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FOR OPG's LOW & INTERMEDIATE LEVEL WASTE

Postclosure Safety Assessment (V1) Report

June 2009

Prepared by:
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Quintessa INTERA SENES Consultants Limited

Note:
The Nuclear Waste Management Organization (NWMO) is managing the development of a Deep Geologic Repository for low and intermediate level radioactive waste, at the Bruce nuclear site, on behalf of Ontario Power Generation (OPG).

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Preliminary

Postclosure Safety Assessment (V1) Report

NWMO DGR-TR-2009-01

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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 site in the Municipality of Kincardine, Ontario. The Nuclear Waste Management Organization, on behalf of OPG, is currently preparing an Environmental Impact Statement (EIS) and Preliminary Safety Report (PSR) for the proposed repository.

The project involves investigation of the site's geological and surface environmental characteristics, conceptual design of the DGR, and safety assessment. The postclosure safety assessment evaluates the long-term safety of the proposed facility. It will provide the basis for a future version of the safety assessment that will support the final EIS and the PSR.

This report provides a technical summary of the work undertaken and results obtained for the Version 1 postclosure safety assessment. 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.

The models and results presented in the report are based on site information available in 2008 and early 2009, the May 2008 conceptual design, and August 2008 waste characterisation information. As such, the results are subject to modification based on the outcome of continuing site characterisation studies, the developing understanding of the DGR system and its processes, and the further verification of safety assessment data sets and numerical modelling approaches.

Approach

The assessment has been undertaken using the following approach.

1. The context of the assessment is defined, documenting the high-level assumptions and the constraints (reflecting the regulatory requirements).
2. Relevant information on the waste, repository, geological setting and surface environment pertinent to postclosure safety is summarised.
3. A range of potential future scenarios is systematically identified.
4. Conceptual and mathematical models are developed for these scenarios.
5. The scenarios are analysed and the results are discussed with respect to the performance of the system, its overall robustness, and the influence of key uncertainties.
6. The implications of the assessment's results for the DGR work programme in terms of potential future studies are noted.

Assessment Context

The purpose of the assessment is:

- to quantitatively assess the postclosure radiological and non-radiological safety of the proposed DGR;
- to determine the key areas of uncertainty with respect to the long-term performance of the repository system;
- to provide information that supports safety case arguments; and
- to provide a basis for a future version of the safety assessment that will be used to support the EIS and PSR required for the DGR.

The other key components of the assessment context for the Version 1 postclosure safety assessment are summarised below.

Audience:	The DGR Project Team
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 species
Uncertainties Management:	Scenario, model and data uncertainties are identified and managed through: the consideration of an appropriate range of scenarios; the use of different conceptual models and calculation tools; and the use of uncertainty and sensitivity studies.
Timeframe:	1 million year baseline Encompasses the period over which the maximum impacts are expected to occur

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

Waste:	Approximately 160,000 m^3 of stored L&ILW, representing a disposal volume of 196,000 m^3, comprised of operational and refurbishment wastes from OPG’s 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 and Ni-63 at short times, and Nb-94 and Zr-93 at long times.
Repository:	The repository is at a depth of 680 m and comprises two shafts, a ring tunnel and associated facilities, two access tunnels and 45 waste emplacement rooms in two panels. The South Panel (footprint 114,000 m^2) contains most of the LLW, whereas the East Panel (footprint 99,000 m^2) holds all the ILW and some LLW. The repository is not backfilled. At closure, concrete monoliths are emplaced at the base of the shafts, which are then 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 200 m of shales above and 150 m of limestones below. Above the Ordovician shales, there are alternating layers of Silurian shales, dolostones and evaporites (325 m thick). The porewater in the Silurian and Ordovician sediments is saline (total dissolved solids of 100 to 350 g L^{-1}), mildly acidic (pH 5.1 to 7.0), reducing, and many millions of years old. Above the Silurian sediments, there are Devonian dolostones (100 m thick), the upper portions of which contain fresh groundwater that discharges to Lake Huron.

Surface Environment:	The present-day environment is relatively flat and includes streams, a wetland, and, at a distance of approximately 1 km, Lake Huron. The annual average temperature is about 9 °C with an average precipitation rate of 0.98 m a^{-1}. The region around the Bruce site is mainly used for agriculture, recreation and some residential development. A significant aboriginal traditional activity in the region is fishing in Lake Huron. Groundwater is used for municipal and domestic water in this region. The lake provides water for larger communities and is used for fishing.

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 surrounding rocks. The slow anaerobic degradation of the waste packages will result in the generation of gases, which will delay or stop the resaturation. Gradual resaturation of the DGR will result in the release of contaminants into water in the repository. C-14 and tritium will also be released as gas within the repository. Most contaminants will be contained within or near the repository by the low-permeability host rock, where they decay. Over timescales of hundreds of thousands of years some contaminants may slowly migrate via the sealed shafts and geosphere into the shallow groundwater zone, 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, fishing, hunting, recreation, and dwelling. Over such long timescales glacial/interglacial cycles are expected to occur, with ice-sheets advancing and retreating over the site with a periodicity of around 120,000 years. This would result in significant changes in the surface and shallow bedrock system, but relatively small changes at repository depth. On longer time scales, the radioactivity will decay to less than the natural activity of the overlying rock. The repository will eventually become fully resaturated.

Disruptive ("What if") Scenarios	Human Intrusion	This scenario considers the same evolution of the DGR system as for the Normal Evolution Scenario with the exception that inadvertent human intrusion is assumed to occur directly into the repository via an exploration borehole at some time in the future. Contaminants are released and humans are exposed via two pathways: direct release to the surface; and release to the shallow groundwater. The direct release to the surface can occur as contaminated gas, slurry, or solid (core samples); release into the shallow groundwater occurs as contaminated groundwater. These releases result in the exposure of drill crew and site dwellers.
	Severe Shaft Seal Failure	This scenario considers the same evolution of the DGR system and the same exposure pathways and groups as the Normal Evolution Scenario with the exception that the performance of the sealed shaft is assumed to be very poor.
	Open Borehole	This scenario considers the consequences of a deep site investigation borehole in the vicinity of the DGR not being properly sealed. 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.
	Extreme Earthquake	The evolution of the system is similar to the Normal Evolution Scenario, except that it is assumed that a very large earthquake (moment magnitude of **M** ≥ 6) occurs in the region around the Bruce site at some time following repository closure. Potential consequences of very large earthquakes are the reactivation of a closed fault and/or failure of shaft seals. The potential impact on the shaft seals is bounded by the Severe Shaft Seal Failure Scenario. Therefore, the focus of the scenario is on the reactivation of a fault. Site characterisation and the underground excavations are expected to verify that there is no evidence of significant faults close to the DGR. Furthermore, although substantial earthquakes are plausible over the long assessment timeframe, the reactivation of a fault is of extremely low probability. Nevertheless, the Extreme Earthquake Scenario considers the hypothetical case of "what if" a vertical fault in the vicinity of the repository is reactivated? Such a fault could provide an enhanced permeability connection between the level of the repository, the overlying groundwater zones and the surface environment. The subsequent exposure pathways and groups are the same as those considered in the Normal Evolution Scenario.

Models, Data and Implementation
Conceptual and mathematical models and data are described. Where available, data have been taken from existing waste characterisation, conceptual design, and sub-surface and surface site information. These have been complemented with data from general literature reviews for certain key parameters such as solubility limits, sorption coefficients, corrosion rates and microbial degradation rates suitable for the expected conditions in the DGR.

The models are implemented in three software codes.

- Assessment-level (system) models are implemented in AMBER 5.2, which is a compartment-model code that can be used to represent package degradation, contaminant transport through repository, geosphere and the 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.
- 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 base calculation case considers two geosphere models. The base case (BC) model uses low host rock permeabilities inferred from the DGR-1 and DGR-2 site investigation boreholes and documented in the Phase 1 geosynthesis reports. An updated geosphere (UG) model uses even lower host rock permeabilities inferred, in part, from the initial measurements from the DGR-3 and DGR-4 boreholes that were unavailable at the time of writing the Phase 1 geosynthesis reports in 2008. It is expected that Phase 2 site investigations will confirm the decreased permeabilities, but a full description of this geosphere is not yet available, so the updated geosphere (UG) model considered here provides an approximate indication of the implications. Conservatively, the measured +140 m hydraulic head in the Cambrian sandstone is assumed to support indefinitely a steady-state vertical upwards hydraulic gradient for both geospheres and the observed underpressures in the Ordovician are assumed quickly dissipated, resulting in advective flow up the shafts and their associated EDZs. Variant calculation cases are also assessed to explore uncertainties associated with the Normal Evolution Scenario. The key results for the base case and variant calculation cases are as follows.

- The full resaturation of the repository is not observed for more than 1 million years for both geosphere models considered, 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 for extended periods of time, thereby limiting their release into the surface environment and their subsequent impacts. For example, calculations show that less than 0.001% of the initial activity disposed in the repository is released into the geosphere and shaft and, of this, less than 0.1% eventually reaches the surface environment. Of the contaminants released from the repository, the vast majority are released into the geosphere, with less than

0.5% being released into the shafts and their associated excavation damaged zone (EDZ).

- Gases are contained within the repository and geosphere, with only small amounts of gases (dissolved in groundwater) reaching the surface. The estimated maximum repository pressure for the base case (NE-BC) is 8.5 MPa, about 1 MPa above the initial steady-state pressure at the repository level, and well below the lithostatic pressure of about 17 MPa at the repository level. For the NE-UG-BC case, the peak pressure is 6.9 MPa.
- The geosphere and shaft attenuate the release of contaminants. For example, peak concentrations in the shallow geosphere are more than 11 orders of magnitude lower than in the DGR and occur around 900,000 years later.
- For the base calculation cases (NE-BC and NE-UG-BC) no radioactivity reaches the surface environment within 10,000 years. The models indicate that some activity could reach the surface by about 100,000 years, but only in negligible amounts. For the updated geosphere base case (NE-UG-BC), the activity that has reached the surface environment by 1 million years is less than 100 Bq (less than the natural radioactivity found in 1 kg of shale from the Bruce site).
- Calculated peak annual doses occur well beyond 1 million years for both base calculation cases (Figure E1). The calculated peak dose for the NE-BC case is almost nine orders of magnitude below the 0.3 mSv a^{-1} public dose criterion for the Normal Evolution Scenario, or about 1 pSv a^{-1}. The calculated peak dose for the updated geosphere case is even lower.

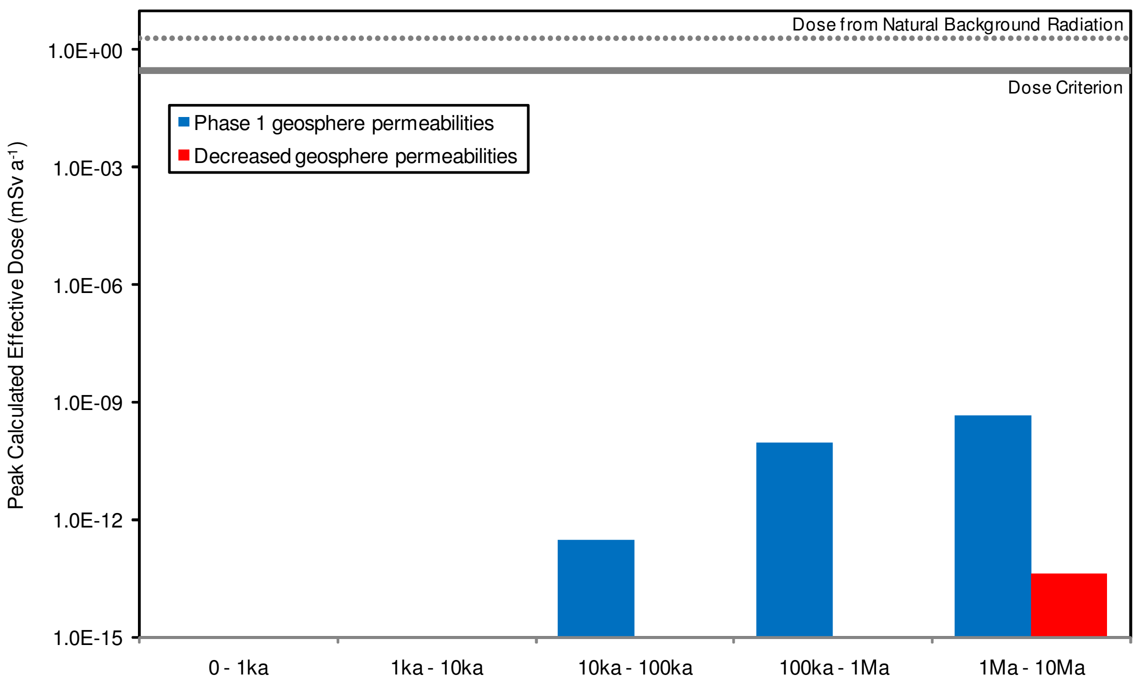
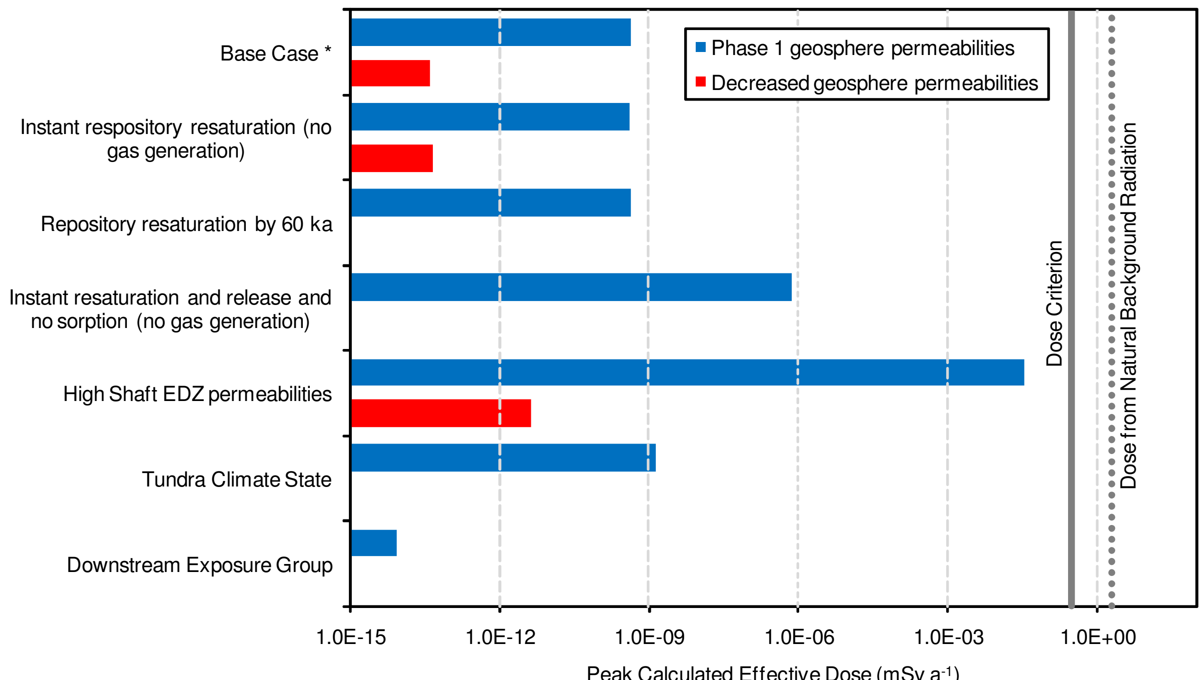


Figure E1: Normal Evolution Scenario: Peak Calculated Doses for the Base Case Geosphere and Updated Geosphere for Different Time Periods

- These results apply to families assumed to be living on the site in the future, and obtaining much of their food from the area. The potential dose would decrease rapidly with distance from the site. For example calculated doses to a “downstream” group exposed via consumption of lake fish and water from the South Basin of Lake Huron are more than four orders of magnitude lower than the dose to the Local Exposure Group.

- Results for most of the variant calculation cases are similar to the base cases, with peak annual doses typically less than 10^{-6} mSv a^{-1} – more than five orders of magnitude below the dose criterion (Figure E2). The single exception is the EDZ variant case based on the base case geology. It takes an upper estimate of hydraulic conductivity for the shaft EDZs and assumes that the shaft seals are ineffective in limiting flow along the shaft EDZs. This results in much faster contaminant migration through shaft EDZs. The peak annual dose for this EDZ case is 0.04 mSv a^{-1} at around 30,000 years after closure resulting from the release of C-14 gas into the shallow groundwater system and the surface environment. Using the updated geosphere model, which is expected to represent the actual geosphere characteristics more closely, the dose impact from this EDZ variant case is reduced to less than 10^{-11} mSv a^{-1}.



* Steady state Cambrian overpressure, no Ordovician underpressure, horizontal gradient in certain Silurian Formations, repository restautation by c. 1 Ma, temperate climate, local exposure group.

Figure E2: Normal Evolution Scenario: Peak Calculated Doses for all Calculation Cases

Disruptive Scenarios

The calculation cases are based on the base case (BC) geosphere model. The likelihood of the events that could initiate the Disruptive Scenarios considered is estimated to be lower than 10^{-5} a^{-1} and the associated scenarios should be seen as low probability, “what if” scenarios. The key results are as follows.

- For the *Human Intrusion Scenario*, if a borehole is drilled into the repository and gases and slurry from the repository are not appropriately contained, the calculated doses could be up to 2 mSv for the drill crew and up to 6 mSv for a farmer using the contaminated drill site (Figure E3). Realistically, the likelihood of drilling into the repository is very low due to the lack of mineral resources and the repository's depth, and high releases are unlikely when following standard deep drilling practices.

- Calculated peak doses for the *Severe Shaft Seal Failure Scenario* are about 0.02 mSv a^{-1}, based on a conservative failure scenario (e.g., immediate failure of the low permeability shaft seals into high permeability engineered fill (crushed rock); no sorption in the shaft, steady vertical gradient from the Cambrian formation) (Figure E3).
- Calculated peak annual doses for the *Open Borehole Scenario* and the *Extreme Earthquake Scenario* are almost nine orders of magnitude below the dose criterion (Figure E3). Annual doses are the same as those resulting from the comparable Normal Evolution Scenario case.

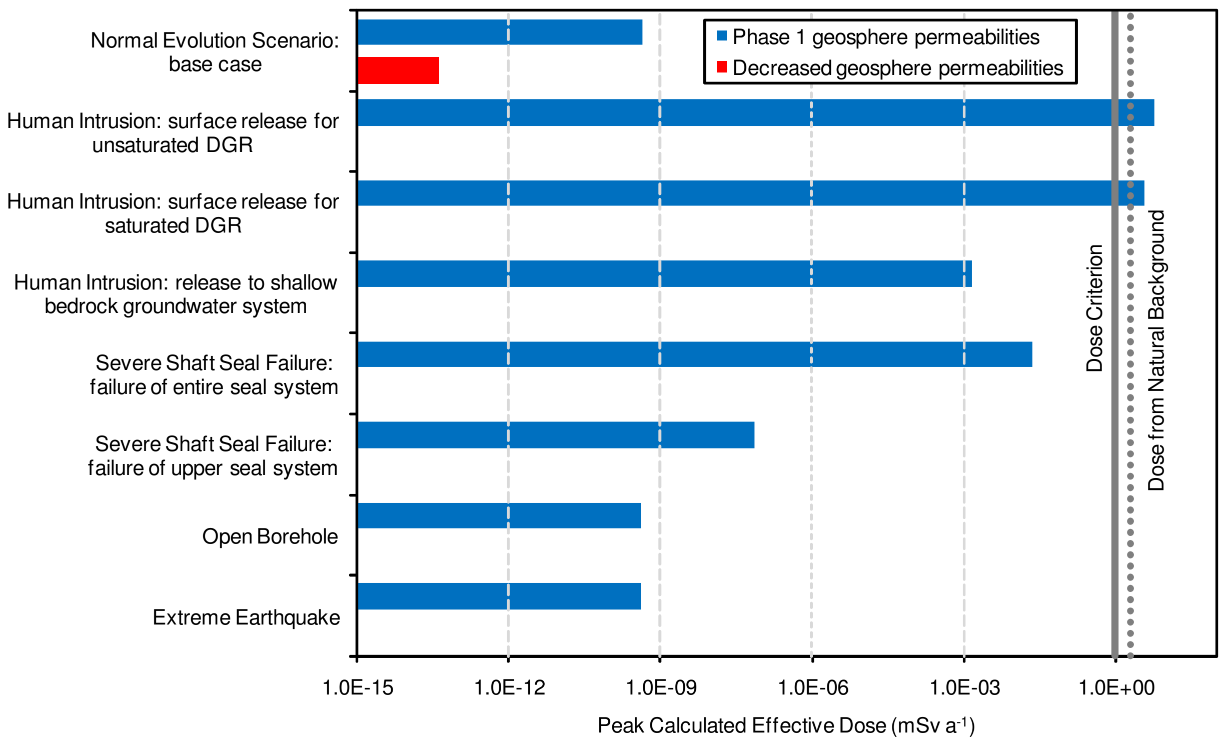


Figure E3: Disruptive Scenarios: Peak Calculated Doses for all Calculation Cases

Key Radionuclides

- Most radionuclides are retained within the repository or geosphere.
- For scenarios and calculation cases that could result in releases of contaminants to the surface environment within 30,000 years of closure, C-14 (mostly from ILW moderator resins) is the key radionuclide.
- For releases that occur at later times, Cl-36 (mostly from ILW pressure tubes and, to some extent ILW moderator resins, ILW end fittings, and ILW IX columns), 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 mostly retained within the shaft and geosphere and so are not significant contributors to the calculated doses.

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 species on humans and the environment. The key results are as follows.

- For the Normal Evolution Scenario, potential impacts of radionuclides on biota, and of non-radioactive species on human and biota, are well below the relevant criteria.
- For Disruptive Scenarios, impacts are also low. Most species are well below their concentration criteria. Some contaminants (Cd, Cr, Cu and Pb, and C-14, Cl-36 and Nb-94) may exceed their concentration criterion for certain cases in the Human Intrusion and Severe Shaft Seal Failure Scenarios. The exceedance is generally less than an order of magnitude, the scenarios are low probability and conservatively modelled (e.g., no sorption of the non-radiological species). Furthermore, the effects are localised around the site.

Implications on Design

- The results indicate that there is no significant benefit to be gained in the base case from backfilling the access and ring tunnels in the repository with concrete due to the significant containment already provided by the host geology and the shaft seals, and the limited impact of rockfall on the performance of the DGR. Backfilling could delay and limit the groundwater flux to the Shallow Bedrock Groundwater Zone by a factor of 30 but causes a marginal increase in gas flux.
- The calculations have emphasised the importance of the shaft seals in limiting contaminant fluxes in groundwater and gas flux up through the shafts and the associated EDZ, and possibly diverting upward flow into higher permeability Silurian units. The keying of the seals into the shaft EDZ is important, as are assumptions concerning the extent and permeability of the EDZ, the vertical gradient due to the excess pressure in the Cambrian formation, and the horizontal hydraulic gradients in the permeable units.

Uncertainties

Uncertainties can arise from three primary sources.

- **Scenario uncertainty** has been addressed through assessing five potential future evolutions of the DGR system identified and developed using a systematic, transparent and traceable approach. The range of scenarios identified is comparable with those considered in safety assessments of deep geologic repositories in other countries.

- **Model uncertainty** has been investigated through the use of both detailed and assessment-level models, which use differing conceptualisations of the system and different mathematical approaches. In addition variant calculation cases have been assessed that consider different conceptual models regarding key processes such as resaturation.
- **Data uncertainty** has been investigated through variant calculation cases for the detailed modelling and assessment-level modelling.

The results presented in this report should be seen as being generally conservative and overestimates of impacts. For example, the base case calculations for the Normal Evolution Scenario do not account for the potential impact of Ordovician underpressures in limiting contaminant migration from the repository. Analysis of the results obtained for the current assessment and the associated uncertainties has highlighted two main areas of key uncertainties to be considered further in the next version of the safety assessment.

1) Shaft and EDZ Characteristics and Evolution

The calculations show significant variations (more than nine orders of magnitude at the extreme) in calculated impacts arising from differing assumptions relating to the characteristics and evolution of the shafts and their EDZs, although in all cases the calculated peak doses remain below the dose criterion. These variations highlight the need to give further consideration to the factors that could affect flow and transport via the shafts and their EDZs, notably the extent and permeability of the EDZs, and the extent of alteration of the shaft materials and the EDZs. These uncertainties could be reduced through further modelling, informed by site characterisation information.

2) Geosphere Representation

Calculation cases have also shown that conceptual and parameter uncertainties relating to the geosphere result in variations in impacts of more than four orders of magnitude, although impacts remain many orders of magnitude below the relevant criteria. Particular uncertainty relates to:

- the geosphere permeability, especially in the Ordovician and Silurian (i.e., low or very low);
- the origin and evolution of the hydraulic head distribution in the geosphere (especially under conditions of glacial/interglacial cycling);
- the flow characteristics of the certain Silurian formations in which horizontal flow could occur; and
- gas flow parameters, especially in the formations above the Ordovician.

Of these, calculations have shown that the variations in permeability considered in the assessment have the greatest impact on calculated peak doses, resulting in a range of more than four orders of magnitude. Nevertheless, doses remain many orders of magnitude below the dose criterion even for the higher permeability geosphere. The on-going programme of site characterisation work will yield improved site-specific information on the above issues, which can be expected to reduce associated uncertainties and hence range in calculated impacts.

Conclusions

Consistent with the guidelines for the preparation of the EIS for the DGR, the Version 1 postclosure safety assessment has evaluated the DGR's performance and its potential impact on human health and the environment through pathway analysis of contaminant releases, contaminant transport, receptor exposure, and potential effects for an expected evolution scenario, as well as a number of disruptive ("what if") scenarios.

The calculated impacts for the Normal Evolution Scenario are below the public dose criterion of 0.3 mSv a^{-1} for all calculation cases and occur well beyond 1 million years. The calculated peak dose for the base case is almost nine orders of magnitude below the criterion, and the updated geosphere permeability base case is even lower (about 13 orders of magnitude below the dose criterion). In addition, potential impacts of radionuclides on biota and non-radioactive contaminants on humans and non-human biota are well below the relevant criteria. Although certain impacts for the Human Intrusion exceed the disruptive scenario dose criterion, the likelihood of this scenario is low and conservative assumptions have been adopted in the impact calculations. The safety assessment results provide evidence to support the safety functions and arguments that are being developed for the Preliminary Safety Report.

A variety of measures have been taken to investigate uncertainties in the Version 1 safety assessment. The results of the Version 1 assessment provide information on the importance of the uncertainties regarding shaft and EDZ characteristics and evolution, and geosphere representation. In all cases, even with the uncertainties, the DGR is found to provide good isolation and containment of the waste. They have been used to identify recommendations for further work that can be undertaken to reduce these uncertainties and build further confidence in the next iteration of the safety assessment.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

Page

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) immediately to the north of the existing Western Waste Management Facility (WWMF) at the Bruce site[1] in the Municipality of Kincardine, Ontario (Figure 1-1 and Figure 1-2). The Nuclear Waste Management Organization, on behalf of OPG, is currently preparing an Environmental Impact Statement (EIS) and Preliminary Safety Report (PSR) for the proposed repository.

The project involves investigation of the site's geological and surface environmental characteristics, conceptual design of the DGR, and safety assessment. The Version 1 postclosure safety assessment (SA) evaluates the long-term safety of the proposed facility and will provide the basis for a future version of the safety assessment that will support the final EIS and PSR.

The Version 1 work builds upon a scoping assessment conducted by Quintessa in 2002 and 2003 (Penfold et al. 2003) and has been refined to take account of the revised waste inventory and repository design, and the greater understanding of the site that is being developed as the project proceeds. The models and results presented in the report are based on site information available in 2008 and early 2009, the May 2008 conceptual design (Hatch 2008) and August 2008 waste characterisation information (OPG 2008a). As such, the results are subject to modification based on the outcome of continuing site characterisation studies, the developing understanding of the DGR system and its processes, and the further verification of safety assessment data sets and numerical modelling approaches.

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 Version 1 SA; other aspects of the DGR work programme (e.g., operational safety) are considered in separate reports. The report has been written for a technical audience that is familiar with the scope of the DGR project, the Bruce site, and the process of assessing the long-term safety of a deep geologic repository. The technical terms used in this report are consistent with those defined in the DGR project glossary (NWMO 2009).

The report summarises and draws conclusions from a set of documents that present the detailed results and findings of the Version 1 SA (Figure 1-3). The set of documents comprises: the Normal Evolution Scenario Analysis report (Walke et al. 2009a); the Human Intrusion and Other Disruptive Scenarios Analysis report (Penfold and Little 2009); the System and its Evolution report (Little et al. 2009); the Features, Events and Processes report (Garisto et al. 2009); the Data report (Walke et al. 2009b); the Groundwater Modelling report (Avis et al. 2009); and the Gas Modelling report (Calder et al. 2009).

[1] The 932 hectare site includes two nuclear power stations (Bruce A and B), one shutdown station (Douglas Point) and a waste management facility (WWMF).

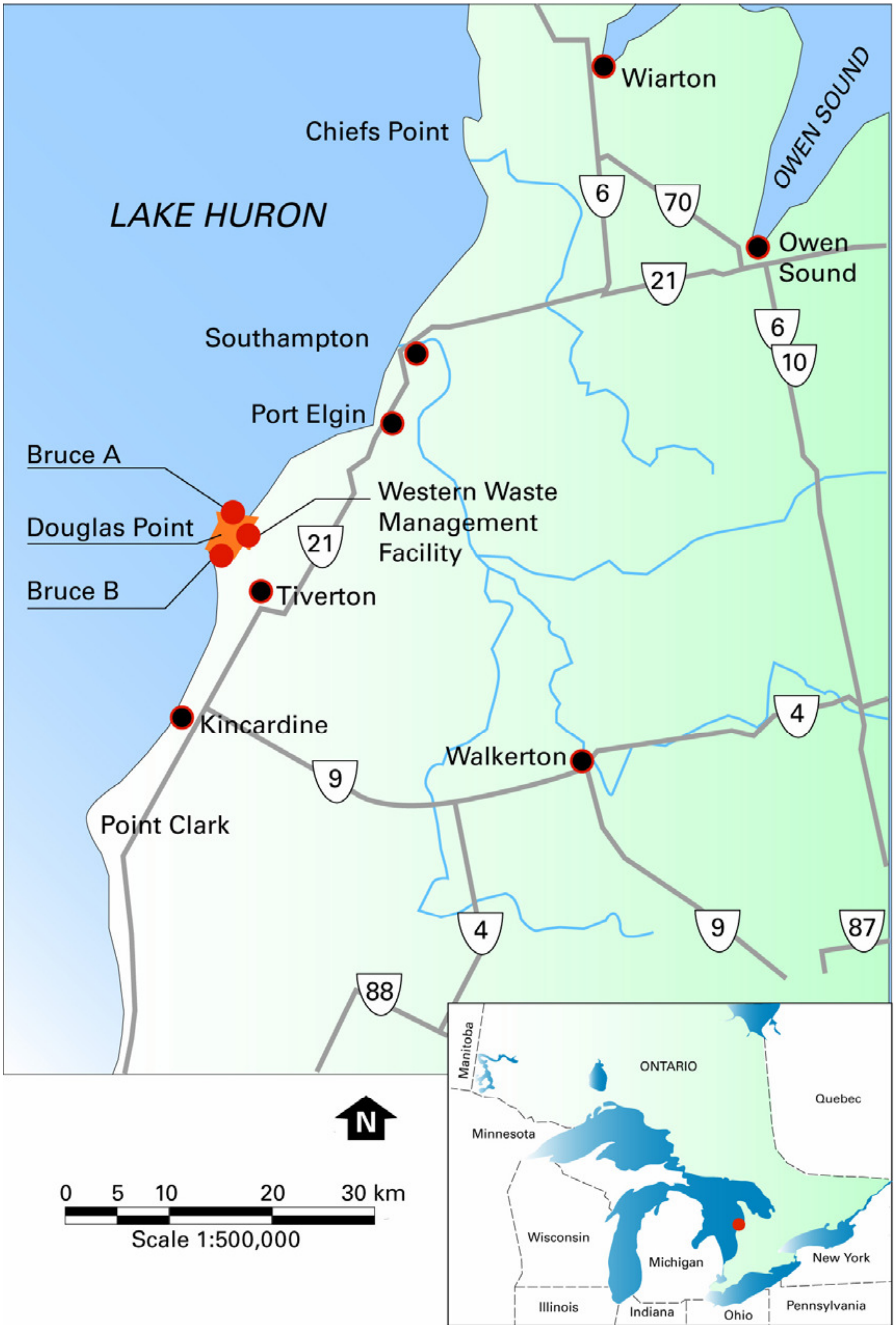


Figure 1-1: Location of the Bruce Site, Ontario

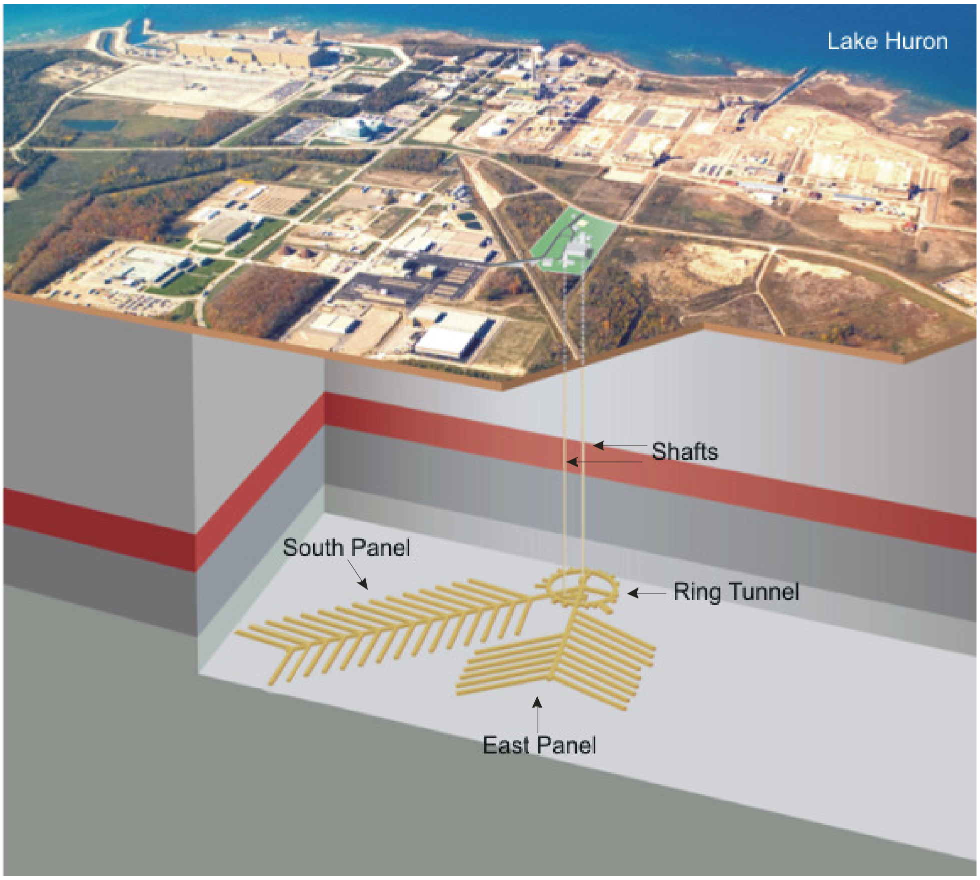


Figure 1-2: The DGR Concept at the Bruce Site

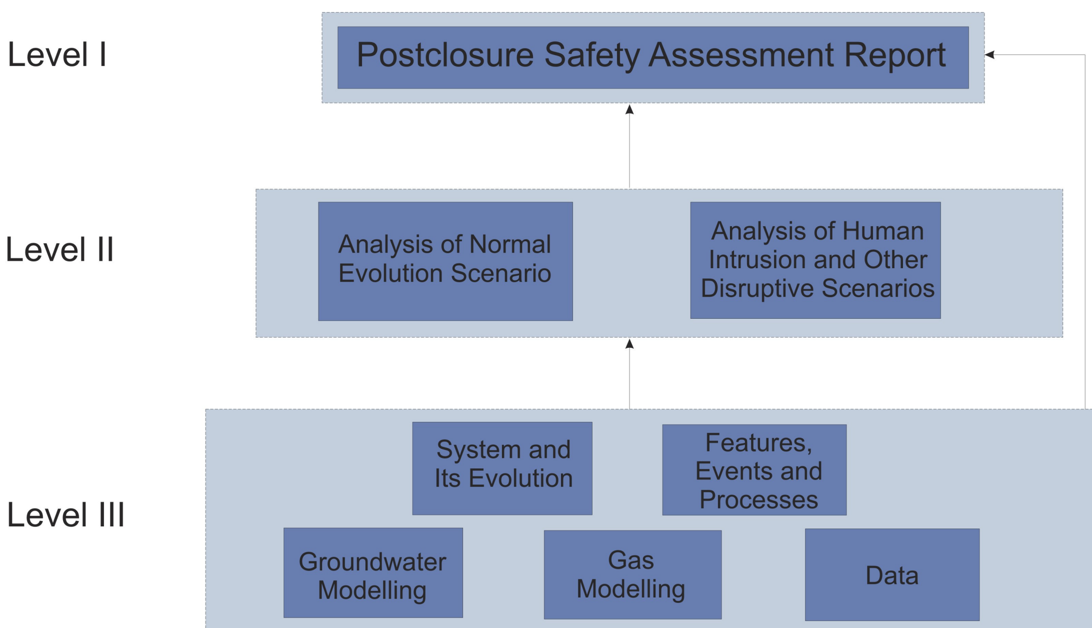


Figure 1-3: Postclosure Safety Assessment Document Structure

1.3 REPORT OUTLINE

The approach used for the Version 1 postclosure SA is outlined in Section 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 Version 1 postclosure SA (Section 3);
- system description (waste, repository, geological setting and surface environment) (Section 4);
- scenario identification and description process (Section 5);
- the models assessed (Section 6);
- the results obtained (Section 7); and
- the implications for the DGR work programme (Section 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 managed; provide clear links to other components of the DGR programme 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 the following elements:

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

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

The Version 1 postclosure SA has been carried out using an approach based on the ISAM safety assessment methodology, which was developed within the International Atomic Energy Agency's (IAEA's) ISAM project (IAEA 2004) (Figure 2-1). The ISAM methodology has been used as a basis for the DGR assessment approach for the following reasons.

- It provides a generic, high-level framework that encourages a well-structured, transparent and traceable approach (e.g., providing rationales for the assumptions and clear audit trails for the models and parameters). This is recognised in G-320, which states that ISAM documentation provides useful recommendations on a structured and iterative methodology for performing and documenting assessments (CNSC 2006).
- There is flexibility in the detailed application of the methodology to allow it to be developed for application to specific facilities and specific assessments. For example, the ISAM approach emphasises the need to develop scenarios but does not prescribe the exact approach that should be used – this is a programme-specific choice. As described in subsequent sections, DGR-specific approaches have been applied to identify scenarios and develop conceptual and mathematical models.
- Though initially developed for the assessment of near-surface disposal facilities, the ISAM methodology drew on the experience gained from the assessment of geological facilities and is considered to be applicable to such facilities. Indeed, G-320 states that the ISAM methodology "could be applied to any type of waste management system" (CNSC 2006).
- The ISAM methodology was used in the preliminary safety assessment of concepts for a permanent waste repository at the Bruce site (Penfold et al. 2003).

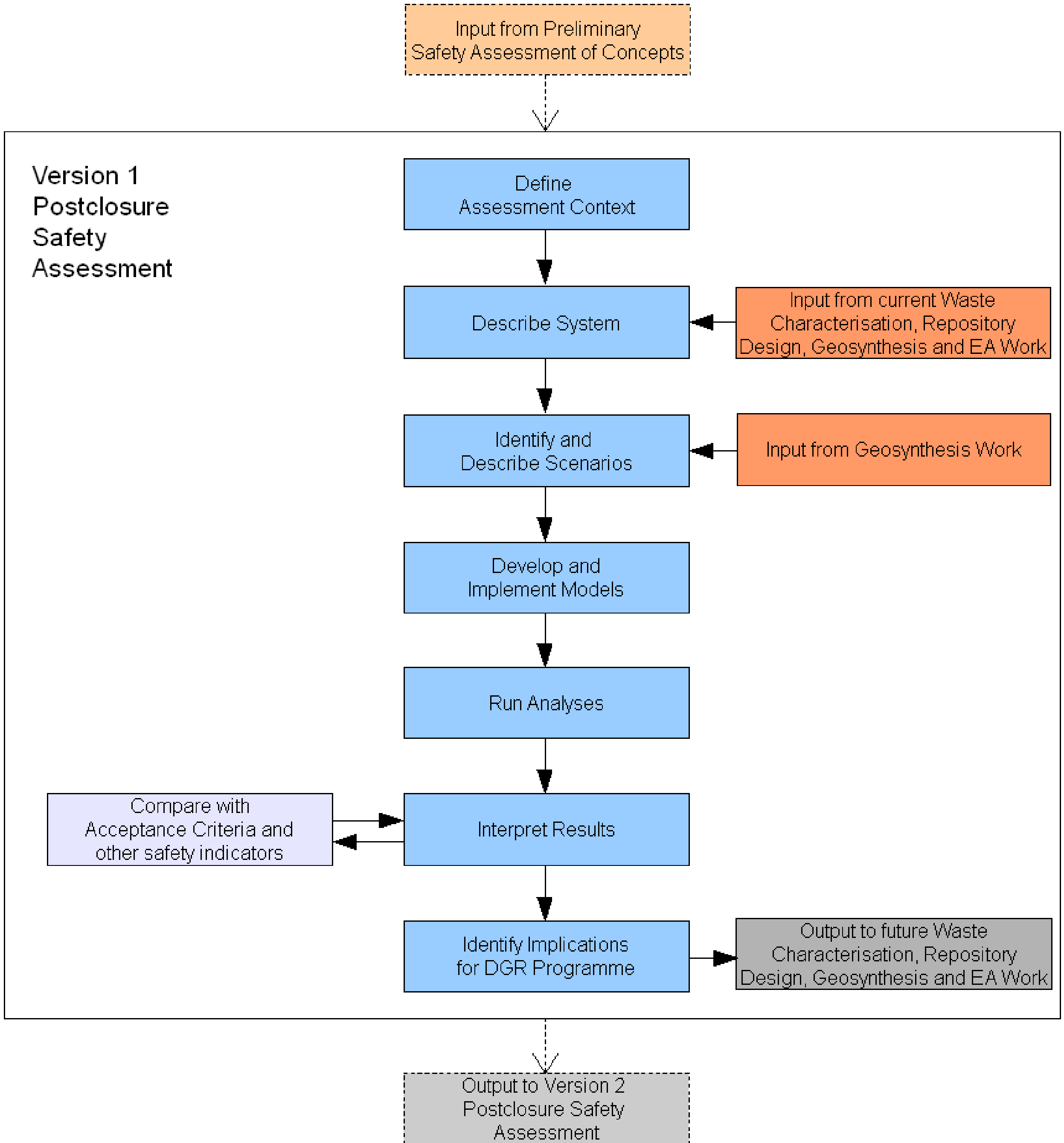


Figure 2-1: Postclosure Safety Assessment Approach Used in Version1 SA

The approach comprises the following basic steps.

- The context of the assessment is defined, documenting the high-level assumptions, the constraints (reflecting the regulatory requirements), and the assessment's purpose, focus and timeframes (presented in Section 3).
- The current information and knowledge relating to the waste, repository, geological setting and surface environment pertinent to postclosure safety are reported, along with identified areas of uncertainty (presented in Section 4).
- A range of internally consistent potential future evolutions (scenarios) is systematically identified (presented in Section 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 Section 6).
- Following the running of the software tools and the generation of results, the results are analysed, interpreted and discussed to inform on the performance of the system, its overall robustness, and the nature and role of key uncertainties (presented in Section 7). Particular emphasis is given to the analysis of the performance of the safety functions and arguments that form the basis of the safety case.
- The implications of the assessment's results for the DGR work programme are identified in terms of future SA studies and the studies of other DGR teams (e.g., Waste Characterisation, Geosynthesis, Repository Design and Environmental Assessment) (presented in Section 8).

3. ASSESSMENT CONTEXT

3.1 PURPOSE OF THE ASSESSMENT

The purposes of the assessment are as follows:

- to quantitatively assess the postclosure radiological and non-radiological safety of the proposed Deep Geologic Repository (DGR) at the Bruce site using good practice and appropriate methods with the site information and knowledge available by March 2009;
- to determine where areas of uncertainty[2] lie with respect to the long-term performance of the disposal system, thereby contributing to the design of future studies aimed at reducing these uncertainties;
- to provide information that further substantiates safety case arguments; and
- to provide a basis for future iterations of the safety assessment that will be used to inform the Preliminary Safety Report (PSR) and the Environmental Impact Statement (EIS) required for the DGR (CEAA and CNSC 2009).

3.2 AUDIENCE

The assessment is aimed at informing the DGR Project Team, who will use the knowledge gained to help inform the DGR EIS and Preliminary Safety Report and the associated programme of work (including inventory characterisation, site characterisation, geosynthesis, and design).

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 requirements of the **Canadian Environmental Assessment Act (CEAA)** which stipulates that an Environmental Impact Statement (EIS) is required 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 Licence, and other supporting documentation. The decision to grant the Licence will be made by the Joint Review Panel after it receives the documentation, issues the submitted material for public review, holds a public hearing, and obtains environmental impact statement accepted by the Governor in Council[3].

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2 See Section 3.7.1 for the categories of uncertainty considered.

3 Separate licences will be required for the operation, decommissioning, and abandonment of the DGR.

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, which are listed in Table 3-1.

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 developing a long-term Safety Case, defining acceptance criteria, performing long-term assessments, and interpreting the results. Recommendations from G-320 relevant to the postclosure safety assessment are summarised in Table 3-2.

3.4 ACCEPTANCE CRITERIA

G-320 states that “the applicant is expected to propose justified and scientifically defensible benchmarks and acceptance criteria for the assessment” (CNSC 2006). In light of the Canadian regulatory requirements and guidance (Section 3.3) and international standards and guidance from organisations 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 2008b, OPG 2009). Specific criteria have been proposed for:

- radiation exposure of people that may arise from the expected evolution of the DGR and its environment, referred to as the “Normal Evolution Scenario”;
- 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”;
- 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).

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.

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

- dose constraint 0.3 $mSv{\cdot}a^{-1}$ to critical group;
- optimisation below dose constraint;
- doses are calculated for average adult member of the critical group(s); and
- 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 allows for the potential exposure to multiple sources of radioactivity.

Table 3-1: Relevant Guidance from the EIS Guidelines for the DGR

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 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
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 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.
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 analysed. • 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 characterisation 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 programmes in combination with refinement of mathematical models should be proposed.

Table 3-2: Relevant G-320 CNSC Expectations and Recommended Approaches

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 dose target	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 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.
Optimisation	The design of a nuclear facility should be optimised 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. 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.

Issue	Guidance
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 organisation (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 characterisation 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.
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.

3.4.2 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). In addition, they include speculative or "what if" calculations to test the robustness of the DGR system.

The criteria adopted for public radiological exposure as a result of Disruptive Scenarios, including human intrusion, are as follows (OPG 2008b):

- a dose criterion of 1 mSv a^{-1} for credible scenarios;
- acceptability of any scenarios with calculated doses exceeding 1 mSv a^{-1} would be 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.

In determining the significance of the impacts assessed for Disruptive Scenarios, account has to be taken of the likelihood and nature of the exposure. Where the probability of exposure can be quantified without excessive uncertainty, a measure of risk is calculated based on the probability of exposure and the health effects if the exposure occurs. As a general guide, this is compared with a reference risk value of 10^{-5} a^{-1} (OPG 2008b).

Human Intrusion Scenarios consider the hypothetical inadvertent disruption of the wastes at a time in the future, assuming control over the site is no longer effective. Consistent with ICRP Publication 81 (ICRP 2000), the consequences of deliberate human intrusion into the repository are the responsibility of those intruding and are beyond the scope of the assessment, as are malicious acts that might arise from deliberate human intrusion.

Human intrusion by definition bypasses the barriers isolating the waste, and therefore criteria such as dose and risk targets applied in design of the system are not applicable (ICRP 2000). Because of the fundamental concept of the DGR, the likelihood of any intrusion is expected to be very small. However, it is appropriate to analyse a stylised Human Intrusion Scenario in order to demonstrate the robustness of the DGR. The analysis needs to consider both the intruder and the general public.

The same principles of optimisation apply in relation to Disruptive Scenarios as to the Normal Evolution Scenario. Similar approaches can be applied to determine the potential for mitigation measures to reduce calculated impacts. However, in considering their benefits, it is necessary to take account of the low likelihood of disruption associated with Disruptive Scenarios.

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 criteria, which are currently subject to review and acceptance by the CNSC, are expressed as No-Effect Concentrations (NECs) for 11 representative radionuclides (Table 3-3). These NECs are documented in Garisto et al. (2008) and are derived from Estimated No Effect Values (ENEVs) for indicator species relevant to the Southern Canadian Deciduous Forest environment, representative of current conditions at the DGR location, and an inland tundra ecosystem, representative of potential future conditions at the DGR location. The ENEVs used are the most cautious values provided by Environment Canada and Health Canada (2003) and UNSCEAR (1996).

If the NECs are exceeded for the Normal Evolution Scenario, an Ecological Risk Assessment (ERA) will be carried out for any radionuclides with concentrations estimated to exceed the NECs. The ERA will take into account uncertainties and the potential need for the effect of several radionuclides to be summed. The radiation dose will be calculated for indicator species corresponding to the Valued Ecosystem Components (VECs) identified in the EIS guidelines (CEAA and CNSC 2009). The results will be compared to numerical criteria for the assessment that will be proposed to CNSC.

