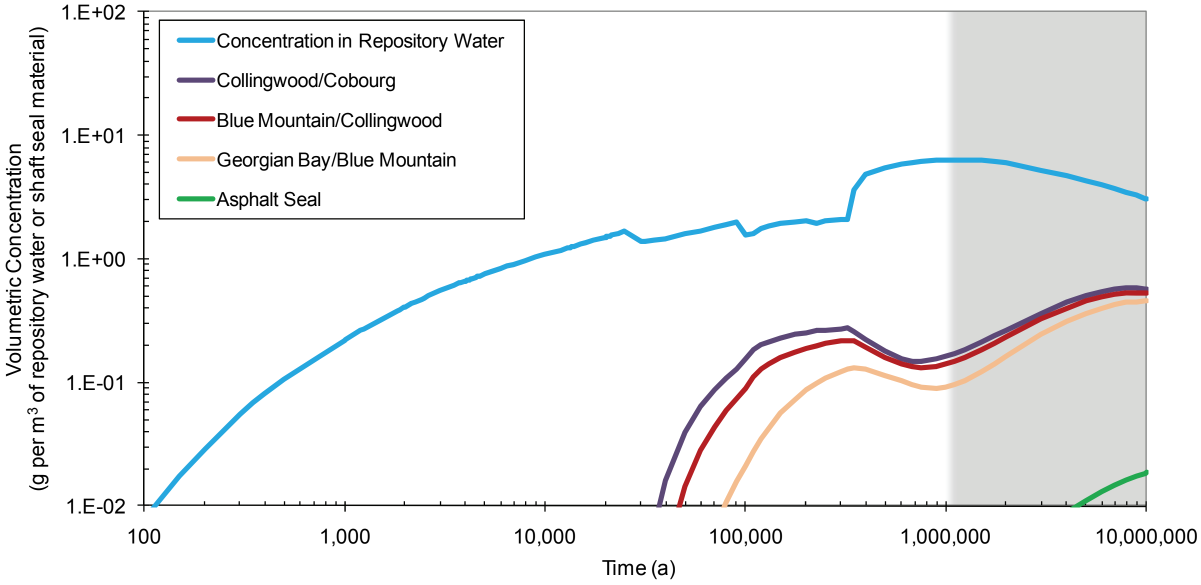
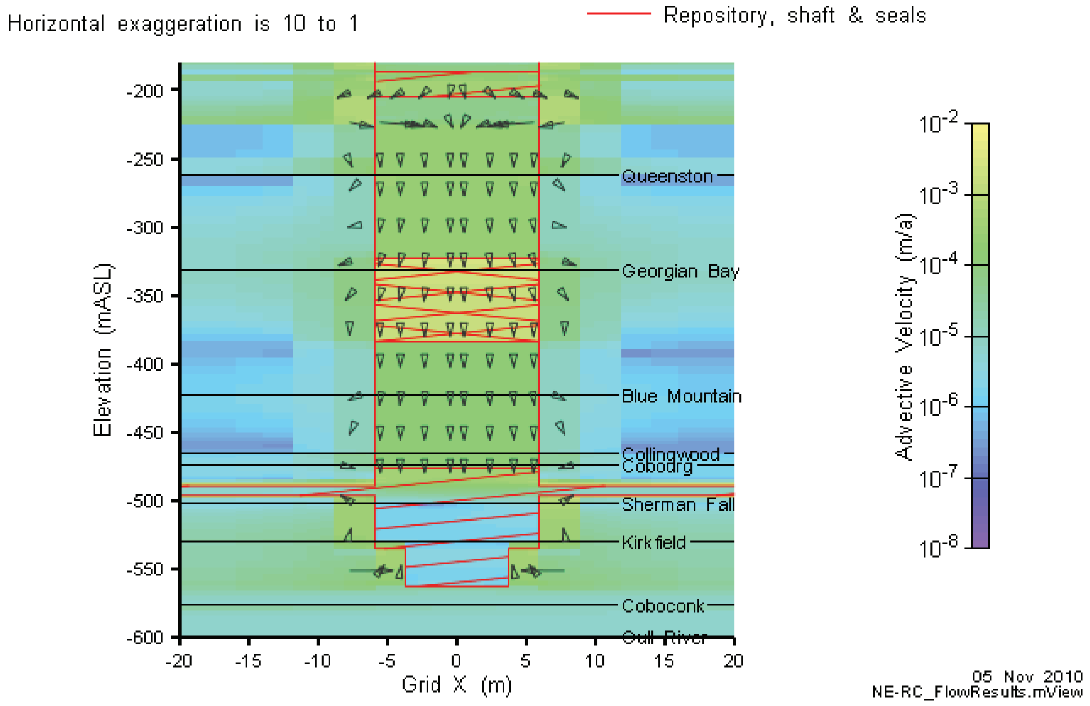


Figure 7.13: Concentration of Ni in Repository Water and in Shaft Seals for the NE-NR Case

The concentrations in the shafts are low are because contaminant transport via the shafts is dominated by diffusion in both the Reference Case and Simplified Base Case. In the Reference Case, in particular, groundwater flow via the shafts in the upper regions of the Ordovician remains downwards throughout the assessment period (see Figure 7.14) due to the underpressure in the Ordovician rocks. Therefore, contaminant transport up through the shaft towards the Shallow Bedrock Groundwater Zone should be both diffusive and against the direction of groundwater flow for the Reference Case.



Note: Figure 5.7 in GEOFIRMA (2011).

Figure 7.14: Advective Groundwater Velocities at 1,000,000 Years for the Reference Case FRAC3DVS-OPG Model

The low and slow level of repository resaturation, combined with the very low permeability of the host rock and the effectiveness of the shaft seals means that effectively no contamination enters the Shallow Bedrock Groundwater Zone (see Table 7.8). I-129 and Cl-36 dominate the small radionuclide flux due to the sorption of other radionuclides to the bentonite/sand seals in the shafts (notably radioisotopes of Zr and Nb). The very small fluxes given in Table 7.8 can be compared against an estimated present-day flux of around 4 MBq/a in the flowing groundwater within the shallow system[30]. Ni, Cr and Cu dominate the small flux of non-radioactive contaminants.

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[30] Based on a gross beta concentration in the shallow groundwater of around 0.04 Bq/L (Section 5.9 of AMEC NSS 2011) flowing through the Shallow Bedrock Groundwater Zone over the width of the AMBER model.

Table 7.8: Maximum Calculated Flux to the Shallow Bedrock Groundwater Zone

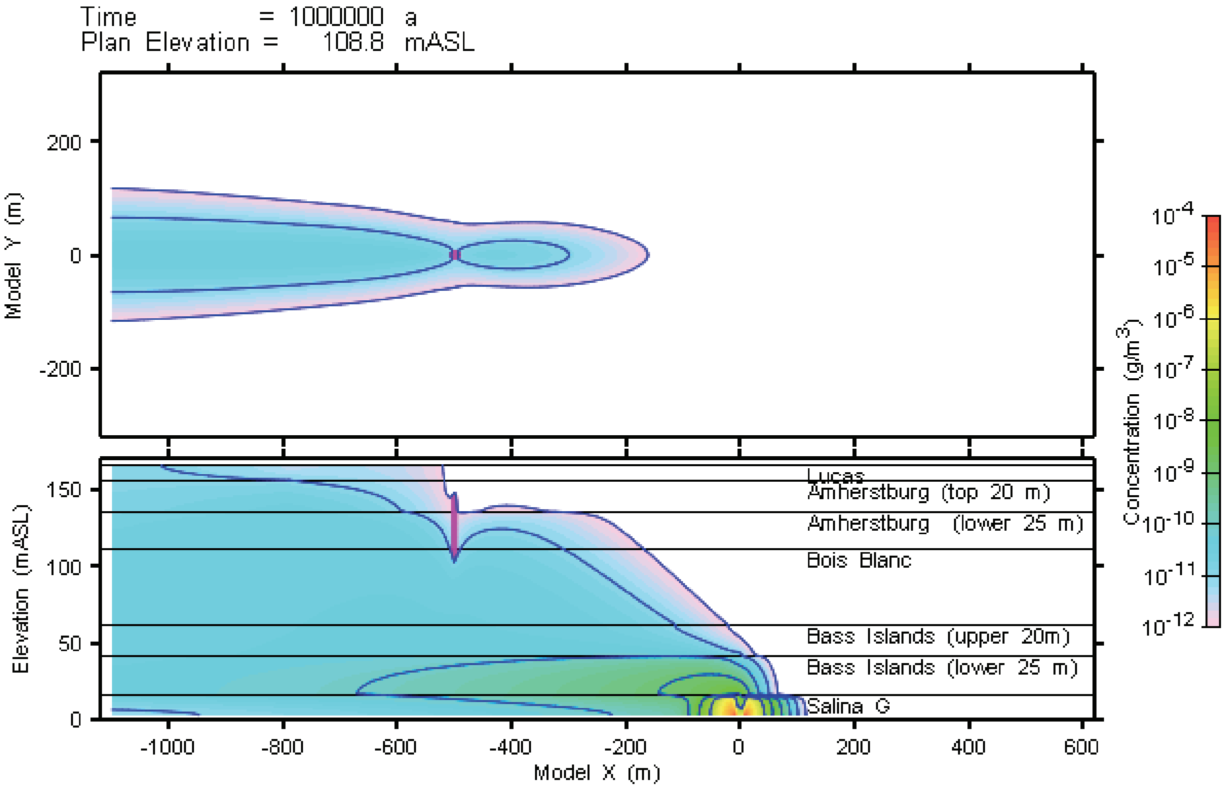
Calculation Case	Maximum Calculated Flux	Time of Maximum Calculated Flux (Ma)	Main Contaminant Contributing to the Peak
NE-RC: Reference Case	3×10^{-6} Bq/a	> 1	I-129
NE-SBC: Simplified Base Case	2×10^{-3} Bq/a	> 1	Cl-36
NE-NR: Reference non-radioactive case	3×10^{-2} g/a	> 1	Ni

After any contaminants enter the Shallow Bedrock Groundwater Zone, at 144 m below ground surface, horizontal groundwater flow takes the contaminants from the shaft release at the base of the Shallow Bedrock Groundwater Zone towards the lake (Figure 7.15).

Vertical dispersion and the draw resulting from groundwater extraction will enable contaminants to reach the groundwater well, which is drilled to a depth of 80 m below ground surface. This is illustrated in the 3DSU FRAC3DVS-OPG case, which modelled a unit source term (1 g/s) at the point where the shaft enters the base of the Shallow Bedrock Groundwater Zone (Figure 7.15).

The well depth is typical of wells in the region. It is consistent with the more permeable near-surface formations (see Figure 4.14), and avoids the higher salinity groundwater at greater depths (see Figure 4.17). The well demand is consistent with the needs for a self-sufficient farm. The well is placed downstream from the shaft, so as to intercept the plume, but not so far downstream that there is much dilution. The 3DSU FRAC3DVS-OPG results show that the well captures about 1.15% of the contaminant plume in the Shallow Bedrock Groundwater Zone (Section 5.2.2.2 of GEOFIRMA 2011).

Consistent with the small calculated fluxes to the Shallow Bedrock Groundwater Zone listed in Table 7.8, Table 7.9 shows the small calculated fluxes to the biosphere for the Reference Case and Simplified Base Case. Two biosphere discharge points are considered – the well and the lake.



Note: The shaft release is at co-ordinate of x, y=0. The well is shown as pink dot or line at x=-500. Figure 5.14 in GEOFIRMA (2011).

Figure 7.15: Steady-state Concentration Contours in Shallow Bedrock Groundwater Zone with Well, for a Constant Unit Source of Cl-36 Calculated with the 3DSU FRAC3DVS-OPG Model

Table 7.9: Maximum Calculated Flux to the Biosphere

Calculation Case	Biosphere Receptor	Max. Calculated Flux	Time of Max. Calculated Flux (Ma)	Main Contaminant Contributing to the Max.
NE-RC: Reference Case	Well Lake	4 x 10^{-8} Bq/a 3 x 10^{-6} Bq/a	> 1	I-129
NE-SBC: Simplified Base Case	Well Lake	2 x 10^{-5} Bq/a 2 x 10^{-3} Bq/a	> 1	Cl-36
NE-NR: Reference Non-radioactive Case	Well Lake	3 x 10^{-4} g/a 3 x 10^{-2} g/a	> 1	Ni

7.1.3 Impact of Contaminants

The very small release of contaminants to the biosphere results in very small calculated concentrations. Maximum calculated total concentrations in biosphere media are shown in Table 7.10 for the Reference Case and Simplified Base Case. For comparison, surface waters have provincial background concentrations ranging from 0.02 to 0.19 Bq/L gross-beta (Section 5.6 of AMEC NSS 2011). Lake sediments from the Regional Study Area have Cs-137 concentrations of around 0.2 Bq/kg, and naturally occurring K-40 of around 250 Bq/kg (Section 5.7.1 of AMEC NSS 2011). Soils have concentrations of K-40 and Cs-137 ranging from 446 to 500 Bq/kg and 2.7 to 3.9 Bq/kg (respectively) at provincial background locations (Section 5.8.4 of AMEC NSS 2011).

Table 7.10: Summary of Maximum Calculated Biosphere Concentrations

Calculation Case	Well Water (Bq/L)	Soil (Bq/kg)	Surface Water (Bq/L)	Sediment (Bq/kg)
NE-RC: Reference Case	6 x 10^{-15}	5 x 10^{-15}	1 x 10^{-17}	1 x 10^{-14}
NE-SBC: Simplified Base Case	3 x 10^{-12}	4 x 10^{-12}	6 x 10^{-15}	3 x 10^{-13}

The calculated radionuclide concentrations in the biosphere for both the Reference and Simplified Base Cases are more than ten orders of magnitude smaller than the screening ‘no effect concentrations’ for impacts on non-human biota given in Table 3.3. The calculated concentrations of non-radioactive contaminants in biosphere media for the Reference Case are also much (more than five orders of magnitude) smaller than the environmental quality standards for groundwater, soils, surface water and sediments designed to protect human health and the environment given in Table 3.4 (see Table 6.1 of QUINTESSA 2011a).

The calculated doses to the Site Resident Group resulting from these very small concentrations are negligible and are summarized in Table 7.11. The calculated doses for both the Reference

Case and Simplified Base Case are much smaller than the dose criterion of 0.3 mSv/a. For comparison, the typical dose from background sources of radiation is 1.8 mSv/a.

Table 7.11 gives the calculated doses to adults. Calculated doses to children and infants are marginally (i.e., less than a factor of two) higher for the Reference Case and the Simplified Base Case and so are also much smaller than the dose criterion of 0.3 mSv/a.

Table 7.11: Summary of Maximum Doses to an Adult

Calculation Case	Max. Calculated Dose (mSv/a)	Time of Max. Calculated Dose (Ma)	Main Radionuclide Contributing to the Max.
NE-RC: Reference Case	2×10^{-15}	> 1	I-129
NE-SBC: Simplified Base Case	1×10^{-13}	> 1	I-129

7.1.4 Reference Case for the Final Preliminary Design

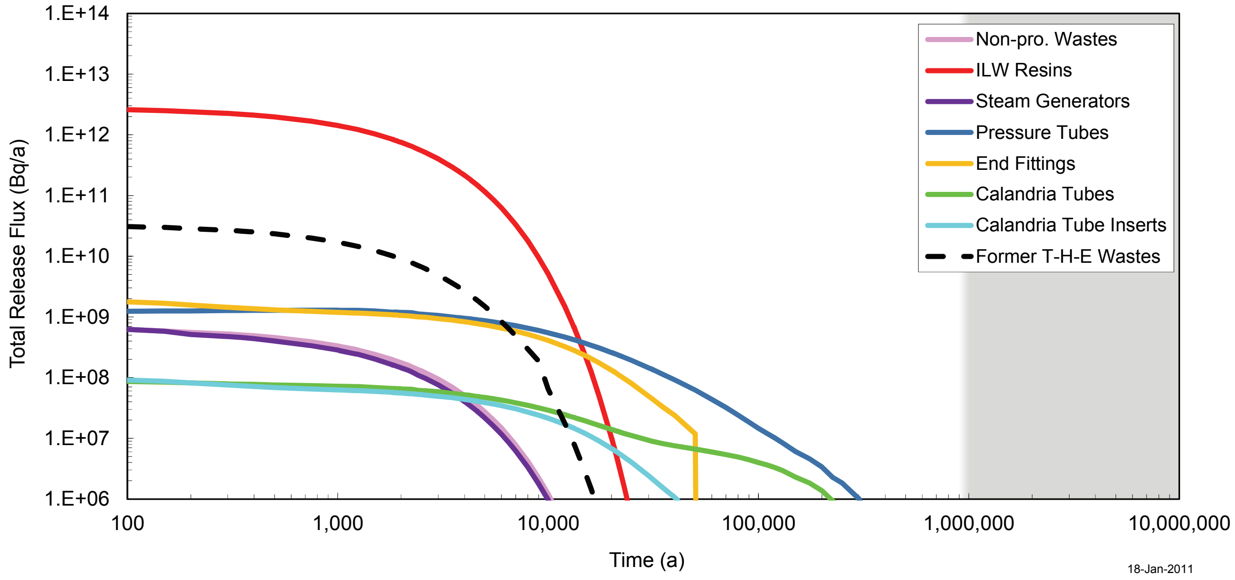
This case is the same as the Reference Case (NE-RC), but based on the final preliminary repository design:

- Added ventilation drifts and service areas, resulting in the increase in the repository void volume from about 4.2×10^5 m^3 to about 4.5×10^5 m^3; and
- Disposal of ILW filters and elements, irradiated core components, and IX columns in ILW shield containers rather than concrete T-H-E arrays.

The ILW filters and elements, irradiated core components, and IX columns waste categories are taken to be disposed in ILW shield containers in the final preliminary design, whereas they were raised off the repository floor in large concrete T-H-E arrays in the Reference Case above the water level in the repository. As with other containers, the ILW shield containers are conservatively assumed to fail from the start of the calculations, allowing contaminants to be released. Figure 7.16 shows the calculated radionuclide release for these waste categories (labelled “Former T-H-E Wastes”) for the NE-PD-RC case. The figure highlights that total releases are dominated by those from the ILW resins, which are about two orders of magnitude higher than the releases from the “former T-H-E wastes”.

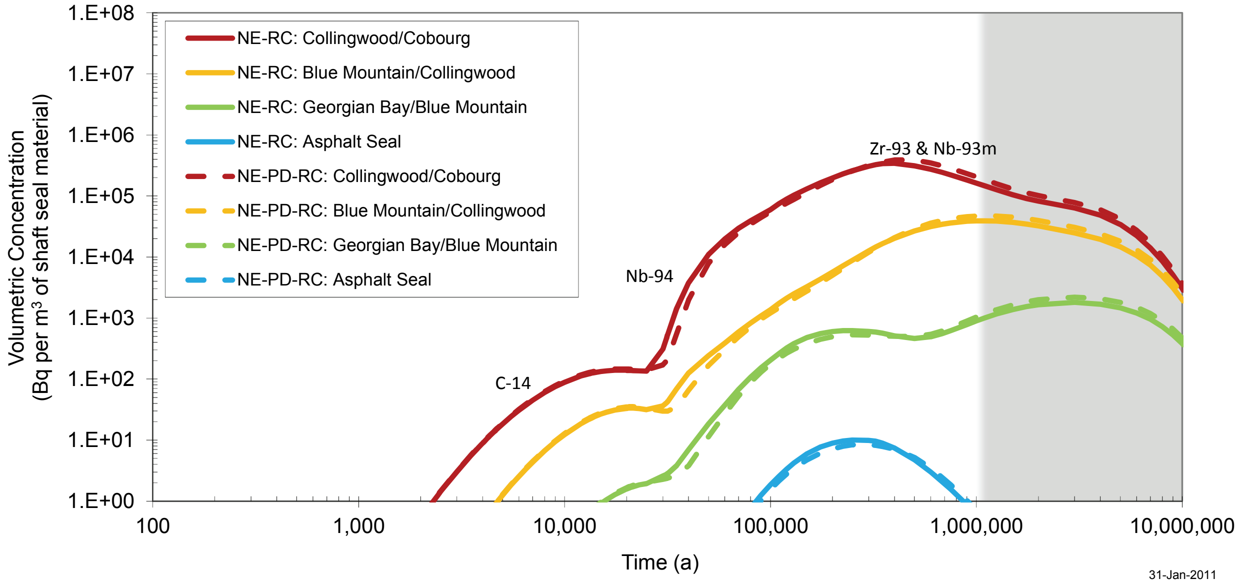
T2GGM indicates that the repository saturation profiles for the original and final preliminary design Reference Case (NE-RC and NE-PD-RC) are very similar. T2GGM and FRAC3DVS-OPG results show that groundwater flows in the vicinity of the DGR are also similar (see Section 5.11 of GEOFIRMA 2011, and Section 5.15 of GEOFIRMA and QUINTESSA 2011). Calculated radionuclide fluxes to the shaft and via the shaft to the Shallow Bedrock Groundwater Zone and biosphere are, therefore, similar (see for example Figure 7.17).

The maximum calculated dose to the adult member of the Site Resident Group is 1.8×10^{-15} mSv/a for the final preliminary design, which compares to 1.5×10^{-15} mSv/a for the Reference Case (NE-RC-A). This result, therefore, indicates that the final preliminary design changes have little impact on the assessment results.



Note: Figure 5.10 in QUINTESSA (2011a).

Figure 7.16: Total Radionuclide Releases from the Disposed Waste for the Final Preliminary Design Case (NE-PD-RC-A)



Note: Figure 5.11 in QUINTESSA (2011a).

Figure 7.17: Volumetric Concentration in Successive Shaft Compartments for the Reference Case (NE-RC-A) and Final Preliminary Design Case (NE-PD-RC-A)

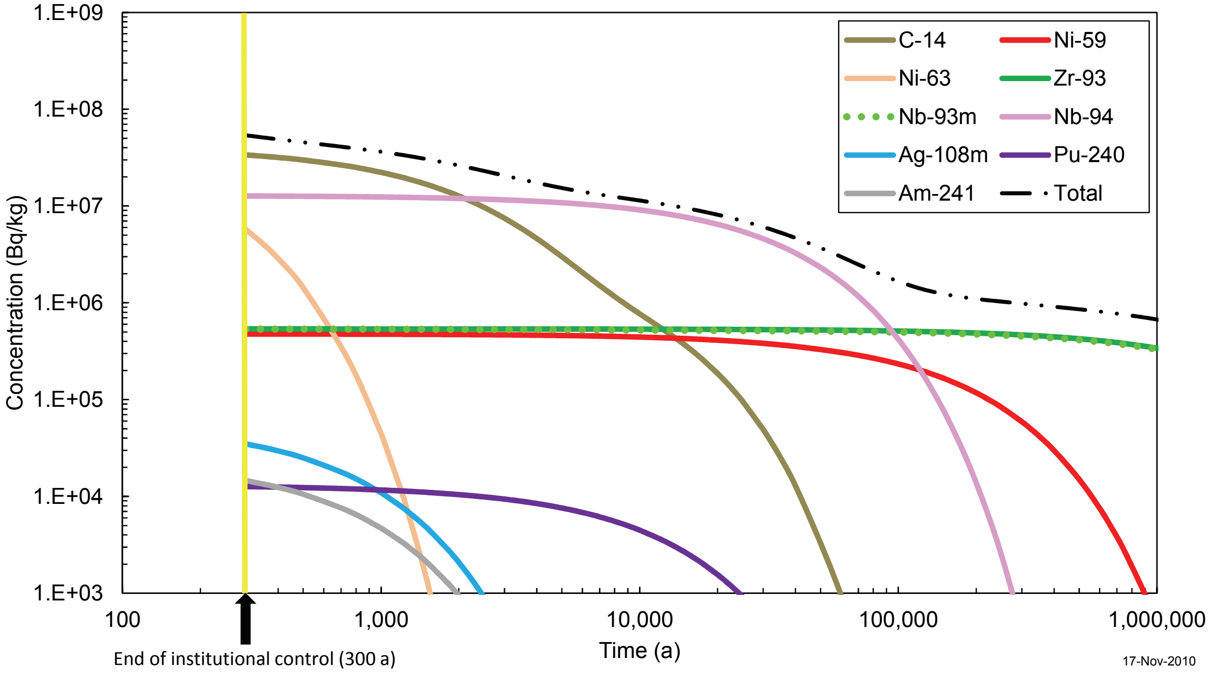
7.2 Disruptive Scenarios

The disruptive events initiating the Disruptive Scenarios considered in the assessment are expected to be very unlikely (see the Analysis of Human Intrusion and Other Disruptive Scenarios report, QUINTESSA and SENES 2011). The likelihood of the as-modelled scenarios occurring is even lower as the scenarios make additional conservative assumptions, for example relating to human practices. Nevertheless, these scenarios provide insight into the robustness of the DGR system to disruptive events to be evaluated.

7.2.1 Human Intrusion

If an exploration borehole struck the DGR, contaminants could be released to the surface and result in exposure of people. The calculations assume intrusion into Panel 1 where radionuclide concentrations are highest.

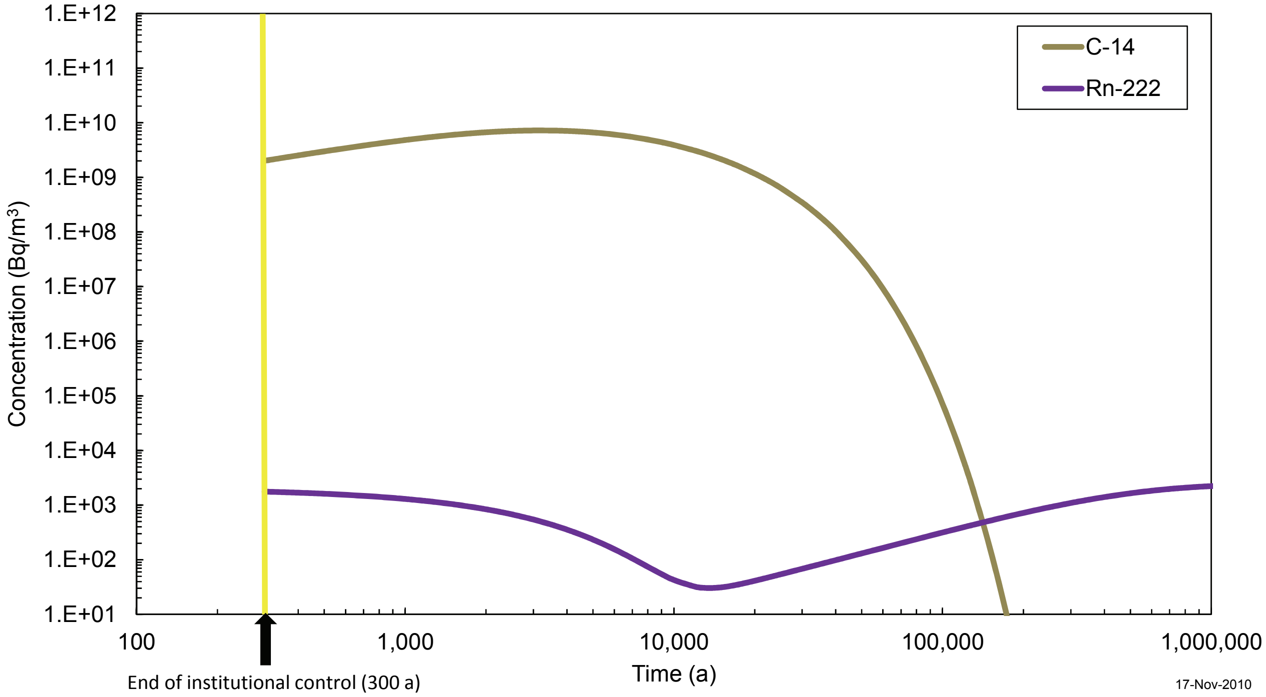
Under the Base Case conditions the saturation of the repository is less than 1% throughout the calculations (Section 8.1 of the Gas Modelling report, GEOFIRMA and QUINTESSA 2011), and under these conditions liquid would not be released from the repository via an intruding borehole since the repository is largely unsaturated. Average calculated concentrations in the wastes in Panel 1 are given in Figure 7.18, which shows that key contaminants include C-14, Ni-59, Nb-93m, Nb-94 and Zr-93.



Note: Figure 2.10 in QUINTESSA and SENES (2011).