Table 3-3: No Effect Concentrations for Non-Human Biota

Radio-nuclide	Media						
	Surface Water (Bq L^{-1})		Soil (Bq kg^{-1})		Sediment (Bq kg^{-1})		Groundwater (Bq L^{-1})
	Southern Canadian Deciduous Forest	Inland Tundra	Southern Canadian Deciduous Forest	Inland Tundra	Southern Canadian Deciduous Forest	Inland Tundra	
C-14	2.40E-1	7.01E-1	3.53E+2	2.39E+2	2.84E+5	1.59E+6	1.58E+6
Cl-36	3.11E+0	6.30E+0	4.97E+0	4.04E-1	4.10E+4	2.85E+5	2.96E+5
Zr-93	1.75E+0	2.94E+2	2.77E+5	9.49E+4	5.04E+6	5.04E+6	5.89E+6
Nb-94	1.57E-2	8.30E-1	1.25E+2	3.43E+0	2.57E+4	4.45E+5	3.58E+4
Tc-99	7.95E-1	5.71E+2	6.05E+1	4.96E+1	2.97E+6	6.11E+6	8.10E+5
I-129	3.23E+0	1.57E+2	1.89E+4	2.36E+3	1.17E+6	6.94E+6	9.04E+5
Ra-226	5.86E-4	1.78E-1	2.77E+2	2.51E+2	9.27E+2	9.27E+2	5.87E+2
Np-237	5.77E-2	5.84E-2	5.02E+1	7.05E+1	1.06E+3	1.06E+3	5.83E+2
U-238	2.30E-2	4.19E-1	4.85E+1	4.15E+1	6.64E+4	5.23E+5	5.57E+2
Pb-210	4.95E+0	4.01E+1	3.71E+3	6.03E+3	6.25E+3	6.25E+3	1.78E+5
Po-210	7.04E-3	2.01E-2	3.03E+1	4.21E+1	1.08E+5	6.68E+5	5.35E+2

Note:
Based on the most cautious ‘Upper Estimate’ NECs in Garisto et al. (2008).

3.4.4 Criteria for Non-radioactive Contaminants

Potential impacts from non-radioactive contaminants are assessed for both Normal Evolution and Disruptive Scenarios in environmental media relevant to human health and environmental protection. The proposed criteria, which are currently subject to review and acceptance by the CNSC, 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. Guideline concentrations for groundwater, soil and sediment are provided primarily from MoE (2008), since these are the most restrictive. The most restrictive guideline concentrations values between MoEE (1994), CCME (2007) and CCME (2005) were generally used for surface waters (Table 3-4).

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 generic guidelines given in Table 3-4. If any exceedances are identified for the Normal Evolution Scenario, these contaminants will be assessed further.

Table 3-4: Environmental Quality Standards for Non-radioactive Contaminants

Species	Groundwater ($\mu g\ L^{-1}$)	Note	Soil ($\mu g\ g^{-1}$)	Note	Surface Water, ($\mu g\ L^{-1}$)	Note	Sediment ($\mu g\ g^{-1}$)	Note
Ag	0.7	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	39	A	-	B	-	B
Be	0.5	A	2.5	A	11	J	-	B
Br	-	B	-	B	-	B	-	B
Cd	0.5	A	1	A	0.017	Q	0.6	A
Chlorobenzene	0.01	C	0.01	C	0.0065	K	0.02	C
Chlorophenol	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	4.3	A	62	A	1	J	16	A
Dioxins/Furans	1.5E-5	F	7E-6	F	0.3	N	-	-
Gd	-	B	-	B	-	B	-	B
Hf	-	B	-	B	-	B	-	B
Hg	0.1	A	0.13	A	0.004	R	0.2	A
I	-	B	-	B	100	I	-	B
Li	-	B	-	B	-	B	-	B
Mn	-	B	-	B	-	B	-	B
Mo	23	A	2	A	40	I	-	B
Nb	-	B	-	B	-	B	-	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	0.2	A	0.001	H	0.07	A
Sb	1.5	A	1	A	20	I	-	B
Sc	-	B	-	B	-	B	-	B
Se	5	A	1.2	A	1	P	-	B
Sn	-	B	-	B	-	B	-	B
Sr	-	B	-	B	-	B	-	B
Te	-	B	-	B	-	B	-	B
Tl	0.5	A	0.81	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

A ‘Full depth background site condition standard’ for Ontario from MoE (2008).
B No value available in MoE (2008) or MoEE (1994) and so not evaluated in assessment.
C As note A; values for hexachlorobenzene used.
D As note A; values for 2,4-dichlorophenol 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).

3.5 SAFETY FUNCTIONS AND ARGUMENTS

According to IAEA guidance on the geological disposal of radioactive waste (IAEA 2006a), the aims of geological disposal are:

- to contain the waste until most of the radioactivity, and especially that associated with shorter lived radionuclides, has decayed;
- to isolate the waste from the biosphere and to substantially reduce the likelihood of inadvertent human intrusion into the waste;
- to delay any significant migration of radionuclides to the biosphere until a time in the far future when much of the radioactivity will have decayed; and
- to ensure that any levels of radionuclides eventually reaching the biosphere are such that possible radiological impacts in the future are acceptably low.

Consistent with this IAEA guidance and the purpose of the NSCA, the overall safety objective of the DGR is to prevent unreasonable risk to the environment, and to the health and safety of the public and the workers, in accordance with the NSCA and its associated regulations. This objective will be met by the DGR through the following safety functions:

- the isolation of the waste away from the surface environment; and
- the long-term containment of the waste.

These two safety functions are supported by several arguments and evidence based on an extensive knowledge base, detailed site characterisation work and thorough analyses that directly support these two safety functions. The postclosure safety assessment provides a quantitative analysis of the performance of the whole DGR system and can therefore contribute substantial evidence to a number of the safety arguments for the DGR system. The list of current safety arguments that can be directly informed by the results from the safety assessment is given below.

1. The location of the DGR at a depth of 680 m underground, absence of economically viable natural resources, and no drinking water below 100 m provide excellent isolation from the biosphere
2. The host rock provides multiple thick low-permeability sedimentary rock barriers.
3. Mass transport is diffusion-dominated at the repository horizon.
4. Hydrogeochemical conditions limit contaminant mobility at the repository horizon.
5. Resaturation of the repository with groundwater will be very slow.
6. Safety assessment studies indicate that any future impacts are likely to be below natural background dose rates.
7. DGR radioactivity will decrease with time due to radioactive decay.

3.6 ASSESSMENT END POINTS

Assessment end points (also known as safety and performance indicators) are quantities used in a safety assessment to measure the impact of a repository and its performance in relation to its safety functions. 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).

In order to demonstrate compliance with the acceptance criteria given in Section 3.4, the following **principal assessment end points** are calculated:

- radiation dose to humans to a “representative person”;
- environmental concentrations of radionuclides[4]; and
- environmental concentrations of non-radioactive hazardous substances[5].

“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 analysed to indicate the dose to other age groups.

As there are significant uncertainties surrounding the calculation of doses in long-term postclosure safety assessments, it is useful to consider alternative end points. Indeed, the regulatory framework (Section 3.3) requires considering a range of safety and performance indicators. Therefore, the following **complementary assessment end points** are calculated in order to help determine the safety of the DGR and assess its compliance with the regulatory framework:

- containment of radionuclides within various spatial domains (e.g., the repository, the host rock, and the wider geosphere) and temporal domains (e.g., 10,000 years);
- groundwater travel times; and
- fluxes of radionuclides and hazardous substances from the repository and geosphere.

These complementary assessment end points, together with the principal assessment end points, can be used to inform the optimisation process and to assess the performance of the safety functions and associated arguments identified in Section 3.5.

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4 If the NECs given in Table 3-3 are exceeded, radiation doses can be calculated for non-human biota.

5 Toxicity calculations can be undertaken if the environmental quality standards given in Table 3-4 are exceeded.

3.7 MANAGEMENT OF UNCERTAINTIES

3.7.1 General Approach

The treatment of uncertainty is central to any assessment to establish the safety of a radioactive waste repository.

In postclosure safety assessment, uncertainty can be considered in three categories:

- **future or scenario uncertainty** – uncertainty in the evolution of the disposal system over the timescales of interest;
- **model uncertainty** – uncertainty in the conceptual, mathematical and computer models used to simulate the behaviour of the disposal system (e.g., due to approximations used to represent the system and to solve the model equations); and
- **data uncertainty** – uncertainty in the data and parameters used as inputs in the modelling (e.g., due to lack of complete set of site-specific data, and parameter estimation errors from interpretation of experimental test results/observations).

The following approaches are adopted to managing these uncertainties, taking account of relevant international guidance and experience (e.g., IAEA 1999).

In the assessment, uncertainty in the future evolution of the site is addressed by assessing an appropriate range of scenarios that describe the potential evolution of the system. The scenario identification process, described in Section 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.

Conceptual and mathematical model uncertainties are identified in the model development process described in Section 6, making use of Feature/Event/Process (FEP) arguments and taking into account conceptual uncertainties in supporting work (e.g., geosphere characterisation). 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 and AMBER) that are capable of representing different conceptualisations and mathematical descriptions of the system[6]. 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 characterised in the assessment Data report (Walke et al. 2009b). Two approaches can be used to analyse data uncertainties.

- Multiple deterministic calculations – in which an alternative set of data 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.
- 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. Where appropriate, the parameters and their distributions should be correlated to avoid unrealistic combinations of parameter values being selected. The model output is a distribution of results.

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

The current assessment uses multiple deterministic calculations. Probabilistic calculations will be used in future assessments.

3.7.2 Use of Conservatism

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 categorised as 'realistic'[7] or 'conservative'[8], 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 assessment work.

However, it is also important to define a general attitude towards conservatism that is applied throughout the assessment. Whilst 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. Furthermore, some analyses (e.g., comparison of the performance of alternative barriers) can become 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 (e.g., the habits and characteristics for representative persons from potential exposure groups), conservative, but physically plausible, assumptions have been adopted to allow the impacts of uncertainties to be bounded, consistent with the recommendations of G-320 (CNSC 2006).

3.7.3 Building of Confidence

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

- the use of a systematic assessment methodology;
- the use of an iterative approach;
- the management of uncertainties;
- the development and demonstration of a robust repository system concept;
- verification, calibration and validation of models;
- quality assurance measures;
- peer review; and
- comparisons with natural systems that have evolved over relevant timescales.

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[7] 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, 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).

[8] 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).

Confidence 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 optimisation. The various measures that are to be used to develop confidence in the assessment at these two levels are summarised in Table 3-5.

Table 3-5: Confidence Building Measures

<table>
<tr><th colspan="2">Confidence in each Stage of the Assessment Process</th><th rowspan="2">Confidence in the Overall Safety of the DGR</th></tr>
<tr><th>Assessment Stage</th><th>Confidence Building Measures</th></tr>
<tr><td>Assessment Context</td><td>• Demonstration of understanding of the key components of the assessment context.</td><td rowspan="6">• Use of a systematic approach.
• Adequate understanding of the disposal 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.</td></tr>
<tr><td>System Description</td><td>• Demonstration of adequate understanding of engineered and natural aspects of the disposal system (repository, geosphere and biosphere) and associated uncertainties.
• Linkage to geosynthesis, waste characterisation, and repository design.</td></tr>
<tr><td>Scenarios</td><td>• The set of scenarios is 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 characterisation, and repository design.</td></tr>
<tr><td>Models</td><td>• The conceptual models and associated data are consistent with the assessment context, disposal 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 characterisation, waste characterisation, and repository design.</td></tr>
<tr><td>Analysis of Results</td><td>• Key assumptions are documented and justified.
• Uncertainties are adequately addressed.
• Compliance with regulatory requirements and recommendations is analysed.
• Key areas for further work are identified.</td></tr>
<tr><td>Review and Modification</td><td>• Modifications are implemented in a structured and well-documented manner.
• Work is specified with the aim of ensuring that key uncertainties will be reduced or better understood.</td></tr>
</table>

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).

3.8 TIMEFRAMES OF INTEREST

The construction phase of the DGR is expected to take approximately five to seven years. The operations phase will then last about 40 to 45 years. This will be followed by a monitoring-only phase of at least 5 years, and a decommissioning phase (including dismantling surface facilities and sealing the shaft), which is expected to take about six 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 inventory assessed 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 reference value of 300 years is adopted for the minimum period over which such controls, as well as societal memory, are effective, consistent with current international practice (e.g., SKB 2006).

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). Peak impacts associated with releases in groundwater might not occur for more than 1,000,000 years due to a number of factors such as the long half-lives of important radionuclides in the waste, the slow resaturation time of the repository, and the slow groundwater travel times. Therefore, some calculations are extended for timescales in excess of 1,000,000 years.

G-320 notes that the reliability of quantitative predictions diminishes with increasing timescale due to growing uncertainties (CNSC 2006). A significant source of uncertainty relates to the evolution of the disposal system. It is anticipated that, over a timescale of around 100,000 years, the DGR will be affected by ice sheet development resulting from cooling of the earth's climate (Peltier 2008). Ice sheet development will have impacts on the surface and sub-surface environment, the precise quantification of which is uncertain. Due to such uncertainties, long-term quantitative estimates of impacts should not be considered as absolute measures, but rather as indicators of safety. As such, they need to be supported by additional safety arguments.

In light of the above discussion, the following timeframes are considered in the Version 1 SA.

- **0 – 10,000 years**: Conditions in repository will gradually evolve with the ingress of water, degradation of wastes packages and generation of gas. Various radionuclides of operational safety concern such as H-3 or Co-60 decay.

- **10,000 – 100,000 years**: All waste packages will have failed or degraded. C-14 will decay. The repository and geological evolution, and health and environmental impacts, are analysed through one glacial cycle.

- **100,000 – 1,000,000 years**: By 1,000,000 years, the residual activity will be approximately equal to that in the overlying rock. Geological events, repository evolution and health and environmental impacts are quantified or numerically bounded to 1,000,000 years.

- **1,000,000 – 10,000,000 years**: Impact estimates are calculated out beyond 1,000,000 years to provide evidence that the peak impact has been addressed. Given the significant uncertainties associated with such timescales that could affect the geosphere as well as the biosphere, the calculations should be seen as being stylised with significant uncertainties.

4. SYSTEM DESCRIPTION

This section summarises 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 (Little et al. 2009) and the Data report (Walke et al. 2009b). The primary data sources are:

- the August 2008 inventory report (OPG 2008a) for the waste and waste packaging;
- the May 2008 conceptual design report (Hatch 2008) for the repository design;
- data provided by the Geosynthesis team during 2008 and early 2009 for the geological setting (see Walke et al. 2009b for details); and
- assorted reports (e.g., CSA 2008, BEAK 2002, Benovich 2003, OPG 2005, and Garisto et al. 2004) for the surface environment.

4.1 WASTE

4.1.1 Categories and Characteristics

The DGR will accept operational and refurbishment L&ILW from Ontario's three nuclear power sites (Bruce, Pickering and Darlington). No consideration is given to decommissioning wastes in this assessment, since OPG is not seeking a licence to emplace decommissioning waste in the DGR. The DGR will not accept used nuclear fuel.

The L&ILW is categorised according to the characteristics of the waste (OPG 2008a) (Table 4-1).

Certain wastes will be processed prior to being sent to the DGR. Most of these are current practice at the WWMF. The main waste processing practices undertaken by OPG are incineration (resulting in the generation of the bottom ash and baghouse ash) and compaction (resulting in the generation of compacted waste bales and boxes). In addition, the assessment assumes that steam generators from the planned refurbishment programmes will be filled with grout and cut into smaller sizes.

4.1.2 Packaging

The range of waste containers and overpacks that will be used by OPG for the storage and eventual disposal of L&ILW in the DGR is described in OPG (2008a). It is recognised that, in practice, 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. However, the Data report (Walke et al. 2009b) has identified the most common waste containers and overpacks for each waste category as "reference", as summarised in Table 4-2.

4.1.3 Volumes

The final volume of L&ILW to be disposed in the DGR has been estimated by OPG (2008a) and is presented in Table 4-3. The raw or net volume refers to the waste material itself, whereas the disposal volume is the volume occupied by the waste packages in the repository including an allowance for the waste containers and any overpacks.

Table 4-1: Waste Categories

Waste Category	Description
LLW Wastes	
Bottom ash	Heterogeneous ash and clinker from waste incineration. Waste disposed in an 'ash bin' with sheet metal overpack.
Baghouse ash	Fine homogeneous ash from waste incineration, with low density. Waste disposed in an 'ash bin' with sheet metal overpack.
Compacted wastes (bales)	Compacted paper, plastic, rubber, cotton etc in a plastic-wrapped bale. Some metals are present. Waste disposed in mild steel bale rack.
Compacted wastes (boxes)	Compacted paper, plastic, rubber, cotton etc. Some metals are present. Waste disposed in a mild steel compactor box (B25).
Non-Processible (drums)	Metal, wood, concrete, glass, absorbent, etc. that cannot be processed. Generally, the bulk density is very low because of the low packing density of irregular objects. Waste disposed in 220 litre steel drums placed in carbon steel drum bin. 10% are overpacked in sheet metal overpack.
Non-Processible (boxes)	Metal, wood, concrete, glass, absorbent, etc. that cannot be processed. Generally, the bulk density is very low because of the low packing density of irregular objects. OPG (2008a) also provides specific data for feeder pipes, but this is categorised as '"non-processible (boxes) wastes" for the purposes of the safety assessment. Waste disposed in a metal non-pro box.
Non-Processible (other)	Large and irregularly shaped objects such as heat exchangers, encapsulated tile holes, tile hole liners, miscellaneous large objects (e.g., fume hoods, glove boxes, processing equipment), reactor refurbishment large objects (e.g., pre-heaters, heat exchangers), and large objects retrieved from trenches. Most of these would be emplaced "as is" in the DGR.
LLW Resins	Polystyrene divinyl benzene copolymer IX resin, approximately 0.5 mm in diameter, granulated active carbon and polymer beads. Waste disposed in low level resin pallet tank.
ALW Resins	Polystyrene divinyl benzene copolymer IX resin approximately 0.5 mm in diameter, arising from liquid effluent treatment plants. Waste disposed in low level resin pallet tank.
ALW sludges	Sludge containing bentonite arising from liquid effluent treatment plant. Waste disposed in ALW sludge box with sheet metal overpack.
Steam generators	Redundant steam generators from refurbishment. The steam generators consist of Inconel 600 tubes, carbon steel shell and shroud, and head and tubesheet. Grouted and cut into smaller sizes before disposal.
ILW Wastes	
CANDECON resins	Polystyrene divinyl benzene copolymer IX resin, approximately 0.5 mm in diameter, containing EDTA and other chelating agents as well as corrosion inhibitor. Waste disposed in steel resin liner with concrete cylinder overpack.
Moderator resins	Polystyrene divinyl benzene resin beads, approximately 0.5 mm in diameter from moderator system. Waste disposed in steel resin liner with concrete cylinder overpack.
PHT resins	Polystyrene divinyl benzene resin beads, approximately 0.5 mm in diameter from the Primary Heat Transport (PHT) system. Waste disposed in steel resin liner with concrete cylinder overpack.
Misc. resins	Miscellaneous polystyrenedivinyl benzene resin beads. Waste disposed in steel resin liner with concrete cylinder overpack.
Irradiated core components	The material is typically alloys such as Inconel-600 or stainless steel and comprises items such as flux detectors and liquid zone control rods. Waste disposed in tile hole equivalent liner which will be inserted into concrete pipe array in the DGR.
Filters and elements	Filters and filter elements from PHT and moderator streams. Waste disposed in tile hole equivalent liner which will be inserted into concrete pipe array in the DGR.
IX columns	IX columns contain polystyrene divinyl benzene resin from the Pickering PHT system. Waste disposed in tile hole equivalent liner which will be inserted into concrete pipe array in the DGR.
Retube Waste (Pressure Tubes)	Zr-2.5%Nb alloy. Waste disposed in retube waste container.
Retube Waste (End Fittings)	Stainless steel (SS-403). Waste disposed in retube waste container.
Retube Waste (Calandria Tubes)	Zircaloy-2. Waste disposed in retube waste container.
Retube Waste (Calandria Tube Inserts)	Stainless steel (SS-410). Waste disposed in retube waste container.

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: • Not yet specified. Therefore the current SA does not take overpack into account	
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: • Not yet specified. Therefore the current SA does not take overpack into account.	

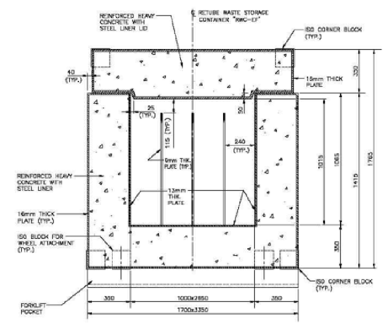
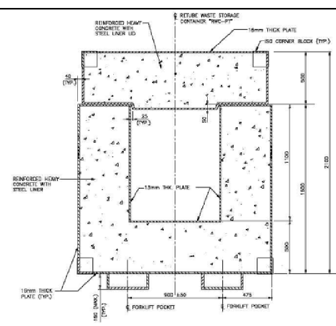
Container name, wastes and overpack*	**Picture**	**Container name, wastes and overpack***	**Picture**
ALW sludge box (NPBSB) • ALW sludges Reference Overpack: • LLW sheet metal overpack (BINOPK)		Resin Liner (RL) • CANDECON resins • Moderator resins • PHT resins • Misc. resins Reference Overpack for RL: • Stainless steel cylinder (RLOPK) Reference Shield (RLSHLD1) • Concrete cylinder each holding 2 overpacked resin liners	
Tile hole equivalent liner (THLIC18) • Filters and Elements • Irradiated Core Components • IX Columns Reference Overpack: • The tile hole equivalent liner will be transported in re-usable shield and will be inserted (from the shield) into concrete pipe array in the emplacement room.	Picture n/a	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 operation (e.g. without lids). All containers will be lidded and overpacked if necessary. Concrete cylinders (ILW shields) will be used for some of the filters, IX columns, bagged wastes, and core components. Steam Generators are not shown in the table, as they will not be placed in containers. Also the 45 LLW resin boxes identified in the inventory report (OPG 2008) are not shown - they will be placed in the LLW sheet metal overpacks (BINOPK).	

Table 4-3: Waste Volumes to be Disposed (OPG 2008a)

Waste Categories	**Raw (Net) Volume (m^3)**	**Number of Disposal Containers**	**Disposal Volume (m^3)**
LLW			
Bottom ash	2,334	1,085	9,222
Baghouse ash	313	181	1,539
Compacted wastes (bales)	2,445	1,491	5,069
Compacted wastes (boxes)	12,185	5,298	14,834
Non-processible (drums)	11,736	6,276	20,858
Non-processible (boxes)	50,617	20,336	70,138
Non-processible (other)	2,396	148	2,396
LLW resins	1,513	2,171	6,203
ALW resins	1,937		
ALW sludges	3,375	1,534	13,039
Steam generators	7,673	512	7,673
Sub-total LLW	**96,524**	**39,032**	**150,971**
ILW			
CANDECON resins	2,154	480	5,318
Moderator resins	2,264	504	5,585
PHT resins	1,595	355	3,941
Misc. resins	2,126	473	5,245
Irradiated core components	25	8,048	11,323
Filters and filter elements	1,453		
IX columns	561		
Retube Wastes (Pressure Tubes)	196	245	1,887
Retube Wastes (End Fittings)	2,479	918	10,038
Retube Wastes (Calandria Tubes)	134	168	1,294
Retube Wastes (Calandria Tube Inserts)	36	45	347
Sub-total ILW	**13,023**	**11,236**	**44,978**
Total	**109,547**	**50,268**	**195,949**

4.1.4 Contaminants and Other Materials

A large number of radioactive and non-radioactive species are present in L&ILW wastes; however, most are short-lived or present in small quantities. Screening calculations for contaminant releases via groundwater, gas and human intrusion have been conducted for the full set of contaminants listed in the 2008 inventory (OPG 2008a) in order to identify those contaminants of potential important to postclosure safety (Walke et al. 2009b).

Table 4-4 summarises the total amounts of radionuclides and chemical species in the LLW and ILW considered in this assessment.

Table 4-4: Total Amounts of Radionuclides, Elements and Chemical Species in LLW and ILW for which Safety Assessment Calculations are Undertaken

Radionuclide	Amount (Bq) at 2062			Elements/ Chemical Species	Amount (kg) at 2062		
	LLW	ILW	Total		LLW	ILW	Total
H-3	1.07E+15	1.68E+14	1.24E+15	Antimony	2.93E+03	2.48E+01	2.95E+03
C-14	3.19E+13	6.93E+15	6.96E+15	Arsenic	2.68E+02	1.50E+02	4.18E+02
Cl-36	1.49E+08	1.13E+12	1.13E+12	Barium	9.81E+03	1.75E+02	9.98E+03
Ni-59	2.63E+10	2.86E+13	2.86E+13	Beryllium	1.94E+00	2.42E+01	2.62E+01
Ni-63	4.13E+12	2.86E+15	2.87E+15	Boron	1.62E+03	1.23E+03	2.86E+03
Se-79	1.36E+06	1.07E+10	1.07E+10	Bromine	7.32E+01	5.04E-01	7.37E+01
Sr-90	1.26E+13	2.03E+13	3.29E+13	Cadmium	1.03E+04	2.21E+01	1.03E+04
Mo-93	0.00E+00	6.48E+11	6.48E+11	Chromium	7.75E+05	1.70E+05	9.45E+05
Zr-93	3.31E+06	1.95E+14	1.95E+14	Cobalt	3.21E+02	3.13E+02	6.34E+02
Nb-94	2.17E+10	4.50E+15	4.50E+15	Copper	2.94E+06	8.05E+03	2.95E+06
Tc-99	2.97E+07	4.42E+10	4.42E+10	Gadolinium	6.56E+00	5.21E+03	5.22E+03
Ag-108m	1.70E+08	1.94E+13	1.94E+13	Hafnium	0.00E+00	2.69E+02	2.69E+02
Sn-121m	0.00E+00	6.82E+13	6.82E+13	Iodine	3.81E+01	1.35E-01	3.82E+01
Sn-126	1.16E+08	7.94E+08	9.11E+08	Lead	6.53E+05	3.21E+02	6.54E+05
I-129	1.15E+06	1.47E+08	1.48E+08	Lithium	1.93E+02	6.71E+03	6.90E+03
Cs-137	8.93E+12	5.21E+13	6.10E+13	Manganese	2.34E+05	1.21E+04	2.46E+05
Eu-152	1.58E+09	1.67E+12	1.67E+12	Mercury	5.79E+01	4.01E-01	5.83E+01
U-232	9.63E+07	2.47E+07	1.21E+08	Molybdenum	2.37E+02	1.02E+03	1.26E+03
U-233	1.56E+08	4.00E+07	1.96E+08	Nickel	2.07E+06	1.58E+04	2.08E+06
U-234	4.60E+08	1.18E+08	5.78E+08	Niobium	9.80E+01	1.13E+04	1.14E+04
U-235	6.83E+06	1.96E+06	8.79E+06	Scandium	2.40E+01	6.37E-01	2.46E+01
U-236	9.68E+07	2.25E+07	1.19E+08	Selenium	7.93E+01	5.90E+00	8.52E+01
U-238	5.80E+08	1.49E+08	7.29E+08	Silver	3.57E+00	2.31E+00	5.88E+00
Np-237	1.57E+07	1.11E+07	2.69E+07	Strontium	2.97E+03	4.15E+01	3.01E+03
Pu-238	1.30E+11	2.92E+10	1.59E+11	Tellurium	1.97E+02	6.87E-02	1.97E+02
Pu-239	4.42E+11	8.08E+10	5.23E+11	Thallium	3.20E-01	3.34E-01	6.54E-01
Pu-240	5.32E+11	1.18E+11	6.50E+11	Tin	1.57E+02	2.40E+03	2.56E+03
Pu-241	1.64E+12	1.63E+12	3.27E+12	Tungsten	9.16E+01	1.55E+02	2.47E+02
Pu-242	1.47E+08	1.08E+08	2.55E+08	Uranium	4.98E+00	2.45E+01	2.95E+01
Am-241	7.60E+11	2.25E+11	9.85E+11	Vanadium	1.25E+02	9.98E+02	1.12E+03
Am-242m	1.21E+09	3.10E+08	1.52E+09	Zinc	1.43E+05	2.47E+03	1.45E+05
Am-243	3.27E+08	1.66E+08	4.93E+08	Zirconium	7.03E+02	6.05E+05	6.06E+05
Cm-243	1.34E+09	3.43E+08	1.68E+09	Cl-Benzenes & Cl-Phenols	7.73E+00	0.00E+00	7.73E+00
Cm-244	4.06E+10	7.20E+10	1.13E+11	Dioxins & Furans	1.15E-01	0.00E+00	1.15E-01
Total	**1.14E+15**	**1.48E+16**	**1.60E+16**	PAHs	3.11E+00	0.00E+00	3.11E+00
				PCBs	2.92E-01	0.00E+00	2.92E-01

Notes:
Radioactive progeny are not included in the table but are considered in the safety assessment calculations.

Table 4-5 summarises the amount of organics, metals and concrete in the wastes and their containers and overpacks.

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
Organics	Cellulose	8.5E+06	-	-	-
	Rubber and Plastics	7.6E+06	2.1E+05	-	-
	Resins	7.2E+06	-	5.4E+06	-
Metals	Carbon steel	3.6E+06	2.8E+07	2.2E+06	2.5E+06
	Stainless steel	1.6E+06	4.0E+06	2.4E+06	9.6E+06
	Zircaloy	-	-	6.1E+05	-
Concrete		9.2E+05	9.0E+06	-	5.6E+07

4.2 REPOSITORY

The current design of the repository comprises two shafts, a ring tunnel and associated facilities, two access tunnels and 45 waste emplacement rooms (30 rooms[9] in a South Panel and 15 rooms in an East Panel) (Figure 4-1). The reference depth for the repository floor is 680 m below ground surface in competent and tight argillaceous limestone (the Cobourg Formation).

4.2.1 Physical Layout

The 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, whilst the Ventilation Shaft will allow the routing of air away from underground operations. It is anticipated that water inflow to the repository will be negligible during construction and operation and that any moisture will be carried by the ventilating air to the surface. The shafts will be located on a central, 120 m diameter, ring tunnel from which the two access tunnels will radiate out to the emplacement rooms to the south and east. Underground support facilities (offices, workshops, refuge bays, maintenance areas, etc.) will be located on the ring.

The ring tunnel and its facilities (together with the access tunnels and emplacement rooms) will have concrete floors (typically 0.2 m thick), with shotcrete on the ceilings and extending half-way down the walls. Rockbolts will be placed in the ceiling to provide roof support.

The dimensions and areas of the emplacement rooms, access tunnels and the ring tunnel, and the shafts are summarised in Table 4-6 and Table 4-7, respectively. The associated volumes

[9] 28 emplacement rooms are considered in Hatch (2008). However, the volumes of LLW specified in the 2008 inventory report (OPG 2008a) require two rooms to be added.

of the emplacement rooms, access tunnels, and the ring tunnel (plus associated features), are presented in Table 4-8.

The total amount of concrete and steel associated with the emplacement rooms, and access and ring tunnels (excluding waste packages) is 43,000 tonnes and 2,300 tonnes, respectively (Walke et al. 2009b).

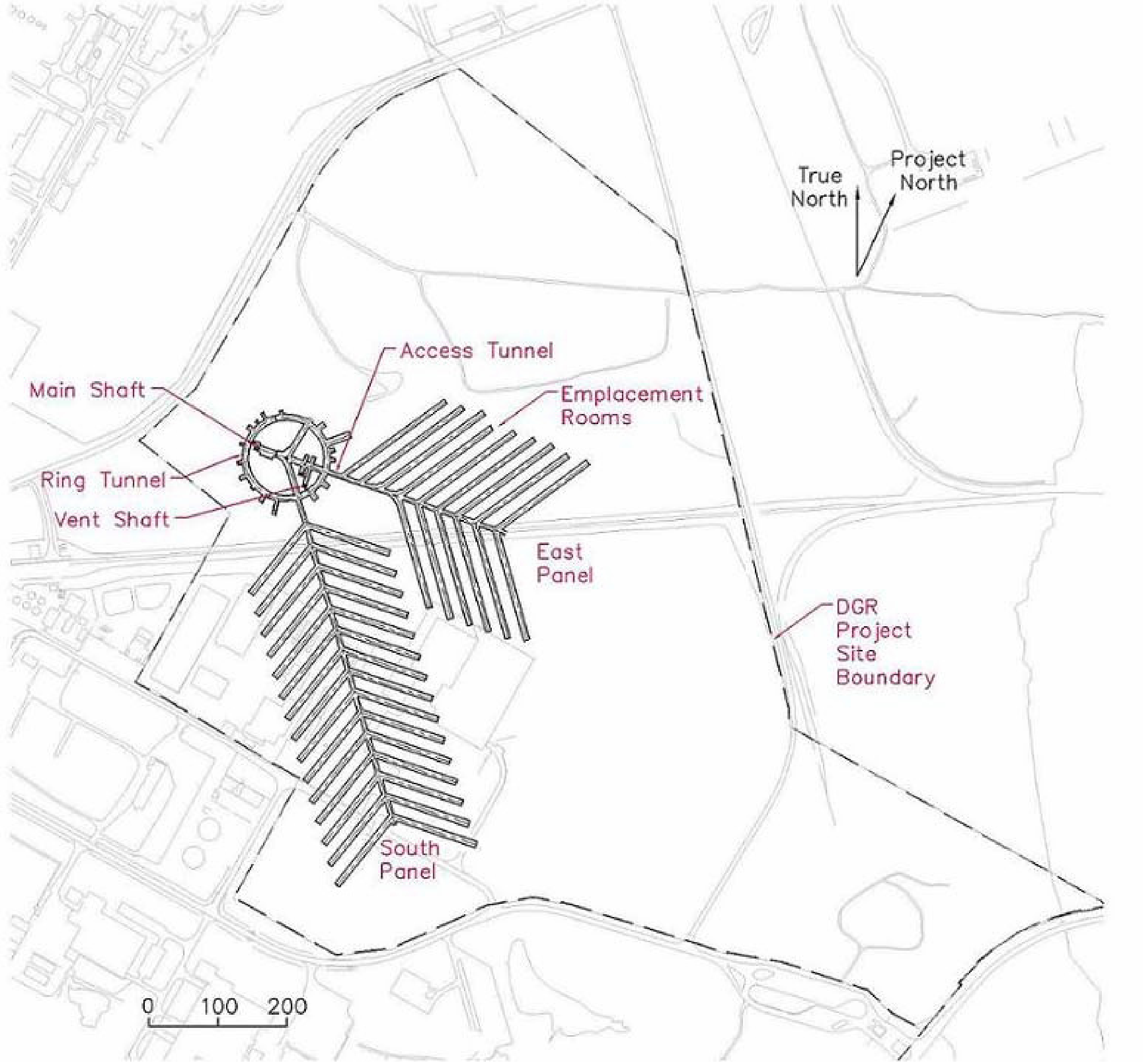


Figure 4-1: General Layout of the Repository Concept

Table 4-6: Excavated Dimensions and Areas of Emplacement Rooms, Access Tunnels and Ring Tunnel

Parameters	South Panel (LLW)	East Panel (ILW+ Large LLW)						Total
Emplacement Rooms:								
Depth (m)	680	680						
Pillar Width between Emplacement Rooms (m)	17.20	16.36 (average)						
Emplacement Room ID	S-A	E-A	E-B	E-C	E-D	E-E	E-F	
Number of Emplacement Rooms	30	2	1	6	3	1	2	45
Length of each room (m)	123.9	164.6	170.5	170.5	162.3	185.5	182.5	
Width of each room (m)	8.6	8.1	8.6	7.7	8.6	8.4	7.4	
Height of each room (m)	7.0	7.2	5.7	6.0	5.7	6.5	6.3	
Total Roof Area (m^2)	31,966	20,456						52,423
Access Tunnels (outside ring tunnel):								
Length from ring tunnel (m)	488	273						
Width (m)	6.5	6.5						
Height (m)	7.0	7.0						
Roof Area (m^2)	3,169	1,775						4,943
Panel (from first emplacement room):								
Length (m)	520	340 (northern rooms) and 255 (southern rooms)						
Width (m)	220	180 (northern rooms) and 150 (southern rooms)						
Footprint (m^2)	114,400	99,450						213,850
Ring Tunnel:								
Length (m)	-	-						377
Width (m)	-	-						8.1
Height (m)	-	-						7.5
Roof Area (including roof area of underground support facilities associated with the ring tunnel) (m^2)	-	-						6,237

Table 4-7: Dimensions and Areas of Shafts at Closure

	Main Shaft	Ventilation Shaft
Surficial Groundwater Zone:		
Length (m)	20	20
Excavated Diameter (m)	9.4	7.2
Finished Diameter (m)	6.5	4.5
Excavated cross-sectional area (m^2)	69.4	40.7
Finished cross-sectional area (m^2)	33.2	15.9
Liner thickness (m)	1.45	1.35
Shallow Bedrock Groundwater Zone:		
Length (m)	163	163
Excavated Diameter (m)	8	5.8
Finished Diameter (m)	6.5	4.5
Excavated cross-sectional area (m^2)	50.3	26.4
Finished cross-sectional area (m^2)	33.2	15.9
Liner thickness (m)	0.75	0.65
Intermediate Bedrock Groundwater Zone:		
Length (m)	265	265
Diameter (m)	8	5.8
Cross-sectional area (m^2)	50.3	26.4
Liner thickness (m)	0	0
Deep Bedrock Groundwater Zone:		
Length to top of monolith (m)	212	219.5
Diameter (m)	8.15	5.95
Cross-sectional area (m^2)	52.2	27.8
Liner thickness (m)	0	0

Table 4-8: Repository Volumes

	South Panel	East Panel	Total
Excavated Volumes (m^3):			
Emplacement Rooms	224,000	126,000	350,000
Access Tunnel (outside ring tunnel)	22,000	12,500	34,500
Ring Tunnel and Associated Features			45,500
Total	**246,000**	**138,500**	**430,000**
Void Volume (m^3):			
Emplacement Rooms (excluding waste and package void volume)	72,500	64,000	136,500
Waste Voidage	60,500	12,000	72,500
Packaging Voidage	46,500	10,000	56,500
Total Emplacement Rooms	*179,500*	*86,000*	*265,500*
Access Tunnel (outside ring tunnel)	21,500	11,500	33,000
Ring Tunnel and Associated Features			36,500
Total	**201,000**	**97,500**	**335,000**

4.2.2 Waste Emplacement

All LLW categories, except the steam generators and non-processible (other) categories (Table 4-1), will be placed in the South Panel. Emplacement rooms will be filled with waste and closed sequentially. Overall packing efficiencies of 63% by volume are anticipated for LLW (Hatch 2008).

All ILW and large-size LLW will be placed in the East Panel. Six sizes of emplacement room are envisaged, with each type being used for the placement of particular types of waste package. Overall packing efficiencies of 43% by volume are anticipated for placement of containers and overpacks, although efficiencies range from 15% to 67% for individual ILW rooms.

Once an emplacement room has been filled with waste, a concrete block wall will be constructed at its entrance to limit access, but allow ventilation.

4.2.3 Closure

On repository closure, the emplacement rooms and access tunnels will not be backfilled, and the ventilation ducts will remain in the rooms/tunnels. Decommissioning of the shafts will consist of: the removal of shaft infrastructure; the removal of the concrete shaft liner from the base of the shaft sumps up to 183 m below ground surface (bgs); and the installation of a shaft seal comprised of a sequence of sealing materials. The shaft seal design assessed is illustrated in Figure 4-2 and comprises[10]:

- a **concrete monolith** that will be placed at the base of each shaft;
- a sequence of 11 **concrete bulkheads** in each shaft; and
- **backfill** between the concrete bulkheads. A 70:30 **bentonite/sand** mix will be used between the majority of bulkheads. It will be emplaced dry in the shaft and compacted. **Asphalt** will also be used in the lower shaft and at the top of the Salina A0 and Salina A2 evaporite zones. The backfill in the upper shaft will be compacted **engineered fill** derived from crushed rock obtained during shaft excavation.

The total amount of materials used for the shaft seal has been estimated as: 22,000 tonnes of concrete for the concrete monoliths; 15,000 tonnes of concrete for the concrete bulkheads; 13,000 tonnes of asphalt for the asphalt backfill and waterstops; 47,000 tonnes of bentonite/sand for backfilling; and 15,000 tonnes of engineered fill for backfilling (Walke et al. 2009b).

[10] After discussion and agreement with NWMO staff, the shaft design has been modified from that presented in Hatch (2008) in two specific ways. First, the asphalt waterstops have been repositioned above the more permeable Guelph/ Salina A0 formation, and above the Salina A2 evaporite formation. Second, the rock around the shaft is not reamed out in an effort to remove the inner EDZ.

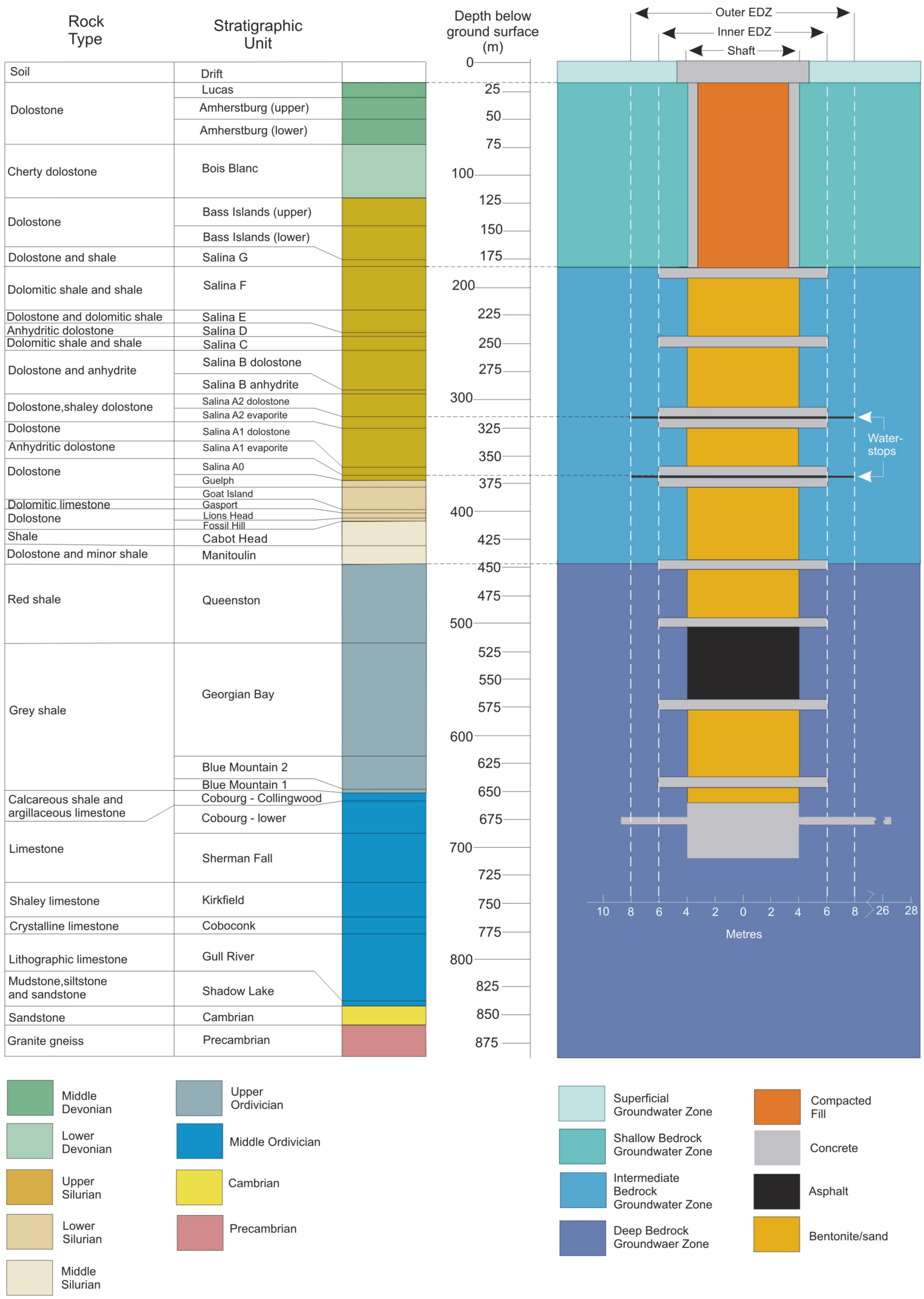


Figure 4-2: Sequence of Reference Shaft Sealing Materials

4.3 GEOLOGICAL SETTING

4.3.1 Structural Geology

The proposed repository location is on the eastern edge of the Michigan Basin (Figure 4-3), a Palaeozoic age intra-cratonic sedimentary basin. The DGR site is located within the Bruce Megablock, a structural domain identified within the sedimentary sequence overlying the Precambrian basement. The Bruce Megablock is bounded to the west by the Grenville Front Tectonic Zone (GFTZ), the Niagara Megablock to the south, and the Georgian Bay Linear Zone to the east (Figure 4-4). The GFTZ has been tectonically stable for the last 1000 million years, and therefore has not affected the deposition or structure of the overlying younger Palaeozoic rocks (Gartner Lee 2008a).

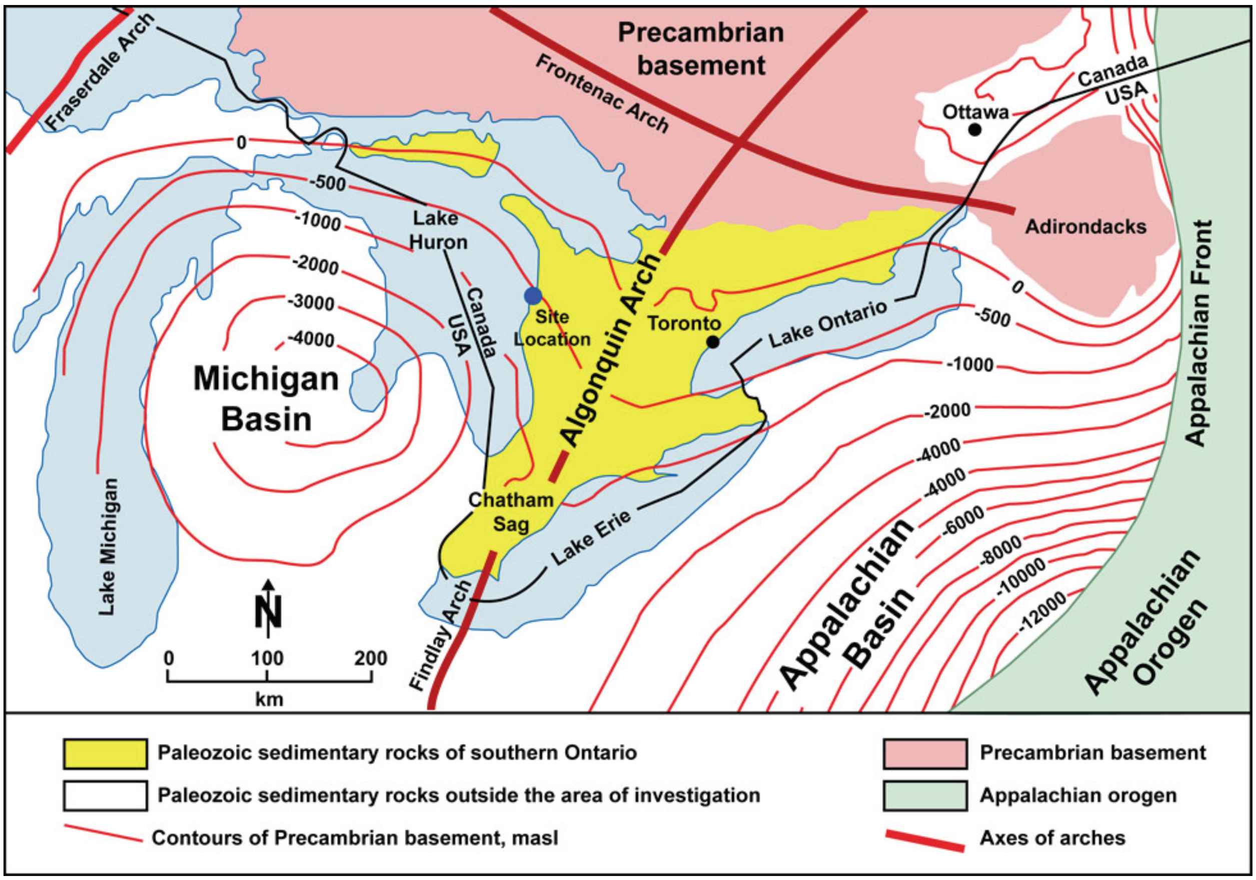


Figure 4-3: Large-scale Tectonic Elements in Southern Ontario[11] (Gartner Lee 2008a)

[11] Note masl = metres above sea level.