Figure 7.18: Calculated Average Concentrations of Radionuclides in Wastes in Panel 1, as a Function of the Time for the Human Intrusion Base Case (HI-BC)

Gas is present in the repository at greater than atmospheric pressure throughout the assessment timeframe and would be released after the borehole penetrates the repository. Gas is expected to mix throughout the repository, so the concentrations reflect the overall average. Radionuclides potentially present in repository gas are H-3, C-14, Cl-36, Se-79, I-129 and Rn-222; however, only C-14 and Rn-222 are present at concentrations above 1 Bq/m^3 (see Figure 7.19). C-14, released primarily from ion exchange resins under saturated and unsaturated conditions, is present with the greatest activity. The concentration of C-14 in gas at repository pressure peaks after 3,000 years, then decreases due to radioactive decay (C-14 has a half-life of 5730 years). The concentration of Rn-222 decreases at first due to the decay of its Ra-226 parent (present as a sealed source in some wastes), but then shows ingrowth from longer-lived U-238/U-234[31].



Note: Figure 2.11 in QUINTESSA and SENES (2011).

Figure 7.19: Calculated Concentrations of Radionuclides in Repository Gas at Repository Pressure, Human Intrusion Base Case (HI-BC)

Calculations of the concentration of non-radioactive contaminants in soils contaminated by the drill core indicate that environmental quality standards given in Table 3.4 are not exceeded. If contaminated drill core is left on soil around the site (assumed to be an area of about 30 m x 40 m), then Pb, Ni, Cu, Mo and Cr concentrations are at about 10-30% of their environmental criteria, while all others are much lower (see Table 2.5 of QUINTESSA and SENES 2011).

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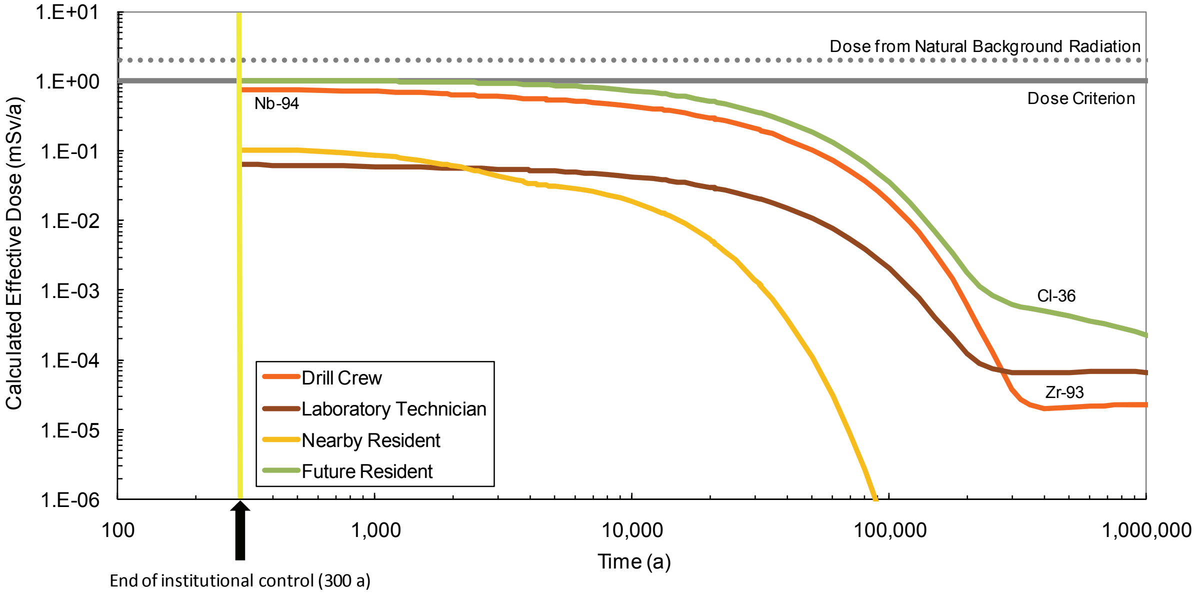
[31] These concentrations do not include loss of C-14 by isotope exchange with stable carbon in the carbonate rock, and trapping and decay of Rn within its source material.

Comparison of radionuclide concentrations in biosphere media against the screening 'no effect concentrations' given in Table 3.3 for non-human biota show that C-14 and Nb-94 exceed the screening criterion by about a factor of 20 within the site assuming that the contaminated drill core debris is left on site and mixed with soil, while other radionuclide concentrations are below their criteria by at least a factor of 7 (see Table 2.4 of QUINTESSA and SENES 2011). Since this intrusion is very unlikely and leaving drilling debris on site is against current regulations, and since any exposure is localized around the drill site, the risk is low. Furthermore, less conservative ecological risk assessment calculations show that the resulting doses to site-specific biota are around 3% of relevant dose criterion (Appendix G of QUINTESSA and SENES 2011).

A wide variety of exposure pathways could occur for this scenario, so a range of critical groups has been assessed – the drill crew[32] and nearby residents (i.e., within 100 m of the drill site) exposed during the drilling, laboratory technicians exposed to the core sample, and future residents exposed to soil contaminated with the extracted core[33] (see Section 6.2.2.4). Calculated doses for these critical groups are shown in Figure 7.20.



Note: Figure 2.14 in QUINTESSA and SENES (2011).

Figure 7.20: Calculated Doses from Surface Release of Gas and Drill Core Resulting from Human Intrusion, as a Function of the Time of Intrusion, for the Human Intrusion Base Case (HI-BC)

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[32] Both short-term exposure to undiluted drill core and gas for one shift (instantaneous) and longer-term exposure (30 days) from working in contaminated area prior to sealing of the borehole (chronic) are assessed.

[33] No account is taken of either radioactive decay in the soil or the leaching of radionuclides from the soil in calculating the dose to the future resident following the mixing of extracted core with the soil. However, as with all other human intrusion exposure pathways, any decay and leaching within the repository prior to the intrusion event is taken into account.

The future resident (i.e., a person subsequently living on the site and using soil contaminated with drill core debris) could receive a peak annual dose of 1.0 mSv, based on the average concentration of radionuclides in Panel 1 wastes, with external irradiation from Nb-94 being the dominant pathway. The drill crew, exposed to contaminated drill core debris receives a dose of 0.8 mSv. A nearby resident assumed to live close to the drilling site and therefore also exposed to the contaminated gas receives a peak dose of 0.1 mSv from the inhalation of C-14. The doses to those involved with inspecting any wastes in retrieved drill core are 0.06 mSv and are dominated by external irradiation by Nb-94. The Human Intrusion Scenario has a low probability of occurrence. As an indication, an exploratory deep borehole drilling rate of around $10^{-10}/m^2/a$ (equivalent to one deep borehole per 100 years per 10 km x 10 km area), and an area of around 0.1 km^2 (0.065 km^2 for waste area, ~0.25 km^2 for total panel area) correspond to a probability of occurrence of about $10^{-5}/a$. This is a low probability per year. Over long time scales, it becomes likely – however, the potential dose impacts also decrease over long times, and in particular intrusion impacts become small after about 100,000 years.

Based on a probability of $10^{-5}/a$, a peak dose of 1 mSv and a health risk of 0.057/Sv (ICRP 2007), the associated risk of serious health effects is around $6 \times 10^{-10}/a$, well below the reference health risk value of $10^{-5}/a$ (Section 3.4.2).

Standard practice requires that any site investigation borehole is sealed once investigations are complete. However, the scenario analysis also considered “what if” the borehole is poorly sealed, resulting in a continuing pathway for contaminants from the DGR to the Shallow Bedrock Groundwater Zone after an intrusion event immediately at the end of institutional control (300 years). In this case, it is found that there are no further consequences, because the repository is not pressurized and there is little groundwater flow up the borehole.

Detailed modelling has shown that contaminants could only be released from the repository through the borehole if the intruding borehole penetrated through the repository and was continued down into the pressurized Cambrian rocks and was not appropriately sealed (see Sections 6.1 and 6.2 of GEOFIRMA 2011). In this highly improbable case, the peak calculated dose to an adult member of the Site Resident Group would be around 30 mSv/a, occurring after 400 years, decreasing to 0.003 mSv/a after 60,000 years assuming that there is a family farming on the site using a well that directly intercepts contaminated groundwater from the borehole. The dose is dominated by exposure to C-14 via plant ingestion, due to the use of contaminated well water for irrigation. Assuming the same probability of occurrence as for intrusion into the repository (thereby conservatively assuming the probability of continuing into the Cambrian and poorly sealing the borehole is unity), the peak dose equates to a risk of around 2×10^{-8} of serious health effects per year, more than two orders of magnitude below the reference health risk value of $10^{-5}/a$.

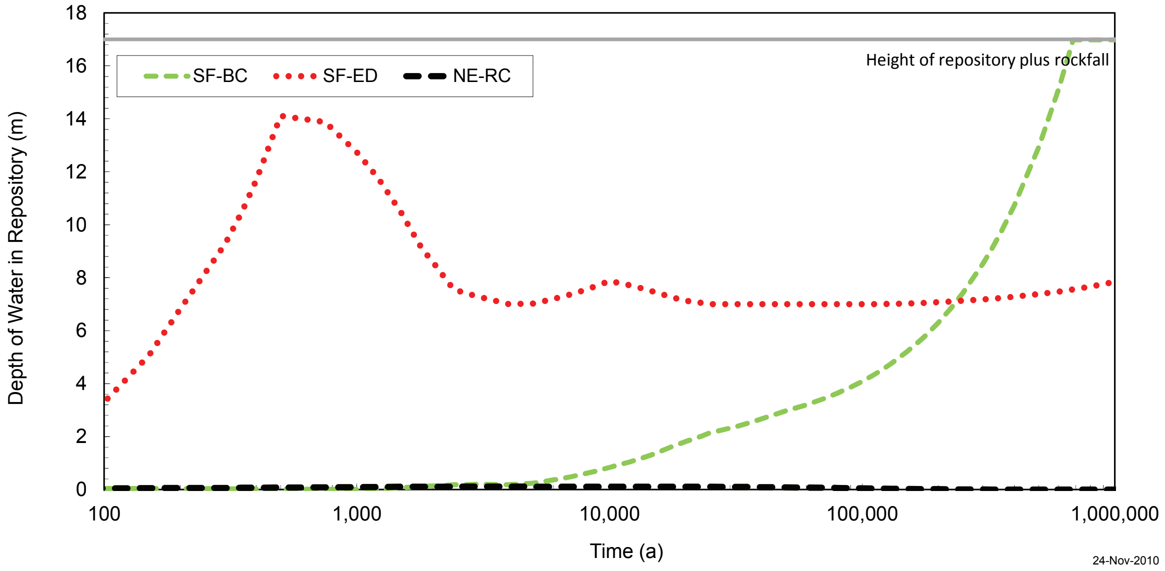
7.2.2 Severe Shaft Seal Failure

The shaft seals are a key element of the DGR system. The shaft seal system includes multiple components and uses a range of materials that act individually and collectively as a barrier to contaminant transport. The “what if” Severe Shaft Seal Failure Scenario assesses a hypothetical situation in which there is a major breakdown in the performance of all of these barriers. Two situations are considered.

- A Base Case for which the hydraulic conductivity of all shaft seals is conservatively set at 10^{-9} m/s (i.e., at the top end of the range for bentonite-sand given in Section 4.5.2.2. of the Data report, QUINTESSA and GEOFIRMA 2011a) with a porosity of 30% (SF-BC).
- An extra conservative case in which the hydraulic conductivity of all shaft seals is set to 10^{-7} m/s with a porosity of 30%, which is equivalent to fine silt and sand (SF-ED). This case is intended to test the parameter values at which shaft seals are not effective.

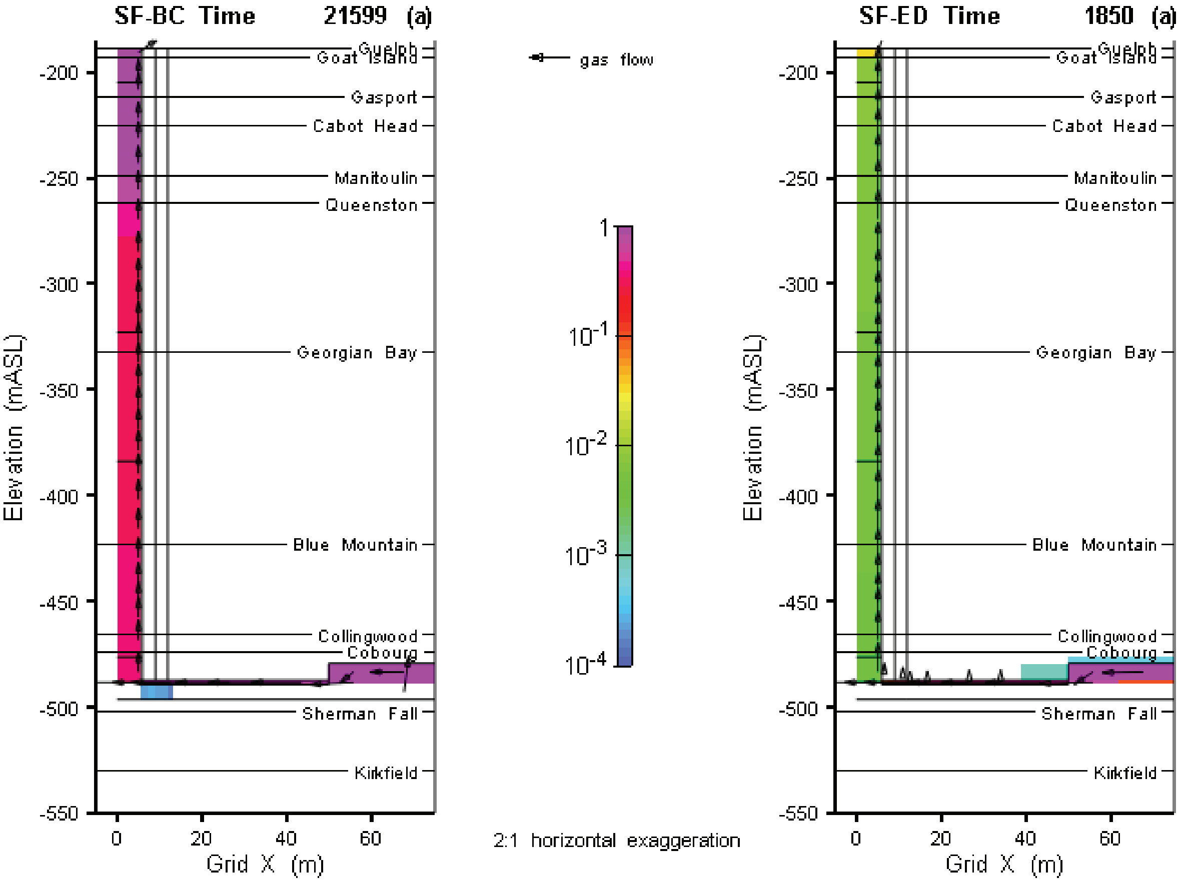
The degradation is assumed to be present at time of closure. The initial conditions at this time also include the underpressures observed in Ordovician formations. The hydraulic conductivity of the repository/shaft damage zones are set at the maximum values given in the Data report (Tables 5-7 and 5-8 of QUINTESSA and GEOFIRMA 2011a).

The degraded shaft seals permit more rapid water inflow into the repository. Detailed modelling shows a greater degree of repository saturation in comparison to the Normal Evolution Scenario’s Reference Case (Figure 7.21). The resulting gas generation and reduced shaft seal capability allows the repository gas pressure to open a pathway that enables the repository gas to vent up the shafts (Figure 7.22). In the case of SF-BC, this gas pathway is established after about 20,000 years. In the SF-ED case, the pathway is established after about 1800 years, with the subsequent gas flow rate fluctuating as the water level in the DGR changes (Sections 6.1.2 and 6.2.2 of GEOFIRMA and QUINTESSA 2011).



Note: Figure 3.2 in QUINTESSA and SENES (2011).

Figure 7.21: Depth of Water in the Repository for the Severe Shaft Seal Failure Cases

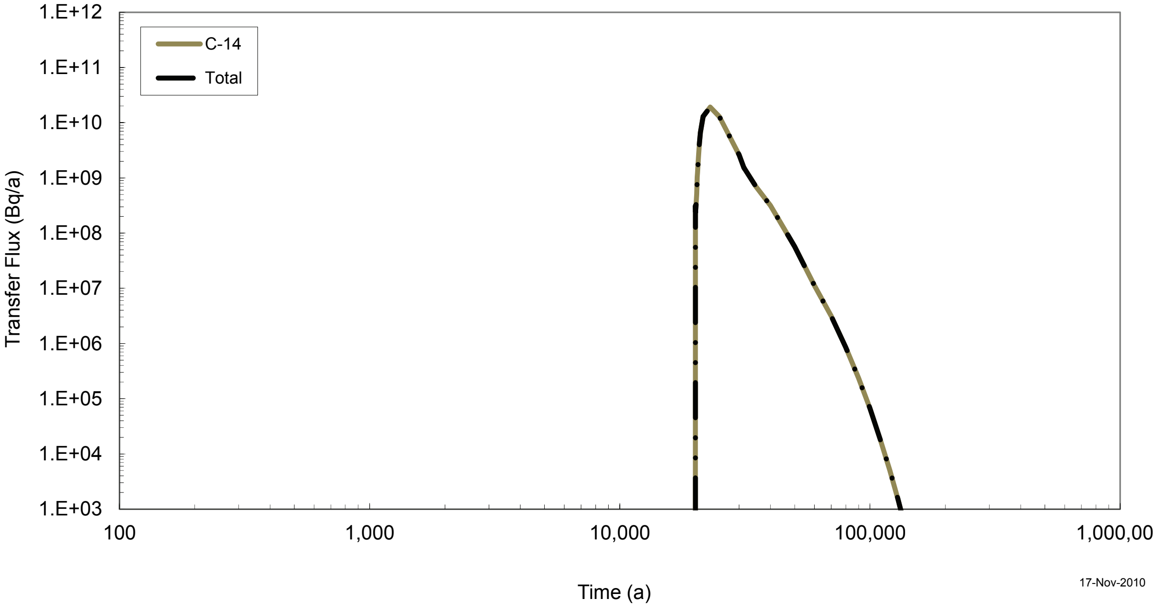


Note: Figures 6.6 and 6.22 in GEOFIRMA and QUINTESSA (2011).

Figure 7.22: Shaft Gas Saturations and Flows for the SF-BC (Left) and SF-ED (Right) Cases Showing Gas Venting via the Shafts

Figure 7.23 shows the calculated flux of radionuclides to the Shallow Bedrock Groundwater Zone for the Base Case (SF-BC). The flux to the shallow system is dominated by C-14 in gaseous form. There is essentially no transfer of radionuclides in groundwater to the shallow system. The gas phase in the DGR at the time that a gas pathway is established to the shallow system is dominated by CH_4 (96%). The bulk gas reaches the shallow system at a rate of up to 840 kg/a at about 22,000 years for the SF-BC case.

At this gas flow rate through the shafts, about 5% of this gas would dissolve in the flowing groundwater in the Shallow Bedrock Groundwater Zone (see Appendix H of QUINTESSA and SENES 2011). The bulk gas carries C-14 labelled gases from the DGR, which can similarly dissolve in groundwater in the shallow system. Calculated concentrations in well water peak at about 3 Bq/L after about 23,000 years for this Base Case.



Note: Figure 3.3 in QUINTESSA and SENES (2011).

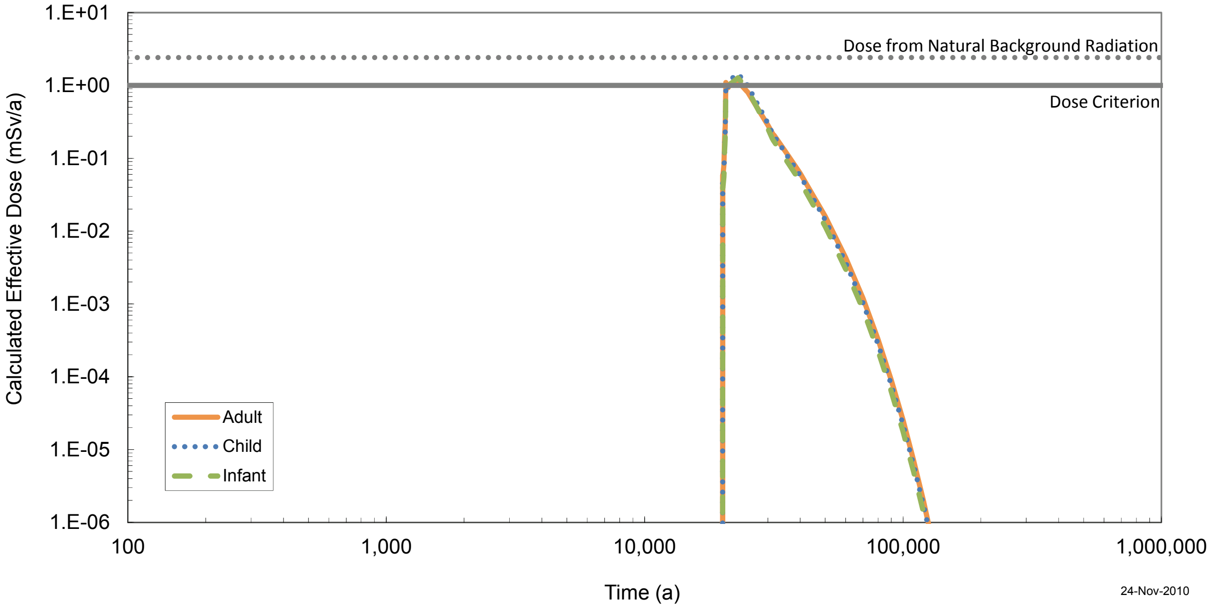
Figure 7.23: Calculated Radionuclide Transfer Flux to the Shallow Bedrock Groundwater Zone the Shaft for the Severe Shaft Seal Failure Scenario, Base Case (SF-BC)

About 95% of the peak gas flux to the shallow system does not dissolve in the groundwater and reaches the biosphere as free gas. Some of this bulk gas enters a house that is conservatively assumed to be positioned directly above the main shaft. The calculated radionuclide concentrations in the air inside the house peak at about 16,000 Bq/m^3 after about 23,000 years based on nominal air exchange rates.

Calculated concentrations in biosphere media (soils, surface water, and sediment) remain relatively low for the Base Case (see Tables 3.5 and 3.6 of QUINTESSA and SENES 2011). The peak calculated concentrations for C-14 in soils and sediments remain below the screening No Effect Concentration criteria for protection of non-human biota given in Table 3.3, but the peak calculated C-14 concentration in local surface water of 0.3 Bq/L is a factor of 1.4 above the associated criteria. Since this scenario is unlikely, the exceedance is local (the nearby stream), and the criteria is conservative, the risk from this disruptive scenario is low. Calculated biosphere concentrations for all other radionuclides are more than seven orders of magnitude below their associated no effect concentrations.

There is a negligible release of non-radioactive contaminants via the groundwater pathway, and all calculated values are at least four orders of magnitude below the environmental quality standards given in Table 3.4.

The Base Case results in a calculated dose to the Site Resident Group that reaches a maximum of 1.1 mSv/a after about 23,000 years (see Figure 7.24). This coincides with the peak release of C-14 labelled gases to groundwater in the Shallow Bedrock Groundwater Zone and directly to the biosphere. The dominant exposure pathways are inhalation within the house, which is positioned directly above the main shaft, and ingestion of plant produce, each of which contributes about 40% of the calculated peak dose. It is noted that a scenario likelihood of around 10^{-1} or less per year would result in the risk of serious health effects being less than the reference health risk value of 10^{-5}/a. The probability of severe shaft seal degradation combined with a house positioned directly above one of the shafts can reasonably be considered to be significantly lower than this.



Note: Figure 3.6 in QUINTESSA and SENES (2011).

Figure 7.24: Calculated Effective Doses to the Site Resident Group for the Severe Shaft Seal Failure Scenario, Base Case (SF-BC)

For the extra degradation shaft seal failure case (SF-ED), the calculated flux of contaminants to the Shallow Bedrock Groundwater Zone is again dominated by the transport of C-14 labelled gases with bulk gases via the shafts. The assumptions for the degradation of the shaft seals in the SF-ED case result in a calculated dose to an adult member of the Site Resident Group that reaches about 80 mSv/a after around 3800 years. The dominant radionuclide is C-14 and the dominant exposure pathway is inhalation within the house, which is positioned directly above the main shaft and contributes about 75% of the peak calculated dose. It is emphasized that this calculation case is an extremely conservative case and was undertaken with the purpose of investigating the sensitivity of dose impacts to shaft seal properties.

These Severe Shaft Seal Failure cases would require around 500 m of low-permeable shaft seals to degrade so as to have an effective conductivity of 10^{-9} m/s or higher. This is very unlikely under the DGR conditions of low-flow, low-temperature, and use of multiple low-permeable seal materials. It is also noted that this scenario would have little consequence if the degradation occurred after about 60,000 years when C-14 would have significantly decayed. This is also the earliest time that ice-sheets from the next glacial cycle might be expected, so glacial cycles are not an important factor.

7.2.3 Poorly Sealed Borehole

Site investigation and monitoring boreholes will be appropriately sealed at the end of their useful lifetime. However, if a borehole was not properly sealed or its seal was degraded, it could bypass some of the barriers of the DGR system. Like the Severe Shaft Seal Failure Scenario, such a situation would be very unlikely as good practice and quality control would prevent such a situation occurring. Nevertheless, it is assessed as a “what if” scenario to inform on the overall robustness of the DGR system.

The scenario considers a poorly sealed borehole that extends from the surface to the Precambrian beneath the DGR and provides an additional pathway for contaminants from the rock in the vicinity of the repository to be transported to the Shallow Bedrock Groundwater Zone. Detailed modelling (Section 6.5 of GEOFIRMA 2011) indicates that the borehole has limited influence on the hydraulic conditions at the repository horizon because of the very low permeability host rock around the DGR. The results also indicate that the flow of water up the borehole is relatively small, discharging up to 15 m^3/a into the shallow system that is flowing at a rate of about 60,000 m^3/a.

Contaminants in the DGR need to diffuse through 100 m of host rock before they can be transported to the Shallow Bedrock Groundwater Zone via the poorly sealed borehole. The calculations are conservatively based on a repository that is resaturated at closure, which maximizes the release of contaminants to groundwater. Figure 7.25 shows the calculated radionuclide transfer flux to the shallow system via the poorly sealed borehole. The figure shows that the poorly sealed borehole provides a pathway for contaminants to the shallow system; however, the calculated total release is small (compared to a present-day flux of 4 MBq/a in the shallow groundwater over the model footprint; see Section 7.1.2) in spite of the extremely conservative assumptions adopted.

Calculated concentrations in biosphere media are very small, such that radionuclide concentrations are more than seven orders of magnitude lower than ‘no effect concentrations’ for non-human biota given in Table 3.3 (see Table 4.3 of QUINTESSA and SENES 2011). Concentrations of non-radioactive contaminants are more than three orders of magnitude lower than the associated environmental quality standards given in Table 3.4 (see Table 4.4 of QUINTESSA and SENES 2011).

The calculated dose to an adult member of the Site Resident Group is very small, peaking at 4×10^{-8} mSv/a after about 900,000 years. Maximum calculated doses to all age groups are much lower than the 1 mSv/a dose criterion[34].

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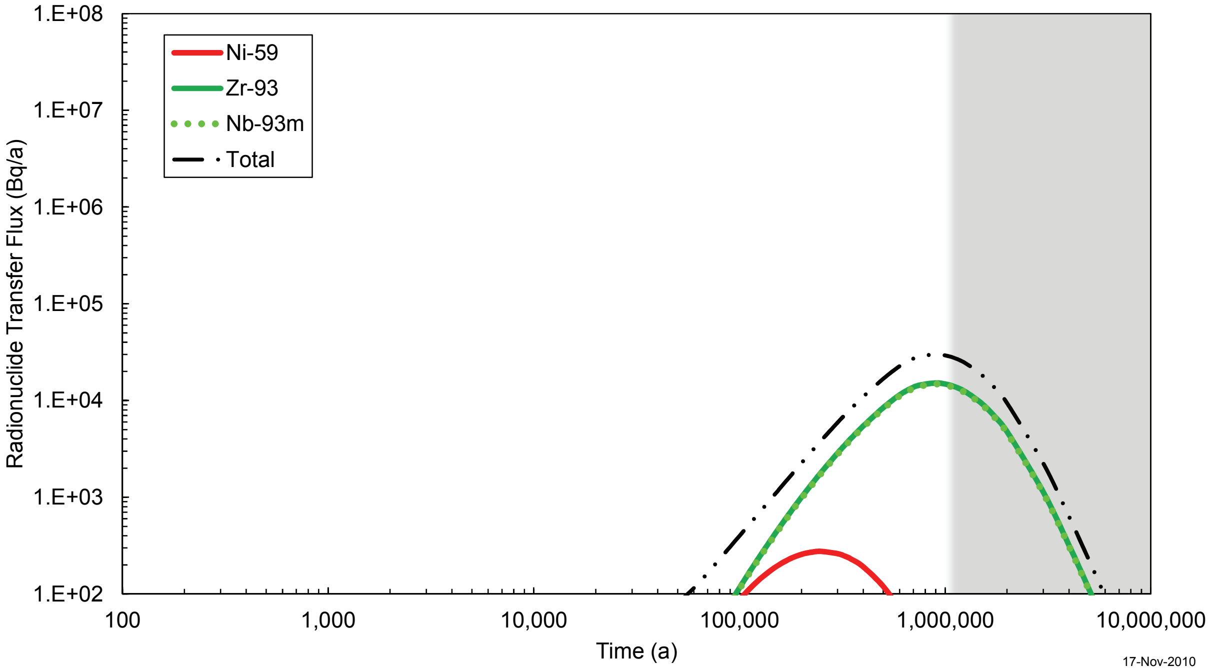
[34] This is based on the calculated well capture rate for a self-sufficient farm well at 80 m depth in the Shallow Bedrock Groundwater Zone (Section 5.2.2.2 of GEOFIRMA 2011). However, even if 100% of the contaminant flux through the borehole were to be captured by a small single-family domestic well of about 520 m^3/year (i.e., no dilution in the Shallow Bedrock Groundwater Zone), the peak drinking water dose would be about $3x10^{-5}$ mSv/a.