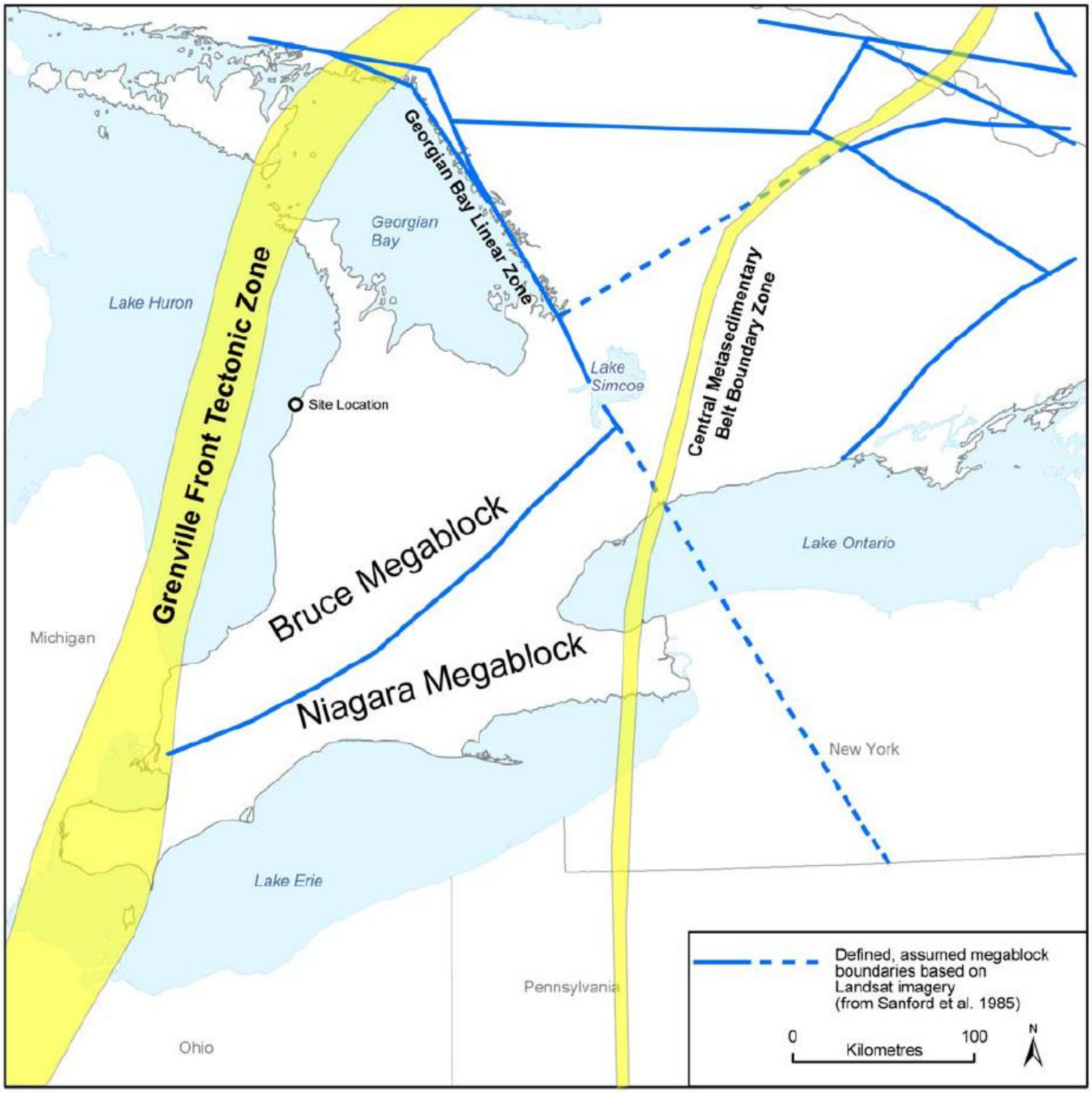


Figure 4-4: Major Structural Boundaries of Southern Ontario (Gartner Lee 2008a)

The Phase 1 Regional Geology report (Gartner Lee 2008a) notes that the study area can be characterised as one of the more structurally simple parts of southern Ontario. This characterisation is supported by the stratigraphy encountered in boreholes DGR-1 and DGR-2, which was consistent with and predicted by the regional geological modelling as described in Gartner Lee (2008a). Available aeromagnetic and gravity data further suggest that no major Precambrian basement structural features underlie the Bruce site. In addition, there are currently no known active faults within the Palaeozoic rocks in the study area, an assessment supported by the low level of seismicity in the Bruce Megablock (Gartner Lee 2008b).

4.3.2 Stratigraphy

The Palaeozoic bedrock sequence overlying Precambrian granitic basement has been measured to be over 800 m thick in the DGR site investigation boreholes (Gartner Lee 2008a). It comprises (from top to bottom) (Figure 4-5):

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

Unconsolidated sediments overlie this bedrock sequence which comprise former beach deposits (sands and gravels) and glacial till (clayey-silt to sand silt). 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.

4.3.3 Hydrogeology

Four groundwater zones have been identified with differing lithological, hydrological and geochemical characteristics (Figure 4-6).

- **The Surficial Deposits (Overburden) Groundwater Zone** – This includes overburden sediments in which fresh water enters from precipitation and percolates vertically downwards into the underlying Shallow Bedrock Groundwater Zone. Layers of sand and gravel constitute local aquifers, while the till layers comprise aquitards (i.e., they restrict groundwater flow). This surficial zone is approximately 20 metres thick. Groundwater flow within the surficial deposits around the Bruce site is directed generally northwestwards towards Lake Huron.
- **The Shallow Bedrock Groundwater Zone** – includes the dolostone sequence of the Lucas, Amherstburg, Bois Blanc and Bass Islands Formations and the top of the Salina Formation (G member). The upper portions of this sequence contain fresh water (where shallow wells are drilled) while at greater depths, brackish water occurs (2.5 g L^{-1}). Groundwater flow is primarily horizontal, driven by topographic features, with near-shore discharge to Lake Huron to the northwest of the site. Gradients in this zone are sufficiently high to create advective dominated flow. The zone is approximately 165 m thick.
- **The Intermediate Bedrock Groundwater Zone** – consists of Silurian sediments from the Salina F down to the Manitoulin (inclusive). Some zones of medium permeability exist in this sequence (in particular the Guelph, Salina A0 and Salina A2 evaporite), but the formations are primarily low-permeability shales and dolostones. Regional horizontal groundwater flow is expected to exist in the medium permeability units, albeit under very low horizontal gradients. Groundwater in the zone is saline (100 to 310 g L^{-1}). The zone is approximately 265 m thick.
- **The Deep Bedrock Groundwater Zone** – located within the Ordovician shale and limestone sequences and contains the repository. The zone also includes the Cambrian sandstones and Precambrian granitic gneiss. The Ordovician shale and limestone sequences have very low rock mass permeability and the porewater is saline (150 to 350 g L^{-1}). Site characterisation results show elevated environmental heads in the Cambrian sandstones and underpressured conditions in the Ordovician sequence. The zone is over 400 m thick.

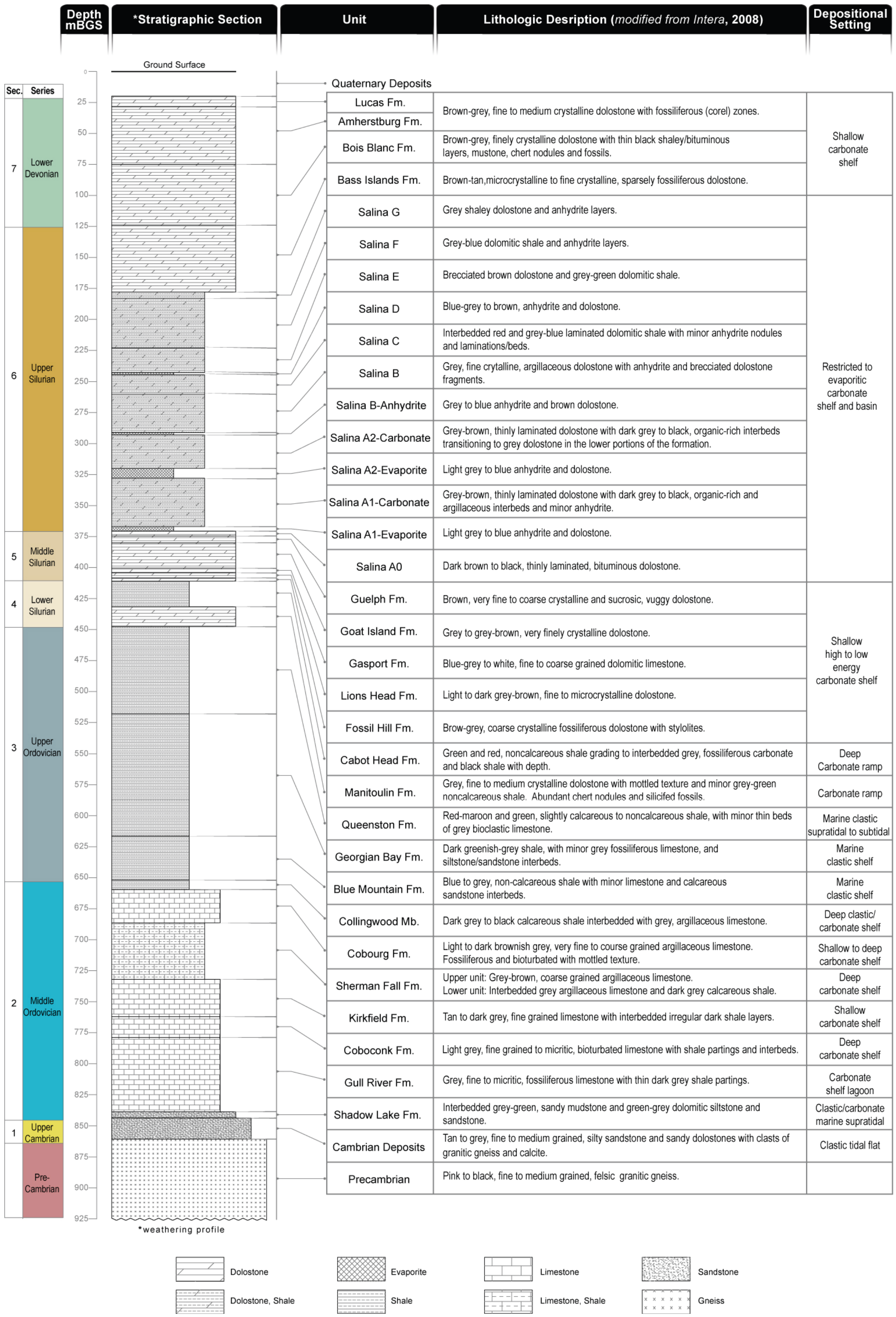


Figure 4-5: Geological Stratigraphy at the DGR Site (Gartner Lee 2008a)

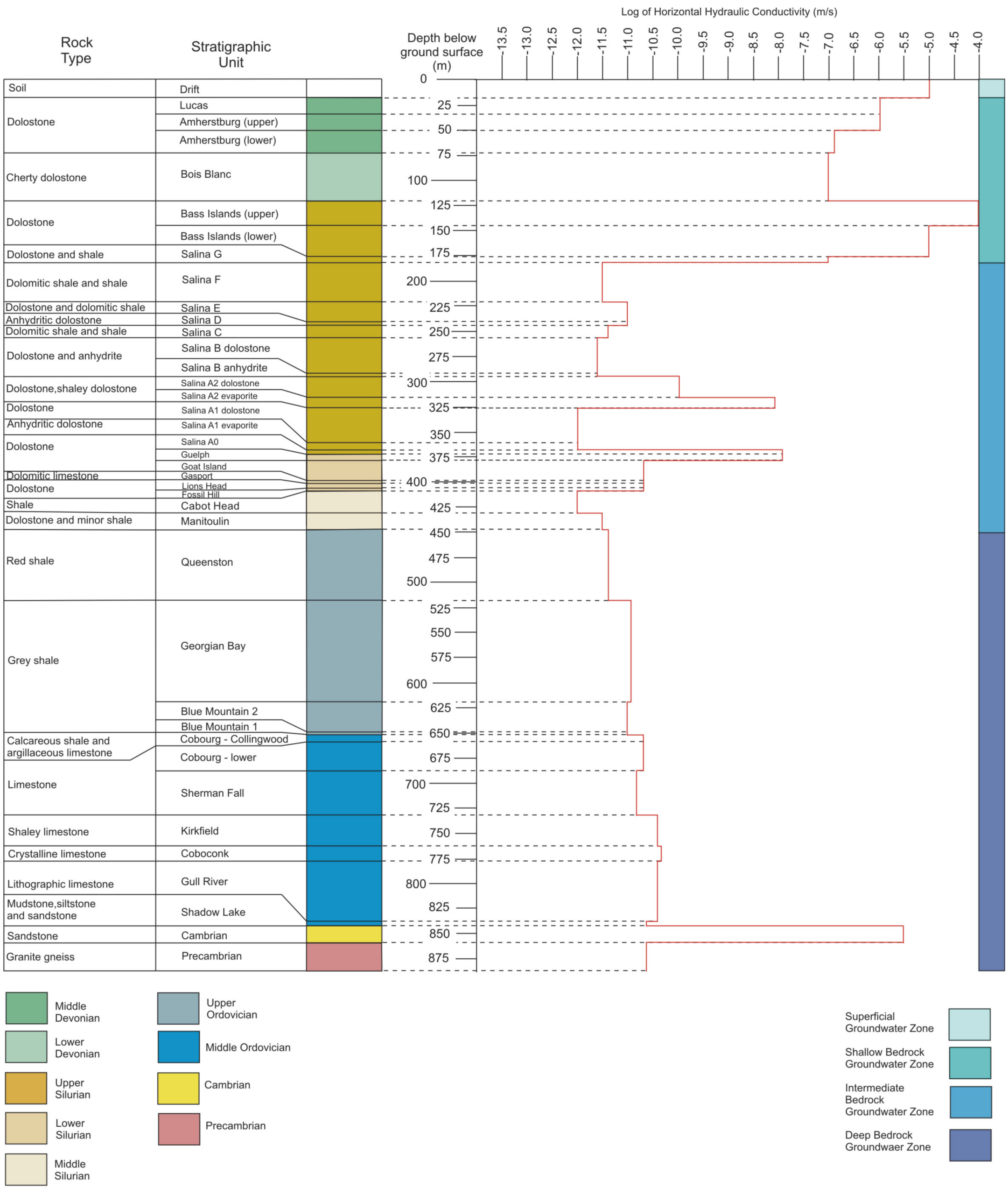


Figure 4-6: Horizontal Hydraulic Conductivity Profile Based on Data from DGR-1 and DGR-2 Site Investigation Boreholes

Figure 4-6 shows the horizontal hydraulic conductivity profile measured at the DGR site based on data from the on DGR-1 and DGR-2 site investigation boreholes, and documented in the Phase I Geosynthesis report (Gartner Lee 2008c). However, further site investigations, including in particular boreholes DGR-3 and DGR-4, have indicated that the host rock conductivities are likely to be even lower. A revised geosynthesis report based on this and other new information was not available when the V1 safety assessment was in preparation. Consequently a base case geosphere has been conservatively defined based on the DGR-1 and DGR-2 hydraulic conductivities, while an alternative updated geosphere case has been defined using lower conductivities derived from initial measurements from the DGR-3 and DGR-4 boreholes.

Vertical hydraulic head conditions within the bedrock formations beneath the Bruce site are described by Sykes et al. (2008). It is evident that significant anomalous over- and under-pressure environmental heads exist within the sedimentary sequence that may reflect past boundary conditions, extremely low formation scale permeabilities, variations in groundwater salinity and/or the basin hydrostratigraphy (Figure 4-7). The origin and longevity of the anomalous heads is currently under investigation with respect to formation properties and long-term barrier integrity.

Numerical simulations by Sykes et al. (2008) at regional and local Bruce site scales illustrate that within the Ordovician barrier formations mass transport is predominantly diffusion dominated for a range of observed conditions. In the overlying Silurian sediments permeable horizons are encountered within the Guelph, Salina A0 and Salina A2 evaporite formations. Horizontal advective flow may occur within these formations, which are otherwise vertically bound by low permeability aquitard formations. The analyses undertaken by Sykes et al. (2008) provide insight for understanding regional groundwater flow patterns within the sedimentary sequences and the transient influence of episodic glacial events.

Hydrogeochemical evidence from regionally based studies (Hobbs et. al., 2008) suggests that the brines typically encountered in bedrock at depths comparable to the intermediate and deep groundwater zones are of evaporated sea water origin, possibly emplaced 250 million years ago.

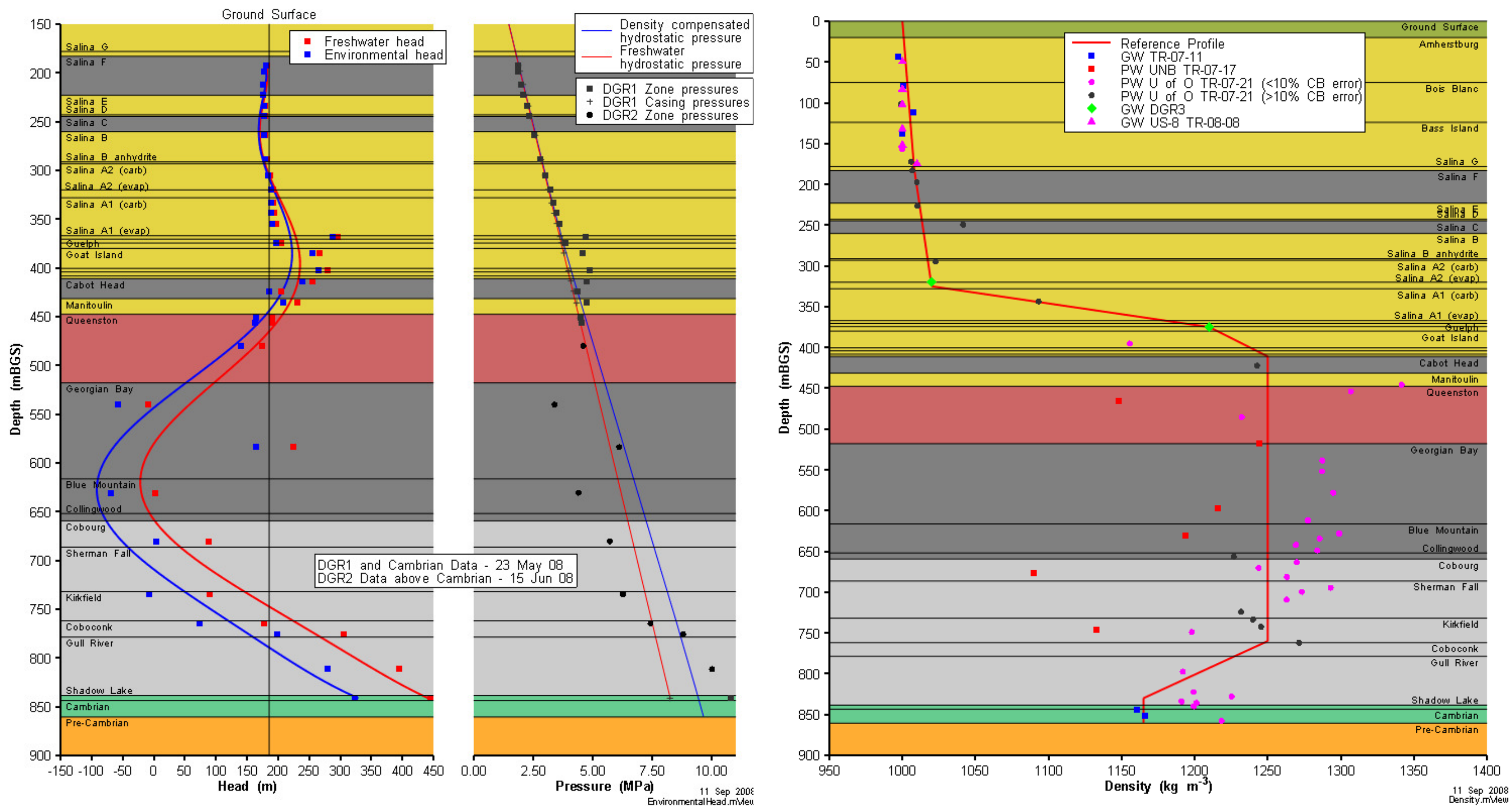


Figure 4-7. Groundwater Vertical Head and Density (Salinity) Profiles

4.3.4 Seismicity

Southwestern Ontario and the Bruce region lie within the tectonically stable interior of the North American continent; the stable interior region of North America is characterised by low rates of seismicity. Most recorded events have a magnitude[12] less than **M** 5. Figure 4-8 shows all known earthquakes in the region up to 2007 (Gartner Lee 2008b). 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.

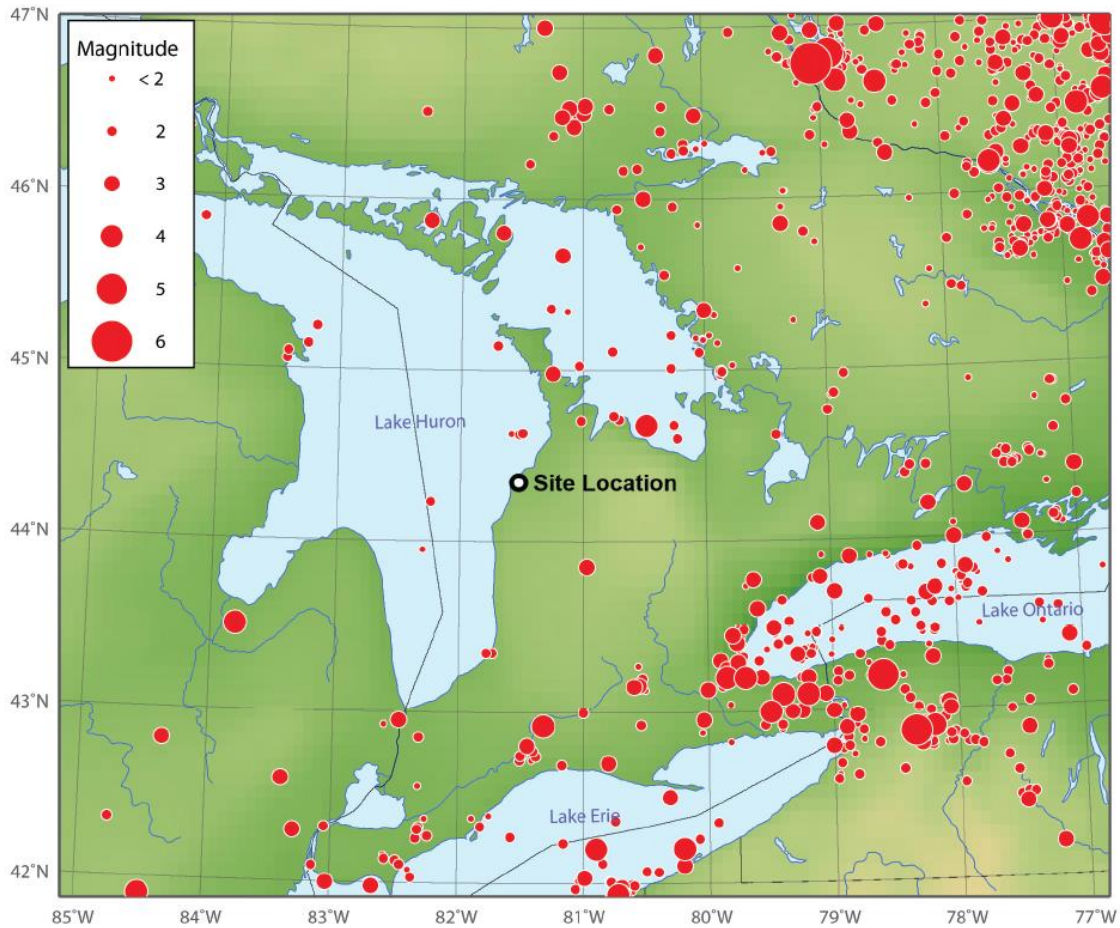


Figure 4-8: Seismicity in the Region around the Bruce Site (Hayek et al. 2008)

Recent studies of seismicity rates in stable cratonic regions by Fenton et al. (2006) and by Atkinson and Martens (2007) report an earthquake occurrence rate of **M** ≥ 6 events of <0.004 a^{-1} per 10^6 km^2 and <0.001 a^{-1} per 10^6 km^2 for the North American (NA) and Central Canadian (CC) Cratons (a subset of NA), respectively. Events of this magnitude are large enough to cause significant fault rupture. Thus an event of **M** ≥ 6 could be expected somewhere within a 20 km radius of the Bruce Site approximately once in every 800,000 years (with an uncertainty of a factor of three on this return period).

[12] Magnitude in this report is presented on the moment magnitude scale, **M**, which is similar to the Richter magnitude, but a more direct indication of earthquake fault size. The moment magnitude scale was calibrated such that moment magnitude equals Richter magnitude in most cases (Hanks and Kanamori 1979).

These findings provide a sense of the seismic recurrence rate of the Bruce region. With no seismic events of **M** > 5 recorded in the past 180 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. However, 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).

Ground shaking due to an earthquake is not normally a critical issue for an underground facility because shaking intensity decreases with depth. Case histories reveal that earthquake damage to underground structures, particularly below 500 m, is rare (Pratt et al. 1979; Backblom and Munier 2002). Damage may occur for near-surface facilities.

4.4 SURFACE ENVIRONMENT

4.4.1 Topography

The Bruce site lies on the eastern shore of Lake Huron on the Douglas Point promontory (Figure 1-1). The topography around the Bruce 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 8.9 °C in the vicinity of the Bruce site. The mean daily temperatures fall below freezing from December through March. The coldest months are January and February, with a mean temperature of approximately -7 °C. The extreme lowest temperature recorded is -37 °C. During June to August, mean daily temperatures range from approximately 15 °C to 19 °C. The extreme high temperature recorded is 36.1 °C.

There is a relatively even distribution of meteoric precipitation between winter and summer seasons (combining rain, snow, drizzle and freezing rain), typically totalling between 800 mm and 1,000 mm annually. Just over 20 percent of this meteoric precipitation falls as snow.

The average wind speed is 3.4 m s^{-1} with the prevailing winds being from the south and southwest.

4.4.3 Surface Water Bodies

The Bruce site is located adjacent to the Lake Huron shoreline. The lake contains about 3,500 km^3 of water, covering an area of 59,600 km^2. There are two small east-to-west drainage courses entering the lake adjacent to the site (Figure 4-9): 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, empties into Inverhuron Bay to the south. Stream “C” is characterised 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) (Figure 4-9). 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.

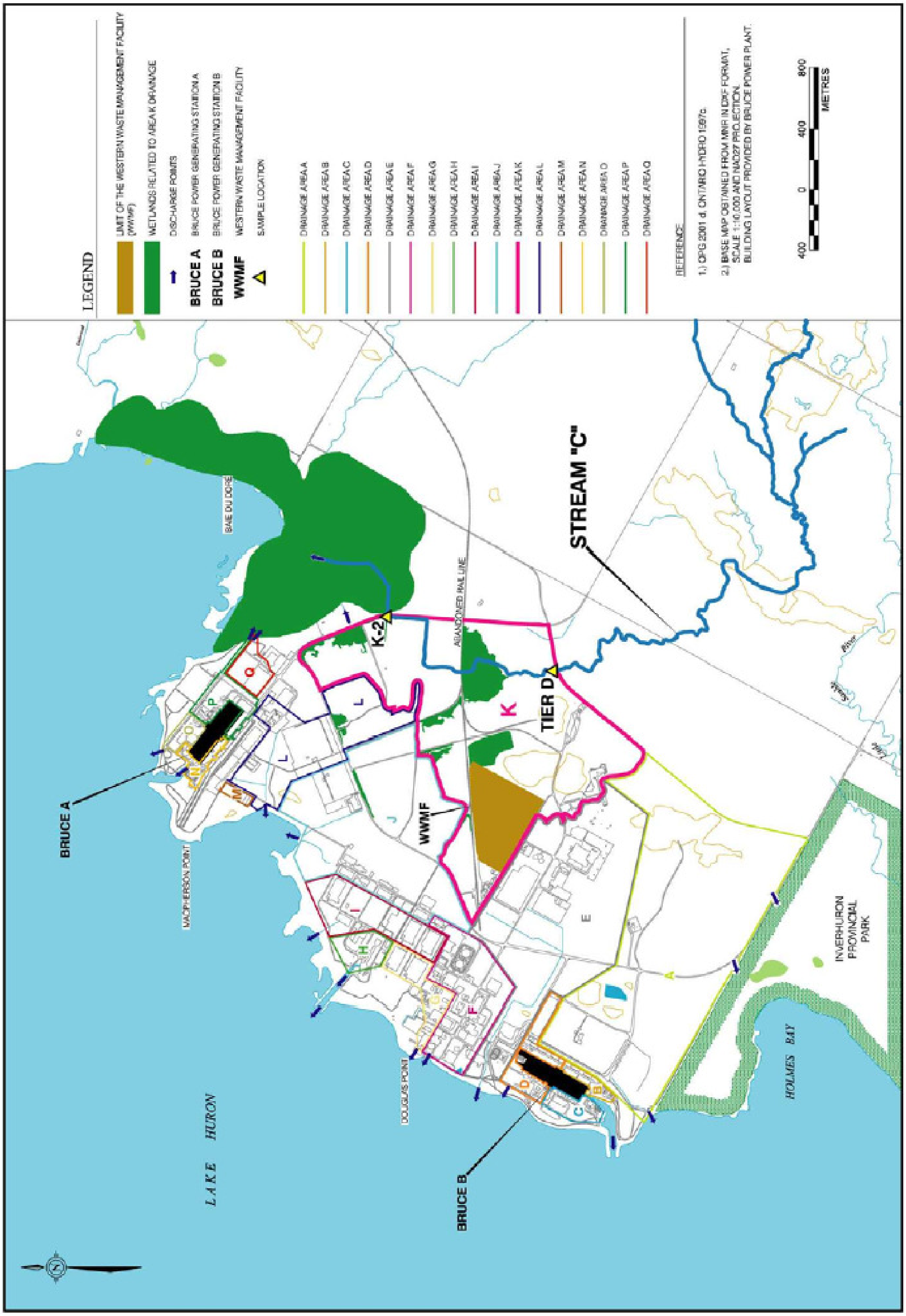


Figure 4-9: Map of the Bruce Site and Surrounding Area

4.4.4 Water Supply

Most of the rural population in the region obtains its water from private or communal wells, whilst the lake provides water for larger communities. In the Kincardine Municipality there are approximately 1000 wells (Golder 2003). 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, typically about 30 cm, with both sandy and loamy/clayey soils present. Soil moisture varies, but it is generally moist and often wet/saturated.

4.4.6 Land Use

Current land uses on the Bruce site are restricted to those associated with the nuclear operations and support activities. The region around the Bruce 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 60% of the land use in Bruce County, with many cattle farmers, as well as farmers of pigs and sheep, and crops such as oats, barley, canola and hay. Local people also hunt wild animals including deer and waterfowl. The lake is used for recreational and commercial fishing, and boating.

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 40.78 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 63.81 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 site consists of agricultural land.

The area is part of the Mixedwood Plains ecozone as identified by Environment Canada (EC 2008).

Several distinct vegetation ecosites have been identified in the vicinity of the Bruce site, the most common being:

- fresh-moist white cedar coniferous forest;
- dry-fresh sugar maple deciduous forest; and
- mineral cultural meadow.

No rare or unique vegetation species have been identified within these ecosites. The WWMF site is vegetated with balsam fir, sugar maple and American beech. There is also a meadow and wetland area on the site.

There is a wide variety of aquatic and terrestrial wildlife in the area including perch, northern pike, lake whitefish, lake trout, green and wood frog, chipping sparrow, American robin, black-capped chickadee, groundhog, red and grey squirrel, snowshoe hare, wild turkey and white-tailed deer. The wetland is habitat for a crayfish species, which is at the edge of its typical range.

The EIS guidelines for the DGR (CEAA and CNSC 2009) give a preliminary list of the valued ecosystem components (VECs) that need to be considered when evaluating the potential impacts of the project. The VECs includes the following biota:

- plants – eastern white cedar, heal-all, common cattail and variable leaf pondweed;
- mammals – muskrat, white-tail deer and meadow vole;
- amphibians and reptiles – midland painted turtle and northern leopward frog;
- birds – mallard, red-eyed vireo, wild turkey, yellow warbler, and bald eagle;
- benthic fish – redbelly dace, creek chub, lake whitefish;
- invertebrates – benthic invertebrates and burrowing crayfish; and
- pelagic fish – smallmouth bass, brook trout, and benthic invertebrates.

4.5 Uncertainties

There are uncertainties associated with each of the four components of the DGR system (i.e., the waste, repository, geological setting and surface environment) described in the previous sub-sections. A significant source of uncertainty is the long-term evolution of these components after closure of the DGR – this is addressed in Section 5. There are also some uncertainties associated with their current status. These are discussed below.

4.5.1 Waste

The total volume of wastes is relatively well constrained, being based on waste volumes already stored, plus historic experience of reactor operation combined with OPG’s forecast scenario based essentially on life of current nuclear reactors. Uncertainties associated with changes to inventory volumes, within the general reference forecast scenario, could result in a change of up to 20% to the inventory volume.

Waste packaging assumptions may be a more important uncertainty. OPG’s waste packages are well defined and no significant changes are planned. However, the extent of overpacking may be larger than assumed in the Data report (Walke et al. 2009b), in which case the amount of carbon steel in the repository could increase but by less than a factor of two. Also, it is possible that the steam generators may be processed such that much of the carbon steel could be free-released, and a smaller volume of active waste supplied to the DGR.

Most waste categories are relatively homogeneous in their physical characteristics, especially incinerator ash, resins and sludges, and retube wastes. However, non-processible and compacted 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 streams) are uncertain. Some physical characteristics of wastes, such as moisture content, have been estimated and are uncertain; however, it is unlikely that the associated uncertainties 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 organisations (IAEA 2009). As the radiological contaminants of most interest are present in the wastes at low levels, they can vary appreciably between packages, with log-dispersion of 5-10 typically observed (OPG 2008a). However, averaged across the many packages in the repository, the total radionuclide inventories have much less uncertainty.

4.5.2 Repository

The design described in Section 4.2 is the current conceptual design for the DGR. It is likely to evolve prior to the construction of the DGR, as a result of the on-going DGR work programme. Furthermore some modifications might be made to the operation and closure processes described in Sections 4.2.2 and 4.2.3. For the purposes of the current assessment, the design is taken as largely “fixed”, although certain design variants are considered (e.g., backfilling the repository).

4.5.3 Geological Setting

A programme of work is currently being undertaken to characterise the geology at the site (Intera 2006, 2008) and results from Phase 1 of the programme have already been incorporated into the current safety assessment. Nevertheless, the following key areas of uncertainty relating to the current status of the site need to be recognised:

- the geosphere permeability, especially in the Deep and Intermediate Bedrock Groundwater Zones(i.e., low or very low);
- the origin and evolution of the hydraulic head distribution in the geosphere, in particular the over/underpressures in the Deep and Intermediate Bedrock Groundwater Zones;
- the flow characteristics of the Guelph, Salina A0 and Salina A2 evaporite formations;
- the flow and transport properties of the Excavation Damaged Zones (EDZs) in the rock around the shafts; and
- the gas flow parameters (in particular capillary pressure and relative permeability parameters), especially in the formations above the Ordovician.

4.5.4 Surface Environment

The present-day surface environment in the vicinity of the Bruce site has been characterised under previous work that had calculated derived release limits (DRLs) for the WWMF (BEAK 2002 and Benovich 2003) and undertaken an environmental assessment of the WWMF (OPG 2005).

The Data report (Walke et al. 2009b) identifies current surface water flow parameters (including partitioning of infiltrating water between surface water courses and recharge, flow rates in water courses, and lake exchange rates) as being a notable source of uncertainty associated with the present-day surface environment at the Bruce site. However, these values are certain to change significantly over the time frame of this study, and so the assumed parameters are sufficient for providing a stylised representation of key features of similar surface environments with respect to contaminant accumulation and transport in the long term.

5. SCENARIO IDENTIFICATION AND DESCRIPTION

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 use scientifically-informed judgement to develop a 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 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.

The DGR system and its evolution are affected by various external, internal and contaminant factors (Figure 5-1). These factors may be further categorised 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 are situated within the spatial boundaries of the DGR system, whereas the external factors originate outside these boundaries. The external FEPs provide the system with both its boundary conditions and with factors that might cause change in the system. If these external factors can significantly affect the system within the assessment timescale, 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 (Garisto et al. 2009). This FEP list is based on lists developed in other programmes, such as the international FEPs database developed by the OECD Nuclear Energy Agency (NEA 1999b), the IAEA’s ISAM FEP list (IAEA 2004), and the FEP 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 effects of less likely External FEPs that might lead to abnormal degradation and loss of containment (Disruptive Scenarios) are considered in Section 5.2.

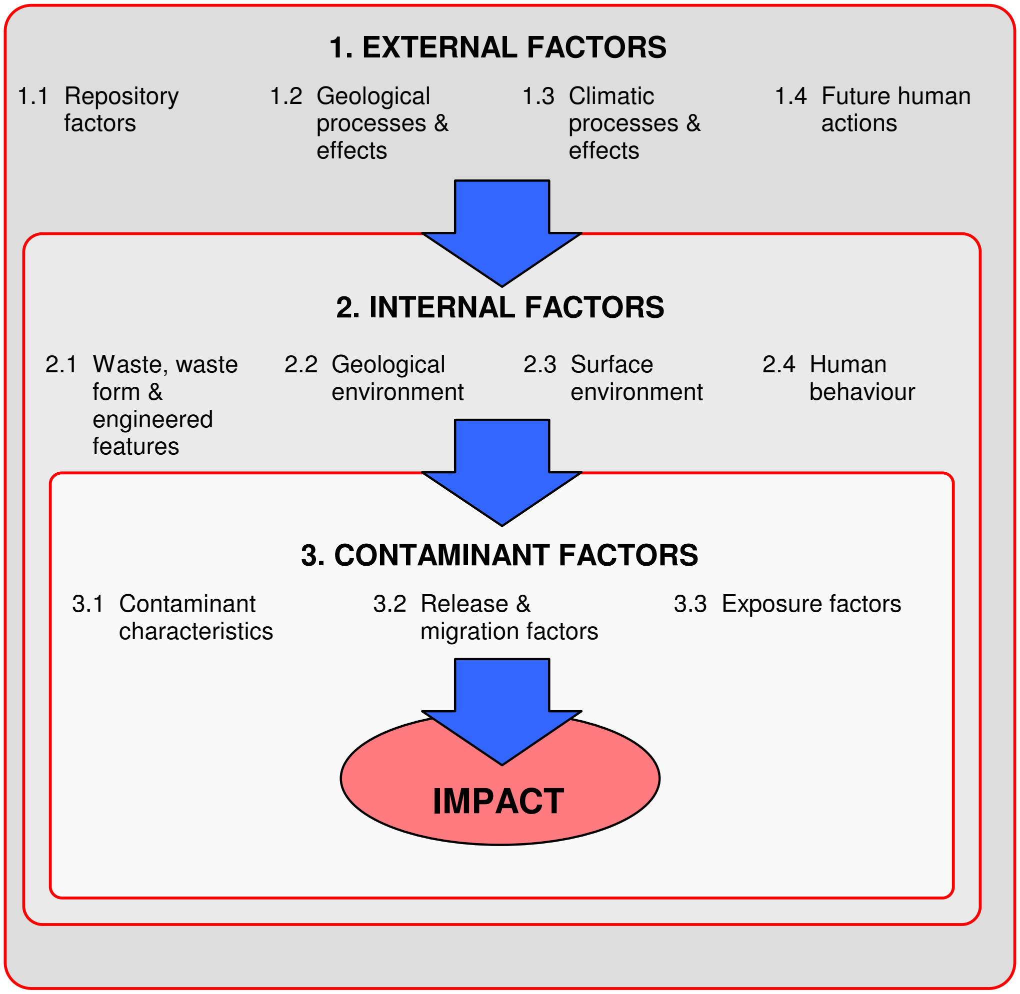


Figure 5-1: External, Internal and Contaminant Factors

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 (Section 3) and the system description (Section 4) and supporting technical documents (such as the various Geosynthesis reports, Damjanac 2008, Gartner Lee 2008a, b and c, Hobbs et al. 2008, Peltier 2008, and Sykes et al. 2008), to identify those that should be included or excluded from consideration when determining the expected evolution of the DGR system over the timescale of interest. 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 FEP report (Garisto et al. 2009).

Table 5-1: External FEPs Considered in the Assessment

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	Retrievability
	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 (Active)	
	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

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 previous site characterisation are included. All site investigation boreholes are appropriately sealed.
	1.1.02	Design of repository	Included	The DGR is built consistent with the description provided in Section 4.2.1, which is based on the Hatch (2008) conceptual design.
	1.1.03	Schedule and Planning	Included	DGR is operated from 2016 to 2056 and finally closed in 2062 (Section 3.8). Account is taken for decay of radionuclides.
	1.1.04	Construction	Included	DGR is constructed as described in Hatch (2008).
	1.1.05	Operation	Included	DGR is operated as described in Hatch (2008).
	1.1.06	Waste allocation	Included	LLW and ILW wastes are disposed in separate emplacement rooms that are laid out in the configuration describe in Section 4.2.1.
	1.1.07	Repository closure	Included	Closure of the DGR 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 to be undertaken under OPG's quality assurance programme.
	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. If they were to occur, then they would be mitigated before the repository was closed.
	1.1.11	Retrievability	Excluded	No retrieval-specific features are included in the DGR design that could impact the long-term safety of the repository, although it is noted that the absence of backfill in the repository rooms and tunnels would simplify retrieval operations.
	1.1.12	Repository records and markers	Included	Any repository records are effectively maintained for 300 years following DGR closure (Section 3.8).
	1.1.13	Monitoring	Excluded	Monitoring during and after closure is carried out such 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 tectonic plate margins with no tectonic activity over the timescales of interest (Section 4.3).
	1.2.02	Orogeny	Excluded	No orogenic activity over the timescales of interest due to the site's location (Section 4.3).

	External FEP	Status*	Comment
1.2.03	Seismicity	Included	Earthquakes will occur over the timescales of interest. 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 4.3.4).
1.2.04	Volcanic and magmatic activity	Excluded	No volcanic or magmatic activity over the timescales of interest due to the site's location (Section 4.3).
1.2.05	Metamorphism	Excluded	No processes occur over the timescales of interest that will cause metamorphism (Section 4.3).
1.2.06	Hydrothermal activity	Excluded	Site is geologically stable and no drivers of hydrothermal activity are present over the timescales of interest (Section 4.3).
1.2.07	Denudation and deposition (large-scale)	Excluded	It is unlikely that large-scale denudation or deposition will occur over the timescales of interest due to low relief topography and low elevation relative to sea level. There is no direct evidence of significant erosion in the past one million years. Small-scale (a few tens of metres) sediment/rock erosion and deposition are likely to occur due hydrological and ice-sheet processes.
1.2.08	Diagenesis	Excluded	Diagenesis that would have an effect on repository safety is unlikely over the timescales of interest.
1.2.09	Pedogenesis	Included	Ice-sheet advance and retreat associated with glacial /interglacial cycling will result in removal and formation of soils over the timescales of interest. The development of soils can impact the nature of plants established in the soils and the uptake of radionuclides by the plants.
1.2.10	Salt diapirism and dissolution	Excluded	No salt deposits are located in the immediate vicinity of the site (Section 4.3). 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	Excluded	Although hydrological/hydrogeological changes will occur, these will be driven by climate change (see 1.3.07) rather than geological change.
1.2.12	Geomorphologic response to geological changes	Excluded	Although geomorphologic changes will occur, these will be driven by climate change (see 1.3.10) rather than geological change.

External FEP			Status*	Comment
	1.2.13	Deformation (elastic, plastic or brittle)	Included	Although deformation due to tectonic movement and orogeny is unlikely over the timescales of interest due to the site's tectonically stable location, deformation due to loading from ice-sheets is likely. Peltier (2008) has estimated that the peak pressure resulting from an ice-sheet over the site might reach 25 MPa and the associated maximum crustal depressions might be in excess of 500 m. An initial assessment of the geomechanical response to ice-sheet loading has identified its potential to cause rockfall in the repository excavations (Damjanac 2008).
1.3	Climate Processes and Effects			
	1.3.01	Global climate change	Included	After an initial period of human-induced global warming, it is likely that Quaternary glacial/interglacial cycling continues (see Section 6.3 of System and its Evolution report, Little et al. 2009).
	1.3.02	Regional and local climate change	Included	Regional/local climate responds to global climate change resulting in continuation of glacial/interglacial cycling on regional/local scale after initial period of human-induced global warming (see Section 6.3 of System and its Evolution report, Little et al. 2009).
	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	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 (see Section 6.3 of System and its Evolution report, Little et al. 2009).
	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 1.3.07), ecosystems (see 1.3.08), human behaviour (see 1.3.09), and surface topography (see 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. Initial period of human-induced global warming will not result in extreme temperature rise resulting in tropical or desert conditions.

	External FEP		Status*	Comment
	1.3.07	Hydrological response to climate changes	Included	Glacial/interglacial cycling impacts on the hydrological conditions in the Superficial and Shallow Bedrock Groundwater Zones. It is very unlikely that previous glaciations had any significant impact on groundwater flow in the Intermediate and Deep Bedrock Groundwater Zones. Key responses are: permafrost formation (but only tens of metres), short-lived meltwater events (which may intrude into the Shallow Bedrock Groundwater Zone and have geochemical consequences) and the formation of a major proglacial lake over the site during ice-sheet retreat (see Section 6.3 of System and its Evolution report, Little et al. 2009).
	1.3.08	Ecological response to climate changes	Included	Flora and fauna at the site change in response to glacial/interglacial cycling (see Section 6.3 of System and its Evolution report, Little et al. 2009).
	1.3.09	Human behavioural response to climate changes	Included	Human behaviour changes in response to glacial/interglacial cycling (see Section 6.3 of System and its Evolution report, Little et al. 2009).
	1.3.10	Geomorphologic response to climate changes	Included	Glaciation results in significant changes to the present-day landforms found at the site (see Section 6.3 of System and its Evolution report, Little et al. 2009).
1.4	Future Human Actions (Active)			
	1.4.01	Human influences on climate	Included	Global warming is likely to delay the onset of the next glacial event that affects the site (see Section 6.3 of System and its Evolution report, Little et al. 2009).
	1.4.02	Social and institutional developments	Included	Repository controls on the development of the site, and societal memory, 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 1.4.08).
	1.4.03	Knowledge and motivational issues (repository)	Excluded	Inadvertent human intrusion into the DGR is unlikely due to its depth and the lack of resources at the site.

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 likely over the assessment timescale since such wells currently exist in the region around the site (Section4.4.4) (see also 1.4.10). The drilling of deep exploration boreholes at the site that penetrate to the depth of the repository is unlikely. The depth (680 m below ground surface) and relatively small footprint of the DGR will mean that the probability of such a borehole intruding into an emplacement room would be very low (5 x 10^{-6} a^{-1}, taking a rate of occurrence of 10^{-10} m^{-2} a^{-1} - Gierszewski et al. 2004, and an emplacement room area of 5.2 x 10^4 m^2 – Walke et al. 2009b).
1.4.05	Mining and other underground activities	Excluded	No mining since no economically viable mineral resources at site. Other underground activities are unlikely at site because the geology is uniform across a large area and so there is nothing unique at this site.
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.
1.4.08	Site development	Included	Site land use changes are likely, once controls are no longer effective (see also 1.4.02). Land uses in the previously controlled area are likely to become consistent with the wider region. In turn, this is likely to be consistent with the land uses currently found in the area surrounding the Bruce 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.
1.4.10	Water management (groundwater and surface water)	Included	The drilling of shallow water wells in the area is likely over the assessment timescale once controls are no longer effective (see also 1.4.04). Wells in the deeper groundwater zones are very unlikely since the groundwater in these zones is not potable (Section 4.3.3). There is present-day abstraction of groundwater in the area from the Shallow Bedrock Groundwater Zone for domestic and agricultural purposes (Section 4.4.6). Lake Huron could also be used as a source of water.
1.4.11	Explosions and crashes	Excluded	Surface explosions and crashes would have no direct impact on repository safety due to depth of repository. Postclosure explosions in the repository are unlikely due to absence of an ignition source and oxygen.

		External FEP	Status*	Comment
	1.4.12	Pollution	Excluded	Impact of surface contaminants on the wastes disposed in the DGR is likely to be insignificant because of the repository depth and buffering capacity of the rocks above the repository.
	1.4.13	Remedial actions	Excluded	Remedial actions are unlikely following closure of repository, and if they occurred, 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 by assessment context (Section 3.4.2) consistent with recommendations of ICRP (2000).
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 repository footprint) and low consequence (due to depth of repository).
	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 considered. General characteristics of biota are assumed to remain similar to current biota.

* 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.

From analysis of the External FEPs in Table 5-2, it can be seen that the repository itself is largely unaffected by External FEPs due to its depth (680 m below the ground surface). Although the effects of climate change resulting from continuing glacial/interglacial cycling are likely to cause major changes in the surface and near-surface environment (see below), the DGR 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/interglacial cycles that have affected the Bruce site in the last one million years. For example, geochemical data indicate that brines in the Deep and Intermediate Bedrock Groundwater Zones are ancient and that glacial meltwaters have not penetrated to depths >130 m (Hobbs et al. 2008). In addition, results of transient palaeoclimate groundwater flow simulations undertaken by Sykes et al. (2008) for the Laurentide glacial episode (~120,000 to 10,000 years BP) showed that heads in the Ordovician and Cambrian formations were little affected by Laurentide glacial loading and unloading.

The analysis of the External FEPs does, however, show that the DGR might be impacted by two External FEPs:

- the occurrence of earthquakes (FEP 1.2.03) potentially resulting in rockfall in the repository and a reduction of the performance of the shaft sealing materials; and
- the loading and unloading of ice-sheets (FEP 1.2.13) potentially resulting a reduction of the performance of the shaft sealing materials.

In terms of evolution of the surface and near-surface system, three groupings of External FEPs are significant:

- global climate change resulting from continuing glacial/interglacial cycling (FEPs 1.3.01, 1.3.02, 1.3.04, 1.3.04, 1.3.07, 1.3.08, 1.3.09, 1.3.10 and 1.2.09);
- 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 site (FEP 1.4.02), and associated drilling, site development and water management (FEPs 1.4.04, 1.4.08 and 1.4.10).

5.1.2 Description

From consideration of the above External FEPs and the Internal FEPs discussed in the FEP report (Garisto et al. 2009), the following high-level narrative of the expected evolution of the DGR system can be developed and used to inform the subsequent development of conceptual models for assessment.

During the first several years following closure, conditions in the sealed repository become anaerobic, owing to corrosion of metals and degradation of organic materials in the wastes. Subsequent slow anaerobic degradation of the wastes and packaging materials in the DGR results in the generation of gases (predominantly CO_2, CH_4 and H_2). The gas pressure rises to a level determined by the gas generation rate, the slow rate of gas migration into the host rock and shaft seals, the repository (gas) headspace, and the gas reactions with minerals and microbes within and around the repository. The formation of a free gas phase delays full saturation of the facility, as does the low permeability of the host rock. The timing of resaturation is slow but uncertain, as it is the net effect of several interacting processes.

Most of the containers (and overpacks) are not long-lived, and will allow groundwater to contact the wastes as the repository resaturates. They may however continue to provide some physical limitation (e.g., diffusion) or local chemistry control (e.g., alkalinity in cement containers) that inhibits the release of contaminants, especially the retube waste containers.