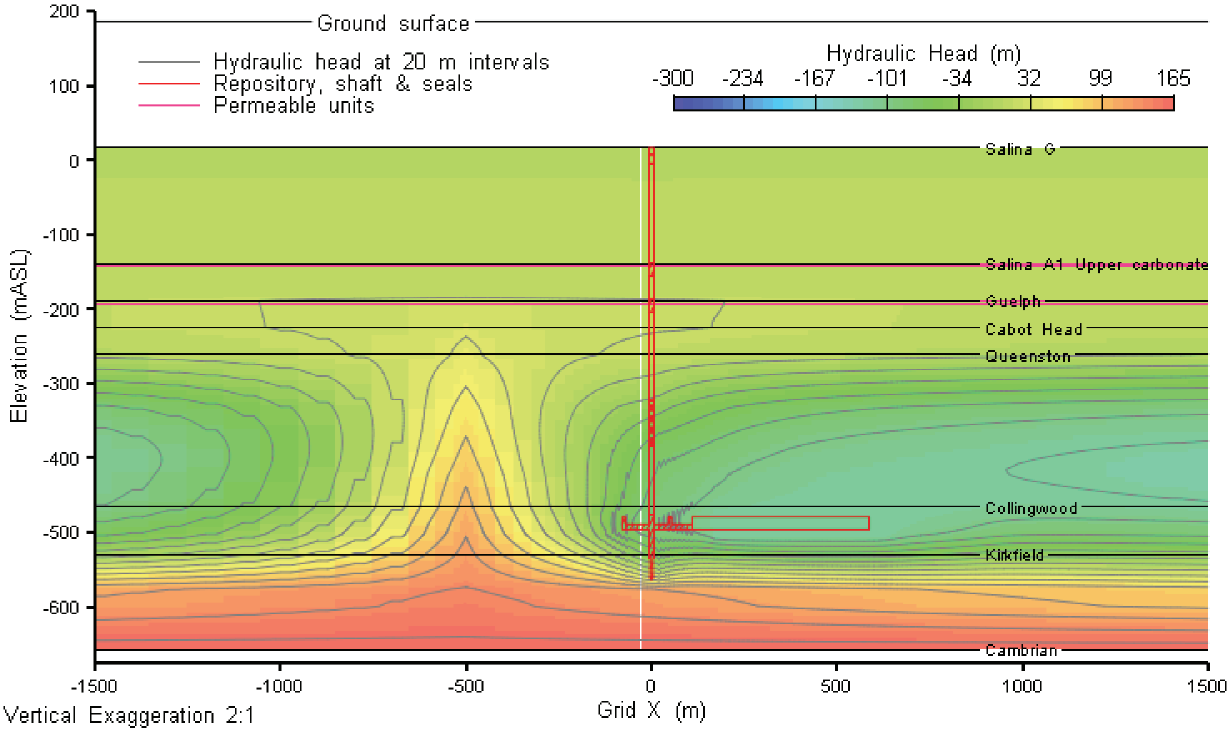
Note: Figure 4.3 in QUINTESSA and SENES (2011).

Figure 7.25: Calculated Radionuclide Transfer Flux to the Shallow Bedrock Groundwater Zone via the Poorly Sealed Borehole

7.2.4 Vertical Fault

There is strong geological, hydrogeological, and geochemical evidence that there are no vertical faults/fracture zones in the vicinity of the DGR that provide enhanced permeability pathways from the repository horizon to higher horizons (Section 4.3.1). Furthermore, the DGR site is located in a seismically stable region, so very large earthquakes that may reactivate any unidentified, existing, closed zone are very unlikely. Also the repository is designed to handle the likely earthquakes for the area. Nevertheless, a “what if” scenario is considered to investigate the safety implications of a hypothetical vertical fault that provides a relatively high-conductivity pathway from the repository depth to the Guelph formation in the Intermediate Bedrock Groundwater Zone. Further, the Guelph formation is assumed to connect to the near-shore lake, 1.25 km away. Two fault locations are considered, one at 500 m to the northwest of the repository (VF-BC) and an alternative case where the fault is located 100 m to the southeast of the repository (VF-AL).

The detailed groundwater modelling shows that the VF-BC case only has a minor impact on the hydraulic conditions in the repository (Section 6.6 of GEOFIRMA 2011). Since any vertical fault would connect to the pressurized Cambrian, a pressure gradient develops which directs groundwater movement away from the fault (Figure 7.26). Contaminants in the repository need to diffuse either directly to the fault (against the hydraulic gradient) or downwards to the Cambrian and then via groundwater flow to the fault, before they can be transported by groundwater advection up the fault to the Guelph formation. The results indicate that the resulting radionuclide transfer flux to the Guelph peak at about 3 MBq/a after more than one million years.



Note: Figure 6.25 in GEOFIRMA (2011).

Figure 7.26: Hydraulic Heads for the VF-BC Case

Horizontal groundwater flow in the Guelph is assumed to discharge to the near-shore of the lake. The resulting dispersion means that calculated concentrations are at least seven orders of magnitude smaller than the 'no effect concentrations' for non-human biota given in Table 3.3 (see Table 5.3 of QUINTESSA and SENES 2011). Calculated concentrations of non-radioactive contaminants are more than four orders of magnitude below the associated environmental quality standards given in Table 3.4 (see Table 5.4 of QUINTESSA and SENES 2011).

Calculated doses for the VF-BC case are similarly very small; the peak calculated dose to the maximally exposed group (the shore group) is 5 x 10^{-10} mSv/a, much smaller than the dose criterion of 1 mSv/a[35].

Diffusion of contaminants over the entire repository footprint down to the Cambrian dominates over diffusion from the side of the DGR as a transport pathway to the fault. Therefore, the closer proximity of the fault to the DGR for the variant fault location case (VF-AL) has relatively little impact on the calculated contaminant fluxes via the fault and the peak calculated dose to the maximally exposed group (the shore group) is the same, at 5 x 10^{-10} mSv/a.

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[35] The peak concentration in the water entering the Guelph from the fault is about 500 Bq/L. Consumption of water at this concentration would result in a dose of around 0.3 mSv/a, if it were assumed that water was pumped directly from the Guelph Formation without any treatment. Note also that the TDS content of Guelph water is around 375 g/L, 13 times higher than seawater, so the water is not drinkable without significant dilution or treatment.

7.3 Assessment of Uncertainties

As noted in Section 3.6, uncertainties can be considered in three categories.

- **Future or scenario uncertainty** – uncertainty in the evolution of the repository system over the timescales of interest. This has been addressed through assessing a range of potential future evolutions of the DGR system.
- **Model uncertainty** – uncertainty in the conceptual, mathematical and computer models used to simulate the behaviour of the repository system. This has been investigated through the application of a range of detailed and assessment-level models, which use differing representations of the system, and through variant calculation cases.
- **Data uncertainty** – uncertainty in the parameters used as input in the modelling. This has been investigated through variant deterministic calculation cases and through probabilistic treatment.

The results from the calculation cases identified in Section 6.3 provide information that can be used to assess the importance of the various sources of uncertainty. The results are summarized below; a more detailed analysis is provided in the supporting modelling reports (QUINTESSA 2011a, QUINTESSA and SENES 2011, GEOFIRMA 2011 and GEOFIRMA and QUINTESSA 2011).

7.3.1 Scenario Uncertainty

A Normal Evolution Scenario and four Disruptive Scenarios (Human Intrusion, Severe Shaft Seal Failure, Poorly Sealed Borehole and Vertical Fault) have been evaluated in the current assessment. The Disruptive Scenarios are unlikely (“what if”) events and are used to test the robustness of the DGR.

Results for the reference/base cases for these scenarios are summarized in Table 7.12. Very low contaminant releases to the Shallow Bedrock Groundwater Zone and very low maximum annual doses are calculated for the Normal Evolution Scenario, well below the dose criterion of 0.3 mSv/a.

For the Disruptive Scenarios, the maximum calculated doses for the Human Intrusion and Severe Shaft Seal Failure cases are at or just below the dose criterion of 1 mSv/a for times up to about 30,000 a. However, when the low likelihood of such scenarios is taken into account, the health risk criterion of 10^{-5}/a is not exceeded. The maximum calculated doses for the Poorly Sealed Borehole and Vertical Fault Scenarios remain well below the dose criterion at all times.

For the Human Intrusion Scenario, "what-if" calculations indicate that significant doses (tens of milliSieverts) via the groundwater release pathways would require that the intrusion borehole is drilled past the repository and down into the Cambrian formation, and that the borehole is not appropriately sealed, allowing for long-term flow of water from the Cambrian through the repository and then to the Shallow Bedrock Groundwater Zone. For the Severe Shaft Seal Failure Scenario, significant doses require that the entire shaft seal system (500 m of low-permeable material) would have to degrade to an effective conductivity of around 10^{-7} m/s, roughly equivalent to fine sand and silt. In both cases, the doses would apply to someone living directly on the repository site; impacts further afield (i.e., off the Bruce nuclear site) would be much lower.

In the Disruptive Scenarios with highest calculated dose impacts (Human Intrusion and Severe Shaft Seal Failure), C-14 is the important radionuclide (as well as Nb-94 in human intrusion). These impacts become small on timescales of 60,000 a due to decay of C-14. This is also the earliest likely time for the onset of the next glacial cycle. Therefore, future glaciations are unlikely to cause larger impacts than calculated for these Disruptive Scenarios.

Table 7.12: Maximum Calculated Doses and Fluxes for the Assessed Scenarios

Scenario	Maximum Dose to an Adult (mSv/a)	Maximum Radionuclide Flux into Shallow Bedrock Groundwater Zone	
		Groundwater (Bq/a)	Free Gas (Bq/a)
Normal Evolution: Reference Case Simplified Base Case	 2×10^{-15} * 1×10^{-13} *	 3×10^{-6} * 2×10^{-3}	 0 0
Human Intrusion Base Case	1	n/a ^	n/a ^
Severe Shaft Seal Failure Base Case	1	5	2×10^{10}
Poorly Sealed Borehole † Base Case	4×10^{-8}	3×10^{4}	n/a
Vertical Fault † Base Case	5×10^{-10} *	n/a #	n/a

Notes:

† Based on repository being fully resaturated at closure. No gas releases.

* Occurs at the end of the calculation period (10 Ma).

^ Release is direct to surface in Human Intrusion Scenario base case.

Releases are intercepted by Guelph and discharged into lake, bypassing the Shallow Bedrock Groundwater Zone.

7.3.2 Conceptual Model and Data Uncertainty

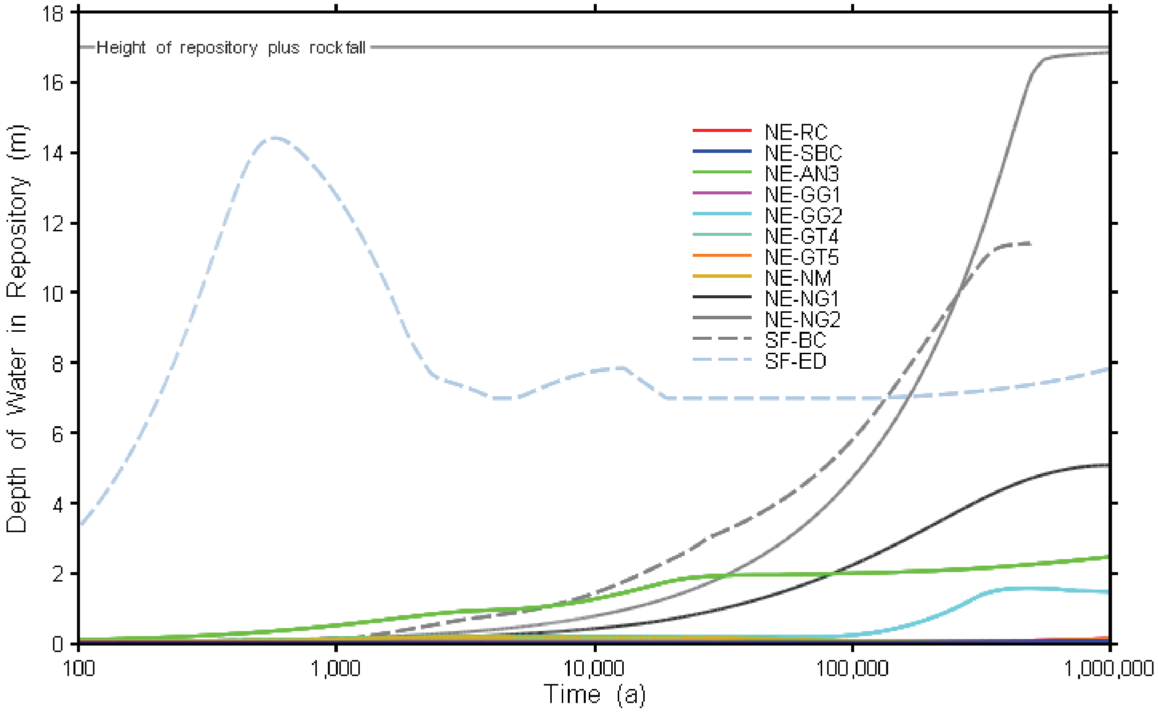
Model and data uncertainties associated with the scenarios are addressed through the evaluation of a set of calculation cases that are designed to bound the effects of these uncertainties. These cases are summarized in Table 6.5 and Table 6.7, and Figure 7.1 and Figure 7.2. The cases are discussed with respect to the following uncertainties:

- Repository resaturation;
- Waste inventory;
- Contaminant release rates;
- Gas generation;
- Geosphere gas properties;
- Geosphere transport properties;
- Shaft seal performance;
- Geosphere over- and underpressures;
- Geosphere horizontal flow;
- Critical groups; and
- Glaciation.

7.3.2.1 Repository Resaturation

The detailed gas and groundwater calculations indicate that the repository will not resaturate over the timescales considered in the assessment (beyond one million years) due to the gas pressure within the repository and the relative impermeability of the host rock and shaft seals. This is important because it increases the volume available for gas and minimizes the potential for radionuclides to be released into groundwater and to migrate from the repository.

Figure 7.27 shows an overlay of the calculated saturation levels from detailed gas modelling results, including modelling of water seepage into the repository but not water-consuming corrosion and degradation reactions. These cases conservatively do not enforce a water balance on the corrosion and degradation reactions, i.e., they ignore the effect of the consumption (or production) of water by corrosion and degradation reactions. The results show that the repository is less than half saturated for all cases except those where the shaft is highly permeable and is able to supply water to the DGR (SF-BC and SF-ED) or where there is no gas generation within the DGR and the Ordovician underpressures are not considered (NE-NG2).



Note: Figure adapted from Figure 8.3 in GEOFIRMA and QUINTESSA (2011).

Figure 7.27: Depth of Water in Repository (Non-Water-Limited Cases)

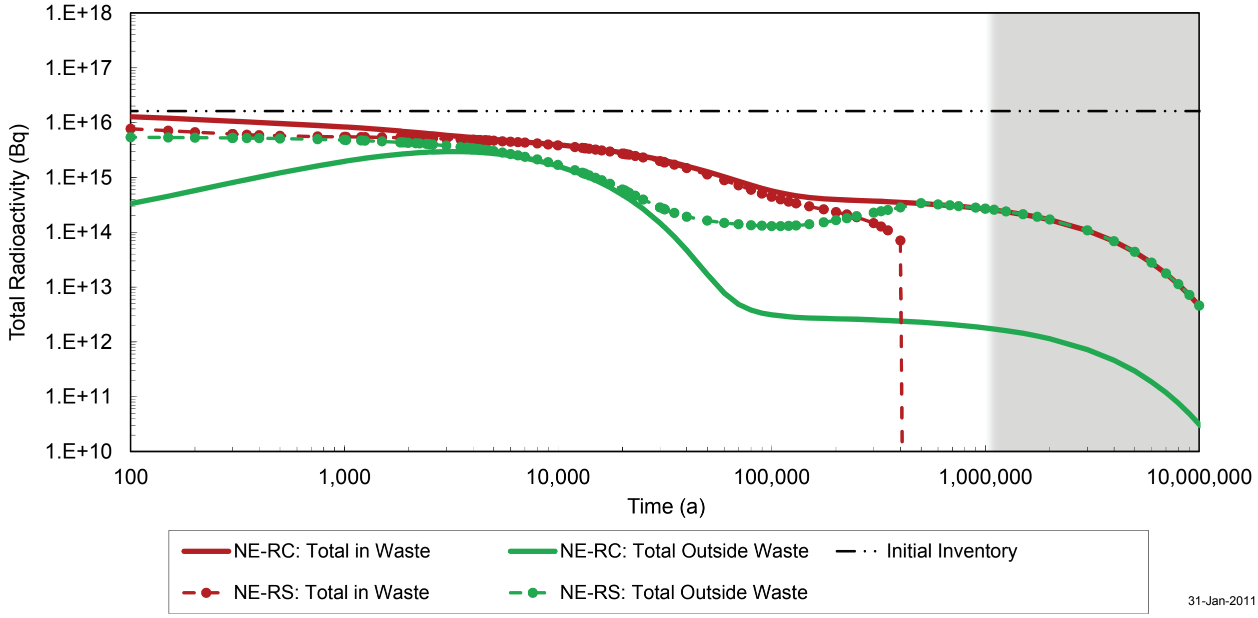
The water saturation levels are even lower if water consumption is included. The lower water levels in the DGR mean that even less contamination is released into the repository water, which results in lower contaminant transport via the shafts and about a 40% to 75% reduction in the calculated doses during the period assessed (see Table 7.13).

Table 7.13: Maximum Doses to an Adult with and without Water Limited Reactions

Calculation Case	Max. Calculated Dose (mSv/a)	Time of Max. Calculated Dose (Ma)
NE-RC: Reference Case	2×10^{-15}	> 1
NE-RC-WL: Water-Limited Reference Case	4×10^{-16}	> 1
NE-SBC: Simplified Base Case	1×10^{-13}	> 1
NE-SBC-WL: Water-Limited Simplified Base Case	6×10^{-14}	> 1

To bound uncertainty surrounding repository resaturation, the NE-RS calculation case represents a fully resaturated repository from closure. This case maximizes the release of radionuclides from the wastes into groundwater, while the gas pathway is not modelled. The AMBER model for this case adopts groundwater flow rates from the reference FRAC3DVS-OPG case; i.e., including the observed underpressures in the Ordovician formations.

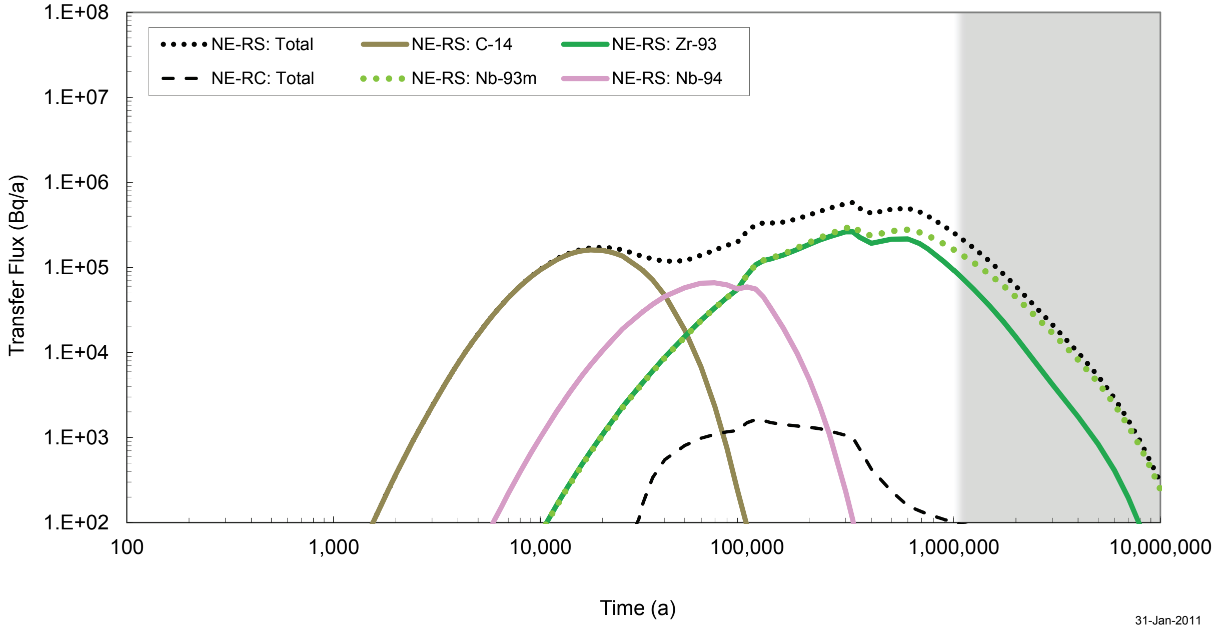
The amount of radioactivity remaining in the waste and the amount released are shown in Figure 7.28 for the NE-RS case. The figure shows that the full inventory is released by the time that the Zircaloy wastes have completely corroded, by 500,000 years. This differs from the Reference Case, in which almost all radioactivity remains within the wastes due to the very low level of repository resaturation.



Note: Figure adapted from Figure 6.5 in QUINTESSA (2011a).

Figure 7.28: Total Radioactivity in Waste and Released for the Instant Resaturation (NE-RS) Case

The calculated radionuclide transfer fluxes from the monolith to the base of the shafts are shown in Figure 7.29 and compared against the total for the Reference Case. The figure shows that the greater amount of water in the repository and the associated greater release of radionuclides from the wastes results in higher calculated radionuclide fluxes to the base of the shafts.



Note: Figure adapted from Figure 6.6 in QUINTESSA (2011a).

Figure 7.29: Radionuclide Flux from the Monolith to the Base of the Shafts for the Instant Resaturation (NE-RS) Case

The greater radionuclide flux into the shafts means that there is also greater migration of radionuclides up the shafts than in the NE-RC case. However, the shaft seals continue to provide an effective barrier, such that calculated radionuclide fluxes to the Shallow Bedrock Groundwater Zone are effectively zero, being less than 1 Bq/a throughout the calculation period.

The calculated releases to the biosphere are similarly small with the maximum calculated dose to an adult member of the Site Resident Group being 4 x 10^{-14} mSv/a at the end of the calculation period (about a factor of 20 higher than for the Reference Case). However, the calculated doses to all age groups remain much smaller than the dose criterion of 0.3 mSv/a.

In summary, although early resaturation of the repository increases the corrosion of the wastes and the release of radionuclides from the wastes and repository via groundwater, the impacts remain very small and the safety of the repository system is not sensitive to repository resaturation.

7.3.2.2 Waste Inventory

The potential effect of uncertainties surrounding contaminant inventories in the wastes has been explored through a variant case (NE-IV) in which the initial inventory is increased by an order of magnitude. The results indicate a linear response in the maximum calculated dose. The linear relationship occurs because of the absence of solubility limitation and because radionuclides, for which more complex repository behaviour is modelled (e.g., C-14), decay before reaching the surface. Since the peak dose results for the Normal Evolution Scenario are many orders of magnitude below the criterion, the safety of the repository is not sensitive to the inventory uncertainties.

7.3.2.3 Contaminant Release Rates

Contaminant release is conservatively represented as instant release on contact with repository water for most waste categories, with congruent release being used for wastes where contamination is bound within the waste itself (Table 6.1). However, the actual release is dependent upon water entering the repository. Tritium and C-14 are also released as gases.

The effect of repository resaturation as a factor in controlling release is tested in a case (NE-RS) with repository resaturation at closure, as well as in a case (NE-RT1) with full release of the contaminant inventory to the repository water at closure together with no sorption/precipitation (NE-RT1). The results are compared in Table 7.14.

Table 7.14: Summary of Maximum Doses to an Adult for Different Contaminant Release Rate Assumptions

Case	Brief Description	Max. Calculated Dose (mSv/a)	Time of Max. Calculated Dose (Ma)
NE-RC	Reference case (with underpressures)	2×10^{-15}	10 *
NE-RS	Resaturation at closure (with underpressures)	4×10^{-14}	10 *
NE-RT1	Resaturation at closure, instant release to groundwater, no sorption/precipitation (with underpressures)	4×10^{-9}	10 *

Notes: * This represents the end of the calculation period.

Table 7.14 shows that when contaminant releases are maximized through resaturation of the repository at closure (NE-RS), the maximum calculated dose increases by a factor of about 20. When release models are bypassed, with instant release to repository water in a saturated repository (NE-RT1), the maximum calculated dose increases by more than six orders of magnitude (although this increase is also affected by the absence of sorption in the shafts and geosphere). However, while relevant to the safety of the system, the maximum calculated dose remains well below the dose criterion, and overall safety is, therefore, not sensitive to realistic uncertainties in contaminant release rates from the wastes.

Uncertainty concerning repository chemistry is treated through adopting conservative assumptions relating to the release of contaminants from the waste and its subsequent release from the repository. These include assuming no solubility limitation (except for C-14 releases) and no sorption on materials within the repository. While siderite formation is included as a (minor) process for precipitating carbon, other precipitation processes, such as calcite formation are conservatively not represented.

7.3.2.4 Gas Generation

The gas generation model within the repository draws on a number of assumptions about the corrosion behaviour of materials in the repository and the extent of microbial activity. The model is intended to maximize the amount of gas generation by assuming that corrosion processes and microbes are active, and by assuming that the organics are fully degraded into CO_2 and CH_4. It is possible however that conditions will be sufficiently dry or saline that there will be little corrosion or microbial activity. The effects of alternative assumptions for gas generation have therefore been tested through several cases:

- NE-GG1 – Increased amount of metal and increased gas generation rates from corrosion and microbial reactions;
- NE-GG2 – Decreased organic degradation rates;
- NE-NM – No methanogenic gas reactions (i.e., no methane generation from organic degradation and no conversion of H_2 and CO_2 to CH_4);
- NE-NG1/NG2 - No gas generation.

The NE-GG1 case includes an increased inventory of metal in the DGR (e.g., reflecting a greater degree of packaging/overpacking), together with increased metal corrosion and organic degradation rates. The case results in increased gas generation, which results in an earlier gas pressure peak, and the repository remains almost completely unsaturated due to the gas pressures.

With the NE-GG2 case, the repository remains relatively unsaturated, and the peak pressure is similar to the NE-GG1 case but occurs later. Note that this case results in a different mix of H_2, CO_2 and CH_4 within the repository and, therefore, affects the extent of methanogenesis, and the pressure evolution. Specifically the gas contains more H_2 and the peak pressure is similar to the high-gas-generation NE-GG1 case.

The NE-NM case assumes that methane generating microbes are not active; this includes organic degradation related reactions as well as gas phase reactions. The primary gas in the repository is therefore H_2 from metal corrosion. This results in a higher gas pressure within the repository.

At the other limit, the bounding case of zero gas generation was also evaluated for conditions with and without Ordovician underpressures (NE-NG1 and NE-NG2, respectively).

The resulting maximum pressures and their timings are summarised in Table 7.15.