Contaminants are released from the waste due to the generation of gases and due to contact with groundwater. The rate varies with the type of wastes, with the longer-lived ILW Zircaloy pressure tubes corroding more slowly than the other waste streams (the pressure tubes contain most of the long-lived Zr-93). Once in gas or groundwater in the repository, the contaminants are contained by the low-permeability shaft seals and host rock.

Although the rocks are expected to be quite sturdy around the emplacement rooms (which will not be backfilled), it is expected that some rockfall from the ceilings of the repository rooms and tunnels will occur periodically, due to eventual degradion of engineered rock support and possibly due to seismic and/or glacial events (Damjanac 2008). This process will continue intermittently, over periods of tens of thousands of years, until the volume of collapsed rock has increased sufficiently to support the roof of the void.

Radionuclides decay within the repository and the surrounding rock. However, slow migration of some dissolved or gaseous contaminants will occur via the geosphere above the repository and the sealed repository shafts. Some contaminants may eventually (after tens or hundreds of thousands of years) discharge to the shallow groundwater system, and then to the biosphere.

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 is likely to delay the onset of the next ice-sheet advance and to curtail its duration, it is likely that glacial/interglacial cycling will resume in the long term and therefore it is necessary to consider its 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 around 120,000 years (Peltier 2008). A stylised climate sequence for the Normal Evolution Scenario has been identified and considered based on the results of the University of Toronto Glacial Systems Model (Peltier 2008) and is reproduced in Figure 5-2 and Figure 5-3 (Little et al. 2009).

The impacts of glacial/interglacial cycles in the Deep and Intermediate Bedrock Groundwater Zones are expected to be limited to changes in the stress regime resulting from ice-sheet loading and unloading which might result in rockfall in the repository (which might also result from seismic activity). The expected stable geological environment, even under conditions of ice-sheet loading and unloading, is expected to limit the degradation of the shaft seals.

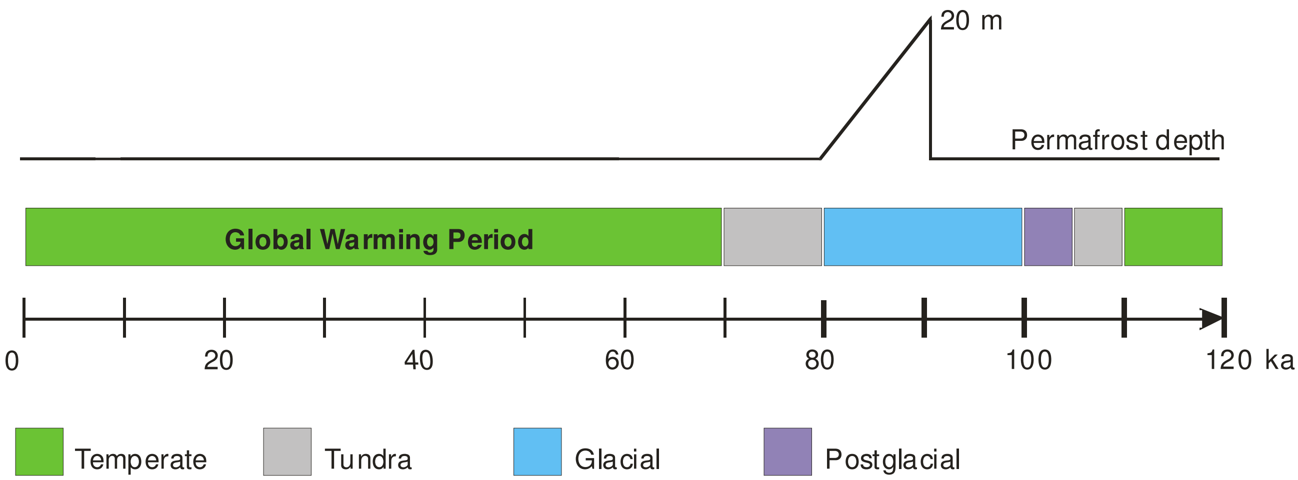


Figure 5-2: Sequence of Climate States for the Next 120,000 years for the Normal Evolution Scenario

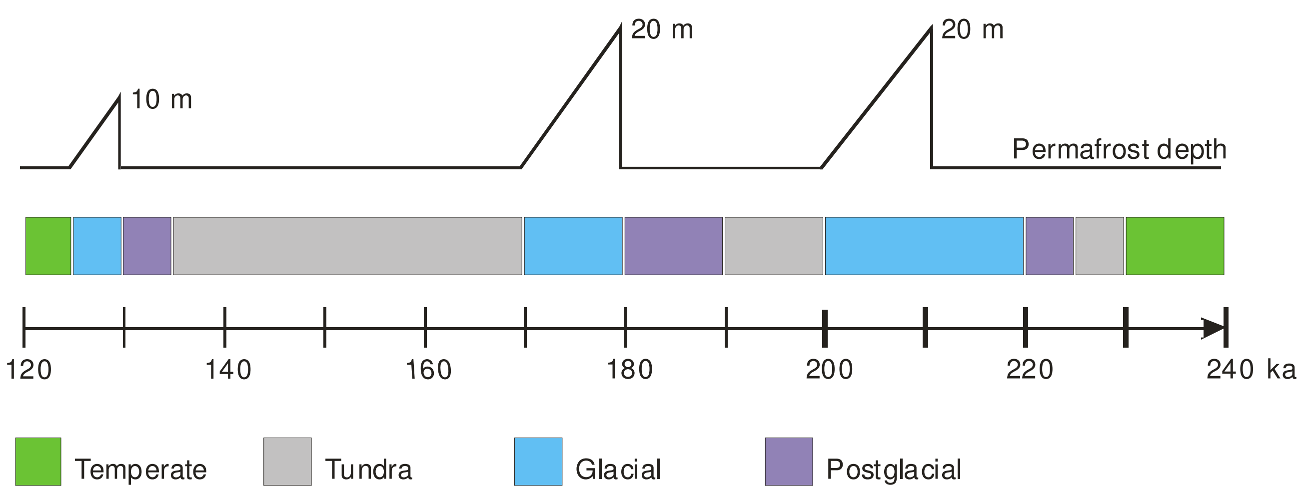


Figure 5-3: Sequence of Climate States from 120,000 years to 240,000 years for the Normal Evolution Scenario (this sequence is assumed to repeat indefinitely)

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 be in a temperate climate and ecosystem. As climatic conditions cool in the long term, ecosystems are expected to change from temperate to tundra. Agriculture and forestry becomes less viable, although small centres of human population may continue based on external supplies of food and energy or by hunting, fishing and trapping, much as is observed in present-day tundra communities. 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. The warming of the climate following ice-sheet retreat can result in re-establishment of tundra and potentially temperate ecosystems and the 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, and the formation of soils).

In the long term, the underground repository will likely develop into a state of porous limestone rock containing magnetite, siderite and other mineral degradation products of the wastes and their packaging, partially saturated with brine and containing predominantly methane gas. Eventually the repository will fully resaturate, potentially over the timescale of millions of years.

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 DGR's isolation or containment and associated safety arguments. The various External FEPs that might compromise these safety functions and associated arguments are listed and screened in Table 5-3 to identify those that need to be considered further. The identified failure mechanisms can be grouped into four Disruptive Scenarios as discussed below and summarised in Table 5-4.

The DGR is sited in an area of low resource potential, it has a small footprint, and is at a depth of 680 m. This limits 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 programme[13]. Even this situation has a low probability of occurrence (5×10^{-6} a^{-1}, using a deep borehole drilling rate of 10^{-10} m^{-2} a^{-1} – e.g. resurveying a 10 x 10 km^2 area once every 100 years, Gierszewski et al. 2004, and an emplacement room plan area of around 52,400 m^2 – Walke et al. 2009b). Nevertheless, it is recognised in Table 5-3 that the possibility of inadvertent human intrusion by this method cannot be ruled out once controls over the use of the site are no longer effective and on the long timescales of interest to the safety assessment[14]. Such a borehole would provide an enhanced permeability pathway to surface environment and potential for direct exposure to waste. The scenario that represents these conditions is referred to as the **Human Intrusion Scenario**.

A second scenario category can be determined that is also related to human activities, but in relation to the reliability of the construction and closure of the repository. This can also be used to test or demonstrate the robustness of the DGR design. Specifically, 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. However, it is highly unlikely but not impossible that the materials may not be fabricated or installed appropriately and this may not be detected by the DGR quality control procedures, or the long-term performance of materials may deviate significantly from that expected due to unexpected physical, chemical and/or biological processes. Either situation could result in an enhanced permeability pathway to the surface environment. The shaft seals are the most important, so a "what if" scenario is considered in which the materials have the properties of engineered fill (crushed rock), and is referred to as the **Severe Shaft Seal Failure Scenario**.

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[13] Deliberate human intrusion is excluded by the assessment context (Section 3.3).

[14] 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 lack of interesting minerals or geologic features in the area would argue against deliberate surveys of the area. Furthermore, it is likely that a cautious approach to drilling would be used if such anomalies were identified, which would minimise the consequences of any intrusion into the DGR.

Table 5-3: External FEPs Potentially Compromising DGR Isolation and Containment

Safety Argument	Potentially compromised by	Need to consider as failure mechanism
The location of the DGR at a depth of 680 m underground, absence of economically viable natural resources, and no drinking water below 100 m provide excellent isolation from the biosphere	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 (due to relatively small repository footprint) and low consequence (due to depth of repository).
	Exploration borehole penetrates into repository providing enhanced permeability pathway to surface environment (FEP 1.4.03 and 1.4.04).	**Yes**, although the depth and relatively small footprint of the DGR means that the annual probability of such a borehole intruding into the DGR will be very low.
	Mining and other underground activities resulting excavation in the vicinity of the repository (FEP 1.4.05).	**No**, due to absence of economic resources at or below repository level.
	Deliberate human intrusion into repository (FEP 1.4.15).	**No**, assessment context (Section 3.4.2 of Quintessa et al. 2009) excludes deliberate human intrusion consistent with recommendations of ICRP (2000).
	Could discover previously undiscovered resources or exploit existing rocks that have become an economically 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 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).
The host rock is old, stable and predictable	High magnitude seismic event results in reactivation of undetected fault and/or failure of shaft seals which provides enhanced permeability pathway to surface environment (FEP 1.2.03).	**Yes**. Technical work is currently being undertaken to evaluate the potential of seismic events on the DGR system. Ahead of the results of this work, it is prudent to consider seismic events as a potential failure mechanism.
	Other external geological processes disrupts 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).

Safety Argument	Potentially compromised by	Need to consider as failure mechanism
The host rock provides multiple thick low-permeability sedimentary rock barriers	An enhanced permeability pathway is introduced through the sequence of rocks by natural processes (seismicity – FEP 1.2.03) or human-induced processes (drilling activities – FEP 1.4.04).	**Yes**, see discussion of seismic events and drilling activities above.
	Glacial erosion resulting from climate change removes significant thickness of rock above repository (FEP 1.2.07, 1.3.01, 1.3.02, 1.3.05).	**No**. No evidence from site investigation of significant erosion in the past million years. Low relief topography and low elevation relative to sea level is expected to limit scope for significant erosion.
	Glacial meltwater penetrates into the Deep and Intermediate Bedrock Groundwater Zones and affects transport in these zones through the introduction of fresh aerobic water (FEP 1.3.07).	**No**. No evidence from site investigation of meltwater from previous glaciations penetrating the Deep and Intermediate Bedrock Groundwater Zones due to their low permeability and the relatively high permeability of the Shallow Bedrock Groundwater Zone.
Mass transport is diffusion-dominated at the repository horizon	Glacial meltwater penetrates into the Deep and Intermediate Bedrock Groundwater Zones and affects flow in these zones (FEP 1.3.07).	**No**. No evidence from site investigation of meltwater from previous glaciations affecting flow in the Deep and Intermediate Bedrock Groundwater Zones due to their low permeability and the relatively high permeability of the Shallow Bedrock Groundwater Zone.
	Glacial erosion resulting from climate change removes significant thickness of rock above 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**. No evidence from site investigation of significant erosion in the past million years. Low relief topography and low elevation relative to sea level is expected to limit scope for significant erosion.
Hydrogeochemical conditions limit contaminant mobility at the repository horizon	Glacial meltwater penetrates into the Deep and Intermediate Bedrock Groundwater Zones and modifies hydrogeochemical conditions in these zones (FEP 1.3.07).	**No**. No evidence from site investigation of meltwater from previous glaciations affecting flow in the Deep and Intermediate Bedrock Groundwater Zones due to their low permeability and the relatively high permeability of the Shallow Bedrock Groundwater Zone.
	Glacial erosion resulting from climate change removes significant thickness of rock above repository and modifies hydrogeochemical conditions around the DGR (FEP 1.2.07, 1.3.01, 1.3.02, 1.3.05).	**No**. No evidence from site investigation of significant erosion in the past million years. Low relief topography and low elevation relative to sea level is expected to limit scope for significant erosion.

Safety Argument	Potentially compromised by	Need to consider as failure mechanism
The geological setting is seismically quiet	High magnitude seismic event results in reactivation of undetected fault and/or failure of shaft seals which provides enhanced permeability pathway to surface environment (FEP 1.2.03).	**Yes**. Technical work is currently being undertaken to evaluate the potential of seismic events on the DGR system. Ahead of the results of this work, it is prudent to consider seismic events as a potential failure mechanism.
The groundwater domain at the repository horizon is resilient to natural external perturbations such as glaciation	Glacial meltwater penetrates into the Deep and Intermediate Bedrock Groundwater Zones and affects transport in these zones through the introduction of fresh aerobic water (FEP 1.3.07).	**No**. No evidence from site investigation of meltwater from previous glaciations affecting flow in the Deep and Intermediate Bedrock Groundwater Zones due to their low permeability and the relatively high permeability of the Shallow Bedrock Groundwater Zone.
	Glacial loading/unloading results in reactivation of fault and/or failure of shaft seals which provides enhanced permeability pathway to surface environment (FEP 1.2.11 and 1.2.13).	**Yes**. Technical work is currently being undertaken to evaluate the potential of glacial loading/unloading on the DGR system. Ahead of the results of this work, it is prudent to consider glacial loading/ unloading as a potential failure mechanism.
	Glacial erosion resulting from climate change removes significant thickness of rock above repository (FEP 1.2.07, 1.3.01, 1.3.02, 1.3.05).	**No**. No evidence from site investigation of significant erosion in the past million years. Low relief topography and low elevation relative to sea level is expected to limit scope for significant erosion.
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, i.e., poorly constructed shaft (FEP 1.1.04), poorly sealed shaft (FEP 1.1.07), or future exploration borehole (FEP 1.4.04). An enhanced permeability pathway via DGR site investigation borehole (FEP 1.1.01) or fault (FEP 1.2.03) is not considered since such a borehole or fault will not penetrate the DGR.	**Yes**, although application of OPG's quality control will ensure that poor construction and sealing is very unlikely, and the depth and relatively small footprint of the DGR means that the annual probability of a future exploration borehole intruding into the DGR will be very low.
DGR radioactivity will decrease with time due to radioactive decay	Mechanisms that can compromise the reduction in activity due to radioactive decay.	**No**, since no mechanisms identified.

Safety Argument	Potentially compromised by	Need to consider as failure mechanism
A repository can be built and operated safely using internationally proven and accepted technologies	Poor construction techniques impact on the performance of the repository and shaft EDZ providing enhanced permeability pathway to surface environment (FEP 1.1.04).	**Yes**, although application of OPG's quality control will ensure that poor construction is very unlikely.
	Repository and shaft poorly sealed providing enhanced permeability pathway to surface environment (FEP 1.1.07).	**Yes**, although application of OPG's quality control will ensure that poor sealing is very unlikely. Nevertheless, long-term performance of seals may deviate from that expected due to unexpected processes.
	Site investigation/monitoring borehole not properly sealed providing enhanced permeability pathway to 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. Nevertheless, long-term performance of seals may deviate from that expected due to unexpected processes.

Table 5-4: Potential Failure Mechanisms and Associated Scenarios

Failure Mechanism	Associated Scenario
Site investigation/monitoring borehole not being properly sealed providing enhanced permeability pathway to surface environment	Open Borehole
Poor construction techniques impact on the performance of the shaft seal and shaft EDZ, providing enhanced permeability pathway to surface environment	Bounded by Severe Shaft Seal Failure
Degradation of shaft seals due to some unexpected process results in enhanced permeability pathway to surface.	Severe Shaft Seal Failure
Seismic event or glacial loading/unloading results in reactivation of fault and/or failure of shaft seals which provides enhanced permeability pathway to surface environment	Extreme Earthquake
Exploration borehole penetrates into repository providing enhanced permeability pathway to surface environment and potential for direct exposure to waste	Human Intrusion

Other human activities that could affect repository performance relate to monitoring and site investigation activities around the repository site. Several such boreholes will be sunk in the vicinity of the DGR down to and beyond the depth of the DGR during the site investigation and operational phases. Some of these may be retained for monitoring during the postclosure period. In all cases, the boreholes will be licensed through the Ontario Ministry of Natural Resources and they will be well outside the repository footprint. Furthermore, they will be sealed on cessation 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, then it could provide a small but permeable pathway for the migration of contaminants from the repository. Like the Severe Shaft Seal Failure Scenario, such a situation would be expected to be very unlikely, as good practice and quality control would prevent such a situation occurring. However, the situation is one of a limited number of potential events that could result in an enhanced permeability pathway to surface environment and therefore merits investigation as a threat to the containment function of the disposal system. The scenario is termed the **Open Borehole Scenario**.

Earthquakes are an external event of potential relevance to postclosure safety. The DGR site is located in a seismically stable region, so large earthquakes are very unlikely and the repository is designed to handle the expected level of earthquakes for the area. However, the assessment timescales are such that, after the repository has been closed, a significant earthquake with a moment magnitude **M** ≥ 6 may occur, even though its annual probability of occurrence within a 20 km radius of the DGR is around 10^{-6} (Atkinson and Martens 2007). Such an earthquake could cause disruption to the repository, reduce the performance of the shaft seals, and reactivate a fault in the vicinity of the DGR. Because the event could have a number of consequences resulting in enhanced permeability pathways to the surface environment, it is useful to assess it as a “what if” scenario, referred to as the **Extreme Earthquake 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 (Section 3) and the system description (given in the System and its Evolution report, Little et al. 2009 and summarised in Section 4), it was possible for it to have one or more alternative states to that considered in the Normal Evolution Scenario. The same set of four additional scenarios, identified using the safety argument approach, was identified (see the System and its Evolution report, Little et al. 2009).

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") considered in the postclosure safety assessments of other deep repositories. A review of a number of major assessments of deep repositories in other countries was undertaken. The results of the review are summarised in Table 5-5. 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 5-5 that are not considered in the DGR Disruptive Scenarios, these are either not relevant to the Bruce 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).

Table 5-5: Additional Scenarios Considered in Other Safety Assessments

Assessment	Reference	Additional Scenarios Considered
SAFIR 2 (Belgium)	ONDRAF/NIRAS (2001)	• Exploitation and exploratory drilling • Greenhouse effect • Poor sealing of repository • Fault activation • Severe glacial period • Failure of engineered barriers • Gas-driven transport
TILA-99 (Finland)	Vieno and Nordman (1999)	• Canister failure
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)	JNC (2000)	• Climate and sea level change • Borehole drilling • Engineering defects
SAFE (Sweden)	SKB (2001)	• Climate change • Barrier defects • Borehole drilling
Opalinus (Switzerland)	Nagra (2002)	• Gas pathways • Borehole drilling
GPA (UK)	Nirex (2003)	• Borehole drilling
WIPP (USA)	USDoE (2004)	• Mining • Borehole drilling
Yucca Mountain (USA)	USDoE (2002)	• Borehole drilling • Seismicity • Volcanic event

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 controls are no longer effective.

In this scenario, an exploration borehole is drilled down through the geosphere. Upon encountering the repository, the drilling crew registers a loss of drill fluid to the repository void if the repository pressure is less than the drill fluid pressure, or a surge upwards of gas and/or slurry (water and some suspended waste) if the repository pressure is greater than the drill fluid pressure. Current technology necessary to drill to 680 m depth would enable the drillers to ascertain the nature of the void 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).

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 routine borehole measurement). In this case the investigators would likely choose to close and seal the borehole, and ensure any surface-released materials were appropriately disposed (again, this is normal drilling practice). Sealing the borehole would avoid any further release of residual radioactivity direct to the surface. Under normal drilling, there would be little impact.

Nevertheless, the Human Intrusion Scenario considers the case where the intrusion is inadvertent, is not recognised to have occurred and no restrictions are imposed, and the borehole and drill site are not managed and closed to current standards. In this "what if" case, contaminants can be released and humans and non-human biota exposed via three pathways:

- direct release to the surface of pressurised gas and slurry prior to sealing of the borehole;
- retrieval and examination of core contaminated with waste; and
- the long-term release of contaminated water from the repository into permeable geosphere horizons via the exploration borehole.

These releases would result in the exposure of the drill crew, laboratory technicians (who examine the core), residents living near the site at the time of intrusion, and site residents who might occupy the site subsequent to the intrusion event.

5.2.2.2 Severe Shaft Seal Failure Scenario

The Shaft Seal Failure Scenario considers the same evolution of the DGR system and the same exposure pathways and groups as the Normal Evolution Scenario, the only difference being that the performance of the shaft seals and shaft EDZs is very poor (e.g., the shaft seals have the hydraulic characteristics of engineered fill/crushed rock). In particular, it is assumed that the shaft seals and the shaft EDZs have pessimistic physical and chemical properties from the time of closure of the repository. 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 Open Borehole Scenario

The evolution of the system considered for the Open Borehole Scenario is similar to the Normal Evolution Scenario with the key difference being that an improperly sealed site investigation/ monitoring borehole provides an enhanced permeability connection between the level of the repository, the overlying groundwater zones and the biosphere, thereby bypassing part of the natural barrier to contaminant migration from the DGR. The subsequent exposure pathways and groups are the same as those considered in the Normal Evolution Scenario.

5.2.2.4 Extreme Earthquake Scenario

The evolution of the system is similar to the Normal Evolution Scenario, except that an earthquake with a moment magnitude of $\mathbf{M} \geq 6$ occurs in the region around the Bruce site at some time following the closure of the repository. The earthquake could cause the reactivation of a fault and/or failure of shaft seals. The impact on the failure of the shaft seals is considered in the Severe Shaft Seal Failure Scenario and so is not considered further under the Extreme Earthquake Scenario. Therefore, the focus of the scenario is on the reactivation of a fault.

Site characterisation and the underground excavations are expected to verify that there is no evidence of significant faults close to the DGR. Furthermore, although substantial earthquakes are plausible over the assessment timeframe, the reactivation of a fault is of extremely low probability on the basis of geological evidence from the Bruce site. Nevertheless, the Extreme Earthquake Scenario considers the hypothetical case of “what if” a vertical fault in the vicinity of the repository and extending from the Cambrian into the Shallow Bedrock Groundwater Zone is reactivated by an earthquake. Such a fault could provide an enhanced permeability connection between the geosphere at the level of the repository, the overlying groundwater zones and the biosphere, thereby bypassing part of the natural barrier to contaminant migration from the DGR. The subsequent exposure pathways and groups are the same as those considered in the Normal Evolution Scenario.

6. ASSESSMENT MODELS

6.1 MODEL DEVELOPMENT APPROACH

The approached used for the development of conceptual and mathematical models and their implementation in the software tool used to assessment impacts is illustrated in Figure 6-1 and described below.

First, a conceptual model is developed for each scenario using input from the assessment context (Section 3), the system description (Section 4), the DGR FEP list (Garisto et al. 2009), and the scenarios for assessment (Section 5). 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. These features, events and processes are audited against the DGR FEP list to ensure that important issues have not been neglected in the conceptual models.

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 parameter 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 parameter uncertainties identified.

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

Learning from analysis of the implemented mathematical model may cause changes in understanding regarding the formulation of the conceptual model. In particular, the results of detailed gas and groundwater modelling can be used to inform the development of the conceptual model to evaluate in the assessment-level modelling. Therefore, there is a process of feedback to the conceptual models, once the detailed mathematical models have been implemented and analysed. The finalised conceptual model is a result of this iteration and feedback.

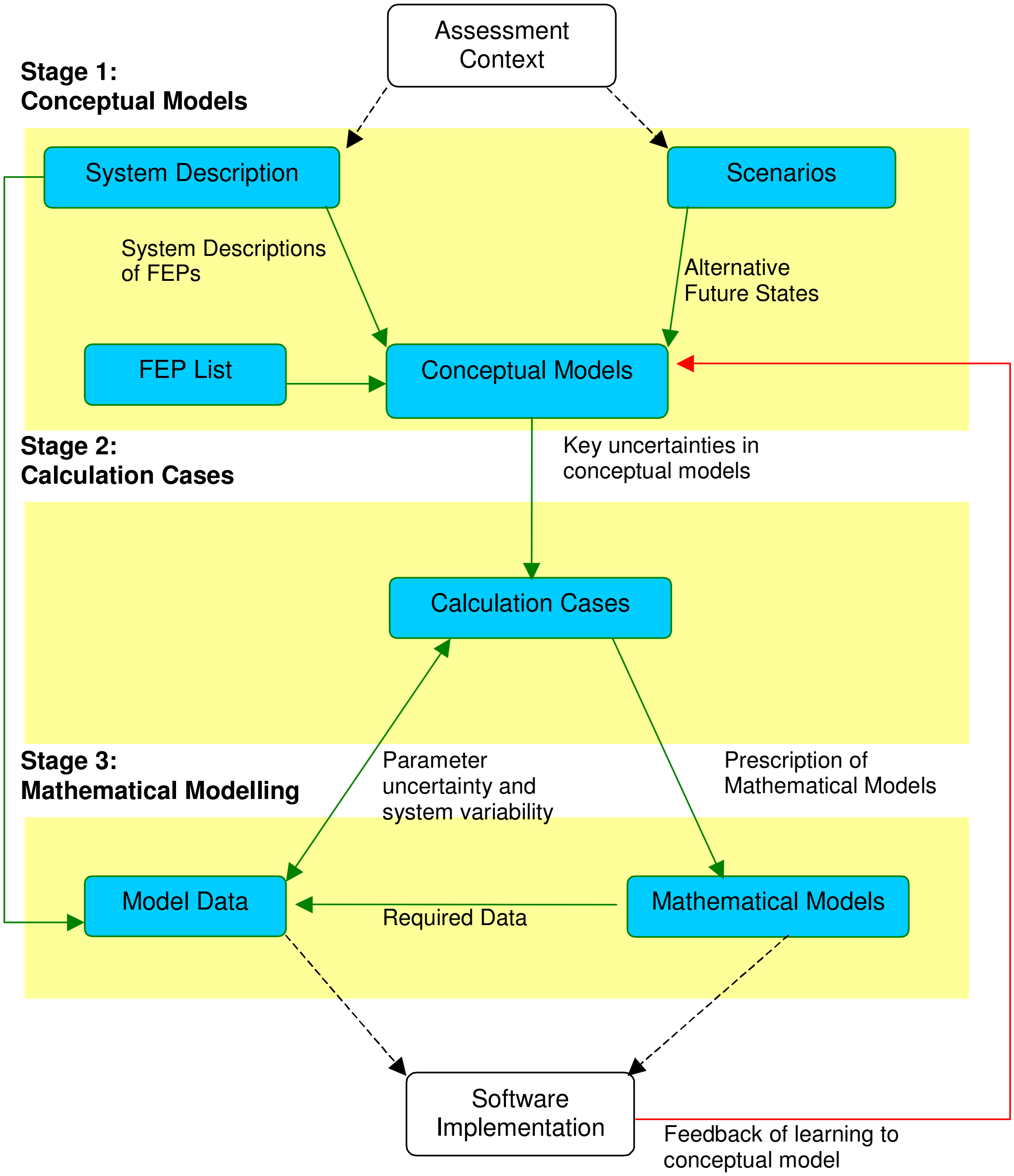

Figure 6-1: Model Development Approach

6.2 CONCEPTUAL MODELS

6.2.1 Normal Evolution Scenario

Figure 6-2, Figure 6-3 and Box 1 summarise the main aspects of the conceptual model for the Normal Evolution Scenario; a more detailed summary is given below based on the detailed description given in the Normal Evolution Scenario Analysis report (Walke et al. 2009a).

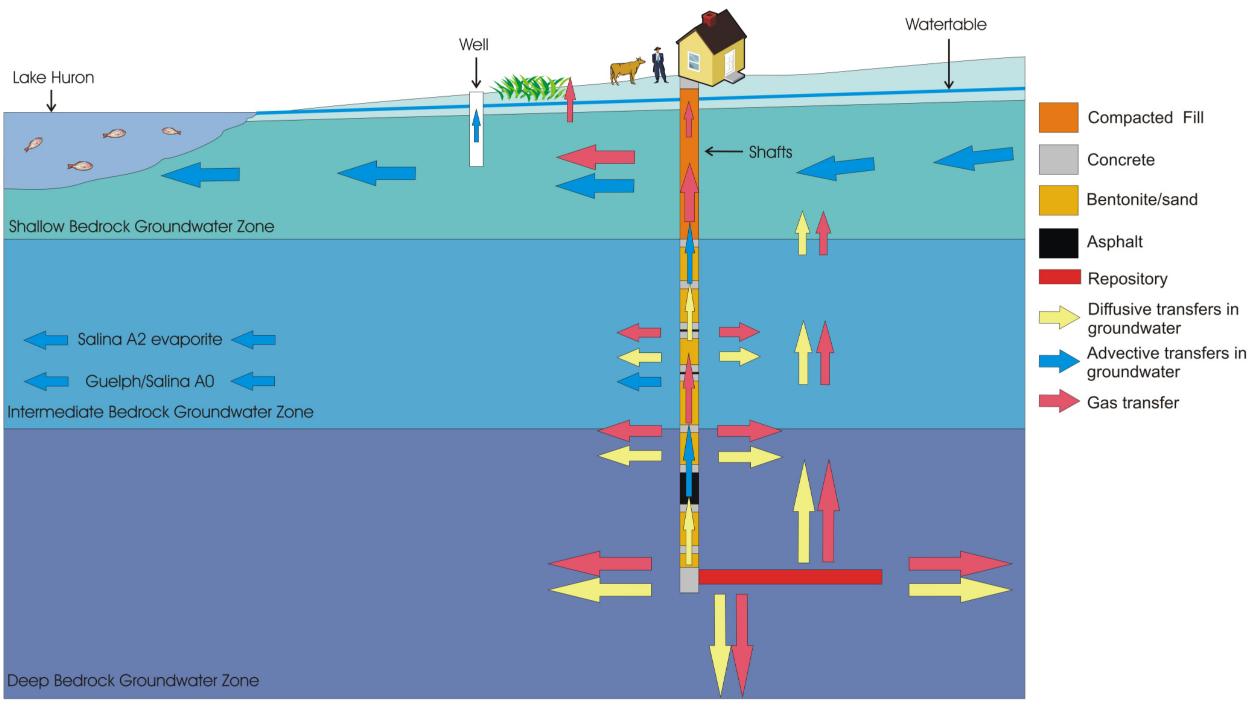

Figure 6-2: Schematic Representation of Potential Transport Pathways for the Normal Evolution Scenario

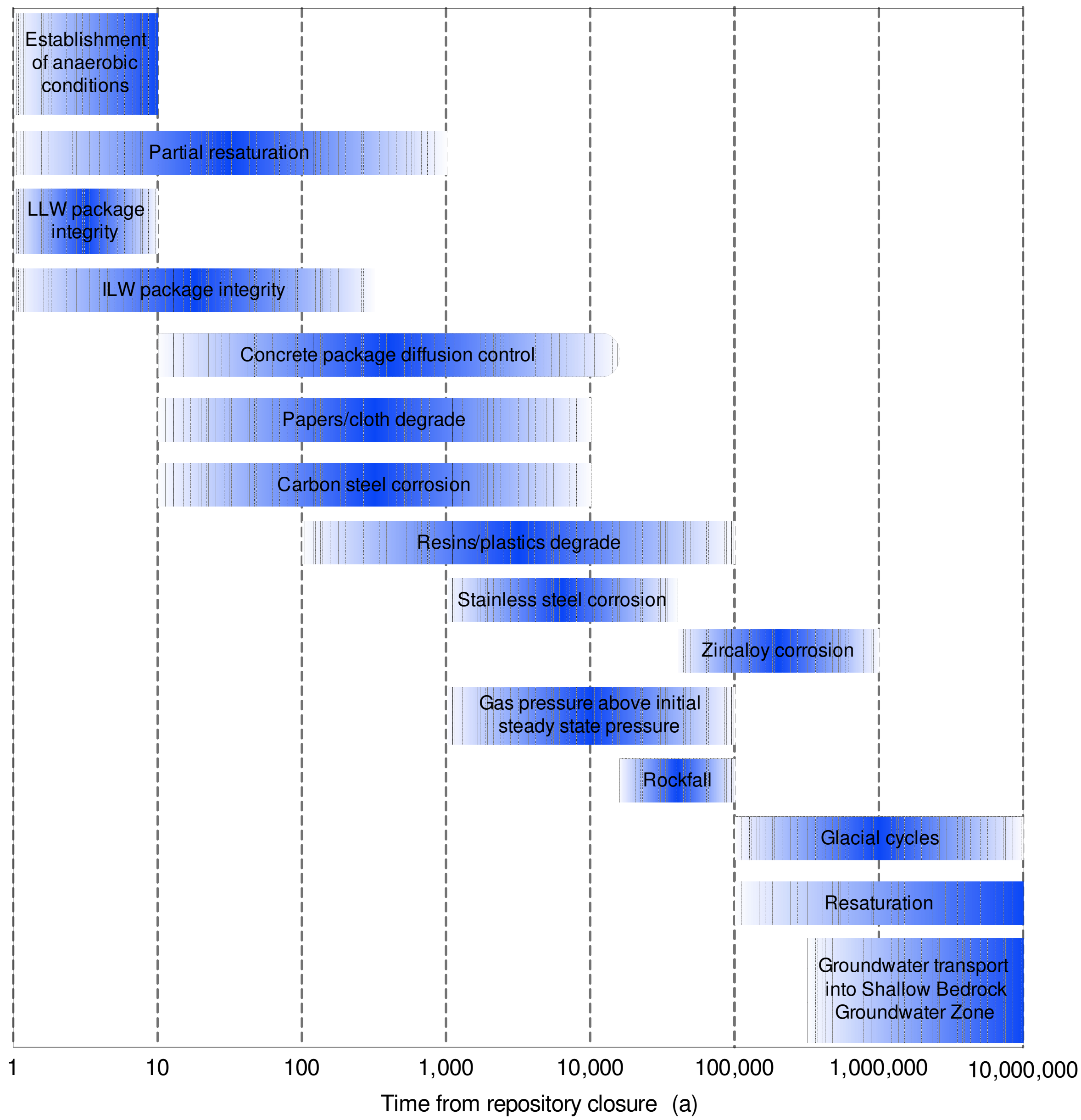

Figure 6-3: Timeframes for Key Processes considered in the Normal Evolution Scenario

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

Waste and Repository:

- Reference waste inventory of 196,000 m^3 (disposed volume) and reference waste concentrations.
- Reference repository design with no backfill (except for the concrete monoliths at the base of the shafts and the overlying shaft seals).
- Contaminants released into water via instant, diffusive and congruent release processes (Table 6-1).
- C-14, Cl-36, Se-79, and I-129 also enter the gas phase as a result of metal corrosion, organic degradation, and/or volatilisation (see Section 6.2.1.1).
- Resaturation of repository determined by water inflow/outflow rate, gas generation rate and gas pressure (see Section 6.2.1.1).
- Sorption of some contaminants on concrete monoliths.
- Contaminants may migrate into the host rock and shafts by diffusion or advection (driven by the pressure head in the Cambrian)[15], or by gas permeation (driven by repository gas pressure relative to the porewater pressure) or by gas dissolution into groundwater[16].
- Rockfall from roof occurs progressively until a stable equilibrium is reached (see Section 6.2.1.1).

Geosphere and Shafts:

- Groundwater flow in the shafts and Deep and Intermediate Bedrock Groundwater Zones is slow but upwards, except in the Guelph, Salina A0 and Salina A2 evaporite Formations in which it is horizontal[15].
- Groundwater flow in the Shallow Bedrock Groundwater Zone is horizontal towards Lake Huron[15].
- Contaminants may migrate through the geosphere by diffusion or advection in groundwater[15] or by gas permeation[16].
- Contaminants may migrate up the shafts by diffusion or advection in groundwater[15] or by gas permeation[16] through the shaft seals or excavation damaged zones (EDZs).
- Sorption in shafts and geosphere for some species.
- Possible release of groundwater contaminants from shaft and intermediate geosphere into the Shallow Bedrock Groundwater Zone.
- Possible release of gas containing C-14 from repository to surface via the shafts and geosphere considered (see Section 6.2.1.1).

Biosphere:

- 300 year site control period (see Section 3.8).
- Constant temperate climate conditions (see Section 6.2.1.3).
- The Shallow Bedrock Groundwater Zone discharges into the near shore lake bed sediments, whilst the Guelph, Salina A0 and Salina A2 evaporite Formations discharge further away under Lake Huron (see Section 6.2.1.3).
- Possible release of gaseous contaminants from shaft and geosphere to house and soil due to gas permeation for certain calculation cases and volatilisation from groundwater with subsequent atmospheric dispersion of gas (see Section 6.2.1.3).
- Surface media may become contaminated following release of contaminants via borehole, shafts, well and groundwater discharge to lake (see Section 6.2.1.3).
- Potential impacts estimated based on assuming a self-sufficient family farm located on the repository site and using groundwater from well and lake (see Section 6.2.1.3).

[15] Based on findings presented in the Groundwater Modelling Report (Avis et al. 2009).
[16] Based on findings presented in the Gas Modelling Report (Calder et al. 2009).

6.2.1.1 Waste and Repository

Evolution of Repository Conditions

Around 151,000 m^3 of LLW and 45000 m^3 of ILW are emplaced in 45 rooms over the operational lifetime of the DGR (approximately 40 years). Once the repository is sealed, saline groundwater begins to infiltrate into the repository. The rate of inflow, and hence resaturation, is slow due to the low permeability of the host rock. Both the wastes and their packaging degrade under the humid conditions. Initially, corrosion and microbial degradation[17] consume oxygen and the chemical conditions in the repository rapidly become anaerobic.

Under anaerobic conditions, metallic wastes and packaging corrode, generating H_2 gas as a by-product. Organic materials are subject to microbial degradation resulting in part in the generation of CO_2 and CH_4. CO_2 formed from degradation of organics is microbially metabolised to CH_4 by reaction with H_2 gas. It also reacts with water and iron to form siderite ($FeCO_3$) and H_2 gas.

The gases generated mix by diffusion throughout the repository. This process is rapid compared with the assessment timescales.

The waste packages (i.e., wastes, containers and any overpacks) in the repository degrade at differing rates due to corrosion and microbial degradation. The carbon steel packaging degrades on timescales of decades to hundreds of years (under anaerobic conditions), while other packaging (i.e., those with stainless steel or concrete overpacks) might take longer. Some corrosion resistant wasteforms such as Zircaloy degrade very slowly, over a million-year timescale.

As the wastes and their packaging corrode and degrade, the gas pressure inside the repository begins to rise (Figure 6-4), with the rate of increase dependent on:

- the rate of gas generation through the degradation of wastes and packaging;
- the rate of loss of gas from the repository by transport or reaction; and
- the available gas headspace in the repository (depending on the water level in the repository).

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[17] 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 (Stroes-Gascoyne and Hamon 2007). Nevertheless, the Version 1 SA assumes that the microbial waste degradation occurs regardless the amount of the microbes in the repository.

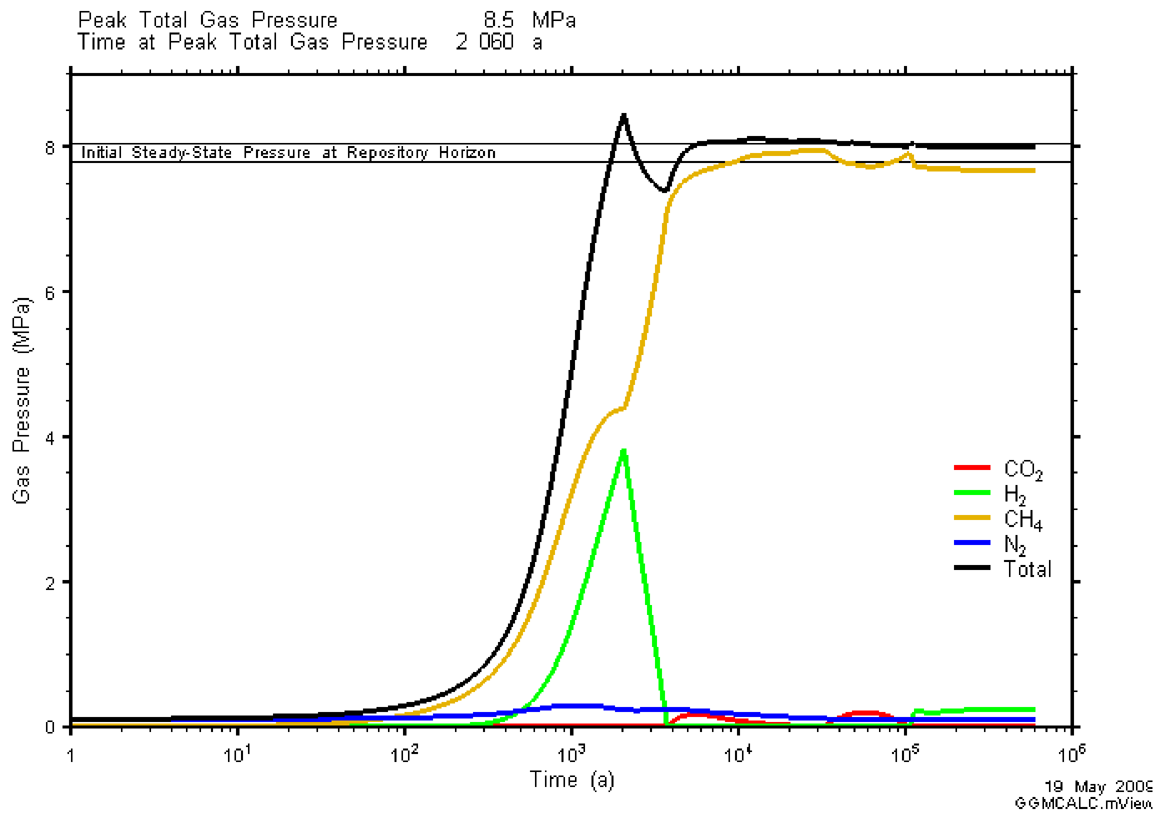


Figure 6-4: Repository Gas Pressures from the T2GGM Base Case Calculation Case for the Normal Evolution Scenario (Calder et al. 2009)

The bulk gas pressure is important because it affects both the repository resaturation time (and hence the groundwater pathway) and the migration of gaseous radionuclides from the repository. Due to the low permeability and low porosity of the host rock, most of the gases are retained within the repository void space and hence gas pressure in the repository can rise to levels that exceed the initial steady-state pressure of around 7.5 MPa. A peak gas pressure of around 8.5 MPa (much less than the 17 MPa lithostatic pressure and around 1 MPa above the initial steady-state pressure) is reached at around 2000 years for reference conditions. However, the value and timing of the peak pressure depends on the assumed repository and geosphere conditions – see the Gas Modelling report, Calder et al. (2009).

The gas pressure influences the saturation profiles for 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 saturation profile is also affected by water generation/loss resulting from the corrosion/degradation of repository materials, and the characteristics of the host rock (see Gas Modelling report, Calder et al. 2009). The interaction of gas pressures, water generation/loss rates and geosphere characteristics results in the range of saturation profiles. Figure 6-5 shows the water saturation profile for the base case calculation and shows an initial resaturation of the DGR up to 75% at about 1000 years followed by desaturation down to about 20% by 100,000 years, followed by gradual resaturation.

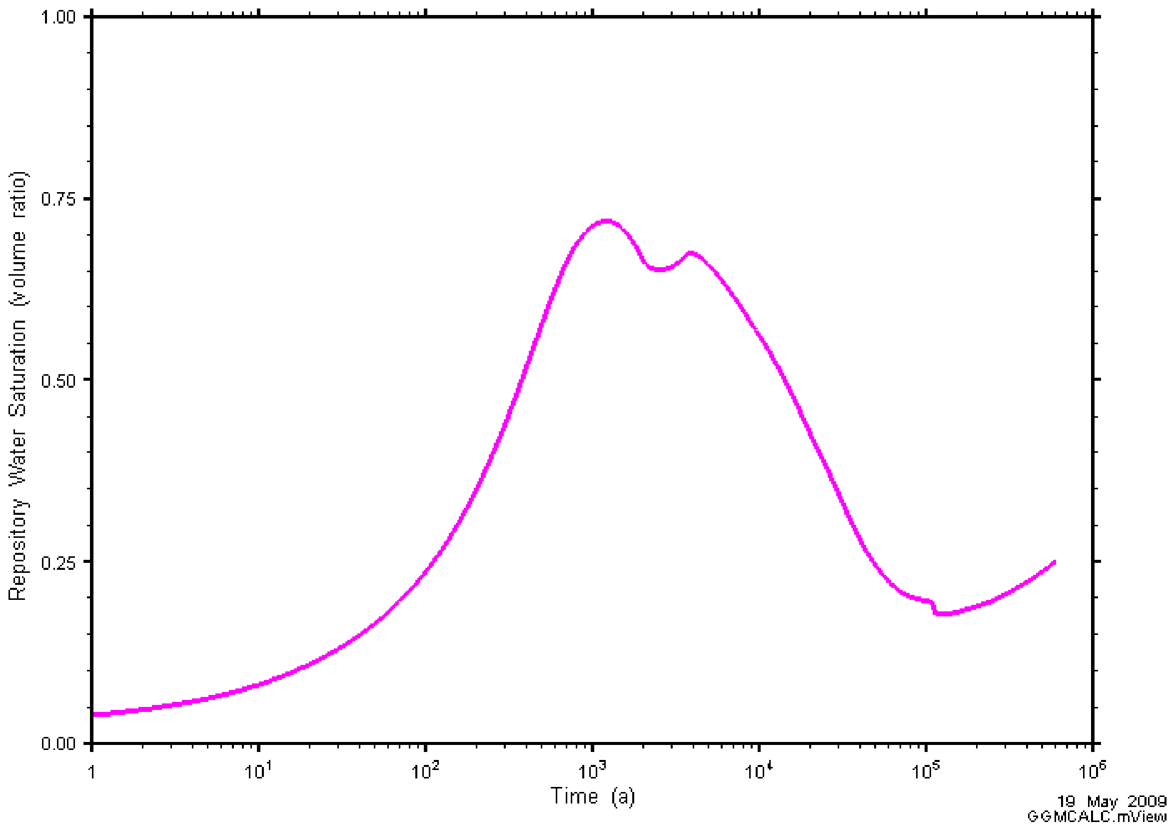


Figure 6-5: Repository Water Saturation Profile from the T2GGM Base Case Calculation for the Normal Evolution Scenario (Calder et al. 2009)

Eventually the gas pressure will fall to a level that allows the ingress of water from the shafts and the geosphere into the repository (around 100,000 years in Figure 6-4 and Figure 6-5) causing the repository eventually to become fully resaturated. The timing of final resaturation is uncertain. Fully coupled modelling of gas generation and resaturation suggests that the DGR might take in excess of a million years to resaturate (Calder et al. 2009) (see Figure 6-5). This long retention of gases within the repository is similar to that observed in natural gas reservoirs in southern Ontario, where a low permeability caprock has maintained significant gas pressures for millions of years even under conditions of glacial loading/unloading.

The quantities of cementitious materials employed in the repository are relatively small (<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.

Some minor localised thermal gradients exist initially due to cement curing (e.g., the concrete monoliths at the base of the shafts) and possibly radiogenic heat, but they are not spatially or temporally extensive. Corrosion of waste metals, and decomposition or degradation of organic materials will be in progress at the time of repository closure and will emit some heat. However, heat production is not expected to have a significant effect on water and gas mixing given the very large thermal sink of the surrounding rock and the limited heating effect (see System and Its Evolution report, Little et al. 2009).

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 glaciations could induce loads on the rock. These events could lead to rockfall in the DGR rooms and tunnels. Geomechanical modelling (Damjanac 2008) suggests that the engineered damage zone will have propagated a distance of 7 m after 15,000 years due to stress relief. Conservatively, the rockfall is taken to occur as soon as EDZ formation is complete. Once a rockfall event has occurred, further stress relief results in the formation of a new EDZ above the rockfall zone. A succession of rockfall events can be envisaged until the rockfall zone becomes self supporting. The maximum extent of rockfall assessed is 20 m for the emplacement rooms and 30 m for the access and ring tunnels, with the rockfall zones modelled as developing stepwise at a rate of 7 m every 15,000 years. Rockfall is cautiously taken to affect all tunnels and rooms (i.e., it is not “patchy”).

Figure 6-6 provides a general illustration of a partially resaturated repository with the lower waste packages standing in water. As the waste packages at the bottom of the stacks degrade there is some slumping of the stacks, although there may not be sufficient space within the emplacement rooms for complete collapse.