Table 7.15: Summary of Maximum Gas Pressures for Different Gas Generation Rates

Case	Brief Description	Maximum Pressure (MPa)[a]	Time of Maximum Pressure (a)[a]
NE-RC[b]	Reference case	8.2	1,000,000
NE-SBC[c]	Simplified base case	7.2	1,000,000
NE-GG1[c]	Increased gas generation rates	7.8	4000
NE-GG2[c]	Decreased organic degradation rates	7.8	36,000
NE-NM[c]	No methanogenic gas reactions	9.2	36,000
NE-NG1[b]	No gas generation (gas pressure results from inflow of gas into repository from surrounding geosphere)	5.5	1000,000
NE-NG2[c]	No gas generation (gas pressure results from inflow of gas into repository from surrounding geosphere)	6.6	1,000,000

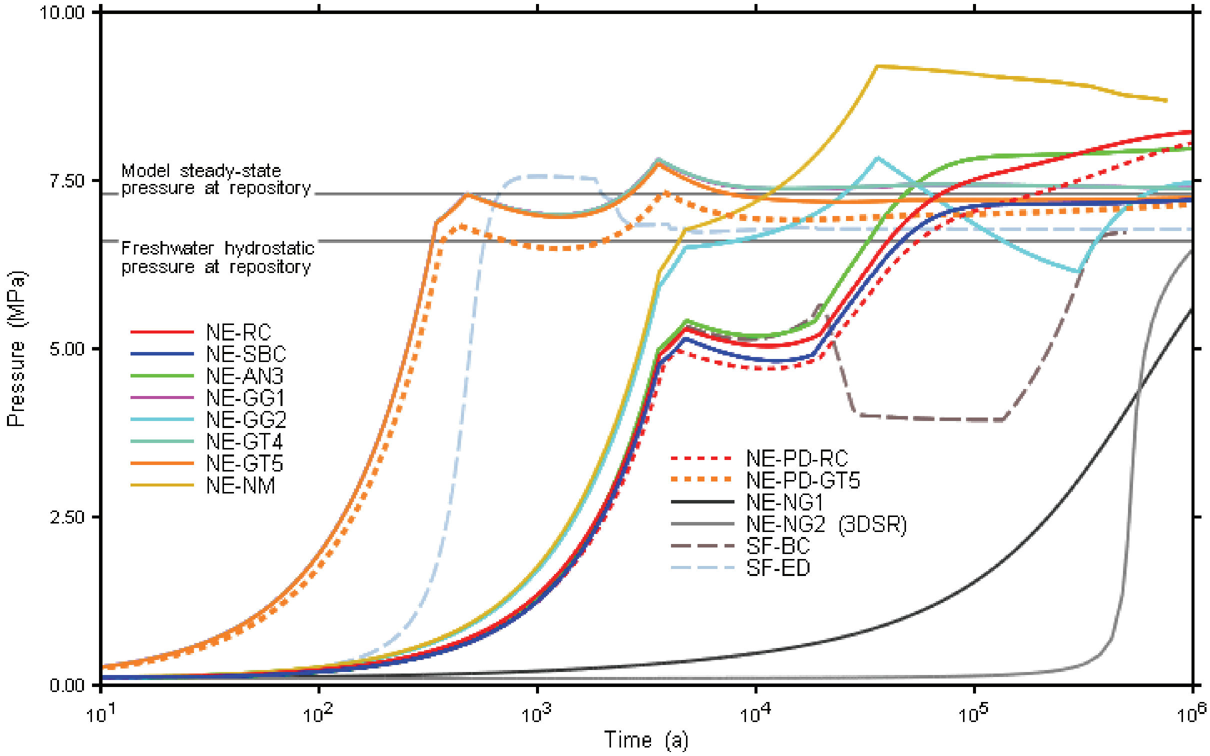
Notes:

a. Results for the non-water-limited model.
b. With Ordovician underpressures.
c. No Ordovician underpressures.

Note: Table 8.1 from GEOFIRMA and QUINTESSA (2011).

Figure 7.30 summarizes the repository pressures calculated using T2GGM for the above cases plus all the other T2GGM cases. The overall conclusion is that the gas pressure within the repository tends towards about 7-9 MPa, a range roughly corresponding to the natural hydrostatic pressure and the steady-state pressure due to the Cambrian overpressure. The balance reflects the tendency of the system to push gas into the rock and shafts at higher pressure, or for water and gas to seep into the repository at lower pressure.

The calculated doses for the NE-GG1, NE-GG2 and NE-NM cases are summarized in Table 7.16.



Note: Figure 8.1 in GEOFIRMA and QUINTESSA (2011).

Figure 7.30: Calculated Gas Pressure Profile in Repository for Various Cases (Non-Water-Limited Case)

Table 7.16: Summary of Maximum Calculated Doses to an Adult for Different Gas Generation Rates

Case	Brief Description	Max. Calculated Dose (mSv/a)
NE-SBC	Simplified base case	1×10^{-13}
NE-GG1	Increased gas generation rates	9×10^{-11}
NE-GG2	Decreased degradation rates	9×10^{-14}
NE-NM	No methanogenic gas reactions	5×10^{-14}

7.3.2.5 Geosphere Gas Properties

The rate of gas transport through the geosphere and shaft is dependent upon the gas pressure in the repository (Section 7.3.2.4), as well as the initial gas saturation conditions and gas permeability properties of the shaft seals and host rock.

Variant detailed gas modelling cases represent the Normal Evolution Scenario with different assumptions relating to partial gas saturations in Ordovician formations (NE-RC1) and different initial gas saturations (NE-RC2). The results of the detailed modelling are sensitive to assumptions on residual gas saturation for the relative permeability curve. The capillary pressure curves are particularly important in defining conditions for the NE-RC and related cases with initial gas saturation, as initial gas pressures in the rock cannot be measured directly, only calculated from liquid pressures and capillary pressures. For the NE-RC and NE-RC2 cases, the capillary pressure assumptions directly impact the repository pressure history during the million year simulation period, while the NE-RC1 case shows that assumptions as to residual gas saturations will also have an impact on long-term pressures in the repository.

The Reference Case uses a representative capillary pressure curve for most of the lower permeability rock units, rather than formation specific curves. Detailed gas modelling variant cases NE-GT1 and NE-GT2 investigated the impact of bounding capillary pressure curves, while NE-GT3 used an alternative relative permeability curve. T2GGM simulation results for these cases showed virtually no sensitivity to these gas-related parameters; in all cases there is essentially no transport of a separate gas phase in the rock when the rock is assumed fully liquid saturated. The NE-RC2 case used formation specific two-phase flow parameters. These did not appreciably impact repository pressures, but did induce a higher level of transient behaviour in the geosphere.

The Guelph and Salina A1 upper carbonate formations are relatively porous and permeable. Detailed gas modelling indicates that the gas pressure in the repository is sufficient in both the NE-GG1 and NE-NM cases to force free gas to migrate from the DGR into the shafts (Figure 7.31). However, although the calculations show the potential for free gas to travel up the shafts, in both cases the gas is captured by the permeable Guelph and does not extend beyond the Salina A2. The results show that there is no free gas pathway to the Shallow Bedrock Groundwater Zone for these cases[36]. Nonetheless, radiolabelled gases in the repository can partition into groundwater within the repository and enter the groundwater pathway.

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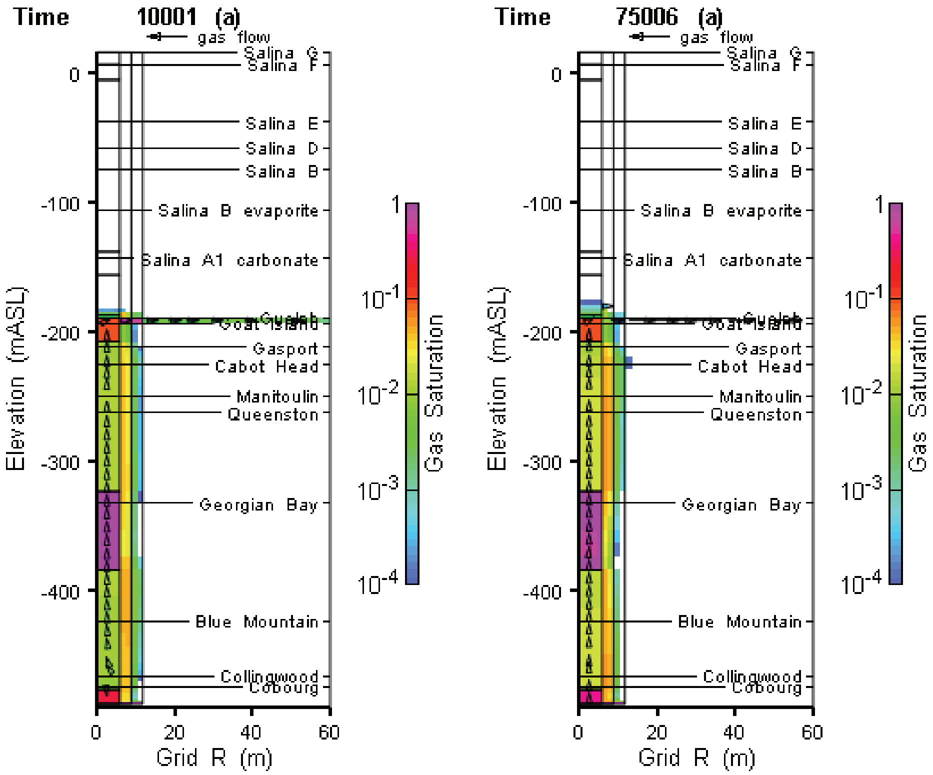
[36] If the free gas is conservatively assumed to reach the Shallow Bedrock Groundwater Zone, then the peak calculated doses would be 3×10^{-3} mSv/a after 9000 years and 2×10^{-6} mSv/a after 35,000 years for the NE-GG1 and NE-NM cases, respectively, due to consumption of plant and animal produce contaminated with C-14.



Note: Figures 5.104 and 5.157 in GEOFIRMA and QUINTESSA (2011).

Figure 7.31: Gas Saturations and Flows for the 2DRS[37] T2GGM Models for the NE-GG1 Case (Left) and the NE-NM Case (Right)

7.3.2.6 Geosphere Transport Properties

The horizontal hydraulic conductivity of the rock is well established from site characterization. However, the vertical hydraulic conductivities have not been directly measured, but have been inferred from modelling and other factors as described in Section 5.4 of NWMO (2011a). They are generally estimated to be about ten times less than the horizontal values. In the detailed groundwater modelling variant case NE-AN1, the horizontal:vertical anisotropy was reduced typically by a factor of five (i.e., increased vertical hydraulic conductivity). This had little impact on the transport results because diffusion is the dominant mechanism for mass transport from the repository.

Increasing horizontal effective diffusion coefficients for the host rock (detailed groundwater modelling variant NE-AN2) increases the spread of contamination at repository depths and results in less contamination migrating up the shafts.

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[37] Two dimensional vertical and radial representation of the shaft system connecting the repository to the Shallow Bedrock Groundwater Zone (see Section 7.3.3)

The Reference Case adopts conservative values for the sorption of contaminants within the host rock. The NE-RT1 and NE-RT2 cases entirely exclude sorption in the shafts and geosphere (and also assume instant resaturation and contaminant release from packages) resulting in an increase in the maximum calculated dose by more than four orders of magnitude (Table 7.14). However, the dose remains well below the criterion.

7.3.2.7 Shaft Seal Performance

Although the shaft seal system is designed to have a low-permeability, its permeability is not as low as that of the host rock and therefore the shafts are the main pathway for any contaminant releases from the repository. Uncertainties in the properties of the seals and damaged rock zone around the shafts are therefore potentially important. The Reference Case considers degraded concrete from the start, as well as a thick damaged rock zone.

The uncertainties in the properties or degradation in properties of the shaft seal have been explored as follows:

- Increased permeability of the EDZ (NE-EDZ1);
- Asphalt replacement by bentonite/sand (NE-GT4);
- Reduced shaft seal performance (NE-GT5); and
- The Severe Shaft Seal Failure Scenario (SF-BC and SF-ED).

The NE cases consider parameter uncertainties or variation within the design basis. The SF cases consider parameter values well beyond the design basis.

Table 7.17 summarizes the hydraulic conductivities assumed in the Reference Case and in the various variant NE and SF cases, for the main geosphere formations, the shaft and repository EDZ, and the shaft seal materials. This shows the range of degradation considered in the assessment. These cases are discussed below.

There is uncertainty in the extent and properties associated with damage to the host rock resulting from the excavations. The values adopted in the Reference Case reflect geomechanical modelling as well as relevant experience from other underground projects in sedimentary rocks (Section 6.3.1 of the Geosynthesis report, NWMO 2011a). In particular, the extent of the shaft EDZ was based on the maximum extent calculated at any shaft position, and assumed to apply uniformly down the entire shaft column. The EDZ was divided into two regions to reflect the variation in hydraulic conductivity, with the inner EDZ assigned 100 times the host rock's vertical hydraulic conductivity and the outer EDZ assigned 10 times the host rock rock's vertical hydraulic conductivity. The EDZ around the repository was assumed to have 1000 times the host rock's horizontal hydraulic conductivity. This uncertainty will be further addressed through DGR site-specific information obtained during and after DGR construction. However, for this postclosure assessment, a variant case considers the potential effect of more severe damage to the host rock surrounding the shafts and repository (NE-EDZ1). In this case, the hydraulic conductivity of the shaft's inner EDZ and repository EDZ is 10,000 times greater than that of the host rock, and that of the shaft's outer EDZ is 100 times greater. This variant case results in an increase in the maximum calculated dose by about two orders of magnitude, but this remains well below the dose criterion.

Table 7.17: Vertical Hydraulic Conductivity (m/s) in Shaft Seal and Rock for Various Cases

Material	Base value	NE-RC / NE-SBC	NE-EDZ1	NE-GT4	NE-GT5	SF-BC	SF-ED
Engineered fill (top 180 m)	10^{-4}	10^{-4}	10^{-4}	10^{-4}	10^{-4}	10^{-4}	10^{-4}
Shallow aquifer zone	10^{-5} – 10^{-7}	10^{-5} – 10^{-7}	10^{-5} – 10^{-7}	10^{-5} – 10^{-7}	10^{-5} – 10^{-7}	10^{-5} – 10^{-7}	10^{-5} – 10^{-7}
Guelph / Salina A1	10^{-7} - 10^{-8}	10^{-7} - 10^{-8}	10^{-7} - 10^{-8}	10^{-7} - 10^{-8}	10^{-7} - 10^{-8}	10^{-7} - 10^{-8}	10^{-7} - 10^{-8}
Concrete monolith and shaft bulkheads	2 x 10^{-12} undegraded	10^{-10} degraded	10^{-10}	10^{-10}	10^{-10}	10^{-9}	10^{-7}
Bentonite / sand	10^{-12} freshwater	10^{-11} brine	10^{-11}	10^{-11}	10^{-10}	10^{-9}	10^{-7}
Asphalt seal	10^{-12}	10^{-12}	10^{-12}				
Silurian rocks	10^{-13} - 10^{-14}	10^{-13} - 10^{-14}	10^{-13} - 10^{-14}	10^{-13} - 10^{-14}	10^{-13} - 10^{-14}	10^{-13} - 10^{-14}	10^{-13} - 10^{-14}
Inner EDZ Silurian rocks	10^{-11} - 10^{-12}	10^{-11} - 10^{-12}	10^{-9} - 10^{-10}	10^{-11} - 10^{-12}	10^{-11} - 10^{-12}	10^{-9} - 10^{-10}	10^{-9} - 10^{-10}
Outer EDZ Silurian rocks	10^{-12} - 10^{-13}	10^{-12} - 10^{-13}	10^{-11} - 10^{-12}	10^{-12} - 10^{-13}	10^{-12} - 10^{-13}	10^{-11} - 10^{-12}	10^{-11} - 10^{-12}
Ordovician rocks	10^{-14} - 10^{-15}	10^{-14} - 10^{-15}	10^{-14} - 10^{-15}	10^{-14} - 10^{-15}	10^{-14} - 10^{-15}	10^{-14} - 10^{-15}	10^{-14} - 10^{-15}
Inner EDZ Ordovician rocks	10^{-12} - 10^{-13}	10^{-12} - 10^{-13}	10^{-10} - 10^{-11}	10^{-12} - 10^{-13}	10^{-12} - 10^{-13}	10^{-10} - 10^{-11}	10^{-10} - 10^{-11}
Outer EDZ Ordovician rocks	10^{-13} - 10^{-14}	10^{-13} - 10^{-14}	10^{-12} - 10^{-13}	10^{-13} - 10^{-14}	10^{-13} - 10^{-14}	10^{-12} - 10^{-13}	10^{-12} - 10^{-13}
Repository EDZ	2 x 10^{-11}	2 x 10^{-11}	2 x 10^{-10}	2 x 10^{-11}	2 x 10^{-11}	2 x 10^{-10}	2 x 10^{-10}

Note: Shaded areas indicate changed values in each column.

Other cases assumed that the shaft seals were more permeable. Two cases have been considered based on the NE-GG1 case (increased gas generation): one in which the asphalt layer was replaced with bentonite/sand (which has ten times higher permeability) (NE-GT4); and one in which the entire bentonite/sand column had degraded (NE-GT5). The latter assumed no asphalt seal, 10 times more permeable bentonite/sand seals, and two times lower gas entry properties for the bentonite/sand seal. Although T2GGM calculations show the potential for free gas to travel more than 200 m up the shafts, the gas is captured by the permeable Guelph and the Salina A1 upper carbonate formations and does not extend beyond the Salina A2. T2GGM, therefore, shows that there is no free gas pathway to the Shallow Bedrock Groundwater Zone for this case[38]. That is, there was no free gas pathway to the Shallow Bedrock Groundwater Zone. However, gas reaching these formations from the repository would contain C-14. If the C-14 were dissolved in the groundwater at these formations, and then moved with the groundwater, the maximum calculated dose is significantly higher than that for either the NE-SBC or the NE-GG1 cases but it is still more than five orders of magnitude below the dose criterion.

Uncertainty surrounding the performance of shaft seals is bounded by the unlikely Severe Shaft Seal Failure Scenario (see Section 7.2.2). In the Base Case (SF-BC), with the shaft seals uniformly degraded to 10^{-9} m/s hydraulic conductivity and the EDZ also more permeable, the peak calculated doses reach about 1 mSv/a due to the C-14 carried with free gas, which breaks through to the Shallow Bedrock Groundwater Zone and surface. If all the shaft seals are degraded to 10^{-7} m/s (SF-ED), then the potential dose impacts are tens of milliSieverts to someone living directly on the repository site.

7.3.2.8 Geosphere Overpressures and Underpressures

Site characterization work has identified that the Cambrian sandstones are overpressured, while the Ordovician sediments are underpressured (Figure 4.16). There are several possible origins of these over/underpressures, and the likely cause(s), as well as their evolution, are currently being investigated (Section 4.3.3).

The Reference Case includes the observed pattern of overpressure and underpressure. However, the Simplified Base Case assumes that the underpressures quickly dissipate after closure, whereas the high pressure in the Cambrian formation remains steady over the timescales of interest, resulting in a steady vertical upwards hydraulic head gradient. This is a conservative assumption, since mass flow from the repository will be significantly reduced as long as underpressures persist in the Ordovician units as prevailing liquid gradients will be towards the underpressures, including the gradients within the shafts.

The maximum doses calculated for the Reference Case and Simplified Base Case are compared in Table 7.18, which shows that excluding the underpressures within Ordovician formations results in an increase by about a factor of 50, confirming that this assumption (used in all SBC-based cases) is conservative.

Another direct comparison is provided by the NE-RT1 and NE-RT2 cases, with instant resaturation and contaminant release and no sorption. NE-RT1 was based on the Reference Case geosphere, while NE-RT2 was based on the Simplified Base Case geosphere. As shown in Table 7.18, the SBC-based case has a higher peak dose, however it is only a factor of 1.2 higher in this case.

The calculated doses remain many orders of magnitude below the dose criterion of 0.3 mSv/a, irrespective of the overpressure/underpressure assumption. While the underpressures are favourable to repository performance, the overall safety of the repository is not highly sensitive to this factor due to the overall low permeability of the host rock and shafts.

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[38] If the free gas is conservatively assumed to reach the Shallow Bedrock Groundwater Zone directly via the shafts, then the peak calculated dose would be 4 mSv/a after 3,500 years due to consumption of plant and animal produce contaminated with C-14.

Table 7.18: Summary of Maximum Doses to an Adult for Different Vertical Head Gradient Assumptions

Case	Brief Description	Max. Calculated Dose (mSv/a)	Time of Max. Calculated Dose (Ma)
NE-RC	Reference case (with underpressures)	2×10^{-15}	10 *
NE-SBC	Simplified Base Case (without underpressures)	1×10^{-13}	10 *
NE-RT1	Instant Resaturation (with underpressure)	4×10^{-9}	10 *
NE-RT2	Instant Resaturation (without underpressure)	5×10^{-9}	10 *

Notes: * This represents the end of the calculation period.

7.3.2.9 Geosphere Horizontal Flow

The DGR site investigation boreholes indicate that the permeable Guelph and Salina A1 upper carbonate formations in the Intermediate Bedrock Groundwater Zone may have small hydraulic head gradients, which could support slow horizontal groundwater flow. The potential for horizontal groundwater flow observed in the Guelph and Salina A1 upper carbonate formations means any contaminants reaching these formations could be diverted laterally away from the direct vertical pathway towards the Shallow Bedrock Groundwater Zone. Due to uncertainty about the future evolution of the gradients in these formations, flow in these formations is ignored in the Reference Case and Simplified Base Case, so that transport is preferentially vertical.

A variant case (NE-HG) considers groundwater flow in the Guelph and Salina A1 upper carbonate. The case is based on the Simplified Base Case, in which there are no underpressures in the Ordovician formations. It is not known where groundwater flow in these formations will discharge to the biosphere, so they are both assumed to discharge a relatively short distance from the DGR (1.25 km) to the lake near shore[39].

The radionuclide flux reaching the Guelph formation is very small, less than 1 Bq/a. The horizontal flow captures more than 80% of the flux via the shafts. The calculated flux reaching the Salina A1 upper carbonate is even smaller. The calculated radionuclide concentration in groundwater in the Guelph formation down-gradient from the shafts peaks at 0.00006 Bq/L[40].

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[39] Site investigation boreholes actually indicate that the Guelph formation flows in a northeasterly direction, i.e., away from the lake.

[40] Consumption of water with this concentration would result in a dose of around 4×10^{-7} mSv/a if it were assumed that water was abstracted directly from the Guelph formation without any treatment. Note also that the total dissolved solids content of Guelph water is around 375 g/L, a factor of 13 times higher than seawater.

The results (Table 7.19) demonstrate the conservative nature of discounting groundwater flow in these formations, through a reduction in the maximum calculated dose by more than two orders of magnitude for the NE-HG case.

Table 7.19: Summary of Maximum Doses to an Adult for Different Assumptions Relating to Groundwater Flow in the Intermediate Bedrock Groundwater Zone

Case	Brief Description	Max. Calculated Dose (mSv/a)	Time of Max. Calculated Dose (Ma)
NE-SBC	Simplified Base Case (excluding underpressures)	1 x 10^{-13}	10 *
NE-HG	Including horizontal groundwater flow in the Guelph and Salina A1 upper carbonate formations	5 x 10^{-16}	10 *

Notes: * This represents the end of the calculation period.

7.3.2.10 Critical Groups

The Site Resident Group considered in the Reference Case and Simplified Base Case is defined on a conservative basis with the aim of maximizing potential exposures. For example, the family is assumed to drill a groundwater well into a contaminant plume in the Shallow Bedrock Groundwater Zone and maximize use of local resources through a self-sufficient farming lifestyle. The habits of the group are defined on a conservative basis, e.g., based on 95th percentile food consumption rates (CSA 2008b).

A variant case (NE-CG) considers potential exposures to two alternative groups, who maximize their use of the lake with a high fish diet. In addition, this case conservatively assumes that contamination in the shaft is intercepted by the Guelph and Salina A1 upper carbonate formations and discharges directly to the lake’s near shore. Despite this conservative assumption, the case shows a reduction in the maximum calculated dose compared with the NE-SBC case by more than two orders of magnitude for a "site shore resident" that takes fish and water from the near-shore lake, and three orders of magnitude for the Downstream Resident Group that takes fish and water from the South Basin of Lake Huron. Given the low doses calculated to someone living directly on top of the repository, these lower "downstream" impacts are completely negligible. The repository will not affect other people living around the lake and using it for food and water.

7.3.2.11 Glaciation

Impact on Intermediate and Deep Geosphere

Although glacial/interglacial cycling will have a major impact on the surface and near-surface systems (see below), its impact is expected not to be as significant in the intermediate and deep geosphere (Section 6.2.1.2). In particular, evidence both from the site characterization and from detailed regional hydrogeology modelling indicates that glacial cycles at the DGR site would have no significant effects on salinity/marker profiles with depth, indicating that solute transport at the repository depth is not affected by glacial episodes (Section 5.4.10 of NWMO 2011a).

Therefore, the impact of glaciation on the repository's overall safety is expected to be limited. Nevertheless, it is recognized that it could:

- Impact the performance of the shaft seals;
- Affect resaturation and rockfall in the repository; and
- Impact the evolution of the disequilibrium heads observed in the Cambrian and Ordovician.

Results from several calculation cases can be used to provide an estimate of each of these potential impacts on calculated doses (Table 7.20), recognizing that these cases did not explicitly model transient glaciation. The results show that the impacts remain many orders of magnitude below the dose criterion.

Table 7.20: Potential Impacts of Climate Change on the Intermediate and Deep Geosphere

Case	Brief Description	Max. Calculated Dose (mSv/a)	Time of Max. Calculated Dose (Ma)
NE-RC	Reference case (including underpressures)	2×10^{-15}	10 *
NE-SBC	Simplified Base Case (excluding underpressures)	1×10^{-13}	10 *
NE-EDZ1	Degraded EDZ performance (excluding underpressures)	2×10^{-11}	1.1
NE-RS	Alternative resaturation assumptions (including underpressures)	4×10^{-14}	10 *

Note: * This represents the end of the calculation period.

Release to a Tundra Biosphere

A variant calculation (NE-CC) considers the potential impacts to a tundra biosphere for the Reference Case releases. In the tundra biosphere, the boundary of the lake is assumed to retreat, so that fluxes from the geosphere that had previously entered the lake shore enter a nearby stream instead. Also human activities and diet are assumed to change.

The colder climate means that, while well water is still used for domestic and farming purposes, a more limited range of exposure pathways are relevant, e.g., through more limited agricultural use of the land. However, the main exposure pathway is the ingestion of contaminated well water, with the contaminant flux to the well being intercepted by a smaller volume of abstracted well water. This results in calculated well water concentrations that are about a factor of six higher than those for the Reference Case. The calculated doses to the Site Resident Group under tundra conditions are about a factor of three to four higher than those calculated for the corresponding Reference Case temperate biosphere. Nevertheless, they still remain much smaller than the dose criterion.

Surface Erosion

A variant case has been considered in which the Surficial and Shallow Bedrock Groundwater Zones are taken to have been eroded away, e.g., as a result of long-term surface erosion and/or glacial action. This is represented by assuming that all of the radionuclide flux from the Intermediate Bedrock Groundwater Zone is intercepted by the well that is used for domestic and agricultural purposes by the self-sufficient Site Resident Group.

The case results in an approximate two orders of increase in the maximum calculated dose compared with the Reference Case, but it remains well below the dose criterion.

7.3.3 Mathematical and Computer Model Uncertainty

The postclosure safety assessment adopts a range of different modelling approaches, including detailed groundwater flow and contaminant transport calculations undertaken in FRAC3DVS-OPG, detailed gas generation and two-phase flow calculations undertaken in T2GGM, a total-systems assessment model implemented in AMBER, and simplified analytical models.

The different codes have been developed to efficiently explore different features, events and processes. The detailed FRAC3DVS-OPG and T2GGM models support the assessment model that is implemented in AMBER, both through identifying the contaminant transport pathways that need to be represented, and quantifying the saturation profiles, gas composition, and groundwater and gas flows. There is also overlap between the different models, e.g., both FRAC3DVS-OPG and T2GGM model groundwater flow, and both FRAC3DVS-OPG and AMBER model tracer transport. The overlap between the codes enables the different modelling approaches to be compared and provides further understanding about the way that the system behaves. A number of variant cases have been undertaken using the same code. In particular, FRAC3DVS-OPG has been used to investigate the impact of using different approaches to representing the salinity profile at the Bruce nuclear site, and T2GGM has been used to assess the impact of the nature of the gas released from the repository and different discretizations of the repository system.

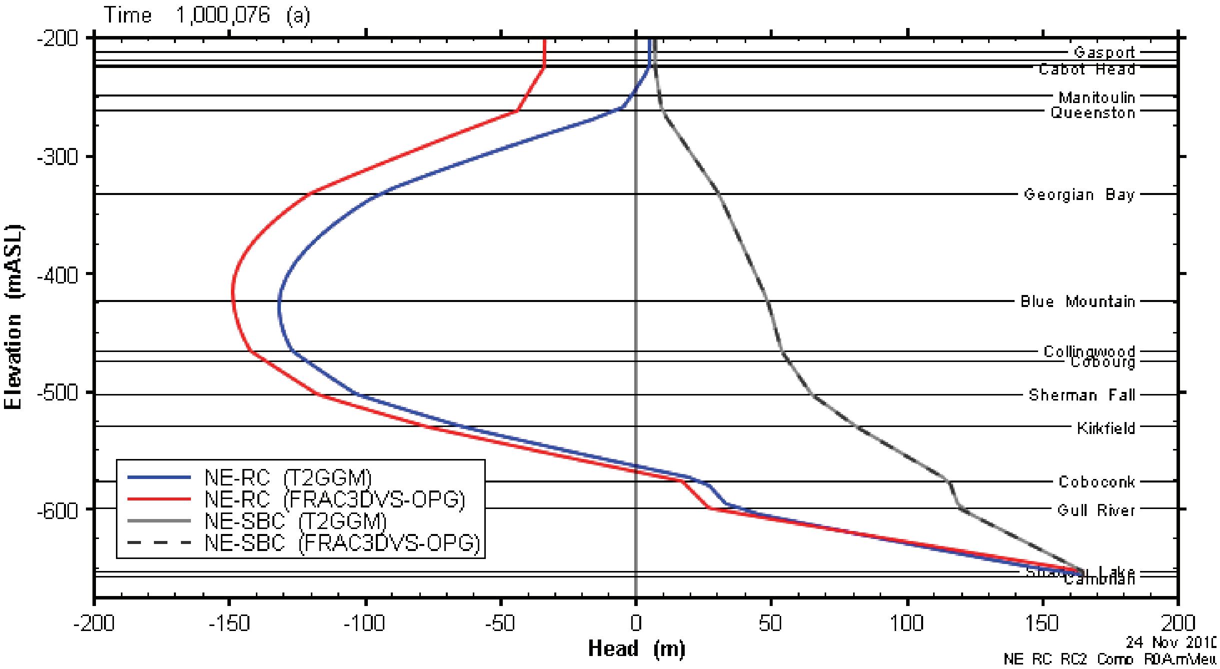
In addition to these numerical models, analytical models have been developed to evaluate transport of contaminants through the repository system. Their results can be compared to those obtained from the numerical models.

Comparison of FRAC3DVS-OPG and T2GGM Results

Comparison of the vertical pressure profiles (expressed as head) calculated in FRAC3DVS-OPG and T2GGM for the NE-RC and NE-SBC cases shows good agreement (Figure 7.32). The head profiles shown are for rock, at a distance removed from the influence of the repository. The agreement shows that the geosphere representation in both the groundwater and gas models is substantially equivalent in spite of the different modelling approaches and discretizations, providing confidence in the results.

Comparison of FRAC3DVS-OPG and AMBER Results

The FRAC3DVS-OPG transport models are based on a fully saturated system and instant release of a radionuclide as tracer – in particular, Cl-36. The NE-RT1 and NE-RT2 AMBER cases also represent a fully saturated repository from closure along with immediate release of contaminants to groundwater and, therefore, can be compared with the FRAC3DVS-OPG transport results.



Note: Both models used zero head upper boundary conditions; the underpressures in the NE-RC FRAC3DVS-OPG case were able to propagate further upwards because the FRAC3DVS-OPG model included the Silurian formations.

Figure 7.32: Comparison between the FRAC3DVS-OPG (Groundwater) and T2GGM (Gas) Vertical Head Profiles Calculated at One Million Years for the NE-RC and NE-SBC Cases

The annual Cl-36 fluxes via both the host rock and shafts calculated by FRAC3DVS-OPG and AMBER at three points in the Deep and Intermediate Bedrock Groundwater Zones are compared in Figure 7.33 for the Reference Case, which includes the initial underpressures observed in the Ordovician (NE-RC compared with NE-RT1). The comparison shows that the AMBER model provides earlier and higher breakthrough than the FRAC3DVS-OPG model, with the calculated fluxes being about one to two orders of magnitude higher.

A similar comparison is made in Figure 7.34 for the Simplified Base Case, which excludes the initial underpressures observed in the Ordovician (NE-SBC compared with NE-RT2), which shows that the AMBER model represents earlier breakthrough and higher fluxes than the equivalent FRAC3DVS-OPG case, with a similar one to two orders of magnitude difference in the calculated fluxes.

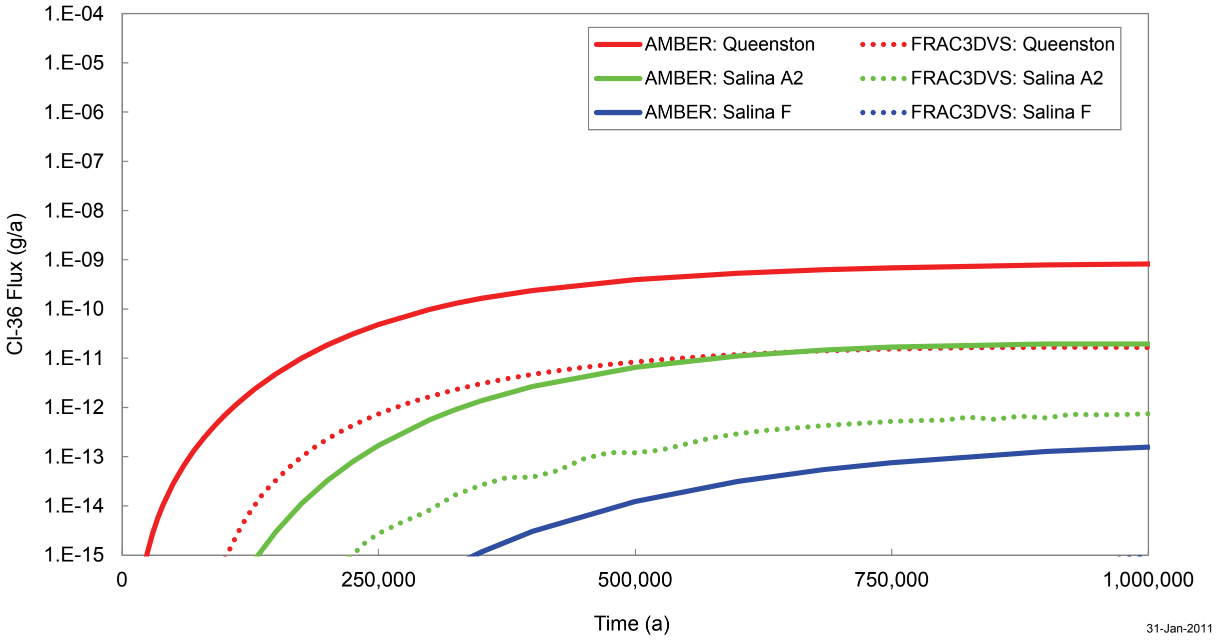


Figure 7.33: Cl-36 Fluxes at Different Geosphere Levels Calculated by FRAC3DVS-OPG (NE-RC) and AMBER (NE-RT1 Case)

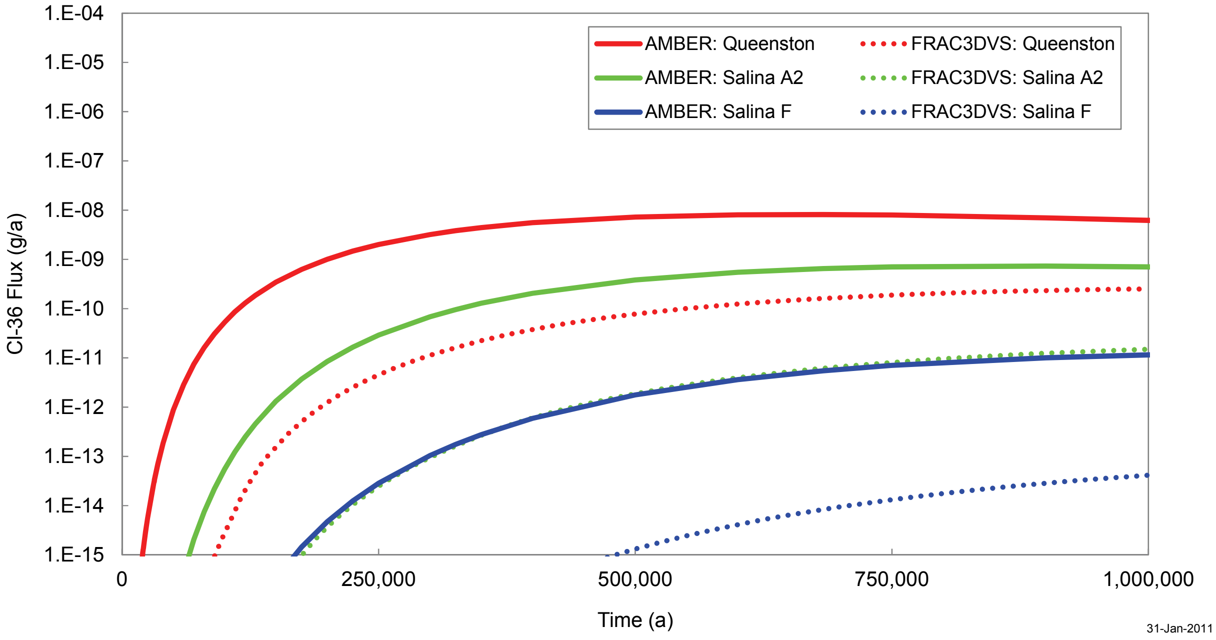
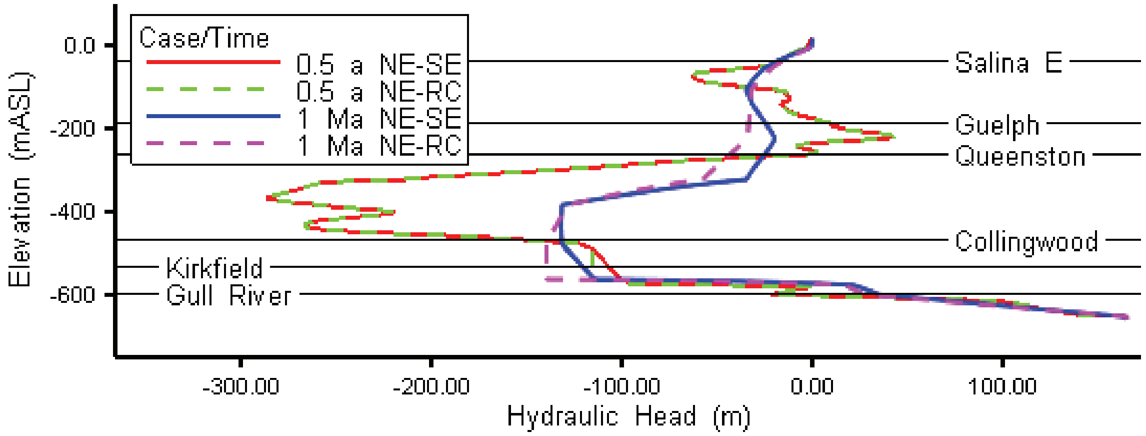


Figure 7.34: Cl-36 Fluxes at Different Geosphere Levels Calculated by FRAC3DVS-OPG (NE-SBC) and AMBER (NE-RT2 Case)

The comparison shows that the assessment results provided by the AMBER model is conservative in comparison to the FRAC3DVS-OPG model. Agreement to within about two orders of magnitude is considered reasonable given the relatively simplified nature of the AMBER model. The early breakthrough provided by the AMBER model is due to numerical dispersion inherent in the more coarsely discretized AMBER model. The level of agreement could be improved with a greater degree of discretization at certain points in the AMBER model; however, the extra degree of complexity is not justified, given the relatively good agreement in the magnitude of the fluxes, the conservative nature of the AMBER results and given that the calculated AMBER impacts remain well below the acceptance criteria.

Comparison of FRAC3DVS-OPG Models

The FRAC3DVS-OPG 3DS model was used to simulate geosphere systems with an explicit salinity profile (NE-SE case) and to simulate an analogous freshwater system where boundary conditions are represented in terms of environmental head for the Reference Case (NE-RC). The comparison of results from the two models in Section 5.10 of GEOFIRMA (2011) showed that environmental head is a suitable proxy for salinity profiles; at least in the local geosphere where gradients are primarily vertically upwards from the overpressured Cambrian (see Figure 7.35).

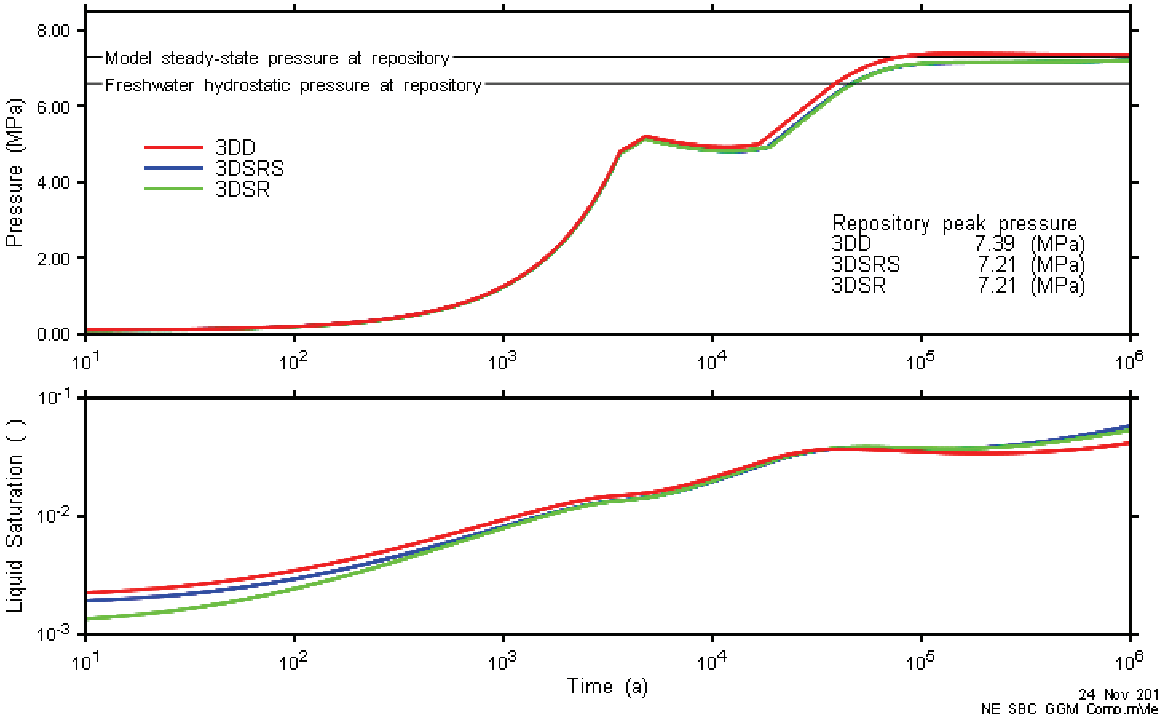


Note: Figure 5.54 in GEOFIRMA (2011).

Figure 7.35: NE-SE and NE-RC Hydraulic Heads at 0.5 a and 1 Ma

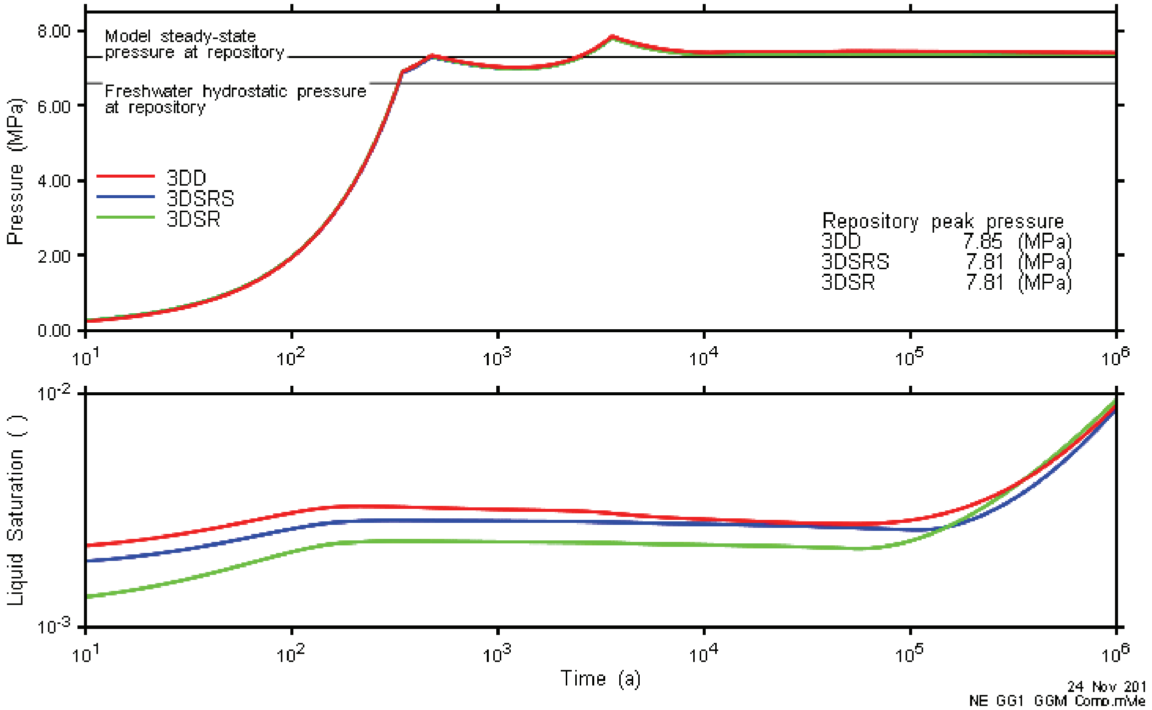
Comparison of T2GGM Models

Several calculation cases (NE-SBC, NE-RC, NE-NG1, NE-NG2, and NE-GG1) were simulated using all three-dimensional T2GGM models (3DD, 3DSR, 3DSRS). In addition to repository pressures and saturations, gas flow rates in the shaft were compared. Figure 7.36 and Figure 7.37 compare repository pressures and saturations for the NE-SBC and NE-GG1 cases for all 3D models. Figure 7.38 presents shaft gas flow rates up the shaft for 3DD, 3DSRS, and 2DRS models for the NE-GG1 case.



Note: Figure adapted from Figure 5.59 in GEOFIRMA and QUINTESSA (2011).

Figure 7.36: Repository Pressures and Liquid Saturations for 3DD, 3DSRS and 3DSR T2GGM Models of NE-SBC Case



Note: Figure adapted from Figure 5.112 in GEOFIRMA and QUINTESSA (2011).

Figure 7.37: Repository Pressures and Liquid Saturations for 3DD, 3DSRS and 3DSR T2GGM Models of NE-GG1 Case

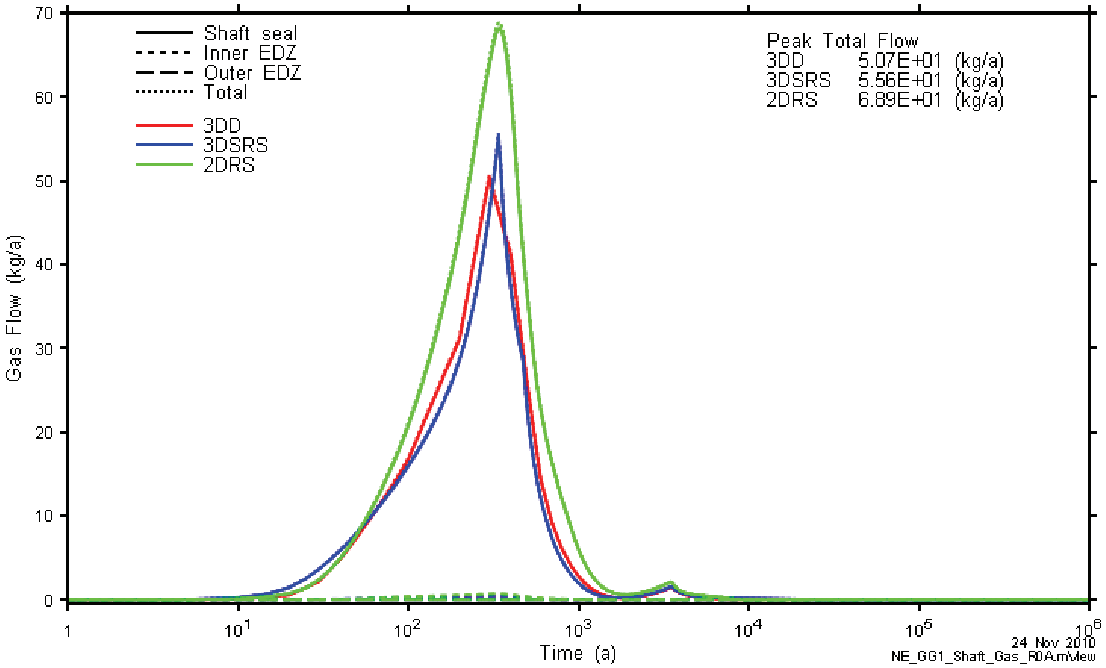


Figure 7.38: Shaft Flow Rates at the Collingwood Formation for 3DD, 3DSRS and 2DRS T2GGM Models of NE-GG1 Case

Results compared well between the 3DD and 3DSRS models, both of which included representations of the shaft. The 3DSR model compared well to the 3DD and 3DSRS model in cases where minimal flow up the shaft occured (NE-SBC and NE-MG, Sections 5.2 and 5.9 of GEOFIRMA and QUINTESSA 2011, respectively). 3DSR results for cases with large overpressures (NE-BF and NE-NM, Sections 5.14 and 5.11 of GEOFIRMA and QUINTESSA 2011, respectively) show higher and longer sustained repository pressures in comparison to the 3DSRS model. This is consistent with the lack of gas flow out the shaft.

Comparison of Analytical and Numerical Results

Simple analytical calculations have been undertaken to estimate the maximum gas pressure within the repository as the waste degrades. The simple calculations provide an estimated maximum gas pressure of 7.4 MPa, which compares well with the peak gas pressures calculated by T2GGM for the NE-RC and NE-SBC cases of 8.2 MPa and 7.2 MPa, respectively (see Appendix B of GEOFIRMA and QUINTESSA 2011).

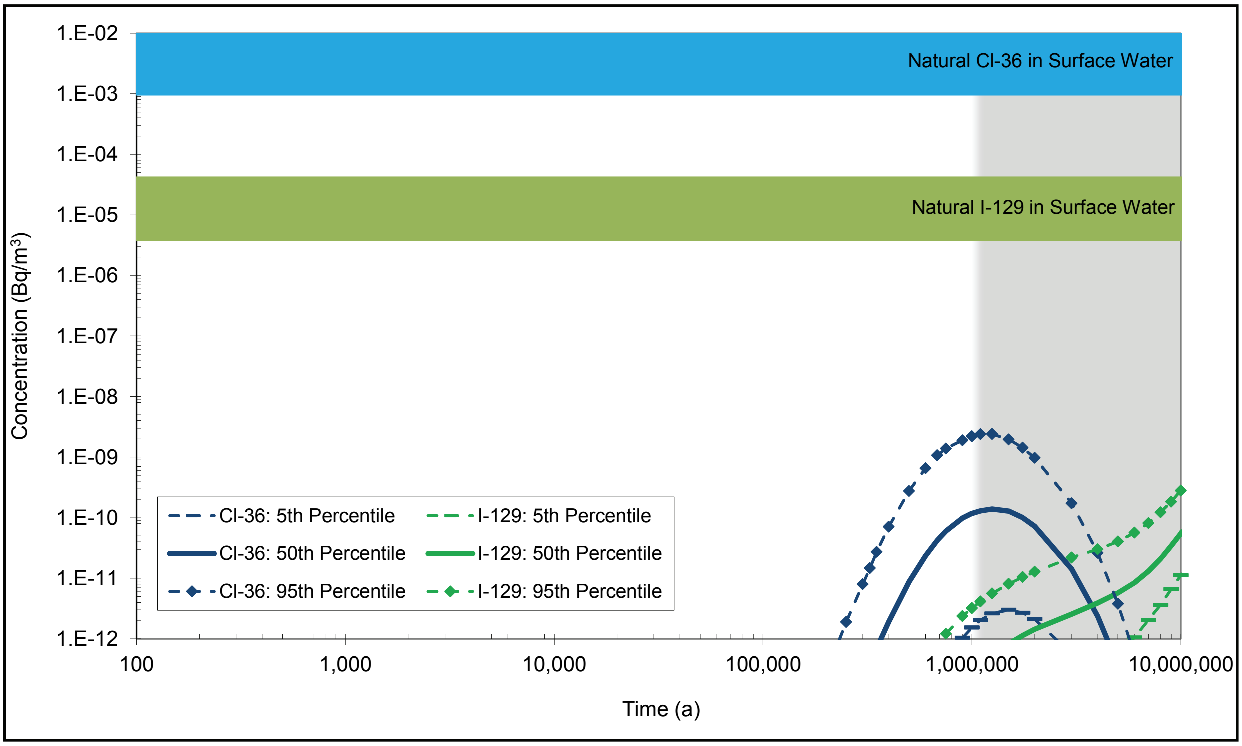
Simple analytical calculations have also been undertaken for gas flow rates via the shafts based on the extra degraded variant to the Severe Shaft Seal Failure Scenario (SF-ED). A gas mass flow rate of 3.1×10^{-6} kg/s is calculated using the simple approach, which compares well to the value of 2.9×10^{-6} kg/s calculated by T2GGM (see Appendix B of GEOFIRMA and QUINTESSA 2011).

In order to test and build confidence in the FRAC3DVS-OPG contaminant transport model results, an analytical model has been developed (see Appendix E of GEOFIRMA 2011). The analytical model considers transport through the access tunnels and up the shaft through advection, dispersion and diffusion, with radial transport into the adjacent rock through diffusion. The results were compared against FRAC3DVS-OPG at the top of the Ordovician formations. The analytical model results confirm that only the very leading edge of the breakthrough curve reaches this location during the modelled timescale (see Appendix E of GEOFIRMA 2011).

7.3.4 Probabilistic Calculation

Probabilistic calculations have been undertaken for leading radionuclides (C-14, Cl-36, Zr-93 and I-129) to investigate sensitivity of consequences to the release and transport parameters. The sensitivity analysis is constrained within the Reference Case geosphere assumptions; in particular, repository saturation, gas and groundwater flows are not sampled as they are drawn directly from the detailed T2GGM and FRAC3DVS-OPG models for the NE-RC case, which are deterministic in nature.

Sampled parameters include the initial inventory, thicknesses and corrosion rates for metaliferous wastes, effective diffusion coefficients and sorption coefficients. The ranges are described in Section 4.4.6 of QUINTESSA 2011a. The effect of varying the sampled parameters on the maximum calculated concentration in the well water have been considered, as this is a key factor in determining calculated dose rates in the biosphere. The results demonstrate that the concentration of leading radionuclides in well water may increase by up to about two orders of magnitude when the Reference Case parameters are varied over plausible ranges (Figure 7.39). The very small calculated impacts indicate that the safety of the system is not sensitive to variations in these parameters.



Note: Figure adapted from Figure 6.24 in QUINTESSA (2011).

Figure 7.39: Calculated Well Water Concentrations for Cl-36 and I-129 from Probabilistic Sensitivity Calculations (NE-PC) Based on the Reference Case

7.3.5 Alternative Repository and Shaft Seal Designs

The DGR preliminary design incorporates postclosure safety assessment feedback regarding design options, for example the increased separation of the emplacement rooms from the shafts. Further design options will be considered during the detailed design phase. The postclosure implications of specific design aspects that have been evaluated in the current assessment are illustrated below.