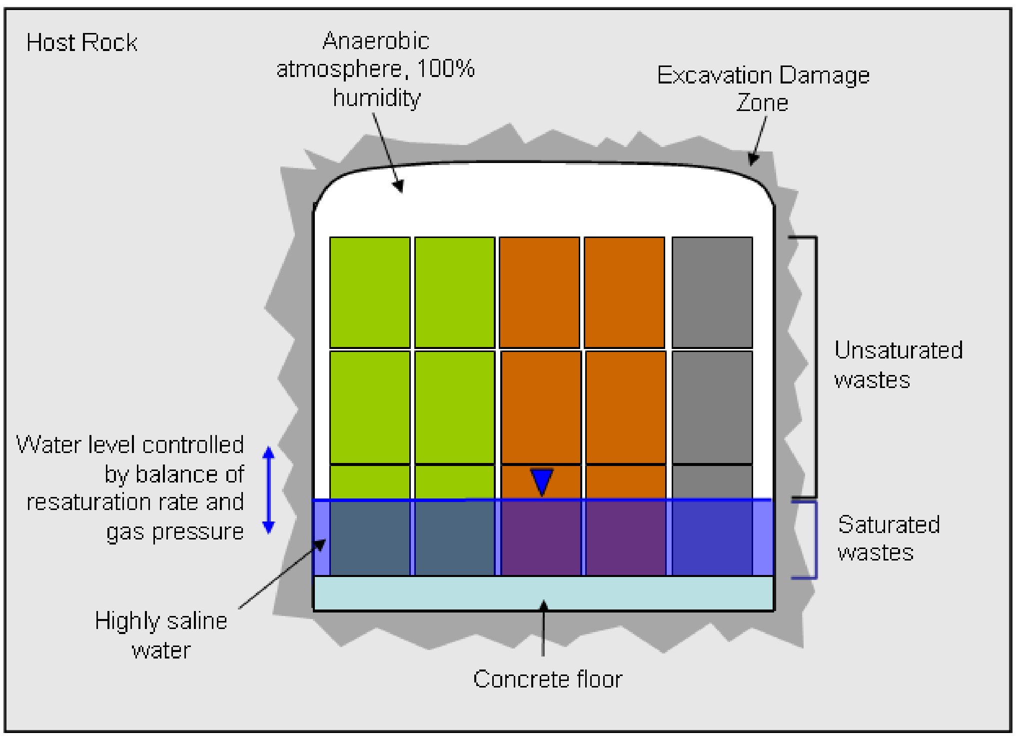


Figure 6-6: General Illustration of Postclosure Conditions in the DGR

Contaminant Releases to Repository Water

Each waste stream is considered individually, in order to capture both its contaminant content and its release processes. Releases to water occur once water in the repository contacts the waste, and so, consistent with the resaturation and package failure history presented above, they are taken to start shortly after repository closure. If the repository partially resaturates, and then subsequently desaturates (as is the case for certain variant cases presented in the gas modelling report, Calder et al. 2009), radionuclides from the wetted waste are still considered to be able to diffuse through the floor of the repository.

The processes considered for releases to water include instant release, congruent release and diffusive release through overpacks. Table 6-1 indicates the release processes to water that are considered for each waste stream.

Table 6-1: Conceptual Models for Contaminant Release to Repository Water

Waste Classification	Waste Categories	Release Model[1]
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
	LLW Resins	Instant
	Steam Generators	Diffusion
	ALW Resins	Instant
	ALW Sludges	Instant
ILW	CANDECON Resins	Diffusion
	Moderator Resins	Diffusion
	PHT Resins	Diffusion
	Miscellaneous Resins	Diffusion
	Irradiated Core Components	Congruent, Diffusion
	Filters and Filter Elements	Diffusion
	IX columns	Diffusion
	Retube Wastes: Calandra Tubes	Congruent, Diffusion
	Retube Wastes: Calandra Tube Inserts	Congruent, Diffusion,
	Retube Wastes: Pressure Tubes	Congruent
	Retube Wastes: End Fittings	Congruent, Diffusion

Note:

(1) See Normal Evolution Scenario Analysis report (Walke et al. 2009a) for details.

The majority of the contaminants associated with the 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 post-closure, for example through corrosion of the carbon steel drums, and because contamination is generally present on the surfaces of the wastes, such that, once it comes into contact with groundwater, it is immediately 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 the System and its Evolution report, Little et al. 2009). For these wastes, the packaging can form a significant barrier to water-waste interaction and contaminant release to repository water. The metal container can prevent any release for a period, until it is breached either as a result of the height of water in repository exceeding the height of the container (most containers are vented or lidded at the top) or failure of the container as a result of corrosion or rockfall, whichever occurs soonest. Once water is able to enter the waste package, contaminant release is controlled by the rate of diffusion through the barrier. Such a process applies to all ILW wastes and also to the LLW steam generators, which will comprise grouted sections. Furthermore, for some of the ILW wastes, the contamination is present in the matrix of the materials in the form of activation products. For these wastes, contaminants only become available for release as the material itself corrodes and dissolves. Such a process is represented with a congruent release model and is relevant to core components and retube wastes.

Gaseous Contaminant Releases

Radioactive trace gases are generated in the form of:

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

Releases of radioactive trace gases from waste packages into the repository can occur under saturated and unsaturated conditions. Furthermore, none of the waste packages are taken to be gas tight (conservative in the case of retube packages which are expected to be gas tight); indeed some of the ILW packages have gas vents to prevent the build up of gases in the packages. Therefore gaseous releases can occur immediately on repository closure, and any losses of gas during storage or waste disposal operations are conservatively neglected. Gaseous radionuclide releases are dependent on the chemical form in which the radionuclides are present.

Given that, even for the most cautious cases, the travel time from the repository to the surface has been calculated to be thousands of years (Calder et al. 2009), any **H-3** decays before reaching the surface and, hence, is not of interest to the Normal Evolution Scenario.

C-14 radiolabelled CO_2 and CH_4 gases are produced through the microbial degradation of both saturated and unsaturated LLW cellulosic & plastic wastes, and ILW resins & filters. C-14 associated with this CO_2 is expected to be subsequently microbially metabolised to CH_4 by reaction with H_2 gas. In addition, C-14 is likely to be released from the saturated metallic wastes as bicarbonate and carbonate ions. C-14 labelled (bi-)carbonate ions will either be trapped in siderite precipitates or microbially mediated to C-14 labelled CH_4.

Cl-36, Se-79 and I-129 can potentially be microbially metabolised forming methylated gases, both within the saturated and unsaturated wastes. However, literature reviewed in Walke et al. (2009a) indicates that methylation and volatilisation of Cl-36 is not likely to be of significance and so is not included in the conceptual model. In the absence of conclusive data, the volatilisation and methylation of Se-79 and I-129 are included in the conceptual model for the current assessment.

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 long (thousands of years - see Gas Modelling report, Calder et al. 2009), such that Rn-222 decays before reaching the surface and so Rn-222 released from the repository is not of interest for the Normal Evolution Scenario.

Migration of Contaminants

The current repository conceptal design has two waste panels joined by connecting access tunnels. The South Panel is for LLW, whereas the East Panel is for ILW and certain bulky LLW

(Section 4.2.2). Any **water** in the repository can mix through diffusion. No credit is taken for the role of the concrete block walls at the ends of the emplacement rooms in limiting water movement since they are not designed to be long-term barriers to groundwater flow and transport.

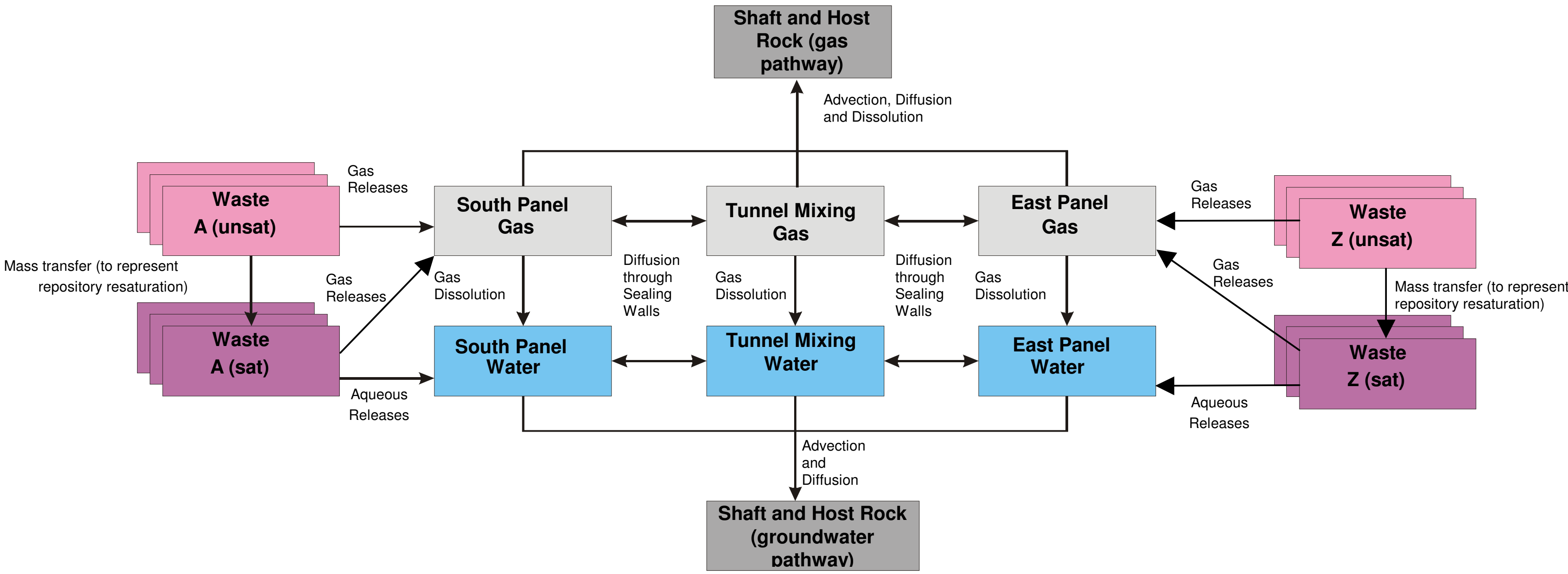
Contaminants can be released from the emplacement rooms and tunnels through dissolution into waters within the repository and subsequent advection/diffusion into the EDZ and then to the geosphere or along the shaft/shaft EDZ. At times when there is no standing water within the repository, there is no release of contaminants into groundwater. When the repository is partially saturated, diffusion of contaminants in groundwater can only occur from the base and part of the sides of the repository. During the period of desaturation of the repository, contaminants in groundwater will be forced from the repository by the enhanced gas pressure.

Radionuclides dissolved in the water may be further retained by sorption and precipitation within the repository. However, the current assessment conservatively neglects sorption in the repository for all elements other than C, Ni, Zr, Nb, U and Np for which minimum credible values for conditions in the repository have been adopted for sorption onto the concrete monoliths and bulkheads (see Appendix A of the Data report, Walke et al. 2009b). It is assumed that no precipitation of elements occurs once they have been released 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 groundwater within the adjacent host rock and subsequent migration away from the repository. Gaseous contaminants can also potentially permeate from the repository into the host rock or shafts as a separate phase (visco-capillary two-phase flow) within the saturated media.

The processes discussed above are illustrated in Figure 6-7, which shows how they apply to and between specific waste and repository components.

Figure 6-7: 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, an EDZ will develop due to mechanical disturbance and relaxation of the rock into the excavations. The hydraulic conductivity within the EDZ is likely to be enhanced by several orders of magnitude (see Data report, Walke et al. 2009b). The shafts' EDZs 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 lower permeability materials, some of which intersect the inner and, in some cases, the outer EDZs (Figure 4-2). The hydraulic conductivities of these sealing materials are low in order to restrict the migration of contaminants up the shafts. There is no degradation of the shaft seals in the Deep and Intermediate Bedrock Groundwater Zones due to the expected stable geological environment even under ice-sheet loading/unloading conditions. However, the concrete bulkhead in the Shallow Bedrock Groundwater Zone and the bulkhead at the boundary between the Shallow and Intermediate Bedrock Groundwater Zones are expected to degrade due to the faster flow conditions promoting leaching and dissolution, and the effects of ice-sheet loading/unloading.

Changes in the stress regime results in rockfall in the repository and the vertical extension of the EDZ into the host rock, as described in Section 6.2.1.1. This effectively reduces the pathlength for contaminant migration through the geosphere immediately above the repository, since it is assumed that the rockfall zone does not form a barrier to contaminant migration.

Significant changes are likely to occur in the Shallow Bedrock Groundwater Zone due to glacial/interglacial cycling (e.g., changes in recharge, development of permafrost, and changes in groundwater chemistry). However, the conceptual model for the current assessment adopts a stylised approach. Specifically, the Shallow Bedrock Groundwater Zone and the surface environment are treated as time-invariant, supporting a self-sufficient farmer and water well at all times. A time-invariant tundra environment with a hunter-gatherer family is also considered.

As noted in Section 4.3.3, the geosphere hydraulic heads measured in the DGR-1 and DGR-2 site investigation boreholes show a significant overpressures and underpressures in the deep rock formations. For the purpose of the conceptual models developed for safety assessment modelling, it is assumed that the underpressures are recent and dissipate relatively quickly. This is conservative because it implies much higher rock hydraulic conductivities than would be the case if these underpressures were ancient.

Site data also show that there is an overpressure in the Cambrian of around 140 m, which creates an upward hydraulic head gradient. The cause of the excess head in the Cambrian is currently uncertain. The head is taken to be maintained for all time, and not to alter in response to future glacial/interglacial cycles.

Migration of Contaminants

Detailed groundwater modelling for the base case conceptual model (Avis et al. 2009) has shown that the transport pathway for contaminants in **groundwater** is slow vertical advection-diffusion upward through the geosphere and shaft in the Deep and Intermediate Bedrock Groundwater Zones, followed by horizontal advective transport in the Shallow Bedrock

Groundwater Zone, with eventual discharge to the biosphere (Figure 6-2). (In the updated geosphere conceptual model with very low permeabilities, the vertical flow in the deep rock is always diffusive.) The migration of containments in the Deep Bedrock Groundwater Zone and much of the Intermediate Bedrock Groundwater Zone is limited by the low permeability of the rocks and the highly saline nature of the porewaters.

Colloids are not expected to be significant in the transport of contaminants through the geosphere for a number of reasons. First, in the high salinity of the Deep and Intermediate Bedrock Groundwater Zones, colloids are expected to be unstable and so susceptible to agglomeration and dissolution. Second, the very small pore size and low permeability of the Ordovician sediments is expected to prevent migration of colloids by filtering. Third, the transport of any colloids is expected to be a diffusion process since diffusion rather than advection is considered the primary mechanism of contaminant transport within the Deep Bedrock Groundwater Zone. The diffusion coefficients for the colloids would likely be smaller than for true solutes.

The Guelph Salina A0 and Salina A2 evaporite Formations lie within the Intermediate Bedrock Groundwater Zone, but are of much higher hydraulic conductivity than the surrounding formations. It is possible that some topographically driven flow occurs within these formations, with discharge where they sub-crop/outcrop below Lake Huron, to the northwest of the Bruce site. Therefore, the conceptual model considers some horizontal advective transport in the Guelph, consistent with groundwater modelling results (Avis et al. 2009).

Certain contaminants (i.e., C-14, Cl-36, Se-79 and I-129) can also migrate from the repository via dissolution into groundwater (and subsequent transport in groundwater) and bulk **gas** transport. Bulk gas is less dense than the surrounding fluid and as such tends to migrate vertically upwards from the repository due to buoyancy effects, while dissolved gas migration follows the groundwater flow pathways for both advection and diffusion.

The rate of bulk gas migration through the rock and shaft materials is a function of the relative density difference, threshold capillary pressure and the permeability of the media under two phase flow conditions. At the Bruce site, the gas movement is impeded by the anisotropy induced by the low permeability limestone and shale horizons.

As bulk gas migrates through the geosphere, some of the gas will dissolve in groundwater. Conversely, dissolved radioactive gases can come out of solution as groundwater is transported upwards and the pressure decreases. The solution and dissolution of gases in the geosphere is considered in the conceptual model (Walke et al. 2009a).

Results presented in the Gas Modelling report (Calder et al. 2009) indicate that bulk gas does not permeate above the Deep Groundwater Bedrock Zone for all but one of the Normal Evolution Scenario calculation cases considered. However, small amounts of dissolved gases do eventually reach the top of the Intermediate Groundwater Bedrock Zone in all cases considered.

6.2.1.3 Biosphere

Evolution of Biosphere Conditions

Climate change can have a significant impact on the biosphere system through the modification of temperature, precipitation, biota, water bodies, sediment/soil, and human activities. A stylised climate sequence has been developed based on the results of the University of Toronto Glacial Systems Model (Peltier 2008) 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 stylised, constant conditions which are comparable with those found at present at the site, since these conditions are expected to result in the highest impacts[18]. It is assumed that land use at the site eventually becomes consistent with the surrounding area (i.e., primarily agricultural and recreational).

Migration of Contaminants Released in Groundwater

The biosphere features into which contaminants are eventually released in groundwater are: soils irrigated by well water and used to grow crops and raise animals (pumped from the Shallow Bedrock Groundwater Zone); and lake water (contaminated by natural groundwater discharge from the Shallow and Intermediate Bedrock Groundwater Zones) which is used as a source of fish (Figure 6-2). Discharge from the Shallow Bedrock Groundwater Zone occurs into the near-shore lake water, whilst discharge from the Intermediate Bedrock Groundwater Zone occurs into more distant off-shore lake water. Subsequent migration of the contaminants in the biosphere results in the contamination of the additional media (Figure 6-8).

Humans are exposed due to the release of contaminants into the biosphere. Human exposure to the features in Figure 6-8 occur by a variety of pathways, as illustrated in Figure 6-9. Contaminants in soil and water are assimilated by plants and animals (that may in turn be ingested by humans) and expose humans by external air irradiation/dermal contact. Inhalation exposure and external irradiation occur if contaminants are volatilised and released from soil and water. The pathways modelled are consistent with recommendations of CSA N288.1 for biosphere modelling (CSA 2008).

In order to assess potential impacts, a critical group is defined that is subject to all of the potential exposure pathways illustrated in Figure 6-9. This group is conservatively assumed to live on a farm over the repository, drawing water from a well drilled into the Shallow Bedrock Groundwater Zone for irrigation, watering animals and for domestic use. The group includes two adults, a child and an infant. The irrigation water is used to grow grain, fruit and vegetables. The livestock include dairy and beef cattle, pigs, lambs, goats and chickens. The group hunts locally for deer and rabbits, consumes local honey, and obtains fish from the stream and from Lake Huron. They swim recreationally in the lake.

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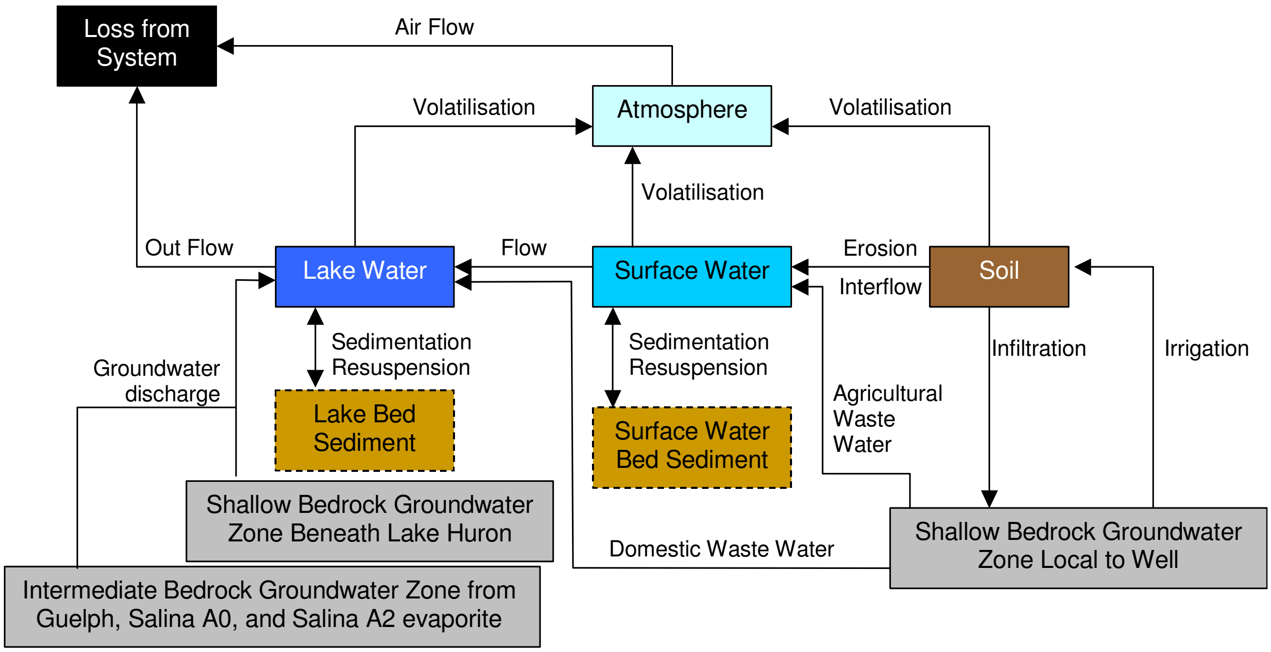
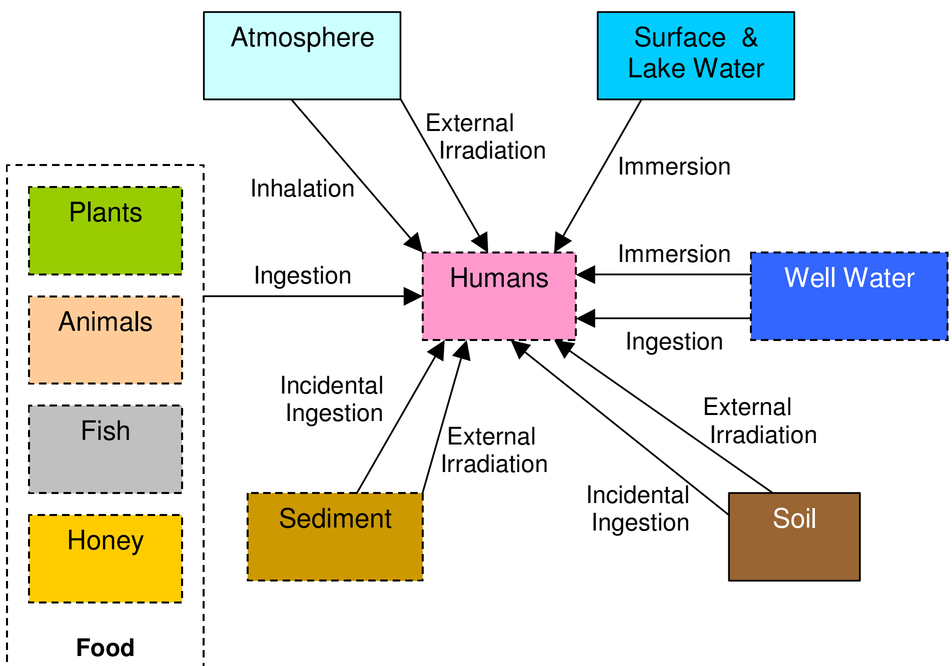
[18] Based on the preliminary modelling results obtained for the assessment of a hypothetical used fuel deep geologic repository located in the Canadian Shield. These showed that peak calculated doses from the sequential modelling of climate change were lower than those obtained assuming constant temperate conditions (Lum and Garisto 2008).



Note: Dotted borders indicate equilibrium compartments.

Figure 6-8: Normal Evolution Scenario: Conceptual Model for the Biosphere – Contaminant Migration Processes for Groundwater Release[19]



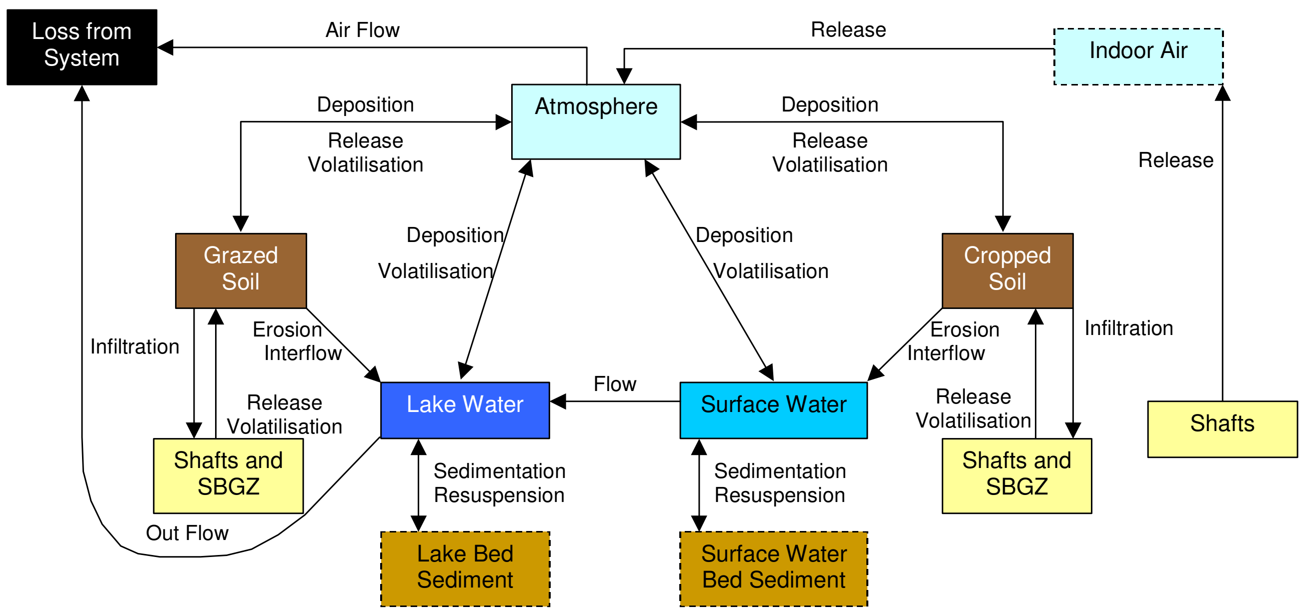
Note: Dotted borders indicate equilibrium compartments.

Figure 6-9: Normal Evolution Scenario: Conceptual Model for the Biosphere – Human Exposure Pathways for Groundwater Release

[19] Note that the domestic and agricultural waste water are included to ensure that all of the water abstracted from the well enters the biosphere model.

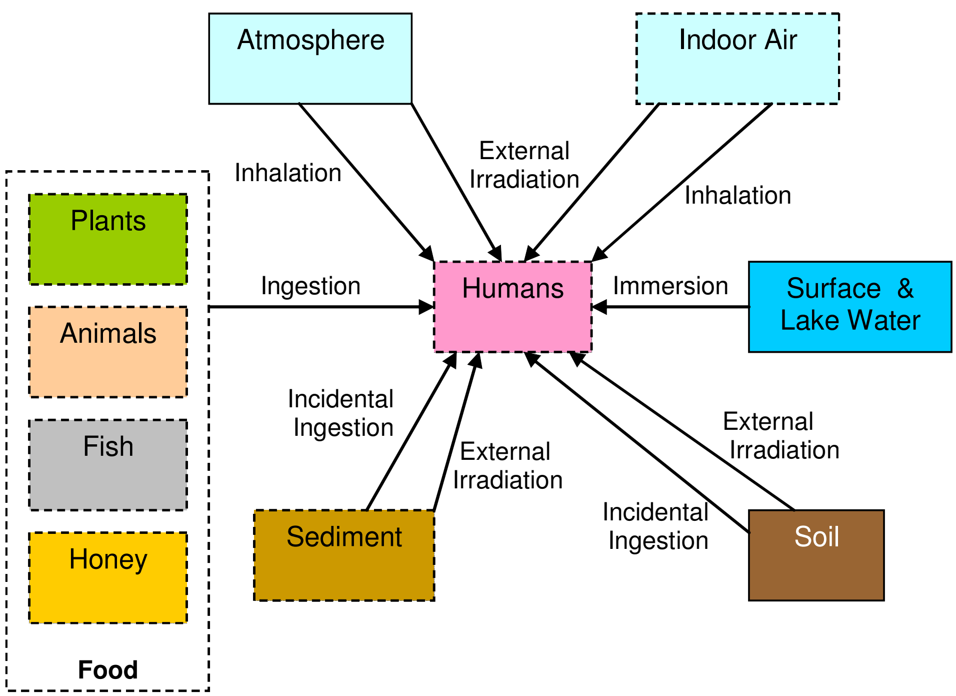
Migration of Contaminants Released in Gas

A house is assumed to be constructed on the site eventually – i.e., 300 years after closure when institutional controls are assumed to have lapsed – Section 3.8). The house is further assumed to cover part of the shaft and its EDZ, which means that any gas released from the part of the shaft and EDZ overlain by the house goes directly into the house. Any gas released into the house subsequently migrates outside, where it is subject to transport and dilution in the local atmosphere, along with any gas released into the soil directly from the shafts/EDZ and geosphere. In addition, gases can volatilise from the groundwater in the Shallow Bedrock Groundwater Zone and migrate through the soil into the atmosphere. Subsequent migration of the contaminants in the biosphere results in the contamination of further media and human exposure (Figure 6-10 and Figure 6-11).



Note: Dotted borders indicate equilibrium compartments.
SBGZ = Shallow Bedrock Groundwater Zone.

Figure 6-10: Normal Evolution Scenario: Conceptual Model for the Biosphere – Contaminant Migration Processes for the Gas Release



Note: Dotted borders indicate equilibrium compartments.

Figure 6-11: Normal Evolution Scenario: Conceptual Model for the Biosphere – Human Exposure Pathways for the Gas Release

6.2.2 Human Intrusion Scenario

Table 6-2, Table 6-3, Figure 6-12, Figure 6-13 and Box 2 summarise 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 Analysis report (Penfold and Little 2009).

Table 6-2: Exposure Situations for the Human Intrusion Scenario

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

* Cautiously assume that solid (intact) waste may be brought to the surface as core samples. It is expected that by the time of intrusion most wastes would not be of sufficient integrity to be retrieved as an intact sample.

Table 6-3: Human Intrusion Scenario: Exposure Mechanisms and Key Characteristics

Exposure Group				
Drill Crew	**Nearby Resident**	**Laboratory Technician**	**Future Site Resident Using Contaminated Soil**	**Future Site Resident Using Contaminated Groundwater**
• Incidental ingestion of slurry and soil • Inhalation of dust and gas • External irradiation from slurry and 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 volatilised contaminants • External irradiation from soil and dust	• Ingestion of water, plants, animal products, fish, honey, sediment, and soil • Inhalation of dust and volatilised contaminants • External irradiation from water, soil, sediment, and dust

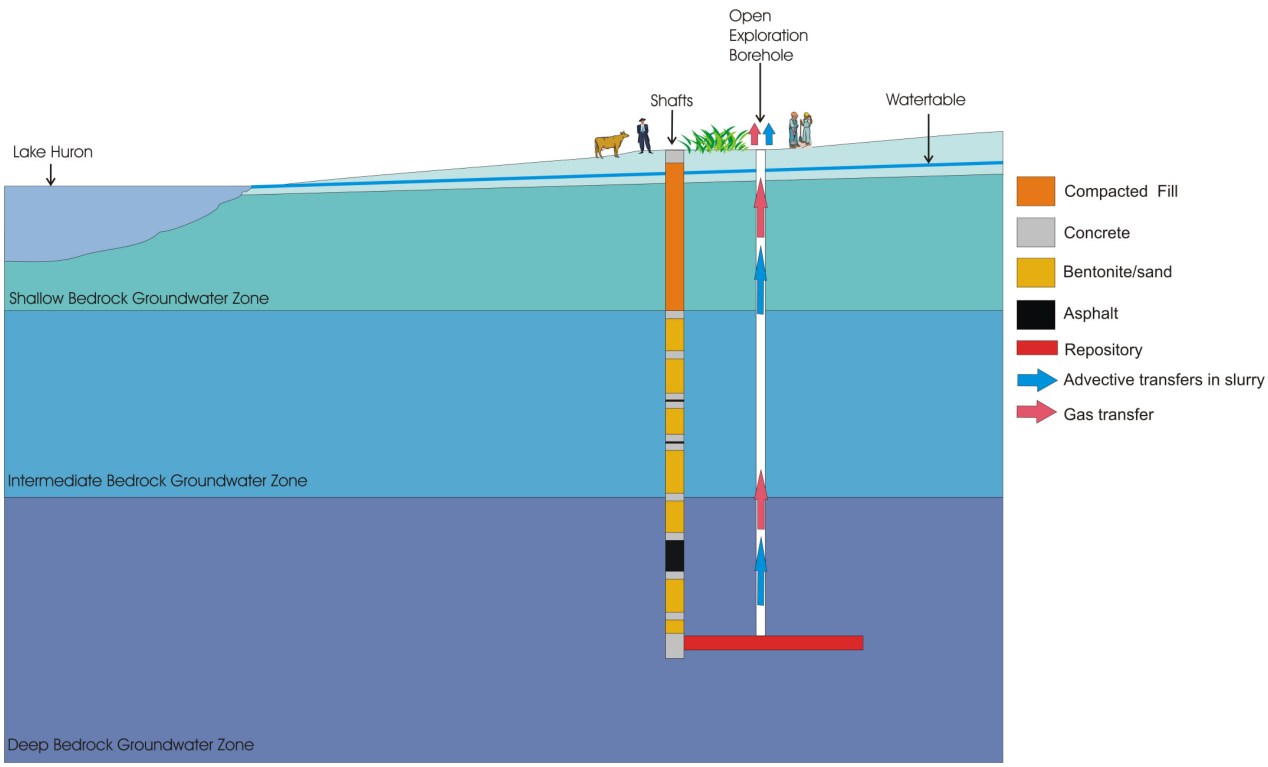


Figure 6-12: Human Intrusion Scenario: Schematic Representation of Short-Term Gas and Slurry Releases

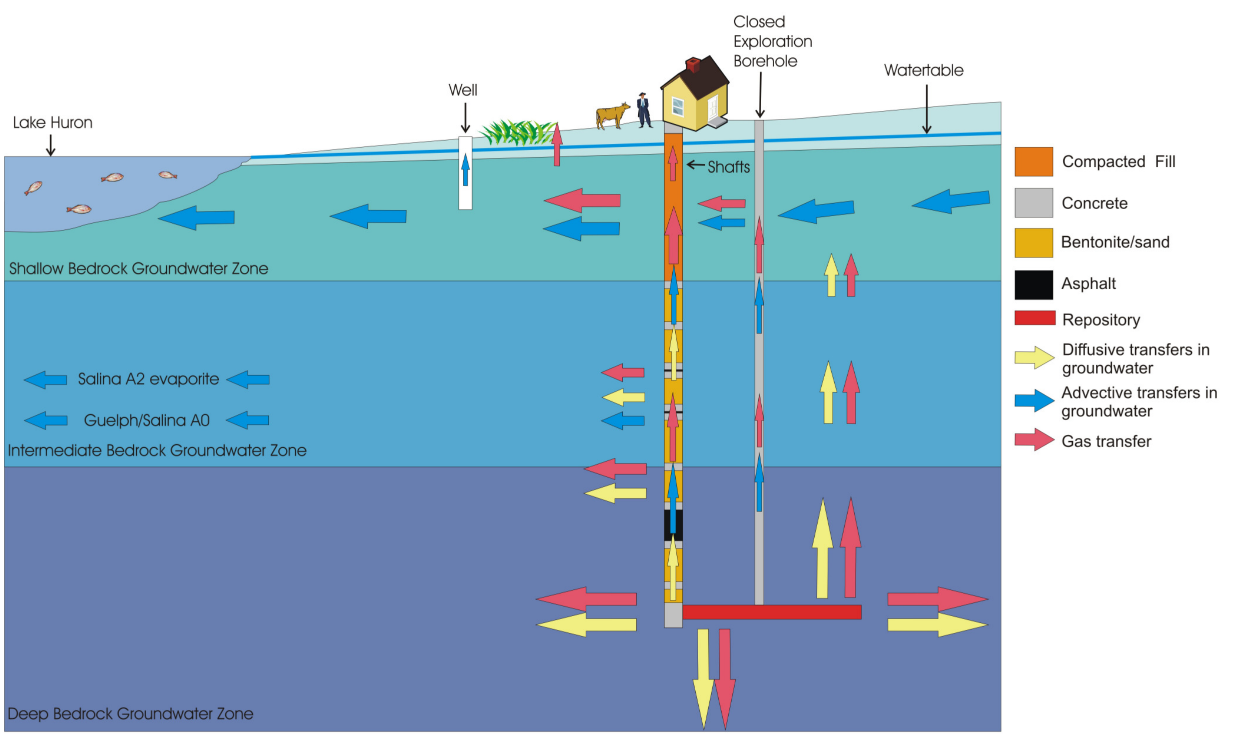


Figure 6-13: Human Intrusion Scenario: Schematic Representation of Long-term Groundwater Release

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

Gas and Slurry Releases:

Consistent with the Normal Evolution Scenario (Box 1 and Section 6.2.1.1), other than:

- Intrusion via exploration borehole into repository occurs at some time after controls are no longer effective (i.e., after 300 years – Section 3.8).
- Resaturation of the repository is rapid after borehole intrusion occurs (Section 6.2.2.2). Resaturation profile prior to borehole intrusion consistent with the Normal Evolution Scenario.
- Some contaminants released from repository into surface environment as drill slurry and, in case of H-3, C-14, Cl-36, Se-79, I-129 and Rn-222, also as gas (Section 6.2.2.2).
- Gas release via the borehole is limited by blow-out preventers, but depressurisation allowed to be completed within a few weeks (Section 6.2.2.2).
- Surface media can become directly contaminated with slurry released at the exploration borehole wellhead (when borehole casing is effective) (Section 6.2.2.3).
- 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).

Solid Release:

Consistent with the Normal Evolution Scenario (Box 1 and Section 6.2.1.1), other than:

- Intrusion via exploration borehole into repository occurs at some time after controls are no longer effective (i.e., after 300 years – Section 3.8).
- Retrieval of an intact sample of waste in borehole core (Section 6.2.2.2).
- Direct impacts on laboratory technician examining core considered (see Section 6.2.2.4).

Groundwater Release:

Consistent with the Normal Evolution Scenario (Box 1 and Section 6.2.1.1), other than:

- Intrusion via exploration borehole into repository occurs at some time after controls are no longer effective (i.e., after 300 years – Section 3.8).
- Resaturation of the repository is rapid after borehole intrusion occurs (Section 6.2.2.2). Resaturation profile prior to borehole intrusion consistent with the Normal Evolution Scenario.
- The borehole is poorly sealed with material that has the properties of engineered fill (crushed rock) and the casing in the Shallow Bedrock Groundwater Zone degrades.
- The borehole allows contaminated water to enter the Shallow Bedrock Groundwater Zone, once casing is no longer effective (Section 6.2.2.3). The rate of release of groundwater into the Shallow Bedrock Groundwater Zone is based on detailed groundwater modelling[20].

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 there has been some such drilling in the region in the past (although it is not widespread), whereas there is no mineral exploitation at depth in the region. 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 Shallow and Intermediate Bedrock Groundwater Zones. It would require casing in the Shallow Bedrock Groundwater Zone (to protect the potable groundwater and due to the low permeability of the rock in the lower geosphere). Through the Deep Bedrock Groundwater Zone, a narrower diameter

[20] Based on findings presented in the Groundwater Modelling Report (Avis et al. 2009).

borehole is drilled (15.24 cm or 6 inch), consistent with typical drilling practice of reducing borehole diameter with depth.

6.2.2.2 Sources

The borehole could in principle penetrate any part of the repository with equal likelihood. For the purposes of the analysis, calculations are made on the basis of the average concentrations of contaminants in gas, slurry, water and waste in the East Panel (the location for the disposal of the ILW and some LLW), which has an order of magnitude higher activity in its inventory than the South Panel (Table 4-4).

Concentrations of the contaminants in the repository will vary with time, as they will be dependent on radioactive decay, the rate of release of radionuclides 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 pressurised **gas** from the repository. Standard drilling techniques involve the use of blow-out preventers during drilling, and the repository gases would be expected to be flared if at pressure. 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 99% of C-14 is present in gas in this form (see Gas Modelling Report, Calder et al. 2009);
- Cl-36, Se-79 and I-129 from volatilisation and methylation; and
- Rn-222 ingrown from Ra-226.

The pressurisation of the repository may also result in a discharge of **water** from the repository. This would contain dissolved radionuclides released from the waste by dissolution and desorption, and could also contain suspended particles[21] generated during the degradation of waste (**slurry**). The volume and character of ejected water and slurry would be dependent on the pressurisation and state of resaturation of the repository, the extent to which wastes had corroded and degraded, and the extent that the drill bit grinds any wastes into particulates. It is possible that the repository could be dry, in which case no significant release of contaminated water and slurry would occur.

Solid (intact) waste may be brought to the surface as core samples (if the borehole is cored). It is noted that by the time of intrusion most wastes would not be of sufficient integrity to be retrieved as an intact sample. However, for the purpose of the assessment, exposure by the examination of a small section of core sample is pessimistically considered. As the borehole could strike any part of the repository, the average concentration of contaminants in waste in the East Panel is assumed to be present in the retrieved sample.

[21] This may include particles of waste, generated during corrosion, or precipitates containing specific radionuclides, e.g., siderite containing C-14.

6.2.2.3 Release Pathways

The borehole itself can be considered to be a “fast” pathway; that is, contaminants would be transported rapidly in comparison with the timescales associated with other processes. This means that contaminants would have limited interaction with other environmental media during transit, although the borehole would determine a particular point of release.

The point of discharge of contaminated material from the repository is dependent on the presence (and proper function) of the borehole casing. Two main points of release are assessed:

- release at the surface (prior to closure and sealing of the borehole), and
- release to the geosphere, circumventing part of the geological barrier (if the casing and backfill seal are not effective).

For the surface release, the pathway can be represented as a transfer of gas, slurry and solid material (i.e., borehole 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 and occurs at the time of intrusion.

It is standard practice (and legally required) to close and seal deep boreholes once complete. However, the scenario considers the “what if” case of the borehole being poorly sealed and the borehole casing failing, resulting in the loss of contaminants into permeable geosphere horizons. This release could persist for many thousands of years as the borehole remains a small but relatively permeable path. The Shallow Bedrock Groundwater Zone is the primary point of release other than the surface, according to groundwater modelling (Avis et al. 2009). 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 and abstracted 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 slurry, gas, and solid waste.

Slurry

The conceptual model for exposure by slurry released from the borehole is shown in Figure 6-14 and Figure 6-15. Two potential exposure groups are assessed:

- those directly exposed to contaminated slurry at the point of release (i.e., the drill crew) (Figure 6-14); and
- those exposed for a longer duration to contamination in the soil (e.g., a resident using the contaminated site for growing food and grazing animals after the completion of drilling) (Figure 6-15).

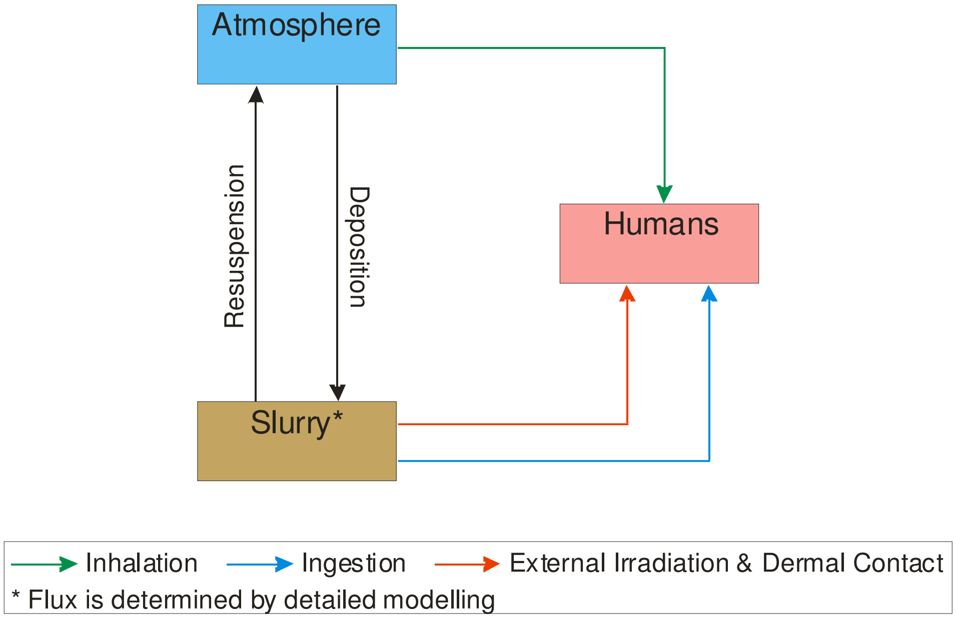


Figure 6-14: Human Intrusion Scenario: Conceptual Model for Exposure of the Drill Crew During the Slurry Release

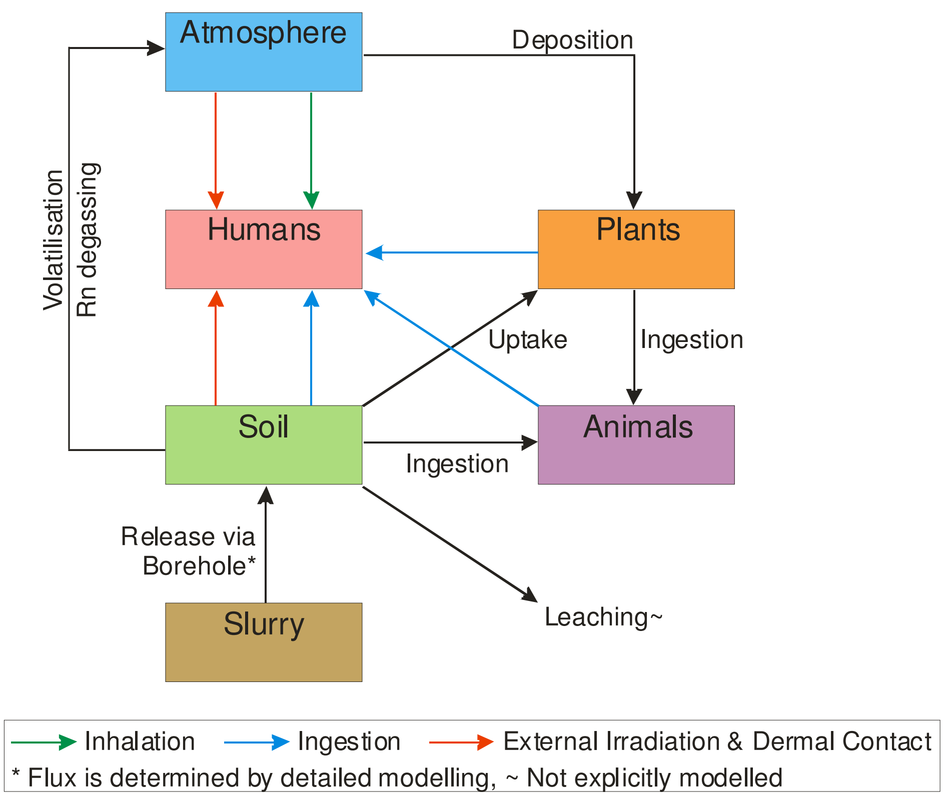


Figure 6-15: Human Intrusion Scenario: Conceptual Model for Exposure of the Site Resident to Soil Contaminated by Slurry

Direct exposure of the **drill crew** can result from contamination of the skin, and inhalation and ingestion of aerosol, while the slurry is being ejected from the borehole. The crew could also be exposed for an extended period by soil contaminated by the slurry. For the soil, relevant modes of exposure include external irradiation, inadvertent soil ingestion and inhalation of suspended dust. Volatilisation of contaminants is not expected to be a significant pathway for the drill crew as the exposure time is relatively short.

A future **site resident** could use the contaminated drill site for growing food and grazing animals immediately after the borehole has been abandoned. (The drill crew are assumed to leave drill slurry on the site, which is contrary to current drilling practice.) The characteristics of the resident are the same as defined for the local exposure group in the Normal Evolution Scenario (Section 6.2.1.3).

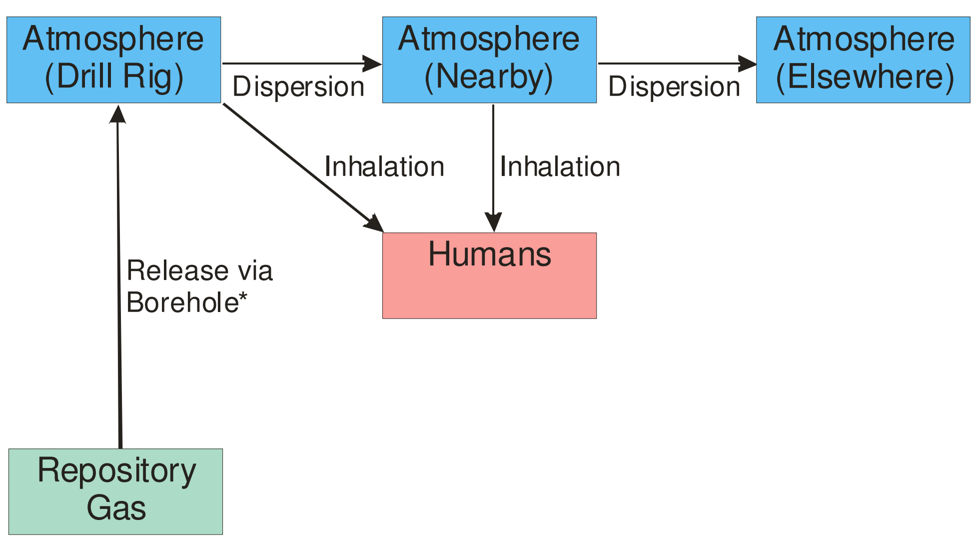
Gas

The conceptual model for exposure following a gas release is shown in Figure 6-16. Two potential exposure 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).

No precautions against inhalation of the gas when the borehole strikes the repository are included in the assessment of the **drill crew**, although borehole blow-out 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.



* Flux is determined by detailed modelling

Figure 6-16: Human Intrusion Scenario: Conceptual Model for Gas Release

Potential Exposure to Solid Waste

Whilst it is very unlikely that an intact sample of waste could be retrieved via a borehole, it cannot completely be disregarded. In this context, the most relevant potential receptor is a **laboratory technician** examining a core sample containing waste. Irradiation from a small (several kg) sample of waste could occur when it is analysed 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 6-17.

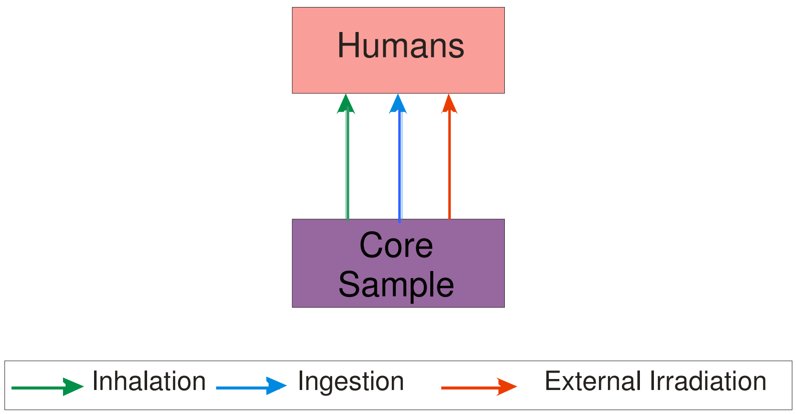


Figure 6-17: Human Intrusion Scenario: Conceptual Model for Core Retrieval

6.2.2.5 Receptors for the Shallow Bedrock Groundwater Zone Release Pathway

Detailed groundwater modelling (Avis et al. 2009) shows that releases to the Shallow Bedrock Groundwater Zone via a borehole (if the casing is not effective) would occur over a long timescale. It is therefore reasonable to adopt for this case the conceptual model of the biosphere and associated exposure 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:

- degraded physical and chemical characteristics of the concrete monoliths, the shaft seals and backfill (from the time of closure);
- absence of sealing of the shaft EDZ by the shaft seals; and
- increased permeability of the inner EDZ.

These differences result in increased advective flow of groundwater and gas up the shafts from the repository into the Shallow Bedrock Groundwater Zone and a resulting increase in the flux of contaminants up the shafts (see discussion in Groundwater and Gas Modelling reports, Avis et al. 2009 and Calder et al. 2009).

The key transport pathways for releases from the repository are summarised in Figure 6-18.

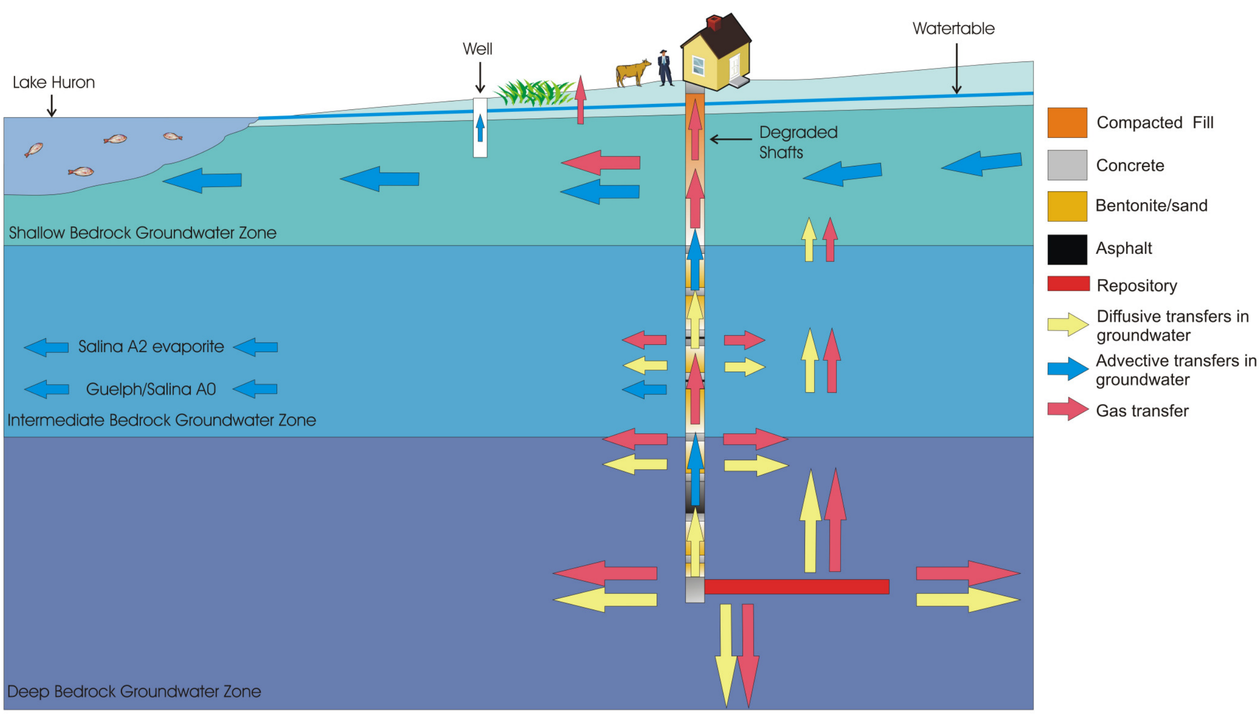


Figure 6-18: Schematic Representation of Potential Transport Pathways for the Severe Shaft Seal Failure Scenario

6.2.4 Open Borehole Scenario

The conceptual model is the same as for the Normal Evolution Scenario (Section 6.2.1) since the status of the FEPs is 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 - via the Deep Bedrock Groundwater Zone into the borehole. From there it can potentially reach the surface via horizontal flow in the Guelph, Salina A0 and Salina A2 evaporite formations; or by release into the Shallow Bedrock Groundwater Zone.

The borehole will also result in a point of low hydraulic head in the repository horizon at the borehole location. Avis et al. (2009) shows however that the flow rates from the repository (South Panel) are very low (around 1 mm a^{-1}) and comparable to diffusion rates, and will only occur in the event of pressurisation of the repository. In practice it is expected that the repository will sit in a low hydraulic head zone and there will be limited gradient between the repository and the borehole. The conceptual model therefore only considers a diffusive flux of contaminants from repository to the borehole.

The key transport pathways for releases from the repository are summarised in Figure 6-19.

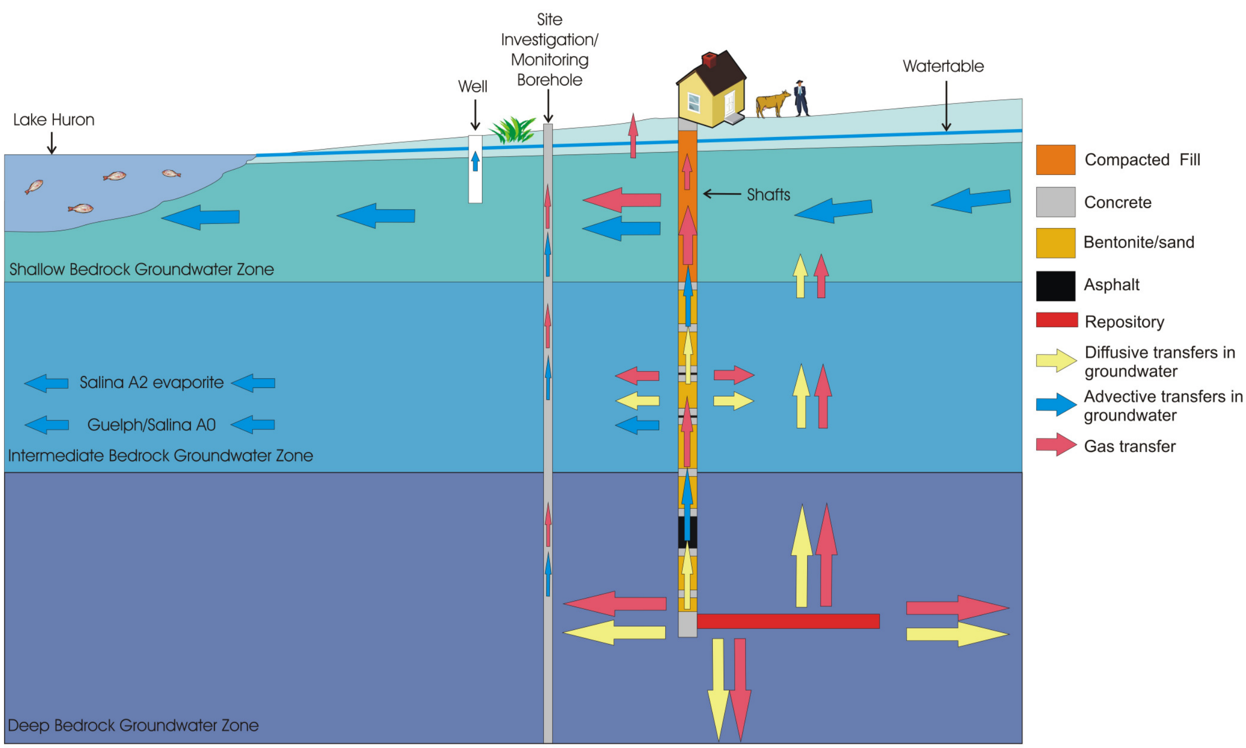


Figure 6-19: Schematic Representation of Potential Transport Pathways for the Open Borehole Scenario

6.2.5 Extreme Earthquake Scenario

The conceptual model is the same as for the Normal Evolution Scenario (Section 6.2.1), since the status of the FEPs is broadly the same. The only difference is that, due to the reactivation of a hypothetical fault by the extreme earthquake, there are two additional pathways for contaminants to migrate from the repository:

- via the shafts into the Guelph Formation and then into the fault that leads into the Shallow Bedrock Groundwater Zone; and
- via the Deep Bedrock Groundwater Zone into the fault that leads into the Shallow Bedrock Groundwater Zone.

The key transport pathways for releases from the repository are summarised in Figure 6-20.

In the conceptual model, the Cambrian overpressured hydraulic head is assumed to be unaffected, despite being connected by a permeable path to the surface.

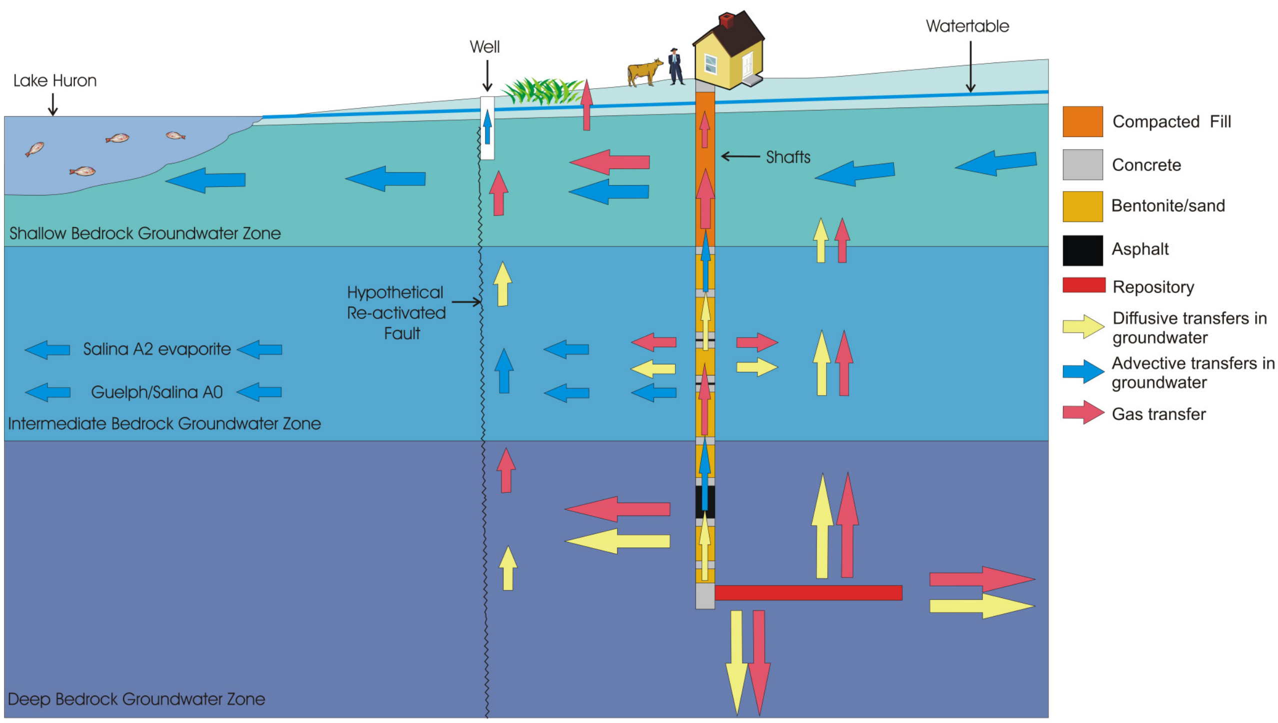


Figure 6-20: Schematic Representation of Potential Transport Pathways for the Extreme Earthquake Scenario

6.3 CALCULATION CASES

Section 6.2 describes the conceptual model for each scenario considered in the assessment. In addition to the uncertainty associated with the future evolution of the system (addressed through considering a range of scenarios), there are uncertainties associated with the conceptual model developed for the scenarios. These are discussed in the reports describing the analysis of the Normal Evolution Scenario (Walke et al. 2009a) and the Disruptive Scenarios (Penfold and Little 2009). The following main sources of conceptual model uncertainties have been identified:

- the impact of future climate change on the DGR system;
- the over/underpressures in the Deep and Intermediate Bedrock Groundwater Zones; and
- the evolution of the repository and shafts.

In addition, there are uncertainties associated with parameter values for use in the models. Key areas of parameter uncertainty highlighted in the Normal Evolution and Disruptive Scenarios Analysis reports (Walke et al. 2009a; Penfold and Little 2009) and Data report (Walke et al. 2009b) are:

- the flow and transport characteristics of the shaft sealing materials and EDZ;
- the hydraulic characteristics of the Guelph, Salina A0 and Salina A2 evaporite formations;
- the permeabilities in the geosphere, especially in the Deep and Intermediate Bedrock Groundwater Zones (i.e., low or very low);
- the gas flow parameters (in particular capillary pressure and relative permeability parameters), especially in the formations above the Ordovician;
- the partitioning of contaminants between phases throughout the system;
- repository gas generation parameters; and
- alternative lifestyles and receptor locations.

In addition, a design and engineering alternative for the repository has been considered that considers the backfilling of the access and ring tunnels in the repository.

Through the consideration of these future uncertainties, model uncertainties and data uncertainties, and the design/engineering alternatives, a set of calculation cases have been identified for evaluation, as listed in Table 6-4 and detailed in Appendix A.

Table 6-4: Calculation Cases for Evaluation in the Version 1 SA

	Calculation Cases*		
	Assessment Modelling	**Detailed Groundwater Modelling**	**Detailed Gas Modelling**
Scenario Uncertainties			
• Normal Evolution	• Base case for low permeability geosphere (NE-BC-A & NE-NR-A) • Base case for very low permeability geosphere (NE-UG-BC-A)	• Base case for low permeability geosphere (NE-RS1-F3) • Base case for very low permeability geosphere (NE-UG-RS1-F3)	• Base case for low permeability geosphere (NE-BC-T) • Base case for very low permeability geosphere (NE-UG-BC-T)
• Human Intrusion	• Short-term release to surface (HI-SR1-A, HI-SR2-A & HI-NR1-A) • Long-term release to Shallow Bedrock Groundwater Zone (HI-GR-A & HI-NR2-A)	• Long-term release to Shallow Bedrock Groundwater Zone (HI-GR-F3)	-
• Severe Shaft Seal Failure	• Failure of entire shaft (SF-ES1-A & SF-NR-A) • Failure of upper shaft (SF-US-A)	• Failure of entire shaft (SF-ES1-F2 & SF-UG-ES1-F2) • Failure of upper shaft (SF-US-F2)	• Failure of entire shaft (SF-ES1-T & SF-UG-ES1-T) • Failure of upper shaft (SF-US-T)
• Open Borehole	• Base case (OB-BC-A & OB-NR-A)	• Base case (OB-BC-F3)	-
• Extreme Earthquake	• OB-NR-A (EE-BC-A & EE-NR-A)	• Base case (EE-BC-F3)	-
Conceptual Model Uncertainties			
• Impact of future climate change	• Reduced shaft seal performance (NE-EDZ-A & NE-UG-EDZ-A) • Varying resaturation profiles (NE-RS1-A, NE-UG-RS1-A, NE-RS2-A & NE-RS1-3) • Tundra climate state (NE-CC-A)	• Reduced shaft seal performance (NE-EDZ-F2 &NE-UG-EDZ-F2) • Disequilibrium in hydraulic heads (NE-UG-NHG-F2) • No rockfall in tunnels (NE-UG-RD1-F3)	• Reduced shaft seal performance (NE-EDZ-T & NE-UG-EDZ-T) • No rockfall in tunnels (NE-UG-RD1-T)
• Over/Underpressures		• Ordovician underpressure allowed to dissipate (NE-UG-NHG-F2)	10% initial gas saturation (NE—UG-GT-T)
• Evolution of repository and shafts	• Varying resaturation profiles (NE-BC-A, NE-UG-BC-A, NE-RS1-A, NE-UG-RS1-A, NE-RS2-A & NE-RS3-A) • Instant resaturation and release, and no sorption (NE-RT-A)	• No rockfall in tunnels (NE-UG-RD1-F3)	• No rockfall in tunnels (NE-UG-RD1-T)

	Calculation Cases*		
	Assessment Modelling	**Detailed Groundwater Modelling**	**Detailed Gas Modelling**
Data Uncertainties			
• Partitioning of contaminants between phases	• All contaminants released into groundwater, no gas (NE-RS1-A and NE-UG-RS1-A) • All contaminants released into groundwater, no gas and no sorption (NE-RT-A)	-	-
• Shaft sealing material and EDZ characteristics	• Hydraulic properties of EDZ increased, seals not keyed into EDZ (NE-EDZ-A & NE-UG-EDZ-A	• Hydraulic properties of EDZ increased, seals not keyed into EDZ (NE-EDZ-F2 & NE-UG-EDZ-F2)	• Permeability of EDZ increased, seals not keyed into EDZ (NE-EDZ-T & NE-UG-EDZ-T))
• Hydraulic characteristics of the Guelph, Salina A0 and Salina A2 evaporite Formations	• Pathlength in Guelph, Salina A0 and Salina A2 evaporite extended to 80 km (NE-GF-A)	• No horizontal gradient in Guelph, Salina A0 and Salina A2 evaporite NE-NHG-F2&F3 & NE-UG-NHG-F2)	-
• Geosphere permeabilities	• Very low permeabilities in Intermediate and Deep Bedrock Groundwater Zones (all NE-UG cases)	• Very low permeabilities in Intermediate and Deep Bedrock Groundwater Zones (all NE-UG cases)	• Very low permeabilities in Intermediate and Deep Bedrock Groundwater Zones (all NE-UG cases)
• Silurian gas flow parameters	-	-	• Modified gas parameters (NE-UG-GT-T)
• Repository gas generation parameters	-	-	• Increased gas generation (NE-GG1-T) • Reduced gas generation (NE-GG2-T)
• Alternative lifestyles and receptor locations	• “Downstream” exposure group with high fish consumption rate (NE-EG-A) • Tundra climate state (NE-CC-A)	-	-
Design and Engineering Options	-	• Access and ring tunnel backfilled with concrete (NE-UG-RD1-F3)	• Access and ring tunnel backfilled with concrete (NE-UG-RD1-T)

Note:
* The ID scheme used is explained at the start of Section 7.

6.4 MATHEMATICAL MODELS AND SOFTWARE IMPLEMENTATION

The mathematical modelling approach used in the assessment is based on the use of a assessment-level 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.

The assessment-level model is implemented in AMBER Version 5.2 (Enviros and Quintessa 2008a). This code can be used to represent contaminant transport within a compartment model approach. AMBER has been used in postclosure safety assessments of deep geologic radioactive waste disposal facilities in a ‘total systems’ manner, including the 2002 and 2003 preliminary SA calculations (Penfold et al. 2003). A brief overview of AMBER is provided in Appendix B.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 (Walke et al. 2009a, Penfold and Little 2009). These have been implemented in four AMBER cases:

- a case file for the repository, shafts and geosphere model – AMBER_V1_NF&GEOv2.cse;
- a case file for the biosphere model – AMBER_V1_BIOv2.cse; and
- variants of these in which the radionuclides are replaced with non-radioactive contaminants.

AMBER has been developed to solve for contaminant movement, with detailed water and gas flows being provided as input rather than calculated. Furthermore, AMBER does not readily allow the use of many small compartments that is needed for detailed water or gas flow modelling. These limitations have 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 models. Two such detailed codes have been used in the current assessment – FRAC3DVS and T2GGM.

FRAC3DVS is a 3-D finite-element/finite-difference groundwater flow and contaminant transport code. FRAC3DVS supports both equivalent-porous-medium and dual-porosity representations of the 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 is provided in Appendix B.2 and its application to the current assessment is described in the Groundwater Modelling report (Avis et al. 2009).

T2GGM is a code that couples the Gas Generation Model (GGM) and TOUGH2. 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 is provided in Appendix B.3 and its application to the current assessment is described in the Gas Modelling report (Calder et al. 2009).

6.5 DATA

Reference data used for the assessment of the Normal Evolution Scenario is documented in the Data report (Walke et al. 2009b). The following references have been used for the safety assessment:

- the August 2008 inventory report (OPG 2008a) for waste and waste packaging data;
- the May 2008 conceptual design report (Hatch 2008) for repository data;
- the data clearance forms from the Geosynthesis team provided during 2008 and early 2009 for geosphere data (see Walke et al. 2009b for details); and
- the CSA N288.1 biosphere model (CSA 2008), Bruce site derived release limit reports (BEAK 2002 and Benovich 2003), Bruce site Environmental Assessment (EA) Study Reports (e.g., OPG 2005), the BIOTRAC model (Davis et al. 1993) and the biosphere data used for the Third Case Study assessment for a used fuel repository (Garisto et al. 2004) for biosphere and exposure data.

In addition, literature reviews (described in Walke et al. 2009b) have been undertaken to derive values for certain key parameters such as solubility limits, sorption coefficients, corrosion rates and microbial degradation rates suitable for expected conditions in the DGR.

Table 6-5 summarises the reference values used for the key parameters in the Normal Evolution Scenario, with repository and geosphere sorption values being summarised in Table 6-6.

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 Analysis reports (Walke et al. 2009a; Penfold and Little 2009).

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 (Walke et al. 2009b) rather than being explicitly given in the report. Such data are documented, together with their derivation, in the relevant report, i.e., Walke et al. (2009a) for the assessment modelling for the Normal Evolution Scenario, Penfold and Little (2009) for the assessment modelling for the Disruptive Scenarios, Avis et al. (2009) for the detailed groundwater modelling, and Calder et al. (2009) for the detailed gas modelling.

Table 6-5: Reference Values for Key Parameter for the Normal Evolution Scenario

PARAMETER	VALUE(S)
Repository	
Repository depth	680 m
Number of emplacement rooms in South Panel	South Panel: 30; East Panel: 15
South Panel emplacement room dimensions	L 123.9 m, W 8.6 m, H 7.0 m (each room)
East Panel emplacement room dimensions	Variable– see Table 4-6
Pillar width between rooms	16 to 17 m
South Panel access tunnels dimensions	L 453 m, W 6.5 m, H 7.0 m
East Panel access tunnels dimensions	L 255 m, W 6.5 m, H 7.0 m
Ring tunnel dimensions	L 377 m, W 8.1 m, H 7.5 m
Panel footprint	2.1×10^5 m^2
Total excavated volume	Excavated: 4.3×10^5 m^3; Void: 3.3×10^5 m^3
Waste conditioning	Two LLW streams incinerated, two compacted and one grouted prior to being sent to DGR. No conditioning of ILW
Total waste volume (as disposed)	140,902 m^3 South Panel, 55,047 m^3 East Panel
Waste inventory	1.1×10^3 TBq LLW, 1.5×10^4 TBq ILW at 2062
Total mass of organics (wastes)	2.2×10^7 kg
Total mass of concrete (packages and structures)	1.3×10^8 kg
Total mass of metals (packages and structures)	5.8×10^7 kg
Backfilling of rooms and tunnels	None except monolith in immediate vicinity of shafts
Excavation Damaged Zone	Emplacement rooms and tunnels: 7 m thick, K_h 1000 x rock mass and $K_v = K_h$, porosity 2 x rock mass; Base of the shafts: 4 m thick, K_h 1000 x rock mass and $K_v = K_h$, porosity 2 x rock mass
Rockfall	Rockfall zones develop stepwise at 7 m every 15,000 years. Maximum extent of rockfall is 20 m for the emplacement rooms and 30 m for the access and ring tunnels. Rockfall affects all rooms and tunnels.
Resaturation profile	Variable – depends on calculation case (see Table A-1)
Corrosion rates	Unpassivated C-steel and galvanised steel: 2×10^{-6} m a^{-1} Passivated C-steel, stainless steel and Ni-alloys: 1×10^{-7} m a^{-1} Zr-alloys: 1×10^{-8} m a^{-1}
Degradation rates	Cellulose: 5×10^{-4} a^{-1} Ion exchange resins, plastics and rubber: 5×10^{-5} a^{-1}
Solubility limitation and sorption in repository	Solubility limitation only considered for C (0.01 mol m^{-3}) and U (0.001 mol m^{-3}). No sorption except for C, Zr, Ni, Nb, U and Np on concrete monolith (Table 6-6).
Shaft	
Internal diameter (lower section)	Main: 8.15 m; Ventilation: 5.95 m. Concrete lining removed to bare rock.
Length (lower section)	257 m (base of shaft to bulkhead at top of Ordovician)
Internal diameter (middle section)	Main: 8.0 m; Ventilation: 5.8 m. Concrete lining removed to bare rock.
Length (middle section)	250 m (bulkhead at base of Silurian to bulkhead at top of Silurian)
Internal diameter (upper section)	Main: 6.5 m; Ventilation: 4.5 m.
Length (upper section)	183 m (bulkhead at base of Devonian to ground surface)
Backfill and seals	Sequence of bentonite-sand, asphalt, concrete and engineered fill – see Figure 4-2. Concrete bulkheads keyed across the inner EDZ. Asphalt water stops keyed across inner and outer EDZ.
Backfill/seal hydraulic conductivity	Bentonite-sand: 1×10^{-11} m s^{-1}; Asphalt: 1×10^{-12} m s^{-1}; Concrete: 1×10^{-11} m s^{-1}; Engineered fill: 1×10^{-4} m s^{-1}
Backfill/seal diffusion and transport porosity	Bentonite-sand: 0.3; Asphalt: 0.02; Concrete: 0.15; Engineered fill: 0.3
Backfill/seal effective diffusion coefficient	Bentonite-sand: 1×10^{-10} m^2 s^{-1}; Asphalt: 1×10^{-13} m^2 s^{-1}; Concrete: 2.5×10^{-12} m^2 s^{-1}; Engineered fill: 3×10^{-10} m^2 s^{-1}
Excavation Damaged Zone	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 same as rock mass

PARAMETER	VALUE(S)
Degradation of concrete	Concrete at base of Shallow Bedrock Groundwater Zone and at surface degrades. Assessment calculations assume linear degradation over 100,000 years. Detailed groundwater and gas calculations adopt degraded values from time of closure. Degraded values are: • Vertical and horizontal hydraulic conductivity - 1×10^{-8} m s^{-1} • Diffusion and transport porosity - 0.25 • Effective diffusion coefficient - 1.25×10^{-10} m s^{-2}
Sorption in shaft and EDZ	No sorption except for Zr, Ni, Nb, U and Np on concrete, bentonite-sand and EDZ and C on concrete (Table 6-6).
Geosphere	
Host rock type	Low permeability argillaceous limestone (Cobourg Formation)
Temperature at emplacement room depth	20 °C
Groundwater composition at depth	Na-Ca-Cl dominated brine; TDS: 150-350 g L^{-1}; pH: 5.1 to 7.0; Eh: reducing
Hydraulic heads	+ 140 m at top of the Cambrian sandstone 0 m at the top of the Lucas Formation (top of the Shallow Bedrock Groundwater Zone) Steady state conditions assumed with no underpressures in Ordovician
Deep Bedrock Groundwater Zone:	
horizontal hydraulic conductivity	5.5×10^{-12} to 5.4×10^{-11} m s^{-1} (3.0×10^{-6} in the Cambrian sandstone)
vertical hydraulic conductivity	10% of horizontal hydraulic conductivity for all formations other than Cambrian which is isotropic
transport porosity	0.01 to 0.08
effective diffusion coefficient	4.4×10^{-13} to 6.98×10^{-12} m^2 s^{-1} (some anisotropy – Walke et al. 2009b)
horizontal gradient	0
Intermediate Bedrock Groundwater Zone:	
horizontal hydraulic conductivity	9.7×10^{-13} to 1.3×10^{-8} m s^{-1}
vertical hydraulic conductivity	10% of horizontal hydraulic conductivity for all formations other than Salina A1 and A2 evaporites and Salina B anhydrite which are isotropic
transport porosity	0.01 to 0.08
effective diffusion coefficient	7.5×10^{-13} to 7.4×10^{-12} m^2 s^{-1} (some anisotropy – Walke et al. 2009b)
horizontal gradient	0.002 in Guelph, Salina A0 and Salina A2 evaporite. 0 in all other horizons
Shallow Bedrock Groundwater Zone:	
horizontal hydraulic conductivity	1.0×10^{-4} to 1.0×10^{-7} m s^{-1}
vertical hydraulic conductivity	10% of horizontal hydraulic conductivity for all formations other than Quaternary which is 50%.
transport porosity	0.08 to 0.1
effective diffusion coefficient	7.4×10^{-12} to 6.0×10^{-11} m^2 s^{-1}
horizontal gradient	0.003
Sorption in geosphere	Only for Zr, Ni, Nb, U and Np (Table 6-6).
Biosphere	
Average annual surface temperature	8.9 ºC
Average total precipitation	0.98 m a^{-1}
Ecosystem	Temperate climate, Mixedwood Forest ecozone
Geosphere-biosphere interface:	
Groundwater release	1) 80 m deep well located 500 m down gradient of Main Shaft (for discharge from Shallow Bedrock Groundwater Zone) 2) Nearshore lake bed sediments (for discharge from Shallow Bedrock Groundwater Zone) 3) Sediments in Central Basin of Lake Huron (for discharge from Guelph, Salina A0 and Salina A2 evaporite)
Gas release	1) House located above repository 2) Soil located above repository
Land use	Agriculture, recreation, forestry
Potential exposure group	Local group making use of land for farming, fishing, recreation and dwelling (habit data provided in Walke et al. 2009b)

Table 6-6: Repository and Geosphere Sorption Coefficients

Element/ Substance	Concrete and Cement (m^3 kg^{-1})	Bentonite/ Sand (m^3 kg^{-1})	Asphalt and Engineered Fill (m^3 kg^{-1})	Limestone and Dolostone (m^3 kg^{-1})	Shale (m^3 kg^{-1})
C	0.001	0	0	0	0
Ni	0.01	0.1	0	0.05	0.05
Zr	1	0.1	0	0.05	0.05
Nb	0.1	0.1	0	0.05	0.05
U	1	0.5	0	0.7	0.05
Np	1	0.5	0	0.7	0.05
All other elements/ substances	0	0	0	0	0

7. RESULTS AND DISCUSSION

This section presents safety assessment results that demonstrate how the DGR performs in respect of its criteria (Section 3.4) and the associated safety functions and arguments (Section 3.5). Results are presented for the Normal Evolution Scenario and the Disruptive Scenarios. A public dose constraint of 0.3 mSv a^{-1} has been defined for normal evolution of the system, while a public dose criterion of 1 mSv a^{-1} 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 long half-life of some radionuclides, and the slow groundwater and gas movement, impacts are calculated out beyond 1 Ma to provide evidence that the peak impacts have been identified (consistent with Canadian regulatory policy P-290, CNSC 2004). Over such long time periods, the results should be seen as indicative and not predictive, and complementary assessment end points (e.g., contaminant fluxes, groundwater travel times) are used as well as the principal assessment end points (i.e., radiation dose and environmental concentrations).

The results are presented in graphical and tabular format using a variety of approaches. Where possible, results presentations are limited to the data ranges that are physically relevant. However, in some cases it is necessary to present very low results, which in the case of some concentrations can be below detectable limits, in order to allow effective comparison of different calculation case results.

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 analysed in the supporting reports for the Normal Evolution Scenario (Walke et al. 2009a), Disruptive Scenarios (Penfold and Little 2009), Groundwater Modelling (Avis et al. 2009) and Gas Modelling (Calder et al. 2009).

A summary of the calculation cases considered in the Version 1 SA is given in Table 7-1. Further details concerning these cases are given in Appendix A. The ID scheme used is as follows.

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
- OB – Open Borehole Scenario
- EE – Extreme Earthquake Scenario

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

- F2 – FRAC3DVS 2DR model
- F3 – FRAC3DVS 3DS model
- T – T2GGM
- A – AMBER

Table 7-1: Version 1 SA Calculation Cases

Calculation Case	Purpose	Code		
		FRAC3DVS	T2GGM	AMBER
Normal Evolution Scenario				
NE-BC-	Base case (static head, no change after 1 Ma, Guelph/Salina A0 and Salina A2 evaporite gradient)	-	T	A
NE-UG-BC-	Base case using latest geosphere data	-	T	A
NE-RS1-	Instantaneous re-saturation	F3	-	A
NE-UG-RS1-	Instantaneous re-saturation using latest geosphere data	F3	-	A
NE-RS2-	10 to 20 ka re-saturation	-	-	A
NE-RS3-	50 to 60 ka re-saturation	-	-	A
NE-RT-	Instantaneous release, no solubility limits and no sorption	-	-	A
NE-GG1-	Increased metals inventory	-	T	- (1)
NE-GG2-	Reduced degradation and corrosion rates	-	T	- (1)
NE-EDZ-	Increased K in EDZ	F2	T	A
NE-UG-EDZ-	Increased K in EDZ using latest geosphere data	F2	T	A
NE-UG-RD1-	Backfilling of access/ring tunnels with seal through access tunnel EDZ	F3	T	- (2)
NE-NHG-	No horizontal gradient in Guelph, Salina A0 or Salina A2 evaporite	F2 & F3	-	- (3)
NE-UG-NHG-	No horizontal gradient in Guelph, Salina A0 or Salina A2 evaporite but transient and with latest geosphere data	F3	-	- (3)
NE-GF-	Pathlength extended to 80 km in Guelph Formation	-	-	A
NE-UG-GT-	Modified gas transport parameters	-	T	- (1)
NE-CC-	Tundra climate	-	-	A
NE-EG-	Downstream exposure group	-	-	A
NE-NR-	Non-radioactive species	-	-	A
Human Intrusion Scenario				
HI-SR1-	Surface release for unsaturated DGR	-	-	A
HI-SR2-	Surface release for saturated DGR	-	-	A
HI-GR-	Release to shallow groundwater system	F3	-	A
HI-NR1-	Surface release of non-radioactive species for saturated DGR	-	-	A
HI-NR2-	Release to shallow groundwater system for non-radioactive species	-	-	A
Severe Shaft Seal Failure Scenario				
SF-ES1-	Failure of entire seal system from t = 0	F2	T	A
SF-UG-ES1-	Failure of entire seal system from t = 0 using latest geosphere data	F2	T	- (2)
SF-US-	Failure of upper (shallow and intermediate bedrock groundwater zones) seal system only	F2	T	A
SF-NR-	Non-radioactive species with total failure of seal from t = 0	-	-	A
Open Borehole Scenario				
OB-BC-	Base case for open borehole	F3	-	A
OB-NR-	Non-radioactive species	-	-	A
Extreme Earthquake Scenario				
EE-BC-	Base case for earthquake	F3	-	A
EE-NR-	Non-radioactive species	-	-	A

Notes

1. T2GGM case allows impact on gas fluxes to be assessed.
2. FRAC3DVS and T2GGM cases allow impact on groundwater and gas fluxes to be assessed.
3. FRAC3DVS case allows impact on groundwater fluxes to be assessed.

Other letters (and number) – unique identifier to indicate the particular case being considered:
- UG – base case using updated geosphere data (based on preliminary information from DGR-3 and DGR-4)
- BC – base case using reference geosphere data (based on information from DGR-1 and DGR-2)
- RS – repository resaturation variant
- RT – radionuclide transport variant
- GG – gas generation variant
- EDZ – excavation damaged zone variant
- RD – repository design variant
- NHG – no hydraulic gradient variant
- GF – Guelph/Salina A0 and Salina A2 evaporite Formations variant
- GT – gas transport variant
- CC – climate change variant
- EG – exposure group variant
- NR – non-radioactive species variant
- SR – surface release (for Human Intrusion Scenario)
- GR – groundwater release (for Human Intrusion Scenario)
- ES – entire shaft failed (for Severe Shaft Seal Failure Scenario)
- US – upper (shallow and intermediate bedrock groundwater zones) shaft failed (for Severe Shaft Seal Failure Scenario)

7.1 NORMAL EVOLUTION SCENARIO

The normal evolution scenario considers two geosphere models. The BC model uses low host rock permeabilities inferred from the DGR-1 and DGR-2 boreholes; an updated geosphere (UG) model uses much lower host rock permeabilities inferred from DGR-3 and DGR-4 boreholes and supported by the results of Phase 1 groundwater modelling (Sykes et al. 2008). In addition, a steady state vertical hydraulic gradient is conservatively assumed present due to the 140 m hydraulic head in the Cambrian sandstone. The current underpressure in some Ordovician rock formations is assumed to have quickly dissipated.

In the following sub-section particular emphasis is given to these base cases:
- NE-BC (NE-BC-A) – base case with low permeable deep geosphere, horizontal flow in Guelph/Salina A0/Salina A2 evaporite, slow resaturation
- NE-UG-BC (NE-UG-BC-A) – base case plus very low permeable deep geosphere, horizontal flow in Guelph/Salina A0/Salina A2 evaporite, very slow resaturation.

Another calculation case, NE-RS1 (NE-RS1-A), is used to compare with the above base cases. This case is the same as NE-BC, with the exception that the repository is fully resaturated immediately after closure. As such, this case is not realistic, but is used for comparison purpose.

These three cases have been selected since they span a range of geosphere and repository conditions. The case NE-UG-BC is presently considered to be the closest to representing the site's deep geologic conditions, while NE-BC and NE-RS1 are more conservative models. The results from the other calculation cases considered for the Normal Evolution Scenario are presented to illustrate the discussion in Section 7.3 (assessment of safety functions and arguments), Section 7.4 (analysis of design variants) and Section 7.5 (analysis of uncertainties), and in more detail in the Normal Evolution Scenario analysis report (Walke et al. 2009a).

7.1.1 Containment of Contaminants in the Repository

The cumulative release of activity from the waste to the repository is shown in Figure 7-1, with the associated repository saturation in Figure 7-2. Figure 7-1 illustrates the magnitude and timescale of the release of the disposed inventory from the waste packages. Note, however, that it takes no account of subsequent radioactive decay. The total activity disposed at 2062 is about 1.6 x 10^7 GBq. For NE-BC (repository resaturation at around 1 Ma), around 1.6 x 10^6 GBq (9.7%) is released from the wastes to gas and groundwater in the repository over the assessment period. The other 90.3% is lost through radioactive decay within the waste packages. Containment of radionuclides within the waste packages is a function of the wasteform (e.g., congruent release of activation products with corrosion resistant stainless steels, Inconel and Zircaloy), the long repository resaturation time due to the low permeability geosphere, and to a lesser extent, the ILW packaging. The results (Figure 7-1) show:

- the release from ILW resin containers when they are over-topped by the rising water level in the NE-BC case after about 500 a;
- the impact of the assumed rockfall within the repository at 15 ka on the NE-BC and NE-RS1 cases, which crushes the ILW overpacks and enables a more rapid release of contaminants into the repository water (50% saturated for the NE-BC case); and
- the release of contaminants from the unsaturated wastes when the repository resaturates after 1 Ma in the NE-BC and NE-UG-BC cases.

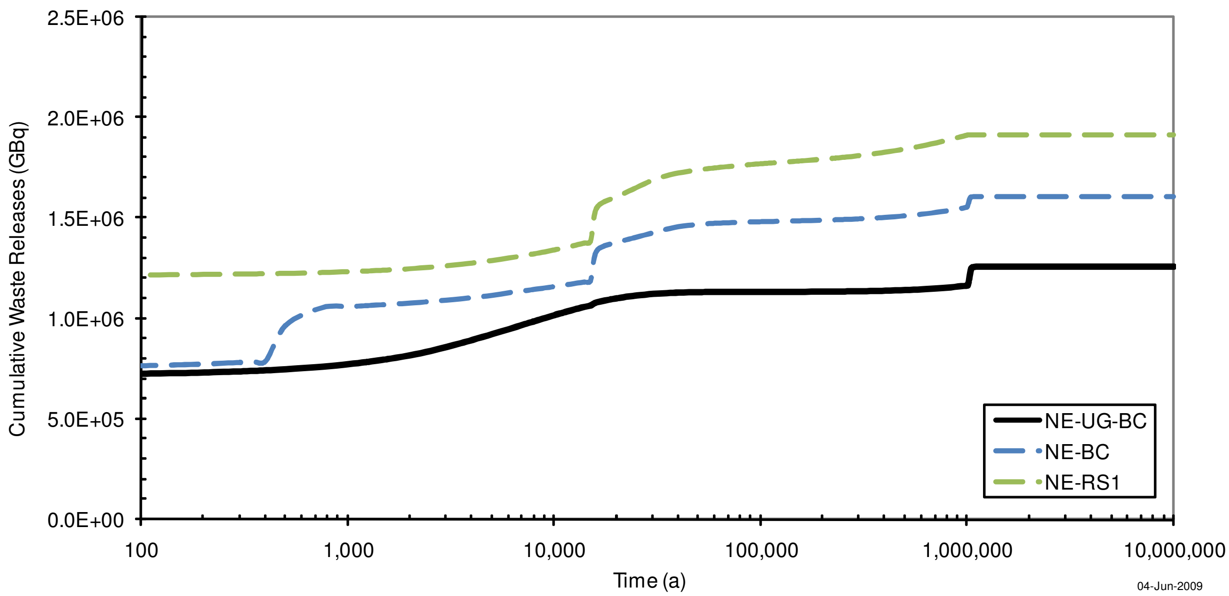


Figure 7-1: Cumulative Release of Activity from the Wastes to Groundwater and Gas in the Repository for the Normal Evolution Scenario

The cumulative release for NE-UG-BC (very low permeable deep geosphere) is lower than for the other cases, because the lower geosphere permeability means that there is no significant resaturation of the repository until after 1 Ma (see Figure 7-2), providing more time for radionuclides to decay in-situ. The water level does not over-top the ILW resin containers and the repository saturation has not exceeded 4% by the time of the rockfall, so no significant impact can be seen. The repository is traken to resaturate between 1 Ma and 1.05 Ma for the NE-BC and NE-UG-BC cases; the logarithmic scale means that the resulting 50 ka resaturation period is seen as a sharp rise after 1 Ma in Figure 7-2.

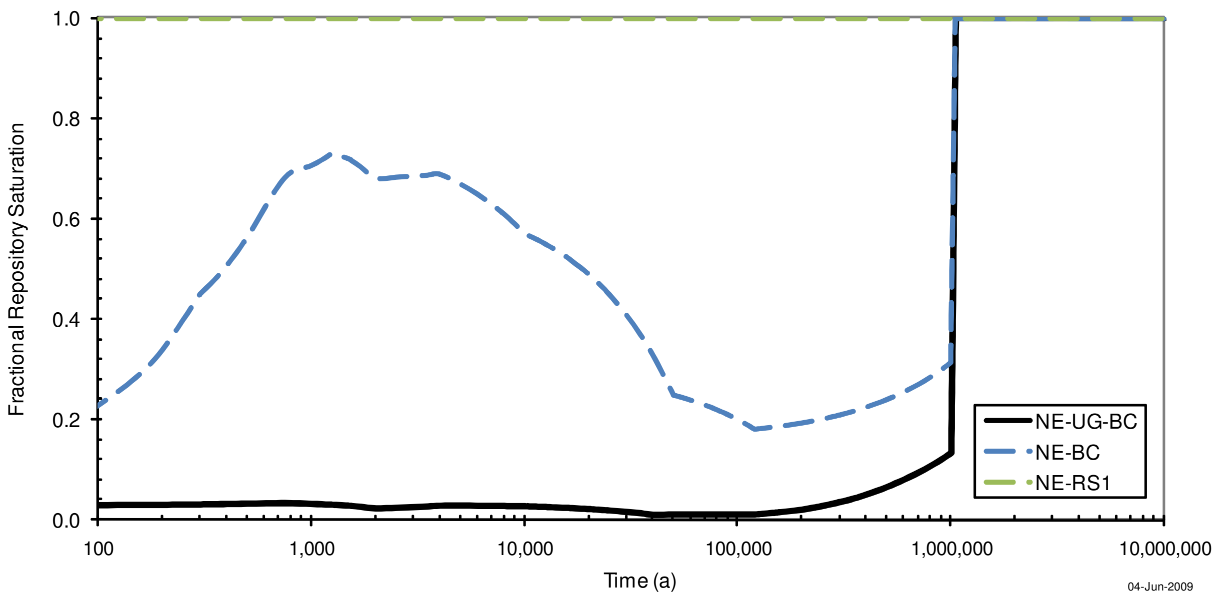


Figure 7-2: Fractional Repository Saturation for the Normal Evolution Scenario

The cumulative release curve for NE-RS1 (instant repository resaturation) shows more rapid release of radionuclides from the wastes compared with NE-BC and NE-UG-BC due to the assumed instant resaturation of the repository, with an associated release of available radionuclides from the low-level waste streams.

Figure 7-3 shows the cumulative radionuclide release as a fraction of the initial (2062) inventory for each waste stream; note that this figure takes no account of subsequent radioactive decay. This figure shows a clear distinction between the LLW streams, which release between 60-99% of their initial contamination and the ILW streams, which release significantly less (e.g., only 7% for the ILW resins). The lower fractional releases from the ILW waste streams are due to the concrete overpacks and/or slower release models (e.g., congruent releases for core components and retube wastes because radionuclides can only become available as the waste forms corrode).

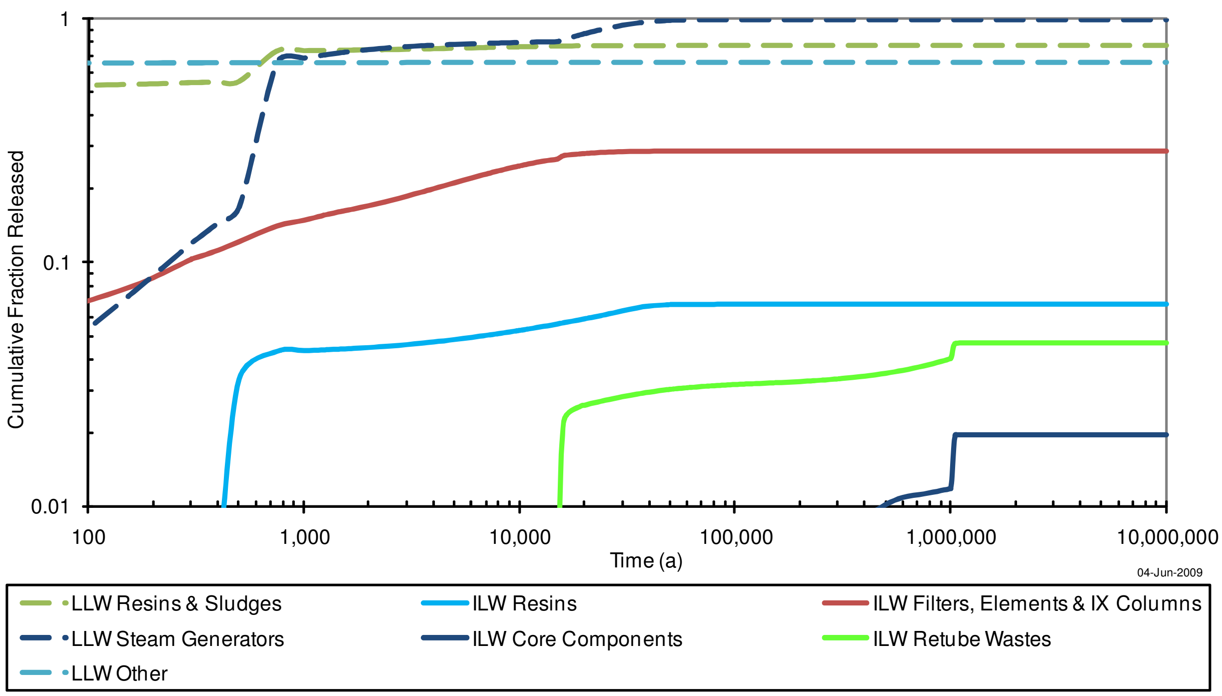


Figure 7-3: Cumulative Release of Activity from the Wastes to Groundwater and Gas in the Repository, as a Fraction of the Initial (2062) Inventory, by Waste Stream[22] for the NE-BC Case

[22] Note that some waste streams with similar release characteristics have been grouped.

Figure 7-4 shows the total activity in the wastes and released from the wastes over time and includes radioactive decay. The figure shows the greater retention of activity within the wastes for NE-UG-BC, due to the lower degree of repository saturation. The figure also shows that the amount released in the NE-BC case is similar to the case with instant resaturation (NE-RS1), once the water level reaches the top of the ILW resin containers and saturates these wastes after about 500 a. The resaturation of the repository for the NE-BC and NE-UG-BC cases, together with the completion of the congruent releases from the ILW pressure tubes and calandria tubes are evident in the releases that occur at around 1 Ma.