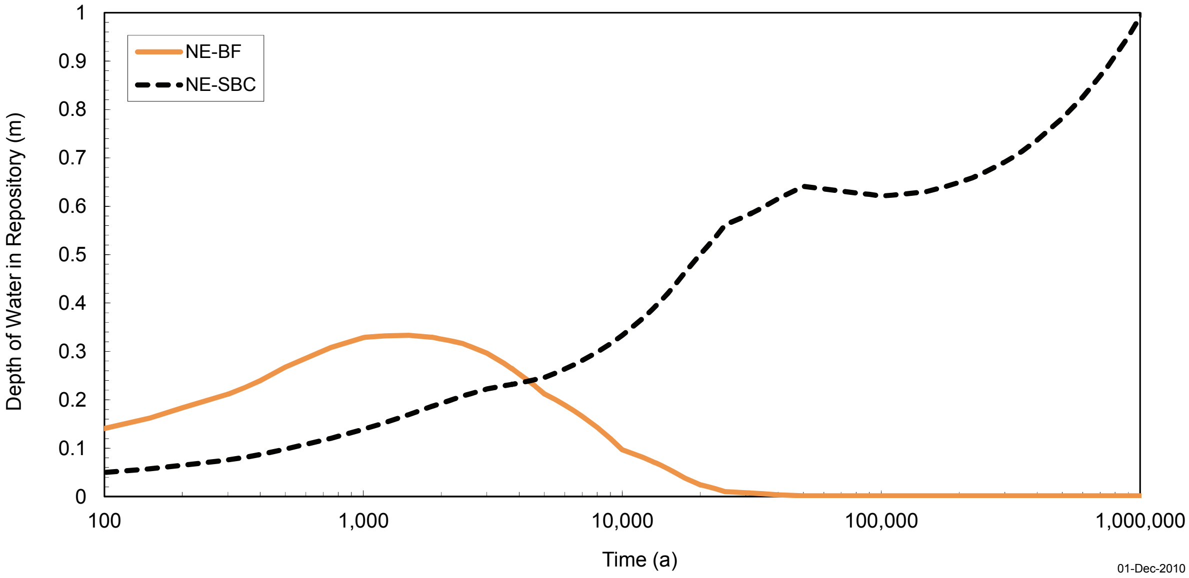
7.3.5.1 Original and Final Preliminary Designs

As noted in Section 4.2, original and final preliminary designs have been evaluated in the current assessment. From a postclosure safety perspective, the key changes from the original to the final preliminary design are the increased repository void volume and the disposal of ILW filters and elements, irradiated core components, and IX columns in ILW shield containers rather than concrete T-H-E arrays. Results for the final preliminary design are very similar to those calculated for the original preliminary design (see Section 7.1.4).

7.3.5.2 Backfilled Repository

The preliminary design is to emplace the packages in emplacement rooms but not to backfill these rooms. The advantages of not backfilling are reduced cost, reduced worker dose and greater retrievability during operations, and increased space for gas during postclosure. The option of backfilling the DGR to increase the stability of the rooms and tunnels and limit rockfall has been investigated through the NE-BF case. In this case, the effective void space in the repository panels is reduced to 30% of the reference value.

The gas modelling results (see Sections 5.14 and 7.4, GEOFIRMA and QUINTESSA 2011) indicate that the reduction in void space within the repository will result in higher repository gas pressures, peaking at 16.2 MPa (for the conservative non-water-limited case) compared to 7.2 MPa in the Simplified Base Case, on which it is based. The gas pressure in the repository exceeds the hydrostatic pressure of around 7.4 MPa after about 2000 years, at which point water is forced from the DGR and the saturation level falls to a point at which the repository becomes essentially unsaturated from around 20,000 years (see Figure 7.40). Note that for the case for which T2GGM enforces a water balance and so has the potential to limit the availability of water, peak pressure is significantly lower at 7.5 MPa due to the reduced availability of water and so reduced gas generation.



Note: Figure 6.15 in QUINTESSA (2011).

Figure 7.40: Depth of Water in the Repository for the Backfilled (NE-BF) Case, in Comparison to the Simplified Base Case (NE-SBC)

The detailed gas modelling indicates that the gas pressure in the backfilled repository for the non-water-limited case is sufficient to force free gas to migrate from the DGR into the shafts. However, the calculations also show that the gas is captured by and diverted laterally into the permeable Guelph and Salina A1 upper carbonate formations and does not extend beyond the Salina A2 formation (Figure 7.41). Therefore, there is no free gas pathway to the Shallow Bedrock Groundwater Zone for this case[41]. Nonetheless, radiolabelled gases can be transported in the gas phase via the shafts and then partition into groundwater in the shafts within the Intermediate Bedrock Groundwater Zone.

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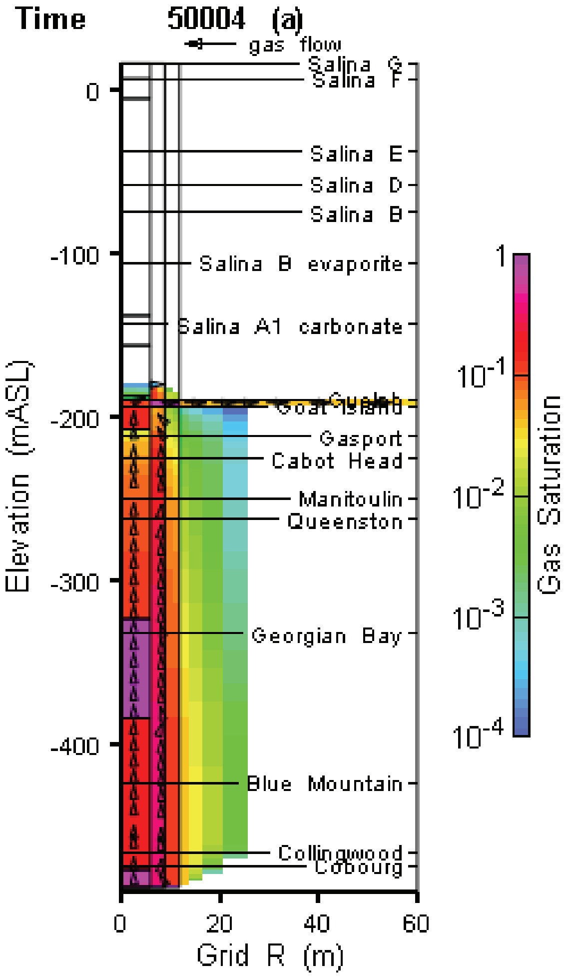
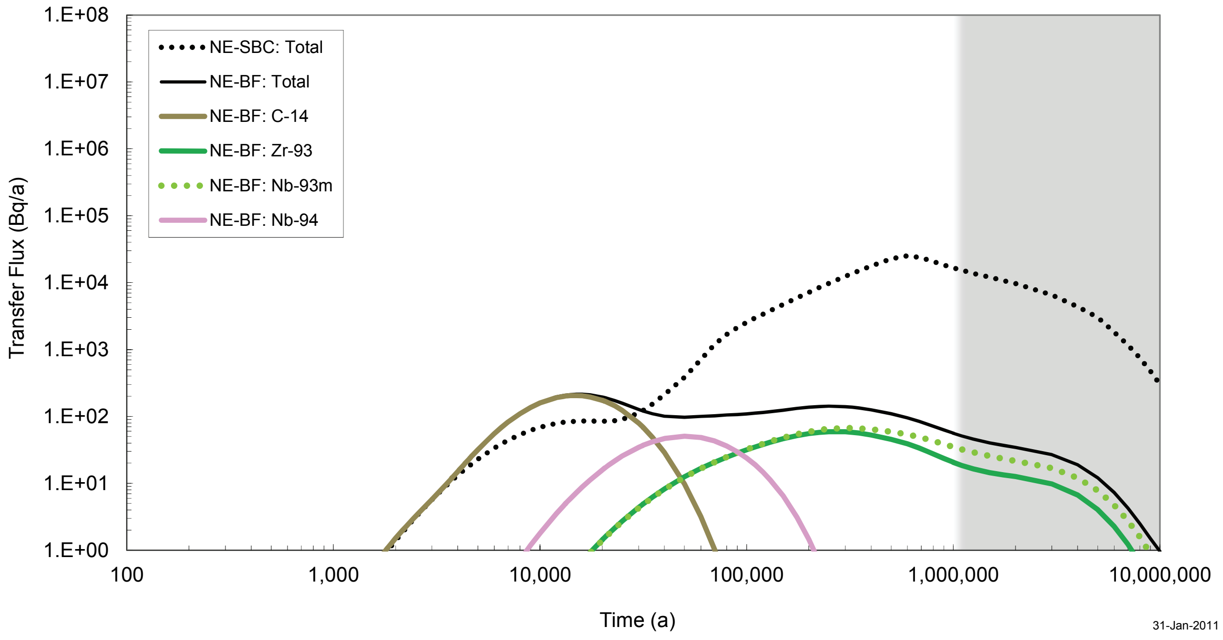
[41] If the free gas is conservatively assumed to reach the Shallow Bedrock Groundwater Zone directly via the shafts, then the peak calculated dose would be 2 mSv/a after 5000 years due to C-14 labelled gas.



Note: Figure adapted from Figure 5.181 in GEOFIRMA and QUINTESSA (2011).

Figure 7.41: Gas Saturation after 50,000 Years from the 2DRS T2GGM Model for the Backfilled Repository (NE-BF) Case, Showing Diversion of Gas into the Permeable Guelph Formation

Figure 7.42 shows the calculated flux of radionuclides in groundwater to the base of the shafts for the backfilled repository case (NE-BF) in comparison to the Simplified Base Case. The figure shows that while the release of C-14 in groundwater to the shafts is slightly greater for the NE-BF case, the very low level of repository saturation beyond 10,000 years reduces the release of other radionuclides in the groundwater pathway (notably for Zr-93 and Nb-93m on longer timescales).



Note: Figure adapted from Figure 6.17 in QUINTESSA (2011).

Figure 7.42: Radionuclide Flux in Groundwater to the Base of the Shafts for the NE-BF Case

While there is a notable transfer of C-14 in gas to the shafts level with the Guelph formation (peaking at about 8 GBq/a after 3,500 years), the effectiveness of the shaft seals means that only a relatively small amount reaches the Shallow Bedrock Groundwater Zone (peaking at about 400 Bq/a after 40,000 years) due to diffusion and groundwater advection in the shafts. Calculated biosphere concentrations therefore remain low, and the maximum calculated dose to an adult member of the Site Resident Group is 8 x 10^{-8} mSv/a after 40,000 years due to C-14. The calculated doses remain much less than the dose criterion of 0.3 mSv/a.

The mechanical effects of the high repository pressure (16 MPa) calculated for the non-water-limited version of this case on the shaft were not assessed. If a pressure of 16 MPa were to cause the shaft seals to fail, then much higher dose rates would result. However, the pressure for the water-limited version of the backfill case is lower at 7.5 MPa and the use of backfill is not currently the design basis.

7.3.5.3 Asphalt Shaft Seal

The design considers an asphalt layer, to provide an independent low-permeable seal material. However, the properties and durability of the asphalt seal are not as well established as those for bentonite/sand. The option of not using an asphalt seal has been considered (NE-GT4 and NE-GT5, which are both based on the high gas generation case NE-GG1). The results show little effect on overall gas pressures and some effect on gas fluxes (Table 7.21, and Section 5.8 of GEOFIRMA and QUINTESSA 2011). That is, the asphalt seal layer is not required for shaft seal performance under expected conditions. Its value is as an independent material that could provide confidence in the shaft performance under unexpected conditions where the bentonite/sand seal is degraded.

Table 7.21: Gas Pressures and Fluxes for the Increased Gas Generation (NE-GG1) and Asphalt Replacement (NE-GT4) Cases

Calculation Case	Repository Gas Pressure		Free Gas		Dissolved Gas	
	Peak Pressure (MPa)	Time (a)	Peak Rate (kg/a)	Time (a)	Peak Rate (kg/a)	Time (a)
NE-GG1	7.8	4000	4.3E-01	8000	4.1E-04	7000
NE-GT4	7.8	4000	1.3E+00	5000	5.8E-04	150,000

7.3.5.4 Keyed-in Monolith

Since the damaged zone around the monolith is an important pathway for contaminant transport, one case was analyzed in which the damaged zone around the monolith was blocked by a section of concrete (NE-EDZ2). This case includes the same increase in EDZ hydraulic conductivities as in NE-EDZ1, but with a design modification to the monolith which involves the removal of the HDZ and EDZ around a 9 metre length of the Reference Case monolith, and replacement of these materials with additional concrete. The results were analyzed with respect to groundwater flow for an instantly resaturated repository. The keyed-in monolith had little effect due to the relatively high hydraulic conductivity of the (assumed) degraded concrete, and the relatively short interruption of the flow path (Section 5.8 of the Groundwater Modelling report, GEOFIRMA 2011).

7.4 Confidence Building Measures

As noted in Section 3.7, a range of measures have been used to develop confidence in the safety assessment and its results. Evidence of the measures that have been used in the current assessment of the DGR are summarized in Table 7.22 and Table 7.23.

The EIS guidelines for the DGR (CEAA and CNSC 2009) identify issues that need to be addressed in the postclosure safety assessment (Section 3.3). Each of these issues is identified in Table 7.24, together with a commentary on how they have been considered in the current assessment. A similar table for the generic guidance on assessing long-term safety of radioactive waste management set out in the regulatory guide G-320 (CNSC 2006) is provided in Table 7.25.

In particular, the quality of the analysis of results obtained in the assessment has been ensured through:

- The use of suitably qualified staff;
- The use of peer-reviewed and published literature;
- An iterative process, building on previous safety assessments as well as improvements in the facility design and site knowledge;
- A formal data freeze and data clearance processes to ensure that a consistent set of parameters for the facility design and site characterization;
- The use of quality-assured software, with verification of calculation input and results; and
- The peer review of results.

Table 7.22: Evidence of Confidence Building Measures Used at Each Stage of the Current Assessment Process

Assessment Stage	Confidence Building Measures	Evidence of Use in the Safety Assessment
Assessment Context	• Demonstration of sound and complete understanding of the key components of the assessment context.	See Chapter 3 in which all the key components of the assessment context are presented and discussed (purpose, audience, regulatory framework, assessment end points, assessment philosophy and timeframes).
System Description	• Demonstration of adequate understanding of engineered and natural aspects of the DGR system (repository, geological setting and surface environment) and associated uncertainties. • Linkage to geosynthesis, site characterization, waste characterization, and repository design.	Chapter 4 provides a summary of the system description. A more detailed description is provided in the System and Its Evolution report (QUINTESSA 2011b) in which the current understanding of the DGR system and its wastes is summarized and the associated uncertainties discussed. Information from the geosynthesis, site characterization, waste characterization and repository design programs has been used in the current assessment (see Chapter 4).
Scenarios	• The set of scenarios is sufficiently comprehensive and is developed in a systematic, transparent and traceable manner. • The approach and screening criteria used to exclude or include scenarios are justified and well documented. • Scenarios are consistent with the geoscience assessment, site characterization, waste characterization and repository design.	The approach used to identify and justify the scenarios is summarized in Chapter 5 and described in detail in the System and Its Evolution report (QUINTESSA 2011b). A wide range of both external and internal features, events and processes has been considered and screened in/out, with justification being documented, in order to generate the set of scenarios for assessment (see Table 5.2 to Table 5.6). The scenarios considered have been developed based on the current understanding of the site and allow the exploration of the key associated uncertainties. It is noted that the scenarios identified are comparable with those considered in other assessments of geologic repositories (see Table 5.7).
Models and Data	• The conceptual models and associated data are consistent with the assessment context, DGR system and scenarios. • The software tools have the ability to adequately solve the problems under consideration. • Alternative models, codes, data and approaches are considered. • Models are consistent with the	The process used for developing the conceptual models for the scenarios is described in Section 6.1 and its application summarized in Section 6.2 and described in the Normal Evolution and Disruptive Scenarios reports (QUINTESSA 2011a; QUINTESSA and SENES 2011). The assessment context, system and scenarios are taken into account when developing the conceptual models (see Figure 6.1). Both detailed and assessment-level software tools have been used to undertake the impact calculations (Section 6.4). These tools have been used in previous assessments of geologic repositories and have associated software documentation that demonstrates their applicability to the problems addressed (see references given in Appendix A). The Gas Generation Model (GGM) component of the T2GGM code has been developed specifically

Assessment Stage	Confidence Building Measures	Evidence of Use in the Safety Assessment
	geoscience assessment, site characterization, waste characterization and repository design.	for the DGR assessment and has an associated set of documentation to demonstrate its applicability to the DGR (GEOFIRMA and QUINTESSA 2011; QUINTESSA and GEOFIRMA 2011b). DGR-specific models, consistent with current DGR system information, have been implemented in the software codes (Section 6.4). These models are applicable to the range of conceptual models and associated calculation cases and data identified (Sections 6.2, 6.3 and 6.5). The development, testing and refinement of the models are documented in the supporting modelling reports (e.g., GEOFIRMA 2011, GEOFIRMA and QUINTESSA 2011) Most of the data are specific to the DGR system and have been taken from the waste and site characterization programs, and datasets required for safety assessment outside of referenceable documents have been released using a data clearance process (Section 6.5).
Analysis of Results	• Key assumptions are documented and justified. • Results are plausible and explainable. • Uncertainties are adequately addressed. • Compliance with regulatory requirements and recommendations is analyzed.	Assumptions relating to each step of the assessment approach are documented and justified in the relevant assessment report on the basis of the current understanding of the DGR system (e.g., scenario assumptions in the System and Its Evolution report, QUINTESSA 2011b; model assumptions in the Normal Evolution and Disruptive Scenarios reports, QUINTESSA 2011a, QUINTESSA and SENES 2011; data assumptions in the Data report, QUINTESSA and GEOFIRMA 2011a). As noted in Section 3.6.2, the current assessment has adopted scientifically informed, physically realistic assumptions for processes and data that are understood and can be justified on the basis of the results of research and/or site investigation. Where there are high levels of uncertainty associated with processes and data, conservative assumptions have been adopted to allow the impacts of uncertainties to be bounded. Uncertainties associated with the current assessment are identified in the System and Its Evolution report (QUINTESSA 2011b), the Data report (QUINTESSA and GEOFIRMA 2011a), and the Normal Evolution and Disruptive Scenarios reports (QUINTESSA 2011a; QUINTESSA and SENES 2011). They are assessed in Section 7.3 of the current report. Compliance with regulatory requirements and recommendations is summarized in Sections 7.1.3 and 7.2 for the Normal Evolution and Disruptive Scenarios, respectively.
Review and Modification	• Modifications are implemented in a structured and well-documented manner.	The assessment results have been subject to a process of internal and external review and revision since 2008, when initial results were produced for the previous assessment (QUINTESSA et al. 2009). The results of the previous assessment were subject to regulatory review and review by an international peer review team. The current assessment takes into account the internal and external review comments on the previous assessment. This review and disposition process has been documented and an audit trail of review comments and responses produced.

Table 7.23: Evidence of Measures used to Develop Overall Confidence in the Current Safety Assessment

Measures to Develop Overall Confidence in the Assessment	**Evidence of Use in the Safety Assessment**
Use of a systematic approach consistent with international practice and recommendations	An approach based on the IAEA’s ISAM methodology (see Chapter 2) has been used to assess the safety of the DGR. G-320 (CNSC 2006) states that ISAM documentation provides useful recommendations on a structured and iterative methodology for performing and documenting assessments.
Adequate understanding of the DGR system and its uncertainties	There are a number of uncertainties associated with the understanding of the DGR system and its evolution. These have been accounted for in the current assessment through: the assessment of a range of scenarios, models and data (Section 7.3); the adoption of conservative scenarios, models and data (Table 7.2 to Table 7.6 and the Data report, QUINTESSA and GEOFIRMA 2011a); and the adoption of stylized biospheres (Section 6.2.1.3). The analysis shows that the DGR system’s safety is robust to these uncertainties (Section 7.3).
Use of multiple safety and performance indicators	A range of safety and performance indicators is considered in the calculations, in addition to doses to adult members of a range of potential critical groups. These additional indicators include doses to infants and children, environmental fluxes and concentrations, impacts of radionuclides on non-human biota, and health effects of non-radioactive contaminants on humans and non-human biota (see Sections 7.1 and 7.2).
Clear presentation of the assessment and its results	The structure of the current document is designed to facilitate the clear presentation of the assessment and its results. Extensive use is made of figures and tables to present information throughout the report. The report is supported by a series of other reports that provide more detailed information on specific issues (see Section 1.2 and Figure 1.4 and Figure 1.5). Within the documentation, the basis for the models has been justified and explained, and all relevant mathematical models and data have been presented.
Application of a quality management system	The quality management system applied to the project is described in QUINTESSA (2010). It is in accordance with the requirements of the International Standard ISO 9001:2008. A number of project-specific procedures have been developed, for example, for the preparation, updating and verification of datasets, and the peer review and verification of deliverables (documents, calculation files and software tools).
Peer review of the assessment	In addition to being reviewed by NWMO staff, the documents for the current assessment have been reviewed by specialists in the QIS Partnership and their comments have been addressed in the final versions of the documents. Furthermore, peer review comments from an international team of experts on the previous assessment approach (QUINTESSA et al. 2009) have been taken into account in producing the current assessment.
Involvement of stakeholders in the development of the assessment	NWMO staff have been heavily involved in the development of the assessment through the specification of the work program, attendance at technical meetings, and the review of the project output. Other technical audiences, such as the CNSC and international peers, have reviewed the previous assessment (QUINTESSA et al. 2009) and their comments have been addressed in developing the current assessment.

Table 7.24: Addressing the EIS Guidelines for the DGR in the Current Safety Assessment

Issue	Guidance	Consideration in the Safety Assessment
Demonstration of long-term safety	Need to provide reasonable assurance that the DGR will perform in a manner that protects human health and the environment through the use of a long-term safety assessment based on a pathways analysis of contaminant releases, contaminant transport, receptor exposure and potential effects based on a scenario of expected evolution of the disposal facility and the site	A Normal Evolution Scenario has been identified (Section 5.1) and its impacts on humans and the environment have been evaluated through a process of identifying contaminant releases (Section 6.2.1.1), contaminant transport (Section 6.2.1.2) and receptor exposure (Section 6.2.1.3). The assessment has indicated that the impacts on humans and the environment are acceptable (Section 7.1.3).
Selection of scenario	Long-term assessment scenarios should be sufficiently comprehensive to account for all of the potential future states of the site and the environment. Scenarios should be developed in a systematic, transparent and traceable manner.	A systematic, transparent and traceable approach has been used to identify and develop scenarios (Chapter 5), which has identified five scenarios (a Normal Evolution Scenario and four Disruptive (“what if”) Scenarios). These scenarios are considered to be sufficiently comprehensive to account for the potential future states of the site and the environment. The range of scenarios identified is comparable with those considered in postclosure safety assessments of other deep geologic repositories (Section 5.2.1 and Table 5.7).
	The anticipated evolution of the repository under different scenarios has to be supported by a combination of expert judgment, field data on the past evolution of the site, and also mathematical models that might need to couple chemical, thermal hydrologic, hydrogeologic and mechanical processes that play key roles in the repository evolution.	The potential evolution of the repository has been developed using judgment based on field data and results of detailed groundwater and gas modelling (Section 6.2). The modelling has included the use of a coupled model of gas generation and repository resaturation (Section 6.4).
	The safety assessment should include a central scenario of the normal (or expected) evolution of the site and facility with time. It should be based on reasonable extrapolation of present-day site features and receptors lifestyles. It should include expected evolution of the site and degradation of the waste disposal system (gradual or total loss of barrier function) as it ages.	A Normal Evolution Scenario has been identified (Section 5.1). The scenario considers the expected evolution of the site and degradation of the DGR system (Section 6.2.1). It is recognized that the system will be subject to change resulting from continued glacial/interglacial cycling. Rather than explicitly representing the sequence of glacial/interglacial cycling, the conceptual model used for the current assessment considers stylized, constant conditions which are comparable with those found at present at the site (Section 6.2.1.3). A variant case with constant conditions based on a tundra system is also considered (Section 6.3).

Issue	Guidance	Consideration in the Safety Assessment
	Additional scenarios should be assessed that examine the impacts of low-probability disruptive events or modes of containment failure that lead to the possible abnormal degradation and loss of containment.	Four disruptive scenarios are identified (Section 5.2.1), described (Section 5.2.2), conceptualized (Section 6.2) and evaluated (Section 7.2).
	The approach and screening criteria used to exclude or include scenarios should be justified and well-documented.	The selection of the scenarios is identified and justified in Chapter 5.
Provision of additional arguments and multiple lines of reasoning	Use of different safety assessment strategies: e.g., using a combination of approaches such as scoping and bounding calculations, deterministic and probabilistic approaches.	A range of approaches has been used in the current assessment including: • screening calculations to identify the contaminants for assessment (see Appendix A, QUINTESSA and GEOFIRMA 2011a); • insight calculations relating to the evolution of the DGR system (see various appendices and boxes in QUINTESSA 2011b); • insight calculations relating to the groundwater transport (Appendix E, GEOFIRMA 2011) and gas generation and transport (Appendix B, GEOFIRMA and QUINTESSA 2011); • detailed groundwater and gas calculations (see associated reports, GEOFIRMA 2011, and GEOFIRMA and QUINTESSA 2011); and • assessment calculations (see QUINTESSA 2011a, and QUINTESSA and SENES 2011). The current assessment uses multiple deterministic calculations and some probabilistic assessment calculations are undertaken (Section 7.3).
	Demonstrating that the waste disposal system will maintain its safety function under extreme conditions, disruptive events or unexpected containment failure.	The results presented in Sections 7.2 show that even when the safety functions are partly compromised by Disruptive Scenarios, the consequences are, nevertheless, acceptable.
	Use of complementary safety indicators to doses and environmental concentrations such as: waste dissolution rates; groundwater age and travel time; fluxes of contaminants; concentrations of contaminants in specific environmental media; and changes in toxicity of the waste	The following complementary safety indicators are considered in the assessment: radiotoxicity of the waste (e.g., Figure 7.3); contaminant amounts (e.g., Figure 7.5, Table 7.7); contaminant concentrations at various points in the DGR system (e.g., Figure 7.11, Figure 7.12, and Figure 7.13); fluxes of contaminants at various points in the DGR system (e.g., Figure 7.7, Figure 7.8, Table 7.8); and groundwater age (Section 4.3.4.1).

Issue	Guidance	Consideration in the Safety Assessment
Demonstration of confidence in mathematical models	Performing independent predictions using entirely different assessment strategies and computer tools.	A range of approaches has been used in the current assessment including: • screening calculations to identify the contaminants for assessment (see Appendix A, QUINTESSA and GEOFIRMA 2011a); • insight calculations relating to the evolution of the DGR system (see various appendices and boxes in QUINTESSA 2011b); • insight calculations relating to the groundwater transport (Appendix E, GEOFIRMA 2011) and gas generation and transport (Appendix B, GEOFIRMA and QUINTESSA 2011); • detailed groundwater and gas calculations (see associated reports, GEOFIRMA 2011, and GEOFIRMA and QUINTESSA 2011); and • assessment calculations (see QUINTESSA 2011a, and QUINTESSA and SENES 2011). The current assessment uses multiple deterministic calculations. Some probabilistic assessment calculations are undertaken (Section 7.3.4).
	Demonstrating consistency amongst the results of the long-term assessment model and complementary scoping and bounding assessments.	Key contaminants identified in the screening calculations described in Appendix A of the Data report (QUINTESSA and GEOFIRMA 2011a) are comparable to those identified in the Normal Evolution and Disruptive Scenarios reports (QUINTESSA 2011a, and QUINTESSA and SENES 2011). There is consistency between insight calculations relating to the groundwater transport, and gas generation and transport calculations and detailed groundwater and gas calculations (see associated reports, GEOFIRMA 2011, and GEOFIRMA and QUINTESSA 2011).
	Applying the assessment model to an analog of the waste management system to build confidence through a post audit of the real data available from an analog.	No appropriate analogs identified and so not undertaken for the current assessment.
	Performing model intercomparison studies of benchmark problems.	The assessment code used (AMBER) has been successfully applied to an extensive range of benchmark problems from international studies including those of the IAEA and NEA (QUINTESSA 2009b).

Issue	Guidance	Consideration in the Safety Assessment
	The choice of solute transport modelling codes used should be justified and supporting information on code verification and validation provided.	The selection of the modelling codes is discussed in Section 6.4 and Appendix A. Further details, including code verification and validation information, are provided in the Groundwater Modelling report (Appendix A, GEOFIRMA 2011), T2GGM software document (Chapters 8 and 9, QUINTESSA and GEOFIRMA 2011b) and the Analysis of the Normal Evolution Scenario report (Appendix G, QUINTESSA 2011a). The review of calculations is documented as part of the quality management system applied to the project (QUINTESSA 2010).
	Scientific peer review by publication in open literature and widespread use by the scientific and technical community will add to the confidence in the assessment model.	The interim results were presented at the 2009 ICEM Conference (Little et al. 2009, Suckling et al. 2009). The codes used have been used in a wide number of studies, and have associated, peer-reviewed, open-literature publications (Appendix A). Further details are provided in the Groundwater Modelling report (GEOFIRMA 2011), the Gas Modelling report (GEOFIRMA and QUINTESSA 2011), and the Normal Evolution Scenario Analysis report (QUINTESSA 2011a).
Interpretation of results and comparison with acceptance criteria	The proponent will establish and justify the acceptance criteria adopted for the assessment	The acceptance criteria adopted for the assessment are identified and justified in Section 3.4.
	Compliance with the acceptance criteria and with regulatory guidance must be evaluated, and the uncertainties associated with the assessment should be analyzed.	Compliance with the acceptance criteria and with regulatory guidance is discussed in Section 7.1.3 for the Normal Evolution Scenario and Section 7.2 for the Disruptive Scenarios. Associated uncertainties are discussed in Section 7.3.
	Demonstration of a thorough understanding of the underlying science and engineering principles which are controlling the assessment results.	The analysis and interpretation of the assessment results is presented in Chapter 7. More detailed analysis and interpretation is provided in the following supporting reports: Analysis of the Normal Evolution Scenario (Chapters 5 and 6 of QUINTESSA 2011a); Analysis of Human Intrusion and Other Disruptive Scenarios (Sections 2.5, 3.5, 4.5 and 5.5 of QUINTESSA and SENES 2011); Groundwater Modelling report (Chapters 5 and 6 of GEOFIRMA 2011); and Gas Modelling report (Chapters 5, 6 and 7 of GEOFIRMA and QUINTESSA 2011). These analyses identify the key processes that control the assessment results.

Issue	Guidance	Consideration in the Safety Assessment
	An uncertainty analysis of the predictions should be performed to identify the sources of uncertainty and determine the effects of these uncertainties on safety. This analysis should distinguish between uncertainties arising from uncertainties in site characterization data, in the conceptual site descriptive model, in assumptions of the scenario, and in the mathematics of the assessment model.	Uncertainties are discussed in Section 7.3. Uncertainties are evaluated arising from scenarios (Section 7.3.1), conceptual models and data (Section 7.3.2), and mathematical and computer models (Section 7.3.3).
	For the uncertainties, which have important impact on long-term safety, follow-up field and laboratory investigation programs in combination with refinement of mathematical models should be proposed.	The analysis presented in Section 7.3 shows that the DGR system’s safety is robust to the uncertainties identified in the current assessment. A Geoscientific Verification Plan (NWMO 2011b) has been developed to identify sub-surface geoscience investigations to support re-assessment of the DGR Safety Case in support of a DGR Operating Licence. Technical issues identified in the plan include: site stratigraphy/structure; geomechanics, EDZ properties; groundwater chemistry; two-phase flow properties; and microbiology.

Table 7.25: Addressing the G-320 CNSC Expectations and Recommendation in the Current Safety Assessment

Issue	Guidance	Consideration in the Safety Assessment
Assessment approach	The CNSC expects the safety assessment to demonstrate the applicant's understanding of the waste management system through a well-structured, transparent, and traceable methodology. 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.	An approach based on the IAEA's DS-355 and ISAM methodology (see Chapter 2) has been used to assess the safety of the DGR. The methodology provides a generic, high-level framework that encourages a well-structured, transparent and traceable approach. Where there are high levels of uncertainty associated with processes and data, conservative assumptions have been adopted (Section 3.6.2). This ensures that calculated impacts are conservative.
Hazardous substances, non-human biota	Long-term assessments should address the impact on humans and on non-human biota from both radioactive and hazardous non-radioactive constituents of the radioactive waste.	The impact of radionuclides and non-radioactive contaminants on humans and non-human biota are evaluated (see Sections 3.4, 7.1 and 7.2).
Time frame	Assessments of the future impact that may arise from the radioactive waste are expected to include the period of time during which the maximum impact is predicted to occur. The assumed performance time frames of engineered barriers and the evolution of their safety function with time should be documented and justified, with reference to current national or international standards where appropriate.	The timeframes considered in the current assessment are identified and justified in Section 3.8.
Institutional controls	A submission from a licence applicant should identify the role that institutional controls play in waste management system safety, and how that role is taken into account in the safety assessment.	A reference value of 300 years is adopted for the minimum period over which institutional controls are effective (Section 3.8). It is assumed that during this control period, inadvertent human intrusion does not occur.
Assessment end points	The principal regulatory requirements are those that address radiation dose and environmental concentrations. Several other safety indicators, such as those that reflect containment barrier effectiveness or site-specific characteristics that can be directly related to contaminant release and transport phenomena, can also be presented to illustrate the long-term performance of a waste management system.	A range of safety and performance indicators is considered in the current assessment (Section 3.5). Safety indicators are: radiation dose to humans; environmental concentrations of radionuclides; and environmental concentrations of non-radioactive hazardous substances. Performance indicators are: radiotoxicity of the waste; contaminant amounts; and fluxes of contaminants. Groundwater travel times are discussed in Section 5.4.5 of NWMO (2011a).

Issue	Guidance	Consideration in the Safety Assessment
Radiation protection	Long term safety assessments of a facility or contaminated site should provide reasonable assurance that the regulatory radiation dose limit for public exposure will not be exceeded. However, to account for the possibility of exposure to multiple sources and to help ensure that doses resulting from the facility being assessed are as low as reasonably achievable (ALARA), an acceptance criterion that is less than the regulatory limit of 1 mSv/a should be used.	A dose constraint of 0.3 mSv/a to the critical group is adopted for the Normal Evolution Scenario (Section 3.4.1).
Environmental concentrations of hazardous substances	Benchmark values for protection from hazardous substances can be found in federal and provincial environmental objectives and guidelines. Where available, the Canadian Council of Ministers of the Environment's (CCME's) Canadian Environmental Quality Guidelines 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 provincial guidelines should be used. Where Canadian jurisdiction has not established human health-based guidelines, benchmarks may be based on those of the United States Environmental Protection Agency. Benchmarks that are proposed based on sources of information other than those identified above may need additional justification for their use.	The values adopted in Section 3.4.4 are primarily based on either federal CCME or provincial (Ontario Ministry of the Environment - MoE) guideline concentrations. Where necessary, other sources are identified.
Optimization	The design of a nuclear facility should be optimized to exceed all applicable requirements. In particular, a radioactive waste management facility should more than meet the regulatory limits, remaining below those limits by a margin that provides assurance of safety for the long term.	The preliminary design considered in this assessment meets or exceeds all applicable requirements. All calculation cases for the Normal Evolution Scenario result in calculated doses more than five orders of magnitude below the dose criterion (Section 7.1.3 and 7.3.2). Similar safety margins exist for non-radioactive contaminants and doses to non-human biota for the Reference and Simplified Base Cases (Section 7.1). The repository design will be subject to further optimization during the detailed design stage, and the shaft seal design will be subject to further optimization based on knowledge gained during the 40 years of operation before seeking a decommissioning licence.

Issue	Guidance	Consideration in the Safety Assessment
Scenarios	A long-term assessment scenario should be sufficiently comprehensive to account for all of the potential future states of the site and the biosphere. It is common for a safety assessment to include a central scenario of the normal, or expected, evolution of the site and the facility over time, and additional scenarios that examine the potential impact of disruptive events or modes of containment failure. Scenarios should be developed in a systematic, transparent, and traceable manner through a structured analysis of relevant features, events, and processes (FEPs) that are based on current and future conditions of site characteristics, waste properties, and receptor characteristics and their lifestyles.	Systematic, transparent and traceable approach has been used to identify and develop scenarios (Chapter 5). Five scenarios have been identified with this approach (a Normal Evolution Scenario and four Disruptive ("what if") Scenarios). These scenarios are considered to be sufficiently comprehensive to account for the potential future states of the site and the environment. The range of scenarios identified is comparable with those considered in postclosure safety assessments of other deep geologic repositories (Section 5.2.1 and Table 5.7).
Intrusion scenarios	Scenarios concerning inadvertent human intrusion into a waste facility could predict doses that are greater than the regulatory limit of 1 mSv/a. 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 risk from the intrusion should therefore be reported. Reasonable efforts should be made to limit the dose from a high-consequence intrusion scenario, and to reduce the probability of the intrusion occurring.	The absence of identified commercially viable natural resources at or below repository level, the DGR's small panel footprint (~0.25 km^2) and its depth (around 680 m below the ground surface) all limit the nature and likelihood of human intrusion into the DGR. The likelihood and the risk from intrusion are around 10^{-5}/a and 10^{-9}/a, respectively (Section 7.2.1).
Receptors	Receptors may be identified through the FEP analysis or from evaluation of valued ecosystem components (VECs). The human receptors in a scenario may be based on the ICRP concept of a critical group for radiological protection of persons. The habits and characteristics that are assumed for the human critical group should be based on reasonably conservative and plausible assumptions that consider current lifestyles and available site-specific or region-specific information. Non-human receptors usually include a range of different plants and animals occurring at various levels of biological organization (e.g., organism, population, community, or ecosystem). Among other criteria, the receptors should	The VECs evaluated in the assessment include a wide range of terrestrial and aquatic flora and fauna (Section 4.4.7). Human groups that are exposed to the contaminants are based on the ICRP concept of a critical group (Section 3.5). Current lifestyles and available region-specific information are used to define the human critical groups evaluated (Section 7.1 of the Data report, QUINTESSA and GEOFIRMA 2011a).

Issue	Guidance	Consideration in the Safety Assessment
	represent the taxonomic groups most likely to receive a higher exposure from a particular pathway.	
Data	The use of generic or default data in place of site-specific data in developing the conceptual and computer models may be acceptable when there is no site-specific data available, such as in early stages of development; however, with the acquisition of as-built information and operational data, and increased understanding of site characteristics throughout the facility lifecycle, site-specific data should be used.	Site-specific data have been used in the current assessment The primary data sources are: the Reference L&ILW Inventory Report (OPG 2010) for the waste and waste packaging; Chapter 6 (Facility Description) of the Preliminary Safety Report (OPG 2011b) for the repository design; the Geosynthesis Report (NWMO 2011a) and the Descriptive Geosphere Site Model Report (INTERA 2011) for the geological setting; and the Technical Support Documents (TSDs) supporting the Environmental Assessment (EA) for the DGR (GOLDER 2011a-g, AMEC NSS 2011) and the EA Study Report for the WWMF (OPG 2005) for the surface environment.
Conceptual and mathematical models	A conceptual model of the waste management system should be developed to the rigour and level of detail that is appropriate for the purpose of the assessment. The conceptual model should account for uncertainties, incomplete information in the system description, and simplifications and assumptions adopted during interpretation of the site characterization data. These simplifications and assumptions, and any resulting restrictions or limitations in the model, should be identified and discussed in the assessment. Justification for rejecting alternate interpretations should be discussed.	The development of the conceptual models for the five scenarios assessed is described in Section 6.2. The associated uncertainties and assumptions are summarized in Table 6.5 (conceptual model uncertainties), Table 6.7 (data uncertainties), and Table 7.2 to Table 7.6 (assumptions).
Computing tools	All software used in an assessment should conform to accepted quality assurance (QA) standards.	The QA standards of the modelling codes are summarized in Section 6.4 and Appendix A. Further details are provided in the Groundwater Modelling report (Appendix A, GEOFIRMA 2011), the T2GGM software document (QUINTESSA and GEOFIRMA 2011b) and the Analysis of the Normal Evolution Scenario report (Appendix G, QUINTESSA 2011a).
Understanding	Demonstrate a thorough understanding of the underlying science and engineering principles that are controlling the assessment results.	The analysis and interpretation of the assessment results is presented in Chapter 7. More detailed analysis and interpretation is provided in the following supporting reports: Analysis of the Normal Evolution Scenario (Chapters 5 and 6, QUINTESSA 2011a); Analysis of Human Intrusion and Other Disruptive

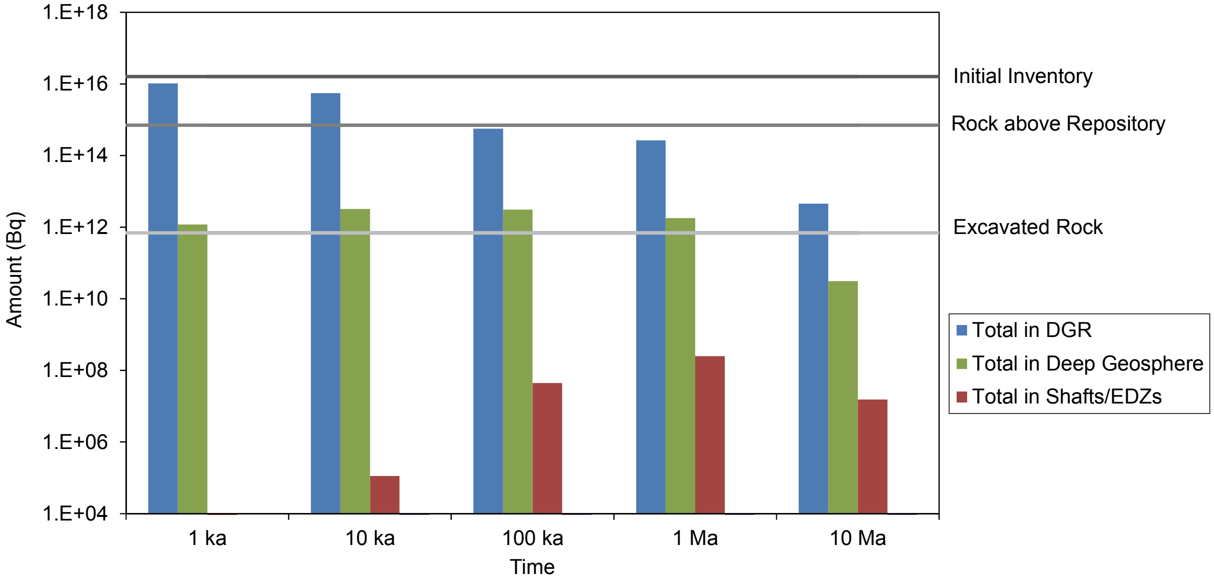
Issue	Guidance	Consideration in the Safety Assessment
		Scenarios (Sections 2.5, 3.5, 4.5 and 5.5 of QUINTESSA and SENES 2011); Groundwater Modelling report (Chapters 5 and 6 of GEOFIRMA 2011); and Gas Modelling report (Chapters 5, 6 and 7 of GEOFIRMA and QUINTESSA 2011). These analyses identify the key processes that control the assessment results.
Uncertainties	A formal uncertainty analysis of the predictions should be performed to identify the sources of uncertainty. This analysis should distinguish between uncertainties arising from input data; scenario assumptions; the mathematics of the assessment model; and the conceptual models.	Uncertainties are discussed in Section 7.3. Uncertainties are evaluated arising from scenarios (Section 7.3.1), conceptual models and data (Section 7.3.2), and mathematical and computer models (Section 7.3.3).
Confidence building	Claims of long-term safety submitted to support a licence application may be evaluated by way of the ‘weight of evidence’ and confidence-building arguments (i.e., scientific evidence, multiple lines of reasoning, reasoned arguments, and other complementary arguments) that support the assessment and its conclusions.	Evidence of the measures that have been used in the current assessment of the DGR are summarized in Table 7.22 and Table 7.23.
Compliance	Interpretation should include evaluation of compliance with the acceptance criteria and analysis of the uncertainties associated with the assessment. Comparison of the assessment results with acceptance criteria to provide a reasonable assurance of future safety should include discussion of the conservatism of the model results and the conservatism built into the acceptance criteria for the safety indicators.	Compliance with the acceptance criteria and with regulatory guidance is discussed in Section 7.1.3 for the Normal Evolution Scenario and Section 7.2 for the Disruptive Scenarios. Associated uncertainties are discussed in Section 7.3. Conservatisms in the models are summarized in Table 7.2 to Table 7.6 and in the criteria in Section 3.4.

8. CONCLUSIONS

Consistent with the guidelines for the preparation of the EIS for the DGR (CEAA and CNSC 2009) and with G-320 (CNSC 2006), the postclosure safety assessment has evaluated the DGR's ability to perform in a manner that will protect human health and the environment. The assessment considered potential impacts through consideration of a range of possible future scenarios.

The most detailed analyses were carried out for an expected evolution scenario (the Normal Evolution Scenario). The assessment calculations for the Normal Evolution Scenario indicate that the DGR system provides effective containment of the emplaced radionuclides (Figure 8.1). Most radionuclides decay within the repository or the deep geosphere.

The release of contaminants from the waste packages is limited by the slow rate of repository resaturation (due to the low permeability of geosphere and shafts, and eventually the repository gas pressure), and the slow corrosion rate of the higher activity metallic wastes. The low permeability of the geosphere and the shaft seals further limit the migration of contaminants in water or as free gas. The amount of contaminants reaching the surface is very small, such that the maximum calculated effective doses for the Reference Case is far below the dose criteria for humans and biota, including people who may live on the site in the far future. The maximum concentrations of non-radioactive contaminants are also far below environmental protection criteria.



Note: The natural radioactivity in the rock above the repository footprint and in the excavated rock volume are shown.

Figure 8.1: Distribution of Activity in System at Different Times for the Normal Evolution Scenario Reference Case

Four disruptive “what if” scenarios have also been evaluated that, although unlikely to occur, could disrupt or bypass the key geosphere barrier.

- Unintentional intrusion into the repository as a result of an exploration borehole (the **Human Intrusion Scenario**).
- The unexpected poor performance of the shaft seals (the **Severe Shaft Seal Failure Scenario**).
- Poor sealing of a site investigation/monitoring borehole in close proximity to the repository (the **Poorly Sealed Borehole Scenario**).
- A hypothetical transmissive vertical fault in close proximity to the DGR footprint (the **Vertical Fault Scenario**).

The analysis of the Disruptive Scenarios shows that the isolation afforded by the location and design of the DGR limits the likelihood of disruptive events potentially able to bypass the natural barriers to a small number of situations with very low probability. Even if these events were to occur, the vast majority of the contaminants in the waste would continue to be contained effectively by the DGR system such that safety criteria are met in the base case calculation for all Disruptive Scenarios, even with conservative assessment modelling assumptions.

The key radionuclide within the first 60,000 years is C-14 (and Nb-94 in the case of human intrusion). In the long term, Cl-36 and I-129 become more important due to their longer half-life and their mobility. H-3, Nb-94 and Zr-93 are retained within the shafts and geosphere and so are not significant contributors to the calculated doses.

Calculations indicate that there is no benefit to be gained from backfilling the repository due to the significant containment already provided by the host geology and the shaft seals. Backfilling results in a higher gas pressure within the repository after closure due to smaller gas space. The calculations have also emphasized the importance of the shaft seals in limiting contaminant fluxes in groundwater and gas from the repository. The damaged zone in the rock around the concrete monolith at the shaft base is a key pathway to the shafts.

The assessment has adopted scientifically informed, physically realistic assumptions for processes and data that are understood and can be justified on the basis of the results of research and/or site investigation. Where there are high levels of uncertainty associated with processes and data, conservative assumptions have been adopted to allow the impacts of uncertainties to be bounded, consistent with the recommendations of G-320 (CNSC 2006). Thus, the results presented in this report should be seen as being generally conservative and liable to overestimate potential impacts.

The long timescales under consideration mean that there are uncertainties about the way in which the system will evolve. These uncertainties have been treated in the current assessment through: the assessment of range of scenarios, models and data; the adoption of conservative scenarios, models and data; and the adoption of a stylized approach for the representation of future human actions and biosphere evolution.

The key uncertainties in terms of their importance to modify potential impacts are as follows.

- **Gas pressure and repository saturation** are important in determining the potential release of radioactivity into repository water, and the potential for C-14 release through gas in the first 60,000 years. Therefore, the processes that control these parameters are important. They were approached in this safety assessment through use of a range of calculation cases to test the importance of uncertainties in those contributing processes.

- **Shaft seal and EDZ properties** and their evolution with time. Variant calculation cases for the Normal Evolution Scenario and the Severe Shaft Seal Failure Scenario calculations emphasize the importance of the shaft seals, particularly in the first 60,000 years following closure.

- **Glaciation effects.** Although geological evidence at the site indicates that the deep geosphere has not been affected by past glaciation events and that the deep groundwater system has remained stagnant, glaciation is expected to have a major effect on the surface and near-surface environment and it is not entirely predictable. It should, however, be noted that ice-sheet coverage of the site is likely to occur only after 60,000 to 100,000 years, at which point the primary remaining hazard will be long-lived radionuclides in groundwater rather than gaseous C-14. Calculations have shown that the deep groundwaters are stable and transport is diffusion-dominated, so dissolved radionuclides in groundwater will be contained in the deep geosphere with large safety margins.

- **Chemical reactions**. Under the highly saline conditions of the deep geosphere at the DGR site, several aspects of the chemistry are uncertain due to the limited database. In particular, this includes the sorption of contaminants on seal materials and host rocks, as well as mineral precipitation/dissolution reactions. Generally conservative values have been adopted in this assessment.

The geosphere is clearly key to the DGR safety. In general, the attributes of the geosphere are sufficiently well known to support the safety assessment (Section 4.3). However, some aspects are still uncertain, such as the cause of the over/underpressures. These geosphere uncertainties have been considered in this assessment through a range of scenarios, calculation cases and conservative parameter values. Although further resolution of these uncertainties is desirable to increase confidence in the safety assessment, they have not been found to be important to the conclusions of this assessment.

The Geoscientific Verification Plan (NWMO 2011b) outlines plans to initiate tests of important processes and materials in the rock during the repository construction - for example, EDZ measurements. Also, the shaft seal design will not be finalized until the decommissioning application several decades from now, and will take advantage of these tests and knowledge gained over the intervening period.

While these tests plus further safety and geoscience modelling work will improve confidence in the assessment, the results presented here show that the DGR meets the postclosure safety criteria, that it provides isolation and containment of the wastes, and that the system safety is robust, i.e., the system will maintain its integrity and reliability under a range of conditions. The uncertainties should be interpreted in the context of the low calculated impacts; for example, calculated doses for all Normal Evolution Scenario variant cases are more than five orders of magnitude below the dose criterion.

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10. ABBREVIATIONS AND ACRONYMS

2DSR	2-dimensional Radial Shaft Gas Transport Model
3DD	3-Dimensional Detailed Gas Transport Model
3DS	3-Dimensional Simplified Model for the Intermediate and Deep Bedrock Groundwater Zone
3DSR	3-Dimensional Simplified Repository Gas Transport Model
3DSRS	3-Dimensional Simplified Repository and Shaft Gas Transport Model
3DSU	3-Dimensional Simplified Upper model for the Shallow Bedrock Groundwater Zone
A	AMBER assessment level model
ALARA	As Low As Reasonably Achievable
ALW	Active Liquid Waste
BH	Poorly Sealed Borehole Disruptive Scenario
BH-BC	Poorly Sealed Borehole Base Case
BH-NR	Poorly Sealed Borehole Non-radioactive Contaminants Case
CCME	Canadian Council of Ministers for the Environment
CEAA	Canadian Environment Assessment Act
CNSC	Canadian Nuclear Safety Commission
DGR	Deep Geologic Repository
DGSM	Descriptive Geosphere Site Model
EA	Environmental Assessment
EDZ	Excavation Damaged Zone
EIS	Environmental Impact Statement
EMDD	Equivalent Montmorillonite Dry Density
ENEV	Estimated No Effect Values
F3	FRAC3DVS groundwater model
FEPs	Features, Events and Processes
GGM	Gas Generation Model
HDZ	Highly Damaged Zone

HI	Human Intrusion
HI-BC	Human Intrusion Base Case
HI-GR1	Exploration Borehole Intersecting the Repository Case
HI-GR2	Exploration Borehole Intersecting the Repository and the Cambrian Case
IAEA	International Atomic Energy Agency
ICEM	International Conference on Environmental Remediation and Radioactive Waste Management
ICRP	International Commission on Radiological Protection
ILW	Intermediate Level Waste
ISAM	Improvement of Safety Assessment Methodologies
IX	Ion-Exchange
L&ILW	Low and Intermediate Level Waste
LHHPC	Low Heat, High Performance Cement
LLW	Low Level Waste
MoE	Ontario Ministry of the Environment
MPC	Maximum Permissible Concentration
NEA	Nuclear Energy Agency
NE	Normal Evolution Scenario
NE-AN	Normal Evolution Variant Anisotropy Cases
NE-BF	Normal Evolution Backfilled Repository Case
NEC	No-Effect Concentration
NE-CC	Normal Evolution Tundra Biosphere Case
NE-EDZ	Normal Evolution EDZ Variant Cases
NE-ER	Normal Evolution Removal of Geosphere by Surface Erosion Case
NE-GG	Normal Evolution Gas Generation Variant Cases
NE-GT	Normal Evolution Gas Transport Variant Cases
NE-HG	Normal Evolution Horizontal Gradient in Permeable Units Case
NE-IV	Normal Evolution Increased Radionuclide Inventory Cases
NE-MG	Normal Evolution Alternative Gas Case

NE-NG	Normal Evolution No Gas Generation Variant Case
NE-NM	Normal Evolution No Methane Gas Generation Case
NE-NR	Normal Evolution Non-radioactive Contaminants Case
NE-PC	Normal Evolution Probabilistic Case
NE-PD-GT5	Normal Evolution Gas Transport Variant Case, based on the final preliminary design
NE-PD-RC	Normal Evolution Reference Case, based on the final preliminary design
NE-RC	Normal Evolution Reference Case
NE-RC1	Geosphere Gas Phase at Residual Saturation Case
NE-RC2	Normal Evolution Variable Geosphere Gas Saturation and Transport Properties Case
NE-RS	Normal Evolution Instant Repository Resaturation Case
NE-RT	Normal Evolution Radionuclide Transport Variant Cases
NE-SBC	Normal Evolution Simplified Base Case
NE-SE	Normal Evolution Salinity Case
NSCA	Nuclear Safety and Control Act
NWMO	Nuclear Waste Management Organization
OPG	Ontario Power Generation
PHT	Primary Heat Transport
PSR	Preliminary Safety Report
PWQO	Provincial Water Quality Objective
QA	Quality Assurance
SF	Shaft Failure
SF-BC	Shaft Seal Failure Base Case
SF-ED	Severe Shaft Seal Failure Extra Degradation Case
SF-NR	Shaft Seal Failure Non-radioactive Contaminants Case
T2	T2GGM gas model
T-H-E	Tile Hole Equivalent
TSD	Technical Support Document

VEC	Valued Ecosystem Components
VF	Vertical Fault
VF-AL	Vertical Fault Alternate Location Case
VF-BC	Vertical Fault Base Case
VF-NR	Vertical Fault Non-radioactive Contaminants Case
WL	Water Limited
WWMF	Western Waste Management Facility

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APPENDICES

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APPENDIX A: OVERVIEW OF SOFTWARE TOOLS USED

A.1 AMBER

A.1.1 DESCRIPTION

AMBER is a graphical-user interface based software tool that allows users to build dynamic compartment models to represent the migration, degradation and fate of radioactive and non-radioactive contaminants in environmental systems. AMBER was originally developed for modelling contaminants from radioactive waste repositories and this remains its core area of application and development.

AMBER also allows text-based 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 range of probability density functions. It has two solvers that permit time-varying, linear/non-linear source terms, environmental properties and transfer processes.

The code allows any number of contaminants, compartments and transfers to be represented. Data can be imported/exported for use with other software tools and databases.

AMBER's capabilities are fully described in a Reference Guide (QUINTESSA 2009a).

A.1.2 QUALITY ASSURANCE

AMBER is managed and developed under Quintessa's ISO 9001:2008 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 tests (e.g., QUINTESSA 2009b).

AMBER has a wide international user base, with over 80 organizations in more than 30 countries owning licences. There are in excess of 75 publications describing assessments in which AMBER has been applied (QUINTESSA 2009c), including several international code intercomparison exercises.

Two DGR-specific models (AMBER_V2_NF&GEOv1 for the repository, shafts and geosphere and AMBER_V2_BIOv1 for the biosphere have been implemented in the AMBER 5.3 code to undertake radiological impact calculations for the five scenarios assessed. In addition, a variant of each of these models has been developed in which the radionuclides are replaced with non-radioactive contaminants (AMBER_V2_NF&GEO_NRv1 and AMBER_V2_BIO_NRv1). The quality assurance of these models is discussed in Appendix I of the Analysis of the Normal Evolution Scenario report (QUINTESSA 2011).

A.2 FRAC3DVS-OPG

A.2.1 DESCRIPTION

FRAC3DVS-OPG is based on the original FRAC3DVS code developed by Therrien et al. (2004). In the past decade, the code has been continuously developed and enhanced to further its simulation capabilities and computational efficiency. The development and use of FRAC3DVS-OPG has been supported by OPG and NWMO as part of its used fuel technology program.