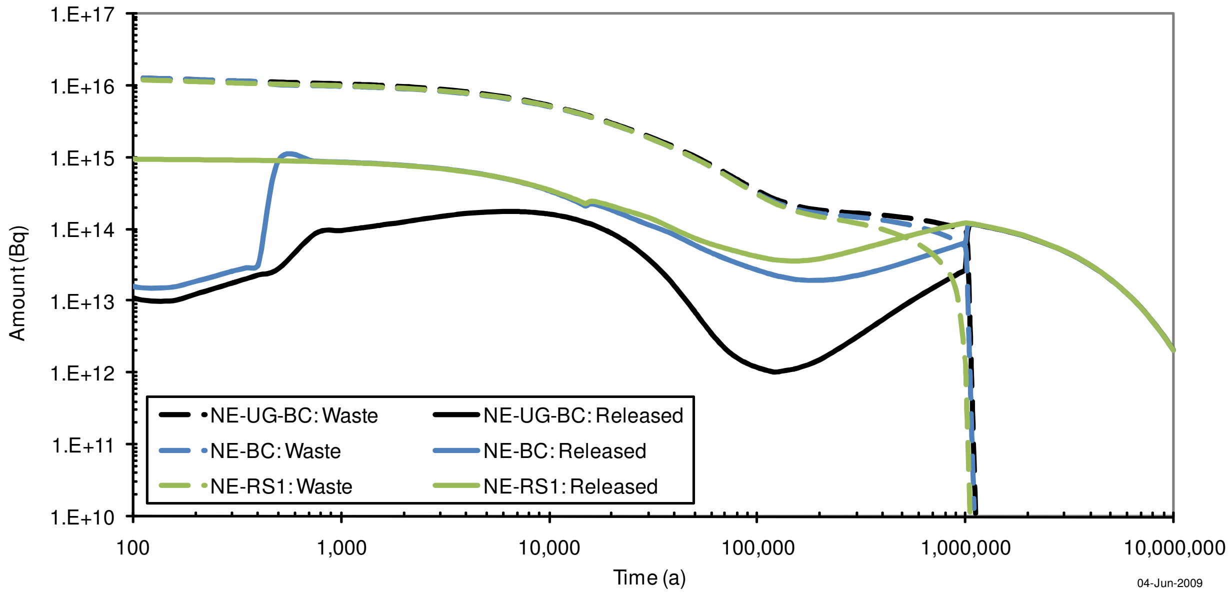


Figure 7-4: Total Activity in Waste and Released for the NE-BC, NE-UG-BC and NE-RS1 Cases

Some radionuclides are released in both the aqueous and gaseous phases. C-14 (half-life 5730 a) is the most important of these, with the gas phase being relatively important (Figure 7-5). C-14 is released from the wastes as CO_2 and CH_4 gases, and as CO_3^{2-} and HCO_3^{-} in repository groundwaters. Detailed modelling (Calder et al. 2009) shows that, in the water phase, C-14 will be trapped in siderite precipitates and is subsequently unavailable for gas or groundwater release from the repository[23]. The detailed gas modelling also shows that no bulk gas reaches the surface for the NE-BC and NE-UG-BC cases.

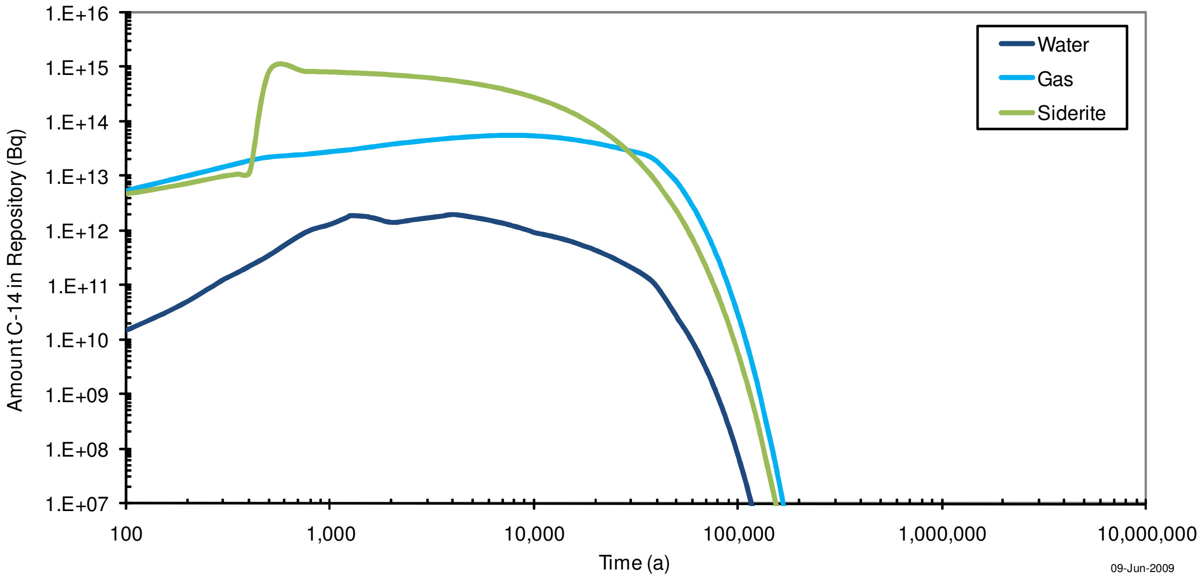


Figure 7-5: Partitioning of C-14 Releases between Water, Gas and Siderite in the Repository for the NE-BC Case

[23] The trapping of C-14 in siderite is represented in the model by 15% of the C-14 in the waste being locked away in siderite as it becomes saturated, based on the distribution of carbon forms in the detailed modelling. The amount of C-14 in siderite in Figure 7-5 therefore represents both C-14 in siderite and C-14 in water that ends up as siderite. The increase in the amount in siderite after about 500 a occurs as a result of the water over-topping the ILW resin overpacks and the resulting saturaton and associated release of C-14 from the wastes, particularly the moderator resins, which contain the bulk of the C-14 inventory.

Figure 7-6 shows the fraction of the disposed inventory that is released from the repository to the shafts and geosphere for the NE-BC, in comparison with the NE-RS1 and NE-UG-BC cases. Table 7-2 details the cumulative fluxes to the shafts and geosphere. Only 0.007% of the disposed inventory is released to the shaft and geosphere for the NE-BC, the majority (99.7%) of which is released to the geosphere rather than to the shafts and their EDZs. The potential for gaseous releases means that initial releases for the NE-BC case exceeds that of the instant saturation case (NE-RS1), for which there are no gaseous releases. The percentage released from the DGR remains extremely small for all three cases, with the ultimate amounts released for the NE-BC and NE-RS1 being very similar, whilst that for the NE-UG-BC, 0.002%, is even lower.

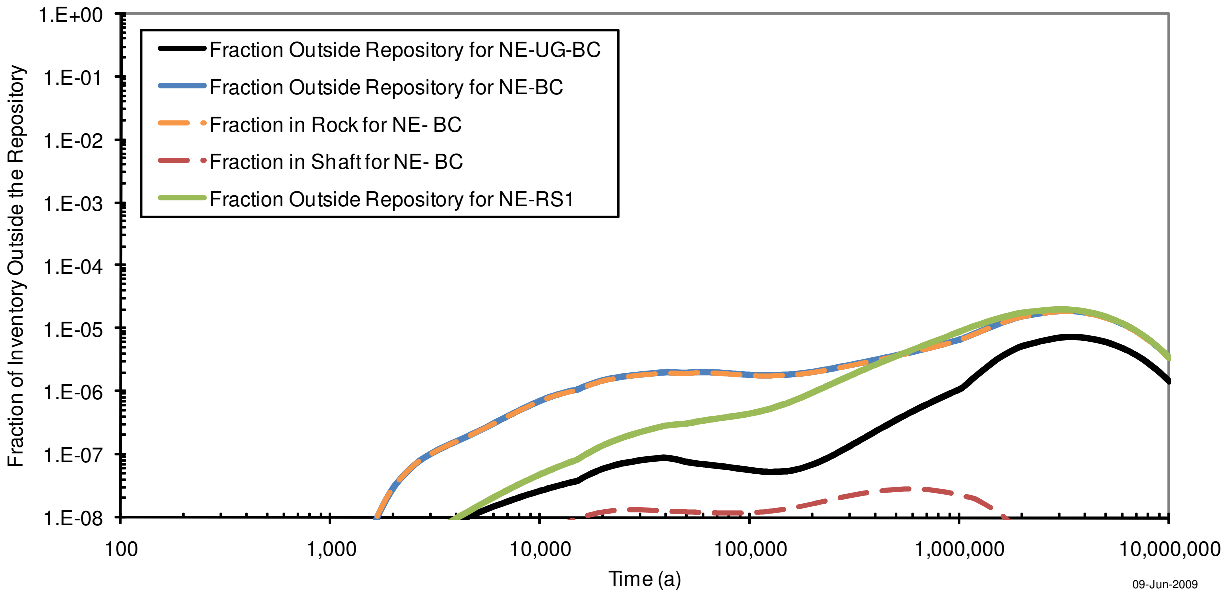


Figure 7-6: Fraction of the Disposed Inventory Outside the Repository for the NE-BC, NE-UG-BC and NE-RS1 Cases

Table 7-2: Total Cumulative Radionuclide Fluxes from the Repository after 10 Ma for the NE-BC, NE-UG-BC and NE-RS1 Cases

Case	Release	Cumulative Flux (Bq)	Percentage of Total to Geosphere/ Shafts	Percentage of Initial Inventory
NE-BC	Groundwater to shafts Groundwater to geosphere	4.7E+08 3.9E+11	0.1% 99.9%	0.000003% 0.002%
NE-UG-BC	Groundwater to shafts Groundwater to geosphere	4.5E+09 1.2E+12	0.4% 99.6%	0.00003% 0.007%
NE-RS1	Groundwater to shafts Groundwater to geosphere	3.7E+09 1.1E+12	0.3% 99.7%	0.00002% 0.007%

Figure 7-7 shows the fraction of the disposed inventory released to the geosphere/shafts for each radionuclide, excluding in-growth of progeny. As expected the fraction is low for many radionuclides, but for long-lived radionuclides such as I-129 (half-life 15.7 Ma) and Pu-242 (half-life 0.37 Ma), a significant fraction of the inventory is ultimately released from the repository to the geosphere/shafts. Some longer-lived radionuclides, such as Zr-93 (half-life 1.53 Ma) and Nb-94 (half-life 20.3 ka) are more effectively retained due to the majority of their activity being disposed in retube waste streams, which slowly release their contamination, and due to their sorption in the repository.

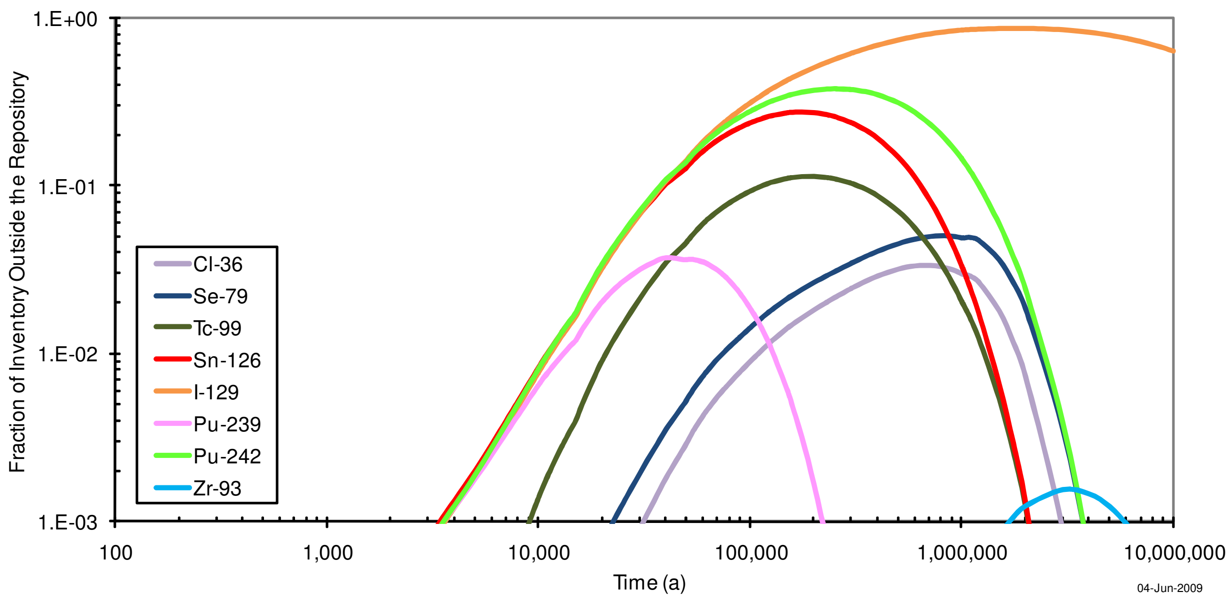


Figure 7-7: Fraction of the Disposed Inventory Released to the Geosphere/Shafts with Time for the NE-BC Case

7.1.2 Containment of Contaminants in the Geosphere and Shafts

Figure 7-8 illustrates the containment provided by the shafts and host rock for the groundwater pathway. The figure shows that peak calculated volumetric concentrations in the rock and groundwater in the Shallow Bedrock Groundwater Zone are:

- extremely small (0.001 Bq m^{-3}), about eleven orders of magnitude lower than that in the water in the DGR; and
- do not occur until about 1 Ma after the peak concentrations in the DGR.

Assessment model groundwater results are corroborated by detailed groundwater model results for Cl-36 (see Section 7.5.2.1). Figure 7-9 shows the cumulative Cl-36 masses calculated with the detailed groundwater modelling code FRAC3DVS at two levels in the geosphere: the top of the deep groundwater flow system (top of Queenston Shale) and the top of the intermediate flow system (Salina F). The cumulative mass transport to the top of the deep groundwater flow system at 1 Ma is about 0.1 g, representing approximately 0.02% of the initial inventory. The mass leaving the intermediate groundwater flow system is significantly further reduced to about 10^{-4} g, or 0.00002% of the initial inventory.

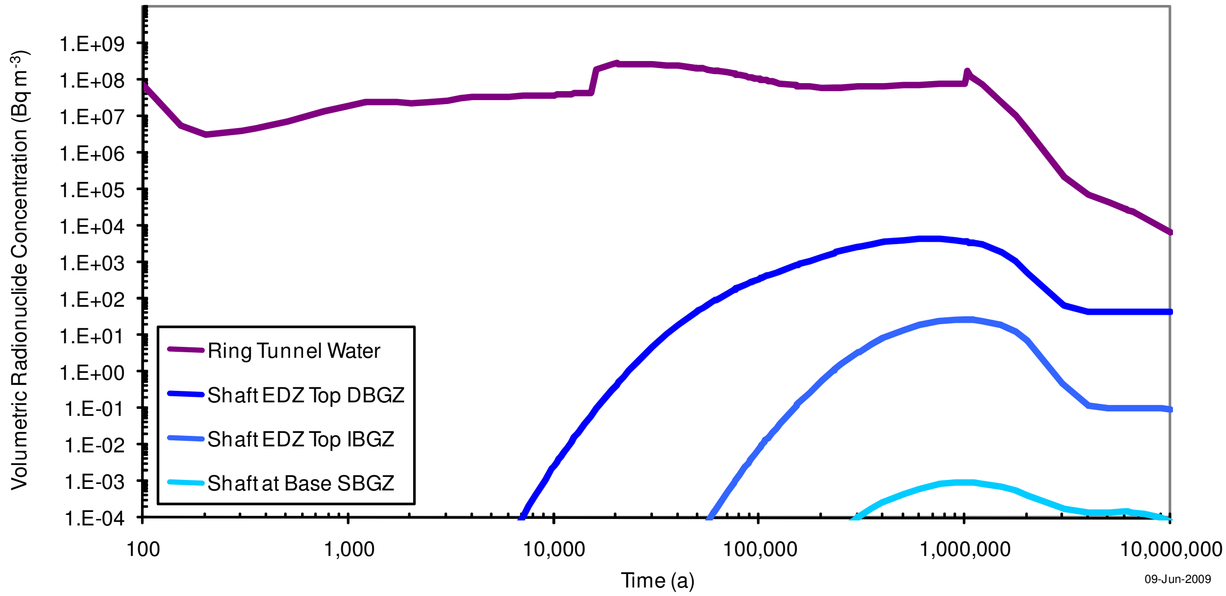


Figure 7-8: Total Calculated Concentrations in the Geosphere and Shafts (Rock and Groundwater) for the NE-BC Case[24]

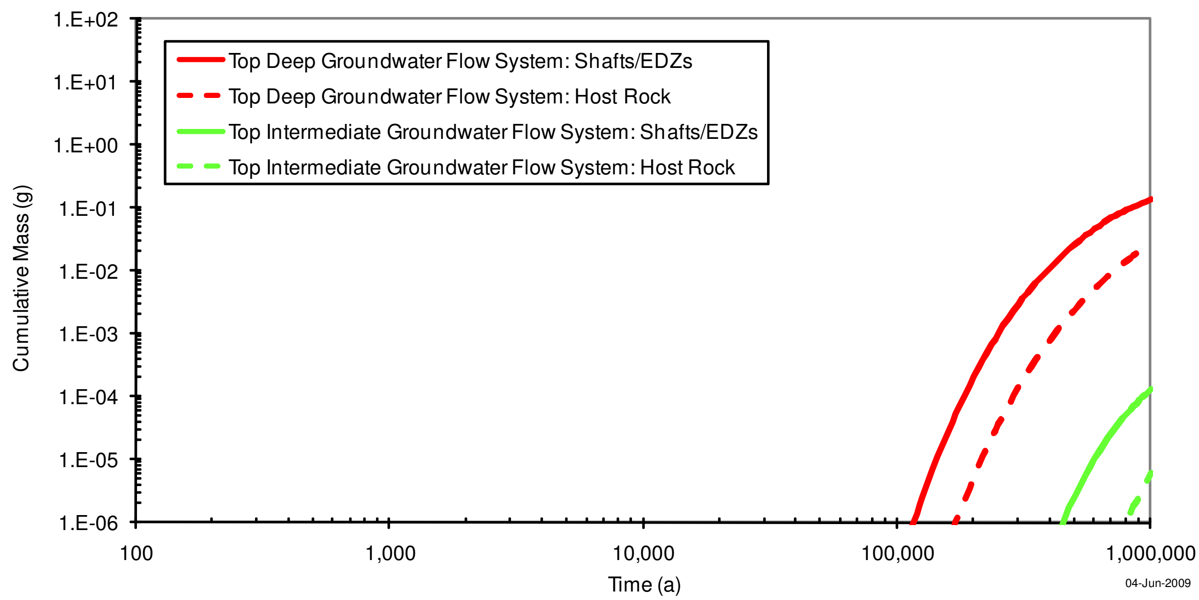


Figure 7-9: Detailed Groundwater Modelling Results - Cumulative Cl-36 Mass Transport for the Normal Evolution Scenario[25] (Avis et al. 2009)

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[24] Note the y-axis has been extended to below 1 Bq m^{-3} to display the calculated volumetric concentration at the base of the Shallow Bedrock Groundwater Zone, which are extremely small.

[25] Based on the results for the reference detailed case NE-RS1-F3 (Avis et al. 2009).

The groundwater travel time from the DGR to the point of well water abstraction can be implied from the relative time of peak concentrations of a long-lived radionuclide, such as I-129 (half-life 15.7 Ma). The peak calculated I-129 concentration in the groundwater within the DGR is observed after 99 ka for the NE-BC, whilst the peak calculated concentration at the location of the well occurs after 6 Ma, which implies a groundwater travel time from the DGR of 5.9 Ma. Most of the radionuclides in the disposed waste have half-lives that are significantly less than this travel time and therefore decay before reaching the well.

Figure 7-10 and Figure 7-11 show detailed modelling results with reference and updated geosphere properties (NE-RS1-F3 and NE-UG-RS1-F3, respectively), which illustrate the development of transport through the geosphere over the 1 Ma calculation period. The results show slow diffusion of Cl-36 outwards from the repository panels in all directions, with preferential transport evident up the shafts/EDZ system due to the steady-state vertical hydraulic gradient assumed in this case. By 500 ka, for the NE-RS1-F3 case, some Cl-36 has reached the Guelph Formation (note the log contours). The plot at 1 Ma shows the effectiveness of horizontal advective transport in the Guelph formation in reducing further upward transport in this case. For the case with the updated geosphere properties (NE-UG-RS1-F3), the lower hydraulic conductivities mean that Cl-36 is effectively shown to remain in the Deep Bedrock Groundwater Zone throughout the 1 Ma period modelled.

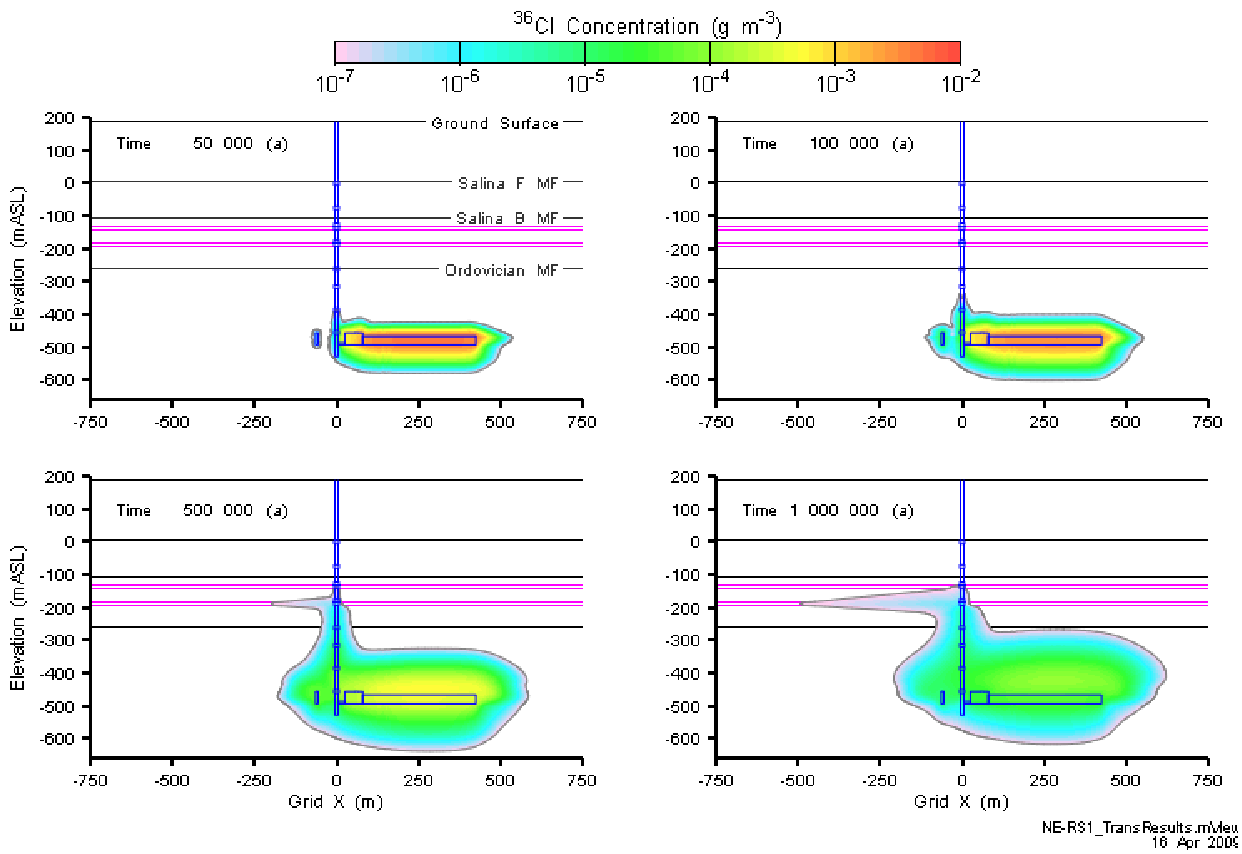

Figure 7-10: Detailed Groundwater Modelling Results - Cl-36 Mass Transport for the Normal Evolution Scenario (NE-RS1-F3 case)

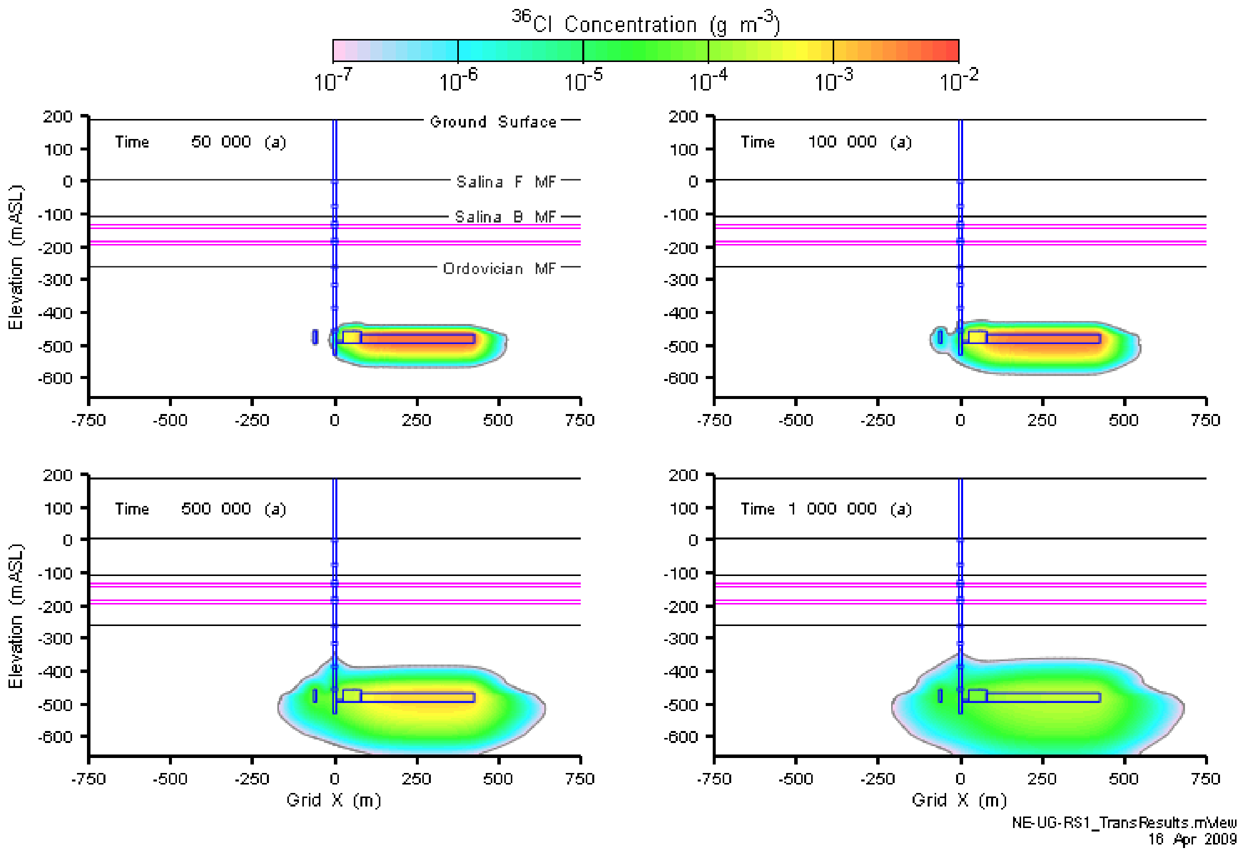

Figure 7-11: Detailed Groundwater Modelling Results - Cl-36 Mass Transport for the Normal Evolution Scenario with Updated Geosphere Properties (NE-UG-RS1-F3 case)

Groundwater radionuclide transport is slow in the Deep and Intermediate Bedrock Groundwater Zones due to the low geosphere hydraulic conductivity. The hydraulic conductivity of the Shallow Bedrock Groundwater Zone is much higher and radionuclides migrating from the intermediate to the shallow zone are significantly diluted within the shallow zone. This is illustrated in Figure 7-8, with peak radionuclide concentrations decreasing by more than four orders of magnitude between the shaft EDZs at the top of the intermediate zone and the shafts at the base of the Shallow Bedrock Groundwater Zone. There is a further decrease by more than two orders of magnitude in peak radionuclide concentrations between the shafts at the base of the Shallow Bedrock Groundwater Zone and the rock and groundwater down-gradient of the shafts at the top of the zone, where the well is located.

Figure 7-12 shows the total calculated radionuclide flux to the biosphere for the Normal Evolution Scenario. The figure shows that calculated releases to the biosphere are small and take a long time to occur, peaking at about 50 Bq a^{-1} after 1 Ma for the NE-BC and NE-RS1 cases and remaining below 1 Bq a^{-1} throughout the calculation period of the NE-UG-BC case. The main radionuclides reaching the biosphere are Cl-36 (half life 301,000 a) and subsequently I-129 (half life 15.7 Ma).

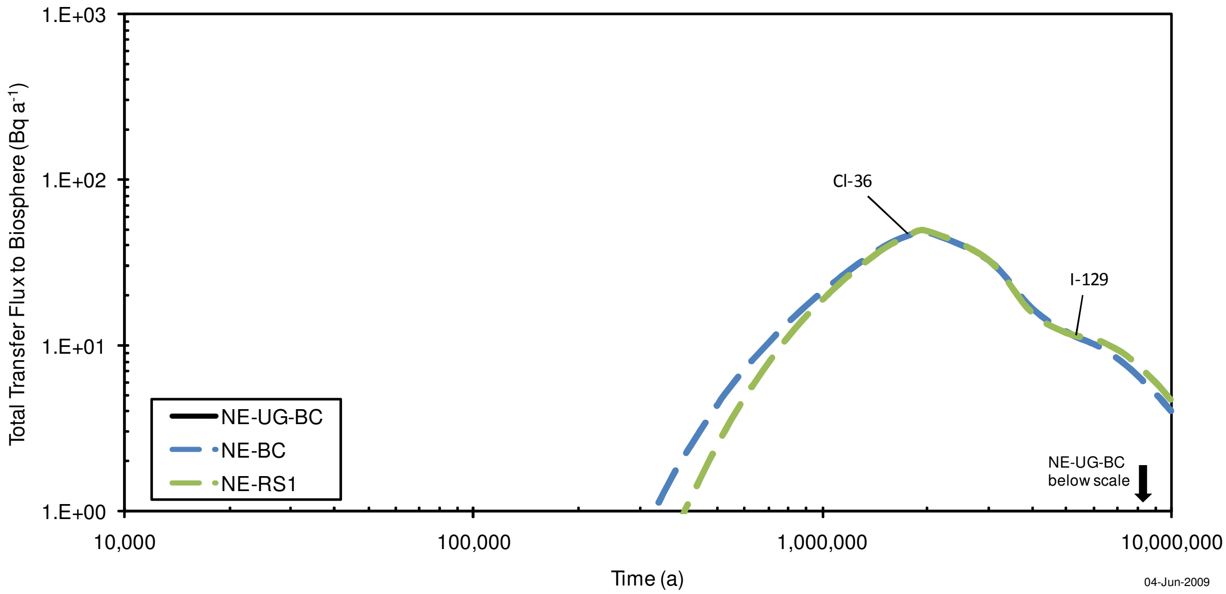

Figure 7-12: Total Radionuclide Fluxes to the Biosphere for the NE-BC, NE-UG-BC and NE-RS1 Cases

The fluxes to the biosphere via groundwater are further broken down by discharge pathway for NE-BC in Figure 7-13, which also shows the calculated groundwater fluxes from the DGR for reference. The groundwater fluxes to the biosphere are dominated by the calculated flux from the Guelph, Salina A0 and Salina A2 evaporite formations to Lake Huron, as this pathway intercepts much of the contamination migrating up the shafts. Nonetheless, the peak calculated flux via this pathway does not occur until about 2 Ma after the peak flux from the DGR, due to the time required for contaminants to reach the formations via the shafts. As a result, the peak calculated flux is less than 1% of the peak flux to the shafts from the DGR due to sorption, dispersion and radioactive decay. The Guelph, Salina A0 and Salina A2 evaporite formations can generally be considered to act as a barrier because:

- they intercept and reduces the radionuclide flux to the biosphere by the shaft/EDZ and local geosphere (as shown graphically in Figure 7-10);
- they effectively increases dilution and dispersion in the geosphere;
- they diverts part of the radionuclide flux into what are currently deeper lake waters, where there is greater dilution and dispersion; and
- the Guelph, Salina A0 and Salina A2 evaporite pathway is many tens of km long. The assessment model has conservatively assumed that a preferential pathway to the lake bed exists only 5 km from the site. There is no evidence that such a path (e.g., fault zone) actually exists. Therefore the model likely underestimates the role of the formations as a barrier.

The peak calculated fluxes to the biosphere via the Shallow Bedrock Groundwater Zone do not occur until about 1 Ma.

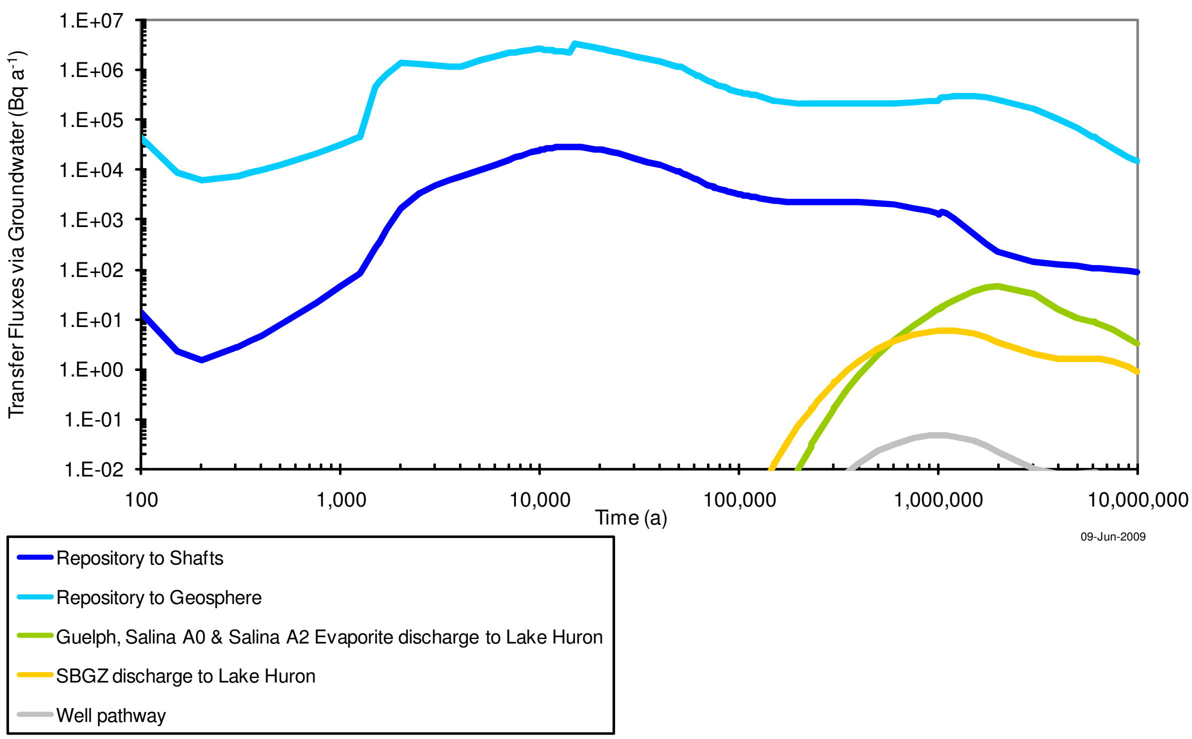

Figure 7-13: Total Radionuclide Fluxes via the Groundwater Pathway for the NE-BC Case

Figure 7-14 shows the key radionuclides for the groundwater pathway to the biosphere via the well for the NE-BC, NE-UG-BC and NE-RS1 Normal Evolution Scenario cases, which are also representative to the key radionuclides for the fluxes to Lake Huron via the shallow system. The extremely small magnitude of the releases is emphasised, which have been plotted to demonstrate the timescale and relative importance of radionuclides.

- The results for the NE-BC and NE-RS1 cases are very similar, with Cl-36 dominating the peak release after about 1 Ma, followed by the I-129, which peaks after about 6 Ma.
- The calculated results for the NE-UG-BC case are even smaller and remain below the chart scale throughout the assessed period.

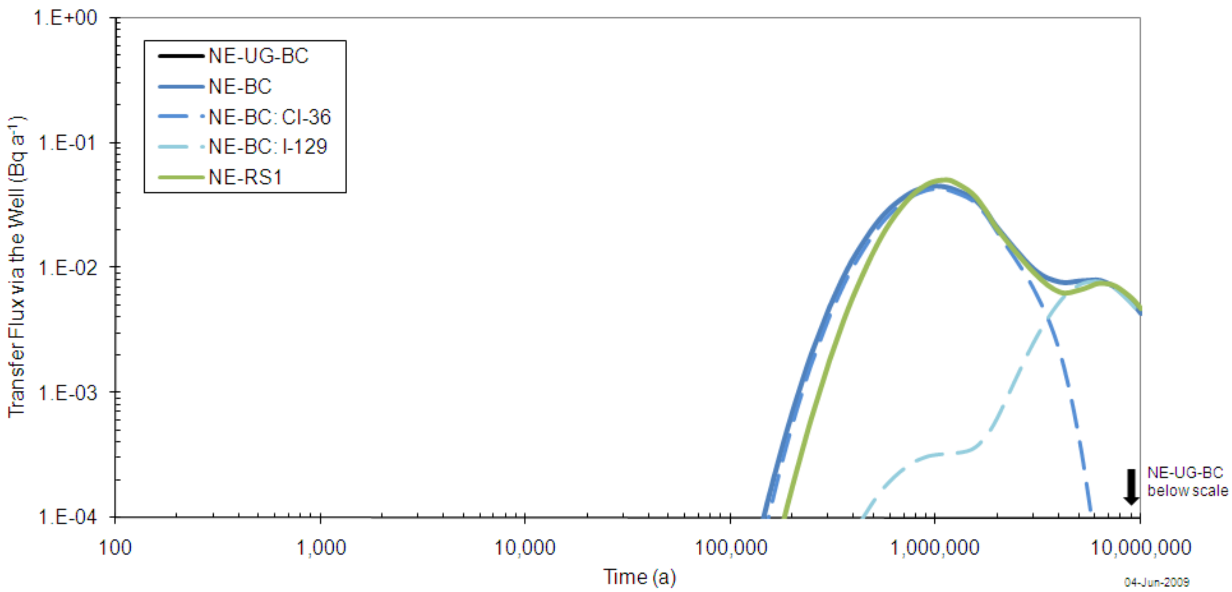

Figure 7-14: Aqueous Radionuclide Fluxes to Biosphere via the Well for the NE-BC, NE-UG-BC and NE-RS1 Cases

7.1.3 Impact of Contaminants

Although much of the activity will be contained and decay in the repository and geosphere, some will eventually migrate into the surface environment.

Figure 7-15 shows the total radionuclide activity in the modelled biosphere with time. Note that for all cases, the peak activity in the biosphere is at least nine orders of magnitude less than the total activity disposed in the DGR and at least seven orders of magnitude lower than the natural radioactivity in Lake Huron.

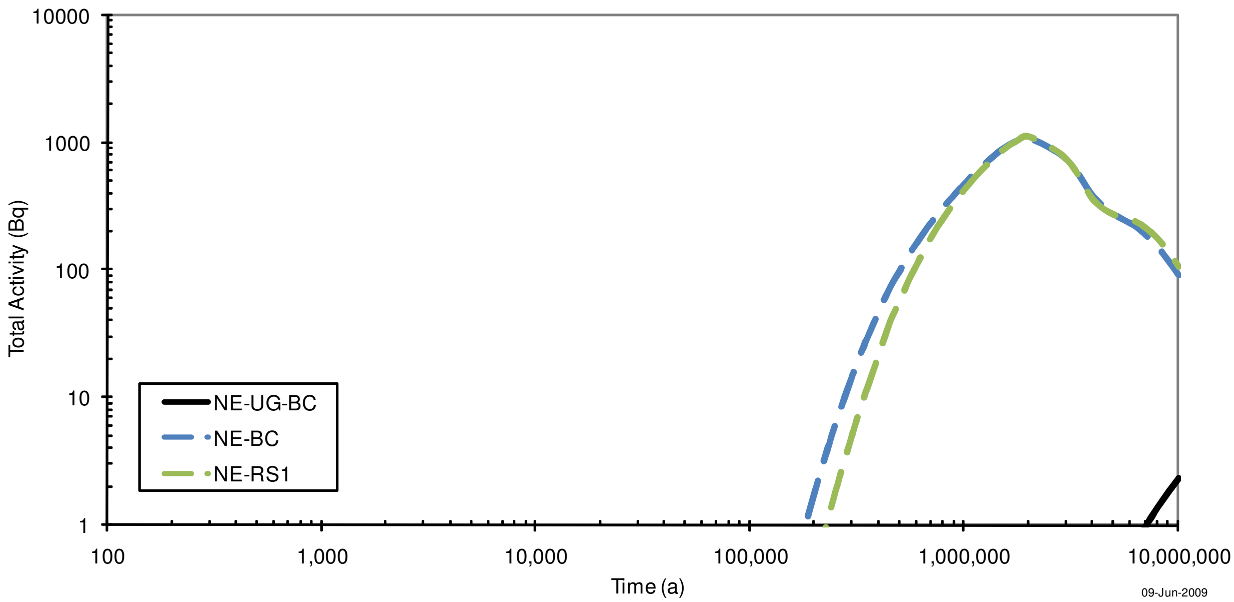

Figure 7-15: Calculated Total Activity in the Modelled Biosphere for the NE-BC, NE-UG-BC and NE-RS1 Cases[26]

[26] Modelled biosphere includes all of Lake Huron, but excludes contaminants that have left the system in flow downstream out of the lake. The total amounts are extremely small and have been extended to 1 Bq so that the calculated results for the NE-UG-BC case are included.

Only extremely low radionuclide concentrations are calculated for the biosphere. The results are shown in Figure 7-16 for illustrative purposes. The highest concentrations occur in the well water and irrigated soils, with the leading radionuclides reflecting those contributing to the fluxes to the biosphere.

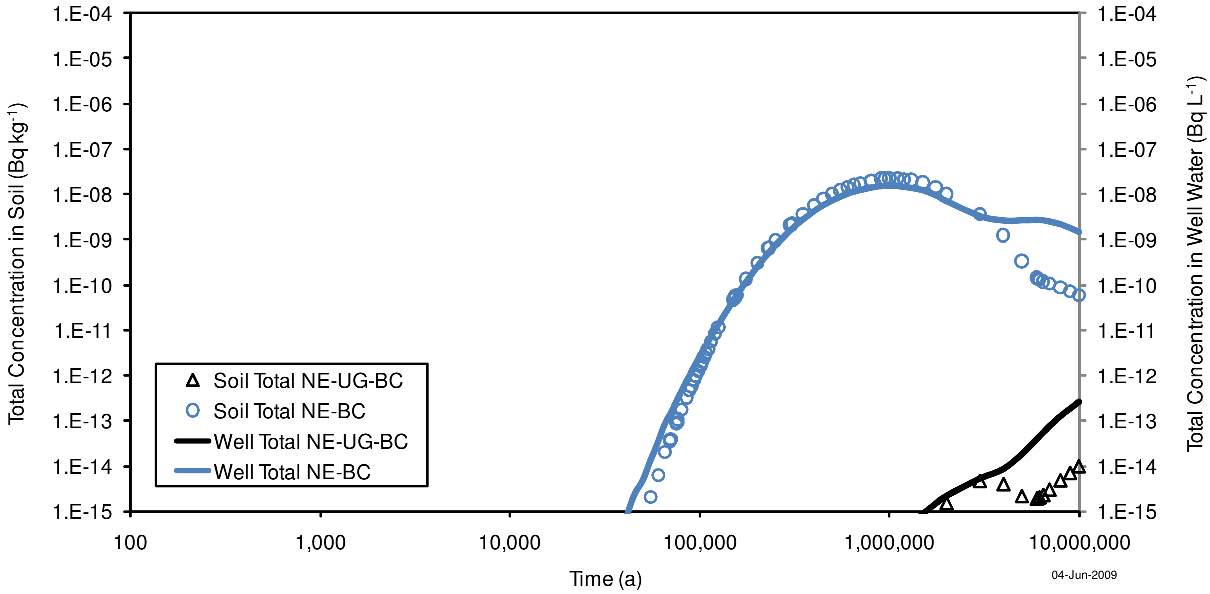

Figure 7-16: Calculated Total Radionuclide Concentration in Well Water and Irrigated Soil for the NE-BC and NE-UG-BC Cases[27]

Peak concentrations in the shore region of Lake Huron in the vicinity of the DGR location are very small - less than 10^{-9} Bq L^{-1} across the three cases (about one billionth of the natural activity of the lake water). Concentrations elsewhere in the lake are about three orders of magnitude lower than this and similar in the different lake compartments due to the relatively rapid mixing of lake waters in comparison to the slow release rate from the geosphere.

[27] Results are not shown for the NE-RS1 case, due to their similarity to the NE-BC case.

The total amounts and concentrations of activity in the biosphere are extremely low. This is reflected in the low calculated annual doses to an adult member of the local exposure group, shown in Figure 7-17, which are almost nine orders of magnitude below the dose criterion of 0.3 mSv a^{-1} for the NE-BC and NE-RS1 cases, with NE-UG-BC case (updated geosphere model) further four orders of magnitude lower. The peak calculated dose does not occur until about 6 Ma. The calculated peak annual doses to infants and children can be up to a factor of about three higher than those for adults for the NE-BC, but remain more than eight orders of magnitude below the dose criterion. The higher calculated annual doses to the children and infants are due to a combination of a greater ingestion rate of cow's milk and higher dose coefficients.

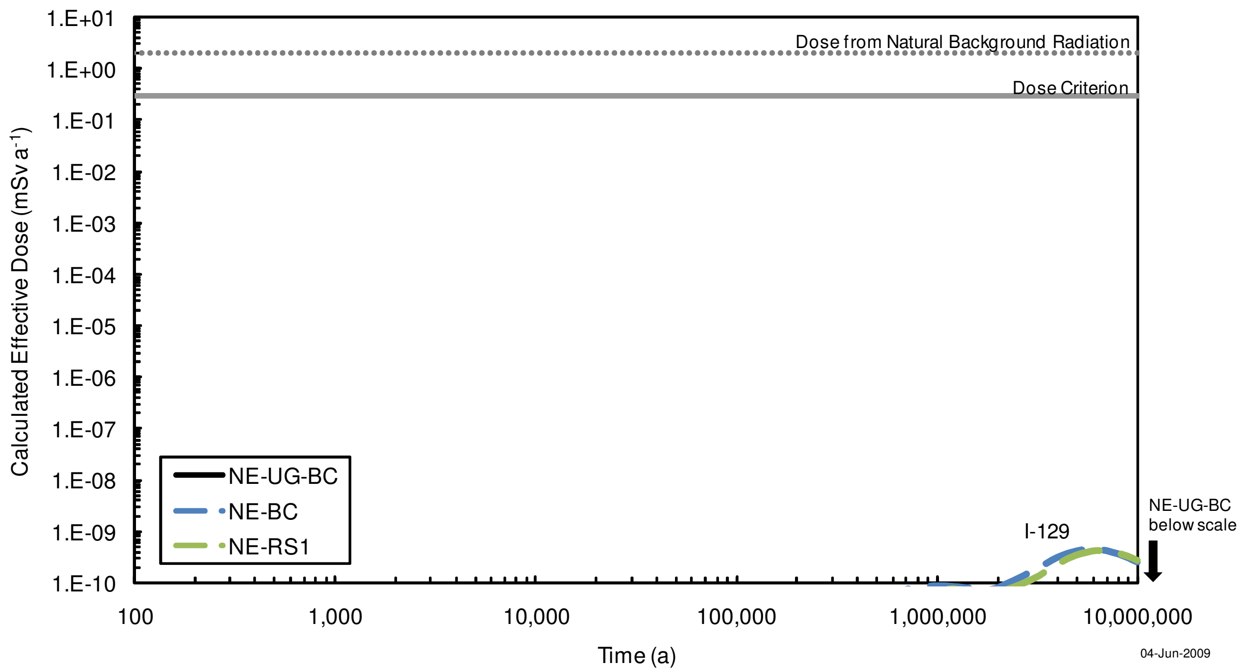

Figure 7-17: Calculated Total Dose for the Adult Member of the Local Exposure Group for the NE-BC, NE-UG-BC and NE-RS1 Cases

The peak calculated dose to the adult member of the local exposure group is broken down by exposure pathway in Table 7-3 for the NE-BC. The results are indicative of the main exposure pathways for cases NE-UG-BC and NE-RS1. The table shows that the ingestion of well water dominates, followed by the ingestion of animal and plant produce. The plant and animal pathways relate to the use of well water. Contamination of the well water therefore dominates calculated exposures over the release of contaminated groundwater to Lake Huron.

Table 7-3: Breakdown of Peak Calculated Local Adult Dose by Exposure Pathway for the NE-BC Case

Pathway	Contribution
Ingestion of water	60%
Ingestion of animal produce	33%
Ingestion of plant produce	6.4%
Ingestion of fish	0.1%
Ingestion of honey	0.03%
Incidental ingestion of soils/sediments	0.002%
External irradiation from soils/sediments	0.001%
Inhalation of Rn-222	<< 0.001%
Inhalation (excluding Rn-222)	<< 0.001%
External irradiation from immersion in water	<< 0.001%
External irradiation from air	<< 0.001%

Table 7-4 shows that the peak calculated radionuclide concentrations in various media in the surface environment are at least eight orders of magnitude lower than screening no-effect concentrations for non-human biota (Table 3-3). These are calculated nearest the repository where the concentrations would be highest. Therefore, the calculations indicate that the repository would have no impacts on non-human biota.

Table 7-4: Ratio of Peak Calculated Concentration of Radionuclides against No Effect Concentrations for Non-Human Biota for the NE-BC Case

Radionuclide	Media			
	Surface Water [1]	Soil [2]	Sediment [3]	Groundwater [4]
Cl-36	1.E-10	4.E-9	<1.E-10	<1.E-10
Ra-226	4.E-10	<1.E-10	<1.E-10	<1.E-10

Notes:

Results for other radionuclides for which no-effect concentrations are available are all less than 10^{-10}: C-14, Zr-93, Nb-94, Tc-99, I-129, Pb-210, Po-210, U-238 and Np-237.

1 Lake Huron water in the shore region close to the DGR;

2 Cropped soil, which receives potentially contaminated irrigation water;

3 Sediment associated with the Lake Huron shore region close to the DGR;

4 Well water abstracted from the Shallow Bedrock Groundwater Zone.

Calculations for non-radiological contaminants have been undertaken with the NE-BC. Table 7-5 shows that the peak calculated concentrations for all of the non-radioactive species considered are lower than the associated Environmental Quality Standard (Table 3-4), indicating that there would be no impacts from these non-radioactive species on humans and non-human biota for the NE-BC. The contaminants that get closest to the relevant standards are Cu and Pb in groundwater; however, the calculated peak concentrations remain less than 5% of the associated standards, even though the calculation is conservative, because it ignores solubility and sorption in the repository and geosphere, which could reduce concentrations potentially by orders of magnitude. Note also that, although no credit is taken for the natural decomposition/degradation of the organic species, the calculated concentrations are three or more orders of magnitude below the relevant EQSs.