FRAC3DVS-OPG uses the control volume finite element approach to solve Richards' equation governing 3D saturated/unsaturated subsurface flow and the classical advection-dispersion equation for problems that involve solute transport and radioactive decay chains. The code is capable of simulating flow through porous and discretely fractured media, as well as accurately handling fluid and mass exchanges between fractures and the matrix.

FRAC3DVS-OPG provides several discretization options ranging from simple rectangular and axisymmetric domains to irregular domains with complex geometry and layering. Mixed element types provide an efficient mechanism for simulating flow and transport processes in fractures (2-D rectangular or triangular elements) and pumping/injection wells or tile drains (1-D line elements). Subgridding and subtiming features are also available to facilitate concurrent multi-scale simulations. The code includes options for adaptive-time stepping and output control procedures along with an incomplete LU factorization preconditioned conjugate gradient solution package and a Newton-Raphson linearization package.

A.2.2 QUALITY ASSURANCE

The version of FRAC3DVS-OPG used in the current assessment (Version 1.3.0, Build Date 2010 06 03 - 64-bit) has been qualified to NWMO Software Quality requirements (NWMO 2010) and is documented in Therrien et al. (2010). The flow and solute code has been verified against other numeric and analytic models. Code verification is documented in Chapter 3 of Therrien et al. (2010).

A.3 T2GGM

A.3.1 DESCRIPTION

The postclosure safety assessment of the DGR requires the calculation of the generation and buildup of gas in the repository and the two-phase flow of gas and groundwater from the repository to the surface environment. The software used to undertake these calculations is called T2GGM (Version 2.0). It is comprised of two coupled codes: a project-specific gas generation model (**GGM**) used to model the detailed generation of gas within the DGR due to corrosion and microbial degradation of the various wastes present, and **TOUGH2** for two-phase gas and water transport in the repository and geosphere. Integration of the TOUGH2 and GGM codes was performed by Geofirma Engineering Ltd. and is described in QUINTESSA and GEOFIRMA (2011).

The **GGM** is implemented as a FORTRAN module that is used by TOUGH2 in its gas transport and repository saturation calculations. The theory behind GGM is documented in QUINTESSA and GEOFIRMA (2011). GGM is based on a kinetic description of the various microbial and corrosion processes that lead to the generation and consumption of various gases. Mass-balance equations are given for each of the species included in the model, including three forms of organic waste (cellulose, ion-exchange resins, and plastics and rubbers), four metallic waste forms and container/overpack materials (carbon and galvanized steel, passivated carbon steel, stainless steel and nickel-based alloys, and zirconium alloys), six gases (CO_2, N_2, O_2, H_2, H_2S, and CH_4), five terminal electron acceptors (O_2, NO_3^-, Fe(III), SO_4^{2-}, and CO_2), five forms of biomass (aerobes, denitrifiers, iron reducers, sulphate reducers, and methanogens), four types of corrosion product (FeOOH, $FeCO_3$, Fe_3O_4, and FeS), and water. The code models the limitation of both microbial and corrosion reactions by the availability of water.

TOUGH2 models the two-phase transport of the gas from the repository through the geosphere. TOUGH2 is a well-known and widely-used numerical code for simulating the coupled transport of water, vapour, non-condensable gas, and heat in porous and fractured media in multi-dimensions. It was developed by the Earth Sciences Division of Lawrence Berkeley National Laboratory (Pruess et al. 1999). TOUGH2 takes account of fluid flow in both liquid and gaseous phases occurring under pressure, viscous, and gravity forces according to Darcy's law. Interference between the phases is represented by means of relative permeability and capillary pressure functions.

T2GGM includes TOUGH 2 Version 2.0 with the EOS3 equation-of-state module for transport of air and water (Pruess et al. 1999), including the modified van Genuchten model provided in iTOUGH2 (Finsterle 1999). The EOS3 equation of state module uses the steam table equations for the properties of water and assumes air is an ideal gas. The integration of TOUGH2 and GGM directly couples gas generation and water consumption within the repository to gas and water flow in the geosphere through gas and water generation rates, water saturation, gas pressure, relative humidity and repository void volume.

A.3.2 QUALITY ASSURANCE

Quality assurance documentation for **T2GGM** is provided in QUINTESSA and GEOFIRMA (2011).

GGM has been developed under the DGR postclosure safety assessment project and so has been subject to the project’s QA requirements (QUINTESSA 2010), which incorporate the requirements of the TickIT software quality system (www.tickit.org).

Developed at the Lawrence Berkeley National Laboratory, **TOUGH2** has been tested by comparison with many different analytical and numerical models, and with results from laboratory experiments and field observations. Originally released in 1991, TOUGH2 is a widely-used code. Various versions of TOUGH2 are qualified for the Yucca Mountain project under YMP procedure AP-SI.1Q. A number of verification and validation reports describing application of TOUGH2 and comparison to other solutions are available, including Moridis and Pruess (1992), Moridis and Pruess (1995) and Pruess et al. (1996).

Modifications to TOUGH2 for GGM integration have been performed by Geofirma Engineering Ltd. using the process specified in the Software Development Work Instruction; a component of Geofirma's ISO 9001:2008 registered Quality Management System.

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APPENDIX B: CALCULATION CASES

B.1 ASSESSMENT MODEL CALCULATION CASES

20 calculation cases have been developed to assess the Normal Evolution Scenario and 11 for the Disruptive Scenarios. The cases are summarized in Tables B.1 and B.2, respectively. Further data relating the Normal Evolution Scenario cases are provided in Sections 4.3 and 4.4 of QUINTESSA (2011), while further data for the Disruptive Scenarios cases are provided in Sections 2.4.3, 3.4.3, 4.4.3 and 5.4.3 of QUINTESSA and SENES (2011).

Table B.1: Assessment Modelling Cases for the Normal Evolution Scenario

Case ID*	Case Description
NE-RC-A**	Reference case parameters based on inventory, original preliminary design and site characterization data summarized in Chapter 4. Based on detailed groundwater and gas modelling reference cases. Considers: • instantaneous and congruent contaminant release; • source terms with release for certain radionuclides (e.g., C-14) partitioned between gas and groundwater; • no sorption or solubility limitation in repository (except for carbon solubility limitation); • gas generation and gradual repository resaturation; • no consumption (or production) of water by corrosion and degradation reactions; • 10 m rockfall at closure; • sorption of limited number of contaminants in shaft and geosphere; • steady state Cambrian overpressure (+165 m); • initial Ordovician underpressures with subsequent transient evolution towards equilibrium; • initial gas saturations of 10% in the Ordovician; • no salinity profile in the geosphere; • no horizontal groundwater flow in the Cambrian, Guelph or Salina A1 upper carbonate; • no explicit representation of glacial cycling; • self-sufficient farming family. See Table 6.8 for summary of data.
NE-PD-RC-A	As NE-RC-A but adopting the final preliminary design, including: • additional ventilation drifts; and • ILW filters & elements, irradiated core components, and IX columns disposed to ILW shield containers rather than concrete arrays. See Section 4.4.1, QUINTESSA 2011, for further information.
NE-SBC-A**	As NE-RC-A but with: • no underpressures in the Ordovician; and • no initial gas saturation in the Ordovician.
NE-RS-A	As NE-RC-A but with: • immediate water resaturation of repository (including shaft); and • no gas generation in repository.

Case ID*	Case Description
NE-EDZ1-A	As NE-SBC-A but with EDZ hydraulic conductivities increased to maximum values in the Data report (Tables 5.7 and 5.8 of QUINTESSA and GEOFIRMA 2011), i.e.: • shaft inner EDZ increased by two orders of magnitude (i.e., four orders of magnitude greater than rock mass); • shaft outer EDZ increased by an order of magnitude (i.e., two orders of magnitude greater than rock mass); and • repository EDZ increased by an order of magnitude, (i.e., four orders of magnitude greater than rock mass).
NE-HG-A	As NE-SBC-A but with: • horizontal groundwater flow in the Guelph (gradient of 0. 0026) and Salina A1 upper carbonate formations (gradient of 0.0077) (Section 5.4.1.1 of the Data report, QUINTESSA and GEOFIRMA 2011); and • 1.25 km travel path along Guelph and Salina A1 upper carbonate to lake.
NE-GT5-A	As NE-GG1-A but with: • asphalt seal in shaft replaced by bentonite/sand; • gas entry pressure for shaft materials reduced by factor of two to 5 x 10^6 Pa; and • bentonite/sand hydraulic conductivity reduced by an order of magnitude to 10^{-10} m/s.
NE-PD-GT5-A	As NE-GT5-A but with final preliminary design (as for NE-PD-RC-A).
NE-BF-A	As NE-SBC-A but with repository backfilled with coarse aggregate material with a porosity of 0.3.
NE-GG1-A	As NE-SBC-A but with: • increased metal inventory (~ 25% increase); and • corrosion and organic degradation rates increased to maximum rates in the Data report (Tables 3.20 and 3.21 of QUINTESSA and GEOFIRMA 2011) (up to an order of magnitude increase).
NE-GG2-A	As NE-SBC-A but with organic degradation rates decreased to minimum rates in the Data report (Table 3.21 of QUINTESSA and GEOFIRMA 2011) (by up to an order of magnitude decrease)
NE-NM-A	As NE-SBC-A but with no methanogenic reactions, which includes both methane generation from organic degradation and also the conversion of H_2 and CO_2 to CH_4.
NE-RT1-A	As NE-RC-A but with: • immediate water resaturation of repository; • no gas generation in repository; • instantaneous release of radionuclides to repository water; and • no radionuclides sorbed or solubility limited in repository or geosphere.
NE-RT2-A	As NE-SBC-A but with: • immediate water resaturation of repository; • no gas generation in repository; • instantaneous release of radionuclides to repository water; and • no radionuclides sorbed or solubility limited in repository or geosphere.

Case ID*	Case Description
NE-IV-A	As NE-RC-A but with radionuclide inventory increased by a factor of ten compared to that given in Table 4.4
NE-ER-A	As NE-RC-A but with removal of 100 m of geosphere due to erosion over 1 million years. See Section 4.4.4, QUINTESSA 2011, for further information.
NE-CC-A	As NE-RC-A but with alternative constant state biosphere (i.e., tundra rather than temperate). See Section 4.4.3, QUINTESSA 2011, for further information.
NE-CG-A	As NE-HG-A but with dose to a Site Shore Resident Group and a Downstream Resident Group exposed via consumption of lake fish and water from the near shore and the South Basin of Lake Huron, respectively. See Section 4.4.2, QUINTESSA 2011, for further information.
NE-PC-A	As NE-RC-A but with probabilistic treatment of certain parameters. See Section 4.4.6, QUINTESSA 2011, for further information.
NE-NR-A	As NE-RC-A but with the inventory of non-radioactive element and chemical species given in Table 4.4 emplaced in the repository. See Section 4.4.5, QUINTESSA 2011, for further information.

Notes:
* See Table 7.1 for explanation of the ID scheme used for the calculation cases.
** A version of this case was also run using gas flow information from the T2GGM water-limited version that accounts for the effect of the consumption (or production) of water by corrosion and degradation reactions – see Appendix B.3).

Table B.2: Assessment Modelling Cases for the Disruptive Scenarios

Case ID*	Case Description
HI-BC-A	As NE-RC-A but with: • exploration borehole drilled from surface down into Panel 1 at some time after controls are no longer effective (i.e., 300 years); • borehole terminated at repository depth; • repository largely unsaturated; • short-term surface release of contaminated gas immediately following intrusion; and • retrieval of contaminated drill core. See Section 2.4.3, QUINTESSA and SENES 2011, for additional information.
HI-GR2-A	As NE-RC-A but with: • exploration borehole drilled from surface down into Panel 1 at some time after controls are no longer effective (i.e., 300 years); • borehole penetrates down to the pressurized Cambrian; • repository rapidly resaturated; • borehole poorly sealed resulting in a hydraulic conductivity of 10^{-4} m/s and porosity of 0.25; and • long-term release of radionuclides in water from the repository to the Shallow Bedrock Groundwater Zone. See Section 2.4.3.4, QUINTESSA and SENES 2011, for additional information.
HI-NR-A	As HI-BC-A but with the inventory of non-radioactive element and chemical species given

Case ID*	Case Description
	in Table 4.4 emplaced in the repository
SF-BC-A	As NE-RC-A but with: • hydraulic conductivity of 10^{-9} m/s for bentonite/sand, asphalt and concrete in shafts; • porosity of 0.3 for bentonite/sand, asphalt and concrete in shafts; • effective diffusion coefficient of 3 x 10^{-10} m^2/s for bentonite/sand, asphalt and concrete in shafts; • sorption values for bentonite/sand given in the Data report (Table 4.25 of QUINTESSA and GEOFIRMA 2011) reduced by an order of magnitude; • zero capillary pressure for shaft sealing material; and • repository and shaft EDZ hydraulic conductivity increased to maximum values in the Data report (Tables 5.7 and 5.8 of QUINTESSA and GEOFIRMA 2011). See Section 3.4.3, QUINTESSA and SENES 2011, for additional information.
SF-ED-A	As SF-BC-A but increased bentonite/sand, asphalt and concrete hydraulic conductivity (10^{-7} m/s) in order to understand the sensitivity of system performance to shaft seal properties. This is in the range of a fine sand/silt material, about 4-5 orders of magnitude more permeable than the design-basis bentonite/sand and asphalt seals.
SF-NR-A	As SF-BC-A but with the inventory of non-radioactive element and chemical species given in Table 4.4 emplaced in the repository
BH-BC-A	As NE-RS-A but with: • poorly sealed site investigation/monitoring borehole from surface down to Precambrian located 100 m from the southeast edge of Panel 2; • hydraulic conductivity of 10^{-4} m/s for borehole seal; • porosity of 0.25 for borehole seal; and • no sorption on borehole seal. See Section 4.4.3, QUINTESSA and SENES 2011, for additional information.
BH-NR-A	As for BH-BC-A but with the inventory of non-radioactive element and chemical species given in Table 4.4 emplaced in the repository.
VF-BC-A	As NE-RS-A but with a hypothetical transmissive vertical fault: • 500 m northwest of the repository; • from Cambrian to Guelph; • width of 1 m; • hydraulic conductivity of 10^{-8} m/s; • porosity of 0.1; and • no sorption in fault. In addition: • horizontal groundwater flow in the Cambrian (gradient of 0.0031), the Guelph (gradient of 0.0026) and Salina A1 upper carbonate formations (gradient of 0.0077); and • ~1 km travel path along Guelph from fault to lake. See Section 5.4.3, QUINTESSA and SENES 2011, for additional information.
VF-AL-A	As for the VF-BC-A case but with hypothetical transmissive vertical fault 100 m southeast of the repository.
VF-NR-A	As for VF-BC-A but with the inventory of non-radioactive element and chemical species given in Table 4.4 emplaced in the repository.

Notes: * See Table 7.1 for explanation of the ID scheme used for the calculation cases.

B.2 DETAILED GROUNDWATER MODELLING CALCULATION CASES

11 calculation cases for detailed groundwater modelling have been developed to assess the Normal Evolution Scenario (GEOFIRMA 2011) (Table B.3).

The Reference Case is consistent with that summarized in Table 6.8 with the following additions/modifications:

- Repository resaturation and contaminant transport is assumed to start immediately after facility closure; and
- Cl-36 in the waste is assumed to dissolve immediately into the repository water.

Table B.3: Detailed Groundwater Modelling Cases for the Normal Evolution Scenario

Case ID*	Case Description
NE-RC-F3	Reference Case parameters based on inventory, original preliminary design and site characterization data summarized in Chapter 4 and Table 6.8, with: • steady-state Cambrian overpressure (+165m); • initial underpressures in Ordovician consistent with present-day site data; • no gas saturations in Ordovician rocks and shaft materials; • immediate repository (including shaft) resaturation; • immediate release of Cl-36 into repository water; • no gas generation; • no salinity gradient; • no surface erosion; and • no horizontal gradients applied to any formation.
NE-PD-RC-F3	As NE-RC-A but adopting the final preliminary design
NE-SBC-F3	As NE-RC-F3 but with no underpressures in Ordovician.
NE-HG-F3	As NE-SBC-F3 but with horizontal gradients applied to the Guelph (0.0026) and Salina A1 upper carbonate formations (0.0077) (Section 5.4.1.1 of the Data report, QUINTESSA and GEOFIRMA 2011).
NE-AN1-F3	As NE-SBC-F3 but with changes in horizontal to vertical anisotropy of hydraulic conductivity. Horizontal:vertical anisotropies of 10:1 and 1000:1 are replaced by 2:1 and 20:1, respectively, with horizontal hydraulic conductivity fixed as in NE-SBC-F3.
NE-AN2-F3	As NE-SBC-F3 but with changes in horizontal to vertical anisotropy of effective diffusion coefficient. Horizontal:vertical anisotropies of 2:1 are replaced by 10:1, with a vertical effective diffusion coefficient fixed as in NE-SBC-F3.
NE-SE-F3	As NE-RC but with a saline fluid density profile based on the measured profile presented in Figure 4.17. A linear increase in density between 1000 and 1185 kg m^{-3} is adopted between the top of the model (Salina F) and the Guelph. Below the Guelph, a constant density of 1185 kg/m^3 is adopted.
NE-EDZ1-F3	As NE-SBC-F3, but with repository and shaft EDZ hydraulic conductivity increased to maximum values in the Data report (Table 5-7 and 5-8 of QUINTESSA and GEOFIRMA 2011), i.e.: • shaft inner EDZ increased by two orders of magnitude (i.e., four orders of

Case ID*	Case Description
	magnitude greater than rock mass); • shaft outer EDZ increased by an order of magnitude (i.e., two orders of magnitude greater than rock mass); and repository EDZ increased by an order of magnitude, (i.e., four orders of magnitude greater than rock mass).
NE-EDZ2-F3	As NE-EDZ1-F3, but with a 9 m wide concrete seal keyed into repository tunnel HDZ and EDZ.
NE-GT5-F3	As NE-SBC-F3 but with: • asphalt replaced by bentonite-sand in shaft; and • hydraulic conductivity of bentonite-sand increased by an order of magnitude to 10^{-10} m/s.
NE-PD-GT5	As NE-GT5 but considering the final preliminary design.

Notes: * See Table 7.1 for explanation of the ID scheme used for the calculation cases.

Seven calculation cases have been considered for Disruptive Scenarios (Table B.4).

Table B.4: Detailed Groundwater Modelling Cases for the Disruptive Scenarios

Case ID*	Case Description
HI-GR1-F3	As NE-RC-F3 but considers the long-term consequences of: • exploration borehole drilled from surface down into Panel 1; • borehole terminated at repository depth; and • borehole poorly sealed resulting in a hydraulic conductivity of 10^{-4} m/s and porosity of 0.25.
HI-GR2-F3	As HI-GR1-F3 but with the exploration borehole drilled from surface through the repository and terminated at the Cambrian. Borehole is also poorly sealed as per HI-GR1.
SF-BC-F3	As NE-RC-F3 but with: • hydraulic conductivity of 10^{-9} m/s for bentonite/sand, asphalt and concrete in shafts; • porosity of 0.3 for bentonite/sand, asphalt and concrete in shafts; • effective diffusion coefficient of 3×10^{-10} m^2/s for bentonite/sand, asphalt and concrete in shafts; and • repository and shaft EDZ hydraulic conductivity increased to maximum values in the Data report (Tables 5-7 and 5-8 of QUINTESSA and GEOFIRMA 2011).
SF-ED-F3	As SF-BC-F3 but increased bentonite/sand, asphalt and concrete hydraulic conductivity (10^{-7} m/s) in order to understand the sensitivity of system performance to shaft seal properties. This is in the range of a fine sand/silt material, about 4-5 orders of magnitude more permeable than the design-basis bentonite/sand and asphalt seals.
BH-BC-F3	As NE-RC-F3 but with: • poorly sealed site investigation/monitoring borehole from surface down to Precambrian located 100 m from the south east edge of Panel 2; • hydraulic conductivity of 10^{-4} m/s for borehole seal; and • porosity of 0.25 for borehole seal.

Case ID*	Case Description
VF-BC-F3	As NE-RC-F3 but with a hypothetical transmissive vertical fault: • 500 m northwest of the repository; • from Cambrian to Guelph; • width of 1 m; • hydraulic conductivity of 10^{-8} m/s; and • porosity of 0.1. In addition, horizontal groundwater flow in the Cambrian (gradient of 0.0031), Guelph (gradient of 0.0026) and Salina A1 upper carbonate formations (gradient of 0.0077)
VF-AL-F3	As VF-BC-F3, but with hypothetical transmissive vertical fault located 100 m southeast of the repository.

Notes: * See Table 7.1 for explanation of the ID scheme used for the calculation cases.

B.3 DETAILED GAS CALCULATION CASES

20 calculation cases for detailed gas modelling have been defined for the Normal Evolution Scenario (Table B.5). Further details are provided in the Gas Modelling report (GEOFIRMA and QUINTESSA 2011). The Reference Case is equivalent to the Reference Case considered for the detailed groundwater modelling (Appendix B.2) with the following additions/modifications:

- Initial gas saturations:
  - Repository 99.88% (based on initial water content of waste);
  - Ordovician rock 10%;
  - Concrete 50%;
  - Bentonite-sand 20%; and
  - Asphalt 100%.
- Gas flow parameters given in Tables 4-28 (shaft materials) and 5-15 (geosphere) of the Data report (QUINTESSA and GEOFIRMA 2011); and
- A single bulk gas (methane).

For each case, two models have been run: non-water-limited and water-limited (Section 2.1, GEOFIRMA and QUINTESSA 2011). The non-water-limited model conservatively does not enforce a water balance on the GGM corrosion and degradation reactions and ignores the effect of the consumption (or production) of water by corrosion and degradation reactions. The water-limited model enforces a water balance through accounting for the effect of the consumption (or production) of water by these reactions. The water-limited cases, although a more accurate representation of processes, have been shown to be very sensitive to assumptions regarding geosphere permeability, which is the most significant control on repository inflow.

Table B.5: Detailed Gas Modelling Cases for the Normal Evolution Scenario

Case ID*	Case Description
NE-RC-T2	Reference Case parameters based on inventory, original preliminary design and site characterization data summarized in Chapter 4 and Table 6.8, with gradual repository (including shaft) resaturation, and gas generation. Assumes: • steady-state Cambrian overpressure (+165m); • initial underpressures in Ordovician consistent with present-day site data; • initial gas saturations in Ordovician rocks and shaft materials; • no salinity gradient; • no surface erosion; and • no horizontal gradient applied to any formation.
NE-PD-RC-T2	As NE-RC but with final preliminary design. Involves: • increase in void volume from 4.2 x 10^5 m^3 to 4.5 x 10^5 m^3; • decrease in mass of unpassivated C-steel from 1.0 x 10^6 kg to 9.5 x 10^5 kg; and • increase in mass of passivated C-steel from 4.3 x 10^6 kg to 4.7 x 10^6 kg.
NE-SBC-T2	As NE-RC-T2 but with: • no underpressures in Ordovician; and • no partial gas saturations in Ordovician rocks.
NE-EDZ1-T2	As NE-SBC-T2 but with repository and shaft EDZ hydraulic permeability increased: • shaft inner EDZ increased by two orders of magnitude (i.e., four orders of magnitude greater than rock mass magnitude greater than rock mass); • shaft outer EDZ increased by an order of magnitude (i.e., two orders of magnitude greater than rock mass); • repository EDZ increased by an order of magnitude, (i.e., four orders of magnitude greater than rock mass); and • a corresponding reduction in EDZ gas air-entry pressure.
NE-AN3-T2	As NE-SBC-T2 but with increased vertical permeability resulting in no anisotropy in Ordovician formations except for Coboconk and Gull River in which anisotropy is reduced from 1000:1 to 10:1 (horizontal to vertical).
NE-NG1-T2	As NE-RC-T2 but with no gas generation.
NE-NG2-T2	As NE-SBC-T2 but with no gas generation.
NE-MG-T2	As NE-SBC-T2 except that gas used is air rather than methane. Case recognizes that the different gases generated in the DGR will have different characteristics than the “bulk” gas (methane) considered in NE-SBC-T2.
NE-RC1-T2	As NE-RC-T2 but with initial gas saturations in Ordovician equal to residual gas saturation of 5%.
NE-RC2-T2	As NE-RC-T2 but with initial gas saturations and two-phase flow parameters on a formation basis as given in INTERA (2011).
NE-GT1-T2	As NE-GG1-T2 but with decreased van Genuchten air-entry pressure and less steep air-entry curve for geosphere. NE-GG1 is used as basis because it generates overpressures in the repository which are more suitable for testing gas transport in the rock near the repository.
NE-GT2-T2	As NE-GG1-T2 but with increased geosphere van Genuchten air-entry pressure and steeper air entry curve.

Case ID*	Case Description
NE-GT3-T2	As NE-GG1-T2 but with geosphere relative permeability curve modified with residual liquid saturation and residual gas saturation set to zero.
NE-GT4-T2	As NE-GG1-T2 but with asphalt layer in shaft replaced by bentonite-sand seal.
NE-GT5-T2	As NE-GG1-T2 but with: • asphalt seal removed from shaft and replaced by bentonite-sand; • hydraulic conductivity of bentonite-sand increased by an order of magnitude to 10^{-10} m/s; and • 1/alpha gas entry pressure for shaft materials reduced by factor of two to 5×10^6 Pa.
NE-PD-GT5-T2	As NE-GT5-T2 but with final preliminary design (as for NE-PD-RC-T2).
NE-BF-T2	As NE-SBC-T2 but with repository backfilled with a coarse aggregate material of approximately 30% porosity. This may increase the structural integrity of the repository and decrease rockfall, but would also decrease the void space available for gas pressurization.
NE-GG1-T2	As NE-SBC-T2 but with increased gas generation achieved by: • increasing the inventory (and hence surface area) of metals emplaced in the repository by about 25%; and • increased corrosion and organic degradation rates using the maximum values given in Tables 3-20 and 3-21 of the Data report (QUINTESSA and GEOFIRMA 2011), which, for anaerobic conditions, are about a factor of ten greater than the best estimate values used for NE-SBC-T2.
NE-GG2-T2	As NE-SBC-T2 but with reduced organic degradation rates, i.e., minimum values from Table 3-21 of the Data report (QUINTESSA and GEOFIRMA 2011), which, for anaerobic conditions, are a factor of ten less than the best estimate values used for NE-SBC-T2.
NE-NM-T2	As NE-SBC-T2 but with no methanogenic reactions which includes both methane generation from organic degradation and also the conversion of H_2 and CO_2 to CH_4. This simulation uses gas parameters (molecular weight, viscosity) consistent with H_2 rather than CH_4.

Notes: * See Table 7.1 for explanation of the ID scheme used for the calculation cases.

The only Disruptive Scenario considered for the detailed gas modelling is the Severe Shaft Seal Failure Scenario; the associated two calculation cases are listed in Table B.6. Other scenarios are not considered. The Human Intrusion Scenario has not been considered, as gases would vent to surface upon intersection of the borehole with the repository, negating the requirement for a detailed gas model. The release rate of gas would be controlled by the operation of a blowout preventer normally installed on such deep boreholes. The Normal Evolution Scenario's Reference Case gas model results can be used to estimate the available repository gas pressure and volumes that could be released. The other two Disruptive Scenarios (Poorly Sealed Borehole and Vertical Fault) have also not considered gas transport, as the results from the Normal Evolution Scenario's Reference Case indicate that they are unlikely to have any effect on gas transport near the repository as transport of gas through the geosphere to the borehole or fault will be insignificant. Results from detailed groundwater modelling (GEOFIRMA 2011) indicate that the cases do not significantly alter the pressure distribution in the vicinity of the repository, and thus do not impact inflow from the geosphere which could potentially change gas generation.

Table B.6: Detailed Gas Modelling Cases for the Severe Shaft Seal Failure Scenario

Case ID*	Case Description
SF-BC-T2	As NE-SBC-T2 but with: • hydraulic conductivity of 10^{-9} m/s for bentonite/sand, asphalt and concrete in shafts; • porosity of 0.3 for bentonite/sand, asphalt and concrete in shafts; • capillary pressure set to zero for bentonite/sand, asphalt and concrete in shafts; and • linear relative permeability curves used.
SF-ED-T2	As SF-BC-T2 but increased bentonite/sand, asphalt and concrete hydraulic conductivity (10^{-7} m/s) in order to understand the sensitivity of system performance to shaft seal properties. This is in the range of a fine sand/silt material, about 4-5 orders of magnitude more permeable than the design-basis bentonite/sand and asphalt seals.

Notes: * See Table 7.1 for explanation of the ID scheme used for the calculation cases.

REFERENCES FOR APPENDIX B

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