Table 7-5: Ratio of Peak Calculated Concentration of Non-radioactive Species against Environmental Quality Standards for the NE-BC Case

Group	Species	Media			
		Groundwater [1]	Soil [2]	Surface Water [3]	Sediment [4]
Elements	Ag	3.E-07	<1.E-10	7.E-08	1.E-08
	As	1.E-06	<1.E-10	1.E-07	1.E-09
	B	6.E-08	6.E-09	2.E-08	-
	Ba	6.E-07	<1.E-10	-	-
	Be	2.E-06	<1.E-10	3.E-09	-
	Cd	7.E-04	3.E-10	7.E-04	2.E-05
	Co	6.E-06	<1.E-10	9.E-07	9.E-09
	Cr	3.E-03	2.E-10	1.E-03	3.E-05
	Cu	2.E-02	2.E-09	4.E-03	1.E-03
	Hg	2.E-05	<1.E-10	2.E-05	6.E-08
	I	-	-	3.E-10	-
	Mo	2.E-06	1.E-10	4.E-08	-
	Ni	<1.E-10	<1.E-10	<1.E-10	<1.E-10
	Pb	1.E-02	4.E-10	8.E-04	7.E-05
	Sb	7.E-05	2.E-10	2.E-07	-
	Se	4.E-07	<1.E-10	7.E-08	-
	Tl	5.E-08	<1.E-10	3.E-09	-
	U	<1.E-10	<1.E-10	<1.E-10	-
	V	1.E-05	<1.E-10	2.E-07	-
	W	-	-	1.E-08	-
	Zn	3.E-05	<1.E-10	9.E-06	3.E-06
	Zr	-	-	<1.E-10	-
Organic Species	Chlorobenzene and chlorophenols	3.E-05	<1.E-10	1.E-06	5.E-06
	Dioxins & Furans	3.E-04	3.E-10	5.E-10	-
	PAH	1.E-06	<1.E-10	5.E-06	2.E-07
	PCB	5.E-08	<1.E-10	4.E-07	5.E-08

Notes:

1 Well water abstracted from the Shallow Bedrock Groundwater Zone.
2 Cropped soil, which receives potentially contaminated irrigation water.
3 Lake Huron water in the shore region close to the DGR.
4 Sediment associated with the Lake Huron shore region close to the DGR.
- No value given in Table 3-4.

7.2 DISRUPTIVE SCENARIOS

The likelihood of the disruptive events initiating the Disruptive Scenarios considered in the assessment is expected to be lower than 10^{-5} a^{-1} (see discussion in Section 7.3 and the Disruptive Scenarios Analysis report, Penfold and Little 2009). The likelihood of the actual scenarios occurring is even lower as the scenarios make additional conservative assumptions, for example relating to human practices and exposure mechanisms. Nevertheless, it is informative to assess their potential radiological and non-radiological impacts to allow the robustness of the DGR system to disruptive events to be evaluated.

7.2.1 Human Intrusion

If an exploration borehole inadvertently struck the DGR, gas, water and suspended particulate could be released to the surface and result in exposure of people. It is assumed that the initial release of these media from the repository is rapid; therefore, the main results are based on calculated contaminant concentrations in the repository gas, water, waste and precipitated siderite ($FeCO_3$, corrosion by-product, contaminated with C-14). The calculations conservatively assume intrusion into the East Panel where concentrations are highest. The key contaminants include C-14, Ni-59, Nb-94 and Zr-93.

Figure 7-18 shows that the concentration of contaminants in the material that could be released via the borehole is high. The highest concentrations are in siderite, which is precipitated in the repository environment and may contain C-14. The model takes a portion (10%) of this material to be suspended in the repository water and transported to the surface. This factor is somewhat uncertain, although it is unlikely that a significant proportion of the contaminated siderite will be suspended in water. This is because in the stagnant conditions that will be prevalent in the DGR, siderite can form as an adherent film on ferrous surfaces, although it is also possible that an amorphous form may occur in lower pCO_2 conditions.

C-14 concentrations in siderite can be seen to increase sharply after 600 a when the waste containers for resins (which contain a large portion of the C-14 inventory) fail. The marked increase in aqueous concentrations at approximately 15 ka is a result of a rockfall that is modelled to occur at that time, resulting in complete failure of all ILW containers (Figure 7-18).

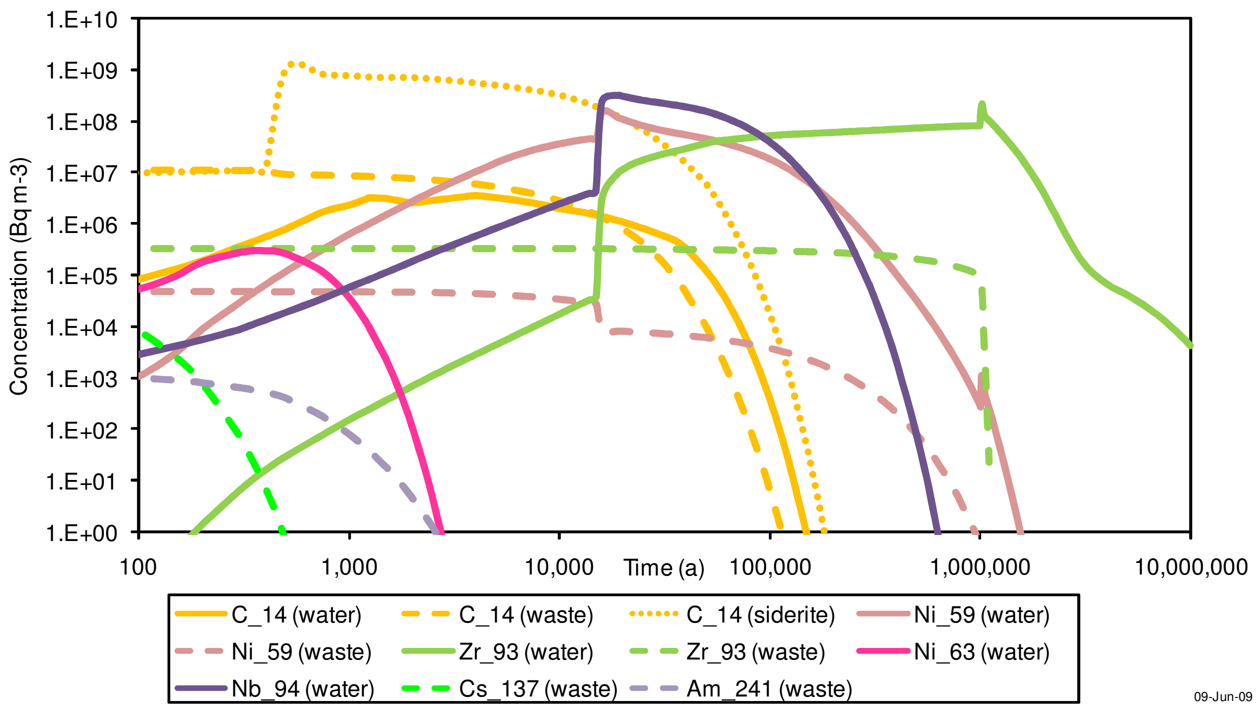

Figure 7-18: Concentrations in Repository Media that could be Released via an Exploration Borehole

The results shown in Figure 7-18 are based on the reference resaturation profile for the base case Normal Evolution Scenario. Assessment calculations have also been undertaken assuming that the repository is permanently resaturated immediately following closure. These do not show any significant differences in peak concentrations, although there is a more rapid release of contaminants in the first few hundred years.

A wide variety of exposure pathways could occur for the material released from the borehole, so a range of exposure groups have been assessed – the drill crew[28] 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 site residents farming on contaminated drill site soil afterwards (see Sections 6.2.2.4 and 6.2.2.5). Calculated doses for these exposure groups are shown in Figure 7-19. Note that all calculated doses decrease sharply after 1Ma when the repository is taken to resaturate completely. From this point, the concentrations in materials in the repository only decrease as contaminants diffuse into the surrounding rock.

[28] Both short-term exposure to undiluted slurry 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.

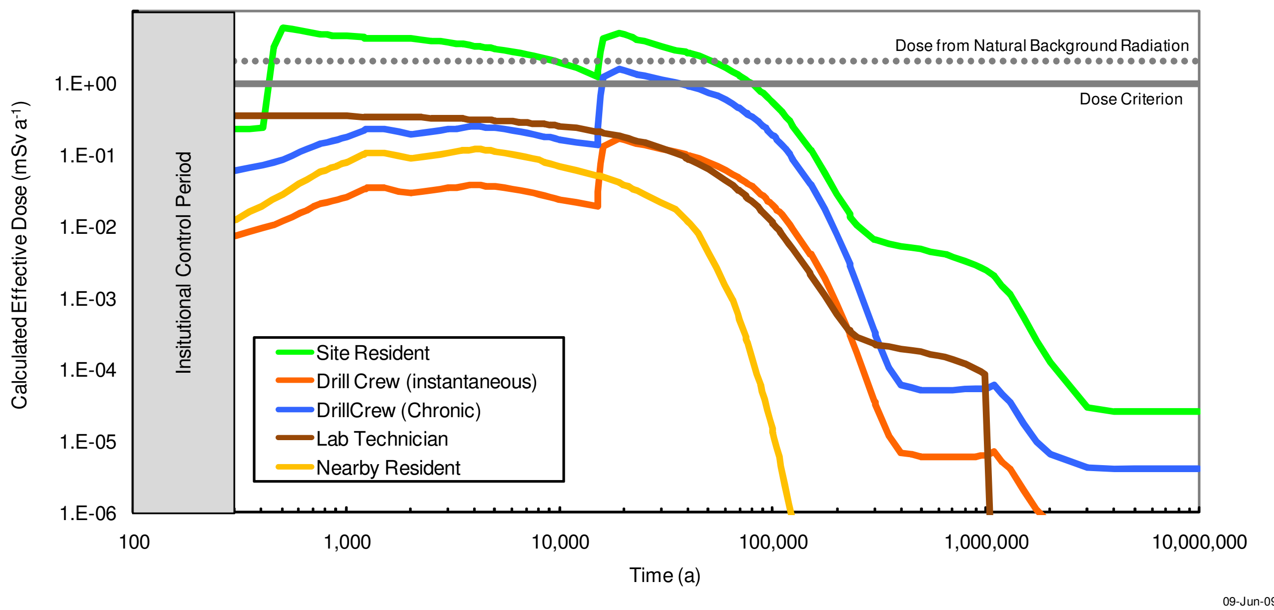

Figure 7-19: Calculated Doses to Exposure Groups following Intrusion of an Exploration Borehole into the East Panel

It is possible that some of the exposed groups that have been assessed could receive more than the dose criterion of 1 mSv a^{-1}. As noted in Section 3.4.2, the acceptability of such results should be 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. In this case, whilst it is impossible to be definitive about exposure scenario probability for future human actions, an estimate of the likelihood of intrusion into the emplacement rooms is 5×10^{-6} a^{-1}. Using a risk conversion factor of 0.073 Sv^{-1} (CNSC 2006), this implies a peak risk of developing a health or genetic effect of around 10^{-9} a^{-1} for the most exposed group (the site resident), well below the reference risk value of 10^{-5} a^{-1} (Section 3.4.2). Furthermore, the exposure mechanisms assessed are cautious in that current drilling standards (which would prevent much of the release from the borehole) are neglected, and the former drill site is also assumed to be rapidly re-used for growing crops and raising animals. In addition, if the intrusion event occurs after 80 ka, Figure 7-19 shows that the calculated dose for the site resident is below the dose criterion, even with these cautious assumptions.

In the case of the site resident[29], who is assumed to farm on the contaminated drill-site after drilling activities are finished, the radiation dose is dominated by ingestion of crops contaminated with C-14 in siderite brought up from the repository with drill slurry and released onto the drill site (contrary to current deep-drilling standards). This pathway is not relevant to the drill crew, whose peak dose is dominated by external irradiation by Nb-94 in water released from the repository. Prior to 15 ka, however, the exposure of the drill crew is dominated by inhalation of C-14 in gas released from the repository via the borehole.

[29] The site resident is distinct from the nearby resident. The former is assumed to live on the area contaminated with drilling slurry after the borehole has been abandoned. The latter is assumed to live 100 m from the drilling site while the borehole is under investigation.

Other exposure pathways are less significant. The examination of retrieved core (containing raw waste) is assessed via the "laboratory technician" exposure group. The "nearby resident" is assumed to inhale dispersed gas from the repository that has been released via the borehole. Despite conservative assumptions, calculated doses to both these exposure groups are below the 1 mSv a^{-1} criterion, if the intrusion were to occur.

Normal practice requires that the borehole is sealed once investigations are complete. However, the scenario considers "what if" the borehole is poorly sealed, resulting in the loss of contaminants into permeable geosphere horizons. In such a situation, detailed groundwater modelling (Avis et al. 2009) has shown that contaminated groundwater from the repository could be released directly to the Shallow Bedrock Groundwater Zone for a prolonged period, if there is a pressure difference between the water in the repository and the shallow zone. The borehole would then act as a pathway to circumvent the geologic and engineered barriers. Detailed groundwater modelling (Avis et al. 2009) has been undertaken to determine the rate and duration of the release of contaminated water from the repository by this pathway. Assessment calculations, shown in Figure 7-20, indicate that the pathway could lead to an increase in the potential annual dose when compared with the Normal Evolution Scenario (see NE-BC line on Figure 7-20). The calculated peak dose to an adult remains small, at about 0.001 mSv a^{-1}.

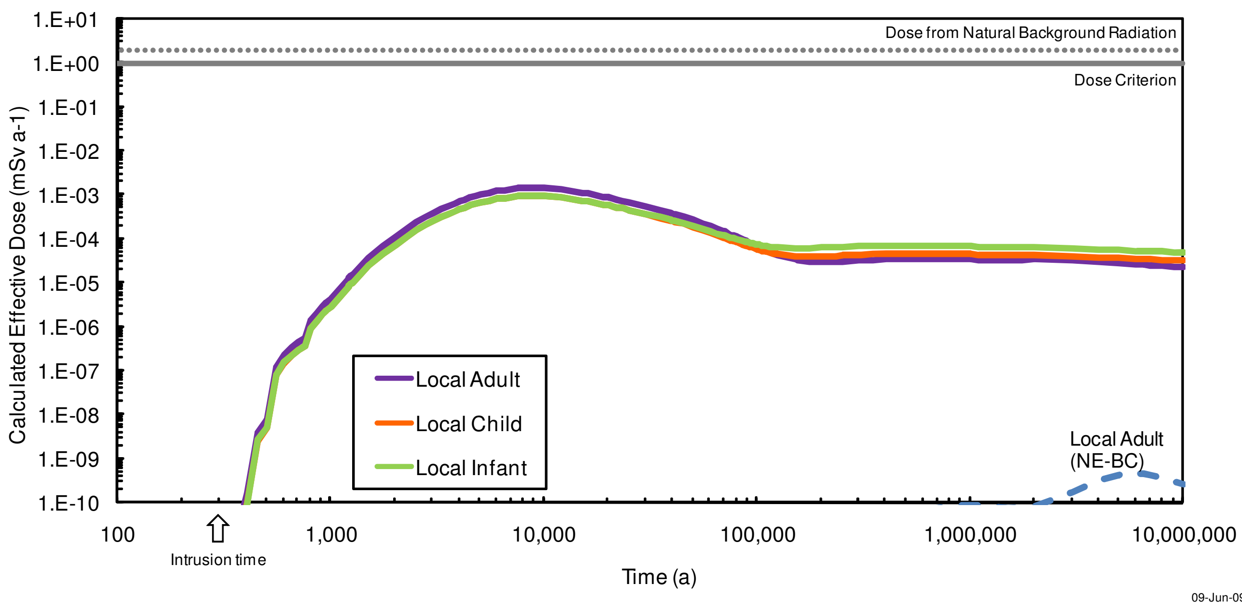

Figure 7-20: Calculated Doses to the Local Exposure Group if an Exploration Borehole Penetrates the East Panel 300 years After Closure, and is Poorly Sealed

The slurry produced from the intrusion borehole would contain high concentrations of various species from the waste. As per current practice, drilling slurry would not be used for any purpose and would be collected for disposal. If it were dumped, against current practice, on soil close to the drilling site, the soil concentrations would not exceed the Environmental Quality Standards (EQS) for any contaminants.

In the case of the release to the Shallow Bedrock Groundwater Zone, peak groundwater concentrations at the well could exceed EQS values for Cu (by about a factor of 6) and Pb (by about a factor of 3). However, these calculations have conservatively ignored any solubility limitation and sorption of these species in the repository. The likelihood of this case is very low because it requires accidental intrusion into the repository, and it assumes that the borehole is not subsequently sealed to current drilling standards. Furthermore, it is noted that soil irrigated from the well would not exceed EQS values.

Calculations for radionuclides show that concentrations in slurry-contaminated drill-site soil exceed the screening no-effect concentrations (Table 3-3) for a variety of contaminants, notably C-14 (a factor of 60), Cl-36 (factor of 2) and Nb-94 (factor of 40). However, the likelihood of this case is very low as it assumes that the drilling slurry is not managed to current drilling standards and that the soil is used for growing food and raising animals immediately after the intrusion event. Furthermore, the model is conservative as the contaminated slurry is dispersed in a relatively small area of soil.

7.2.2 Severe Shaft Seal Failure

The shaft seal is a key element of the DGR system. It includes multiple components utilising a variety 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 these barriers. In effect, the shafts are taken to be filled with a material with the characteristics of crushed rock. It is stressed that no process of credible likelihood has been identified which could lead to this situation.

The degraded shaft seal permits more rapid rates of contaminant migration through the shafts via water and gas pathways. Gas transport of C-14 shows a breakthrough time of 1500 a and transit time of 750 a, based on detailed gas modelling (Calder et al. 2009). Other contaminants also emerge in the Shallow Bedrock Groundwater Zone much earlier; for example, the peak release of Ni-59 occurs after about 35 ka in this case, compared with more than 1 Ma in the Normal Evolution Scenario. Figure 7-21 shows that the degradation of the shaft materials permits greater amounts of this contaminant to be released into the environment via the shafts and their associated EDZs than for the Normal Evolution Scenario.

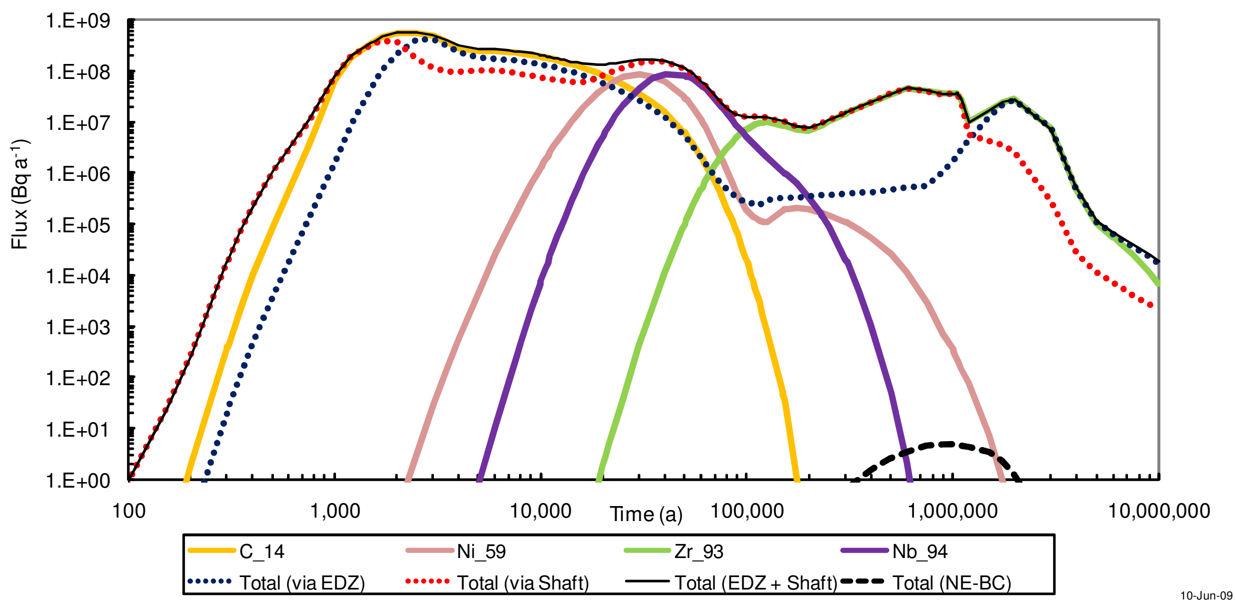

Figure 7-21: Comparison of Releases from the Shaft in the Severe Shaft Seal Failure Scenario and Normal Evolution Scenario (NES)

The consequences of the more rapid pathway from the DGR to the near-surface environment are shown in Figure 7-22, which illustrates that, for this "what if" case, calculated doses could reach 0.02 mSv a^{-1}. C-14 dominates the calculated doses up to 100 ka. The peak at 9 ka corresponds to the ingestion of C-14 in water and foodstuffs contaminated by groundwater released into the Shallow Bedrock Groundwater Zone via the shaft, pumped by the well and used to irrigate the crops. The annual dose beyond 100 ka relates to progeny in the U-238 decay chain (primarily Po-210).

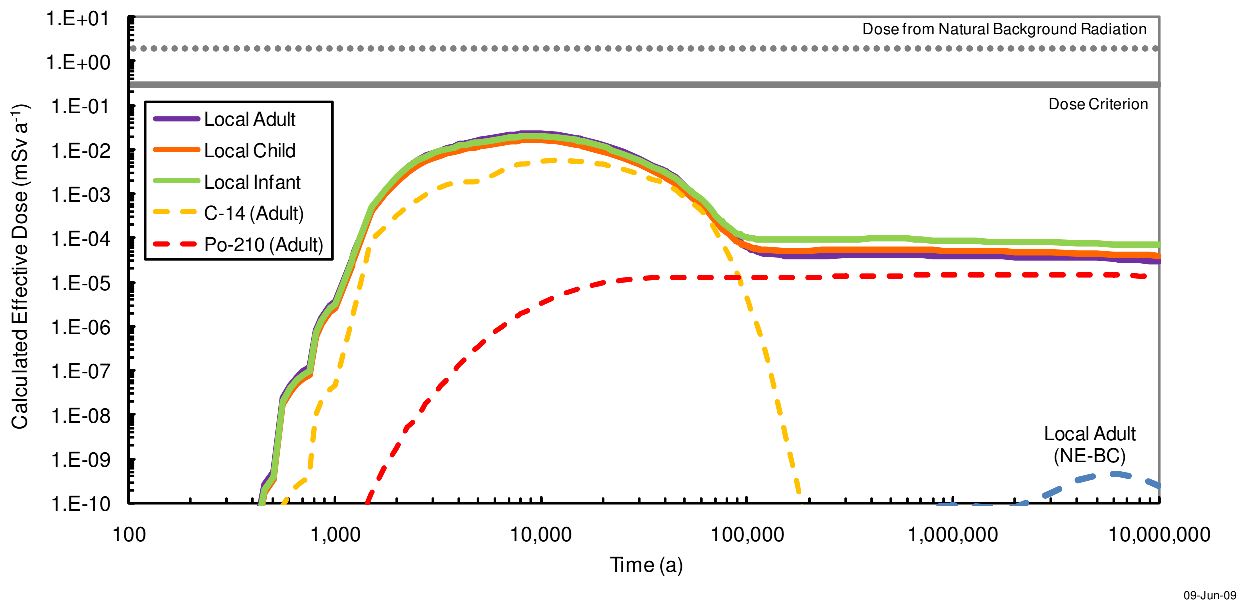

Figure 7-22: Calculated Doses to the Local Exposure Group for the Severe Shaft Seal Failure Scenario and Normal Evolution Scenario

Concentrations of four non-radioactive species in the well water (Cd, Cr, Cu and Pb) could exceed the relevant groundwater EQSs by up to a factor of 50. However, the Severe Shaft Seal Failure Scenario is a "what if" scenario that is on the bounds of plausibility. Furthermore, the calculation case has conservatively ignored any solubility limitation and sorption of these species in the repository, shafts and geosphere, and if these were introduced it would be expected that concentrations would be substantially decreased. Furthermore, calculations show that concentrations in the irrigated soil would not exceed the relevant soil EQS.

Peak calculated concentrations for the 11 radionuclides considered are all lower than the screening no-effect concentrations (Table 3-3), indicating that there are no effects on non-human biota for this scenario.

Whilst the results of this calculation case emphasise the importance of the shaft seal, it should be recognised that the scenario represents a bounding case regarding the performance of the engineered seals in the shafts.

7.2.3 Open Borehole

Site investigation and monitoring boreholes will be appropriately sealed at the end of their useful lifetime. However, if a borehole were not properly sealed, 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 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 (Avis et al., 2009) indicates that the fluxes of water are relatively small (17.5 m^3 a^{-1}), more than 5 orders of magnitude lower than occurs via the shaft and geosphere. The borehole has limited influence, because contaminants must diffuse laterally through 400 m of the very low permeability host rocks around the DGR before the borehole is reached. This is comparable to the distance over which contaminants must migrate upwards through the geosphere and shaft to reach the Shallow Bedrock Groundwater Zone.

The concentrations of non-radioactive contaminants in well water, soil and sediment are well below the relevant EQSs, and the concentrations of radionuclides in environmental media lie well below the screening no-effect concentrations. The calculated radiation doses do not differ to any significant degree from those calculated with the equivalent Normal Evolution Scenario case.

Figure 7-23 demonstrates that the results are unaffected by the presence of a poorly sealed borehole. The peak dose remains at 6.2 x 10^{-10} mSv a^{-1} at 6.2 Ma.

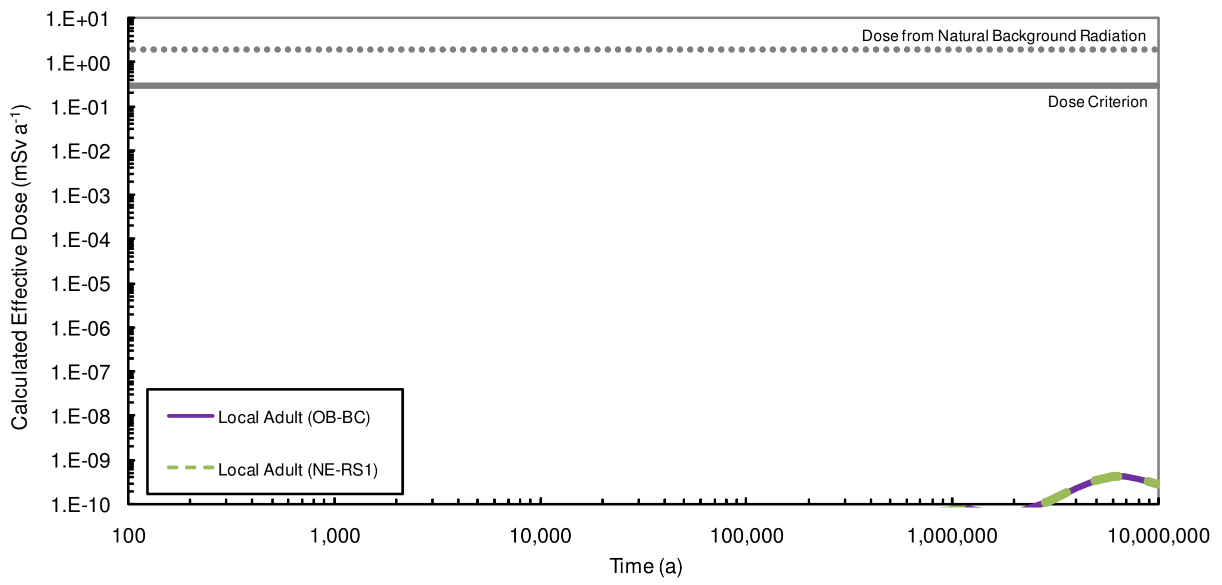

Figure 7-23: Calculated Effective Doses to the Local Exposure Group for the Open Borehole Scenario and Normal Evolution Scenario

7.2.4 Extreme Earthquake

Whilst some earthquakes are expected regionally over the timescales of interest, it is very unlikely that an earthquake would cause any degradation of the performance of the DGR system, including the engineered barriers and natural geological barriers. Nevertheless, it is useful to gain some perspective on the potential consequences of such an occurrence to test the robustness of the DGR. Note that the possible consequences of an earthquake on causing failure of the shaft seals are bounded by the Extreme Shaft Seal Failure Scenario presented in Section 7.2.2.

The case assessed examines another possible (though unlikely) consequence. It is assumed that a high magnitude earthquake would affect the performance of the DGR system by reactivating an old fault in the area, which would partly bypass the natural geological barriers. This scenario assesses the reactivation of a hypothetical fault close to the DGR - the fault is taken to be 500 m down gradient of the DGR. It is emphasised that no such fault is known to exist.

The earthquake and fault reactivation is assumed to occur shortly after repository closure. Detailed groundwater modelling (Figure 7-24)[30] shows that the main effect of the fault would be to provide a pathway connecting the Guelph, Salina A0 and Salina A2 evaporite formations with the Shallow Bedrock Groundwater Zone (Figure 7-24). As a result, contaminants could migrate into the Shallow Bedrock Groundwater Zone more rapidly (through the fault, rather than diffusion through the rock).

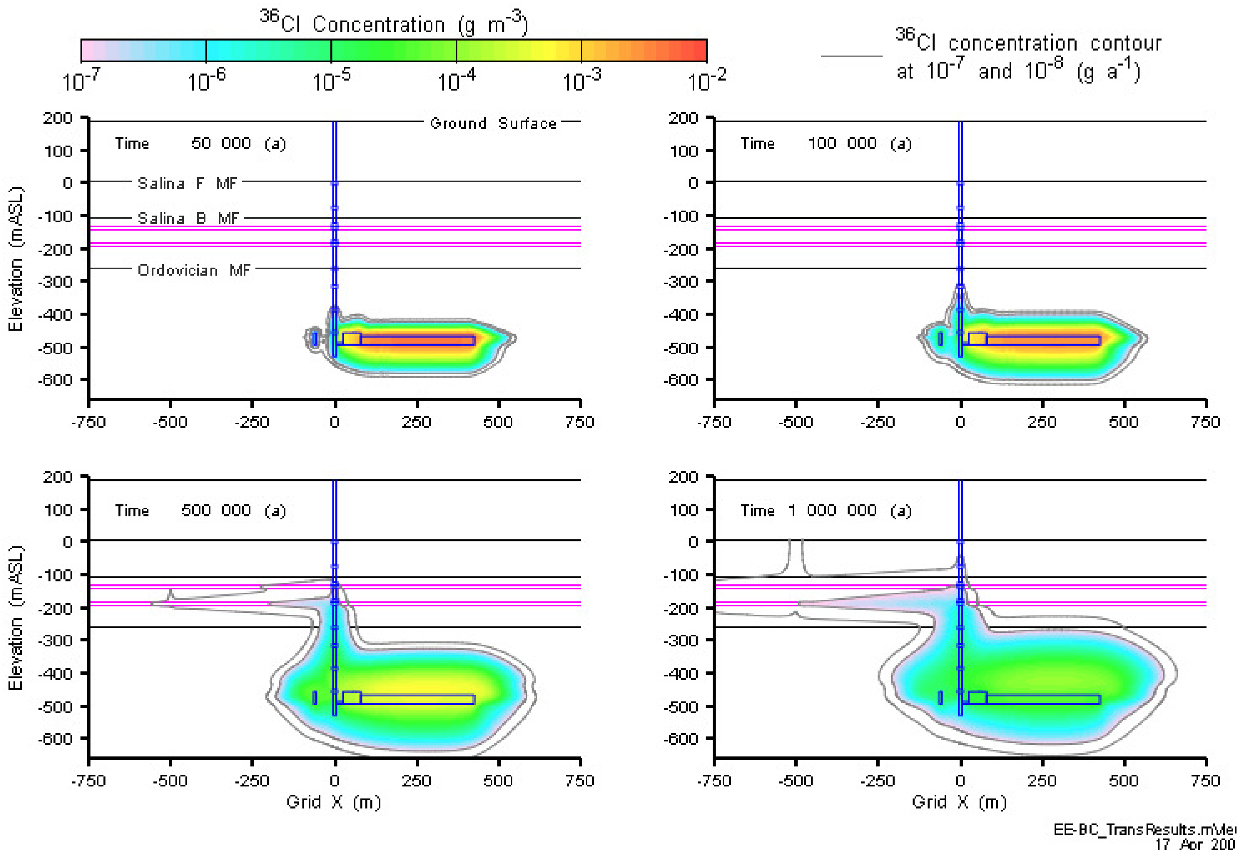

Figure 7-24: Cl-36 Concentration at 50 ka, 100 ka, 500 ka and 1 Ma for the Extreme Earthquake Scenario (Note - the fault is vertical and located at -500 m on the X-axis)

30 Gas modelling has not been undertaken for the Extreme Earthquake Scenario. However, it is expected that the impacts would be several orders of magnitude less than the gas pathway impacts associated with the Severe Shaft Seal Failure Scenario due to the 500 m lateral travel distance for gas through the geosphere to the fault.

The results of the detailed modelling have been used to specify a pathway for the assessment-level calculations. This permits contaminants to be transported via a fault from the Guelph, Salina A0 and Salina A2 evaporite formations to the Shallow Bedrock Groundwater Zone. The case is based on the Normal Evolution Scenario instant resaturation case (NE-RS1) as the focus is on contaminants in groundwater, and that case maximises groundwater releases. The scenario results in the calculated annual doses shown in Figure 7-25. The calculated annual doses are virtually identical to those for the Normal Evolution Scenario (instant resaturation case), given the very similar concentrations in the well water which dominates the exposures. As a guide, the peak calculated dose to a local adult in the Extreme Earthquake Scenario is 4.4×10^{-10} mSv a^{-1}, compared with 4.3×10^{-10} mSv a^{-1} calculated for the Normal Evolution Scenario. The key pathways (ingestion of animal products) and contaminants (Cl-36 and I-129) are also the same.

The calculated concentrations of non-radioactive contaminants lie at least four orders of magnitude below their relevant EQSs.

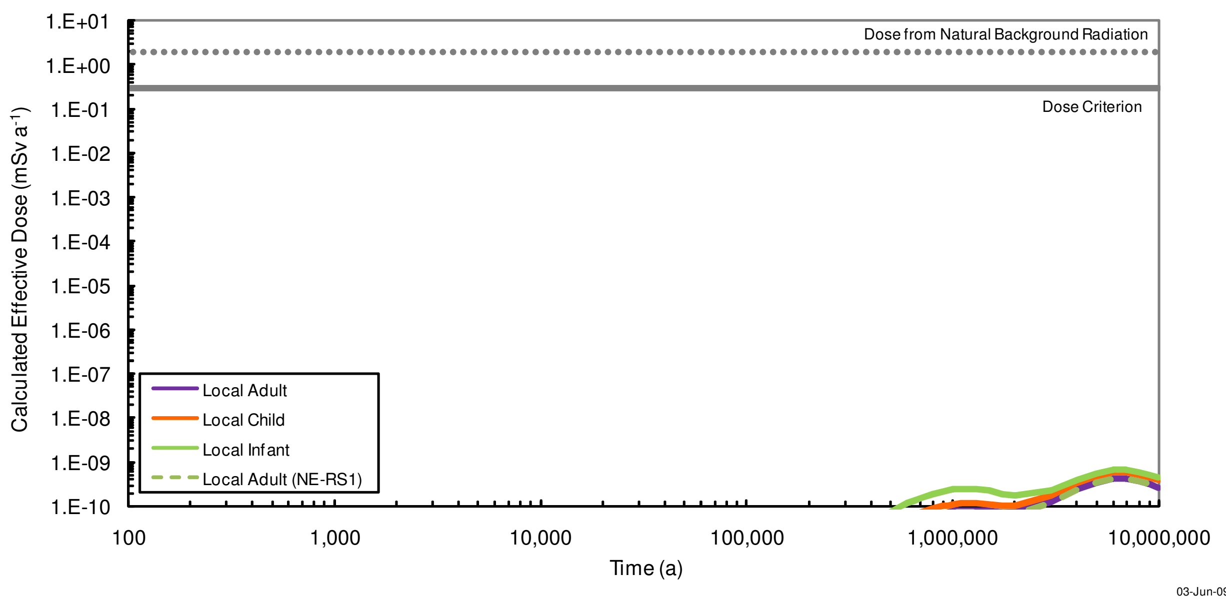

Figure 7-25: Calculated Doses to the Local Exposure Group for the Extreme Earthquake Scenario

7.3 ASSESSMENT OF SAFETY FUNCTIONS AND ARGUMENTS

As noted in Section 3.5, the postclosure safety assessment contributes evidence to support a variety of the DGR's safety functions and arguments. This section sets out key results from the assessment calculations for the current set of seven safety arguments identified in Section 3.5.

7.3.1 Isolation of the Waste from the Surface Environment

The objective of isolation is to seek to provide a period in which radionuclides in the wastes can decay to levels that do not pose a hazard. The isolation of the radioactive waste while it decays is achieved by the location of the DGR, in particular, its geological setting, depth and the absence of natural resources. The location is such that the probability of natural disruptive events or human intrusion is very low.

7.3.1.1 Depth of Repository

Although the effects of climate change resulting from continuing glacial/interglacial cycling are likely to cause major changes in the surface and near-surface environment, the depth of the DGR (680 m) is expected to isolate it from the main consequences of climate change. This expectation is supported by a range of geoscientific observations that indicate the formations at the depth of the DGR have been isolated from surface changes through the nine glacial/interglacial cycles that have affected the Bruce site in the last 1 Ma (see Section 5.1.1). The depth of the repository is also important in reducing the consequences of the impact of meteorite and human space debris to trivial levels (see FEPs report, Garisto et al. 2009).

7.3.1.2 Absence of Economically Viable Natural Resources at Depth

Although gas exploration wells have in the past been drilled in the vicinity of the Bruce site, commercially useful petrochemical resources have not been found. Furthermore, there is no indication of mineral resources or salt seams at depth. Nevertheless, some exploratory drilling can be expected.

Given the depth (reference 680 m) and low resource potential of the DGR site, the rate of deep borehole drilling is estimated to be about 10^{-10} m^{-2} a^{-1} corresponding to a rate of surveying of one deep borehole per 10 x 10 km^2 every 100 a and comparable with the rate used in the assessment of Canadian spent fuel disposal in a deep geologic repository (Gierszewski et al. 2004). This corresponds to a re-survey every three generations or so. The total area of the emplacement rooms is 5.2 x 10^4 m^2 (Walke et al. 2009b), which means that this rate corresponds to a likelihood of intrusion of 5 x 10^{-6} a^{-1} (i.e., an annual probability of about 1 in 200,000).

It is possible that the repository might be detected by remote measurement methods, and be deliberately targeted for study. The uniformity of the sediments and lack of interesting minerals or geologic features in the area would argue against deliberate surveys of the area. Furthermore, if the repository were detected as an anomaly and deliberately targeted, then the nature of the contact with the repository would likely be more carefully managed.

7.3.2 Multiple Thick Low-permeability Sedimentary Rock Barriers

Detailed groundwater and gas and assessment modelling calculations all clearly show that the thick sequence of sedimentary rocks at the Bruce site provides a barrier to contaminant migration.

Figure 7-26 shows the concentrations of Cl-36 in groundwater at various times calculated by the FRAC3DVS code for the NE-RS1 case[31]. The effect of the horizontal flow field in the Guelph and Salina A0 is evident in the horizontal plume extending to the west of the repository.

[31] This case considers complete resaturation of the repository immediately on closure and instant release of Cl-36. As discussed in Section 6.2.1.1, resaturation is expected to be gradual and full resaturation might not occur for in excess of 1 Ma and Cl-36 release will not be instantaneous. Therefore actual travel times are expected to be longer than those estimated for the NE-RS1 case.

The lowest concentration isotherm in Figure 7-26 (10^{-7} g m^{-3}) represents a concentration of 120 Bq m^{-3}, or an equivalent drinking water dose of about 10^{-4} mSv a^{-1} (i.e., more than three orders of magnitude below the dose criterion[32]). Figure 7-27 is the comparable figure for the NE-UG-RS1 case, i.e., with decreased permeabilities in the deep rock inferred from initial Phase 2 site investigation data. Figure 7-27 shows that the geological barriers are even more effective in limiting the migration of the Cl-36.

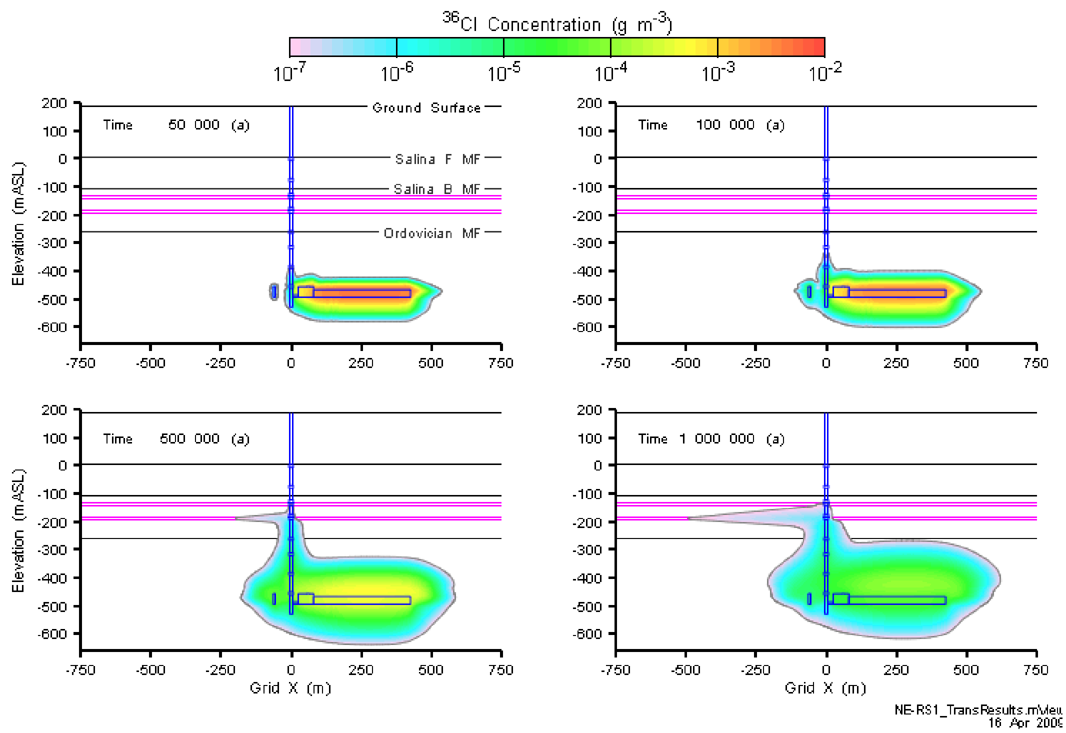

Figure 7-26: NE-RS1-F3 Cl-36 concentration at 50 ka, 100 ka, 500 ka, and 1 Ma

[32] The groundwater in the deep and intermediate groundwater zones is highly saline and so is not potable. Therefore, the dose is hypothetical and provided as an indicative value.

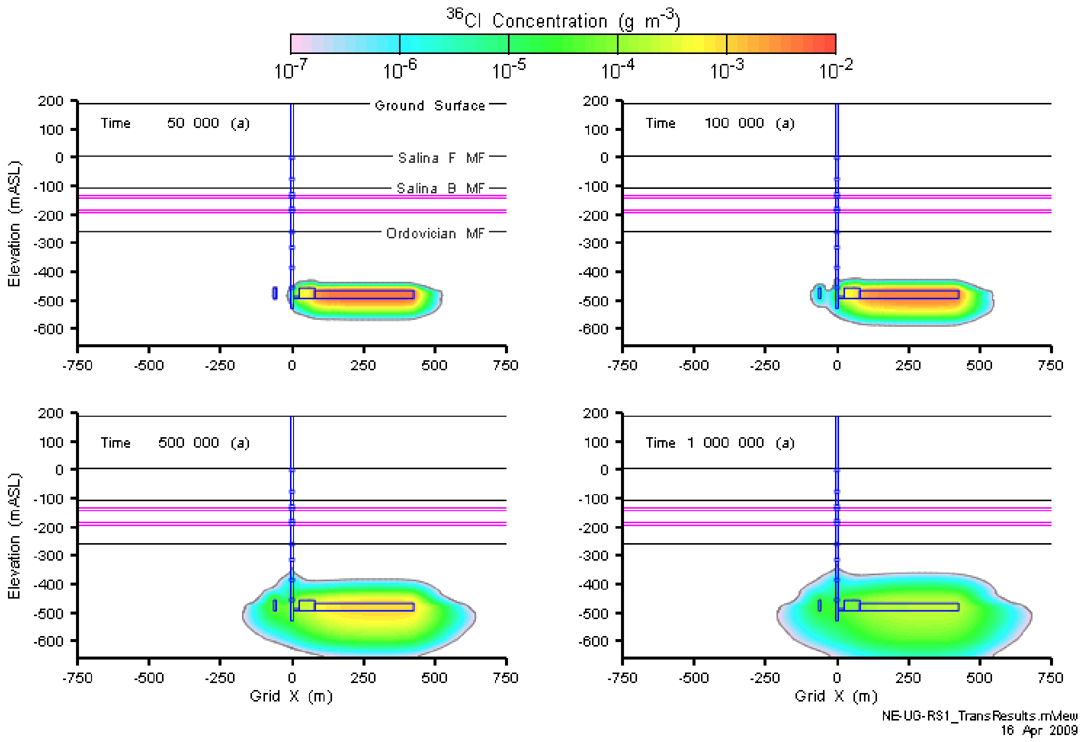

Figure 7-27: NE-UG-RS1-F3 Cl-36 concentration at 50 ka, 100 ka, 500 ka, and 1 Ma

Table 7-6 summarises the T2GGM gas modelling results for the NE-BC and NE-UG-BC cases. It shows that for both cases the majority of the gas generated (almost 90%) is contained within the repository due to the low permeability host rock. Furthermore, the thick sequence of overlying low permeability rocks ensures that no bulk gas reaches the Shallow Bedrock Groundwater Zone.

Table 7-6: Gas Migration for the NE-BC-T and NE-UG-BC-T Cases

		NE-BC Case (600 ka simulation time)	NE-UG-BC Case (1Ma simulation time)
Total mass of gas generated in repository (kg)		3.1E+07	3.1E+07
Total mass of gas leaving repository in kg and as % of gas generated	Bulk gas	3.9E+06 (12%)	4.3E+06 (14%)
	Dissolved gas	1.6E+05 (0.5%)	0
Total mass of gas leaving Intermediate Bedrock Groundwater Zone in kg	Bulk gas	0	0
	Dissolved gas*	8.9E+02	2.0E+01

*Includes dissolved gas in the geosphere that is generated outside the repository, i.e., by initial gases in the shaft.

Results from the AMBER assessment model can also be used to illustrate the role of the geological barriers in containing and attenuating radionuclides. Figure 7-28 and Figure 7-29 show that the cumulative fluxes of radioactivity decrease as successive barriers retard the migration of contaminants via the groundwater pathway for the NE-BC and NE-UG-BC cases, respectively. This permits radioactive decay to reduce the amount that reaches the next part of the system. A cumulative flux of about 10 MBq is released to the Shallow Bedrock Groundwater Zone for the NE-BC case, which is nine orders of magnitude less than the initial inventory disposed and five orders of magnitude lower that the activity released into the geosphere. The cumulative fluxes into the biosphere are even smaller and later for the NE-UG-BC case (see Figure 7-29).

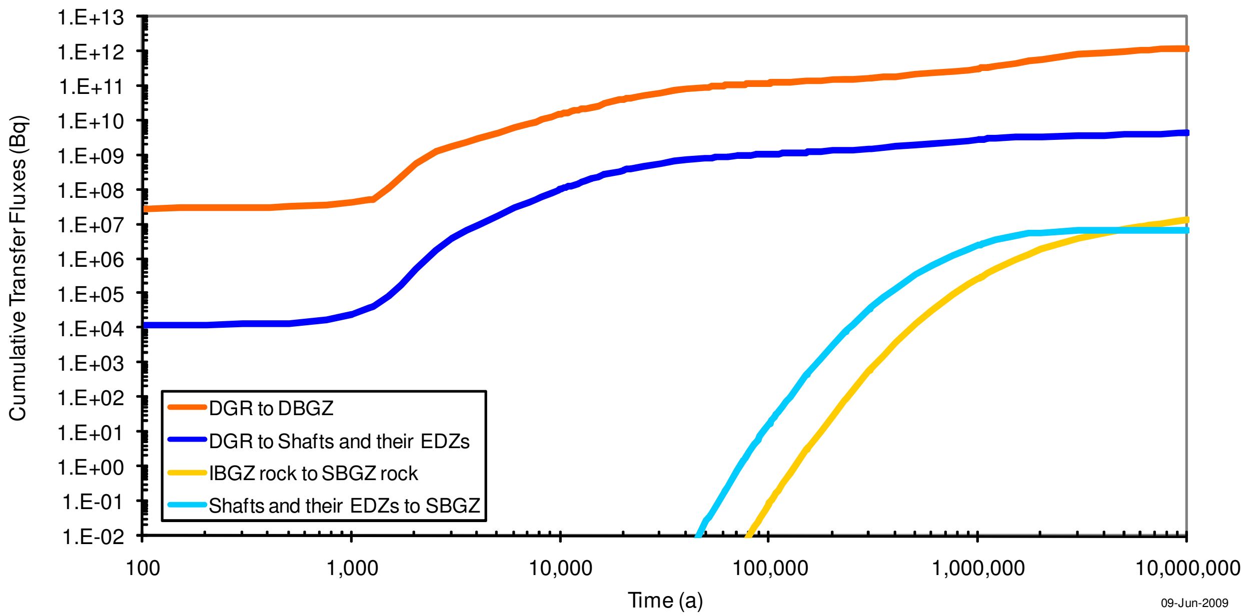

Figure 7-28: Cumulative Groundwater Fluxes through the Shafts/EDZs and Geosphere with Distance from the DGR for the NE-BC-A Case

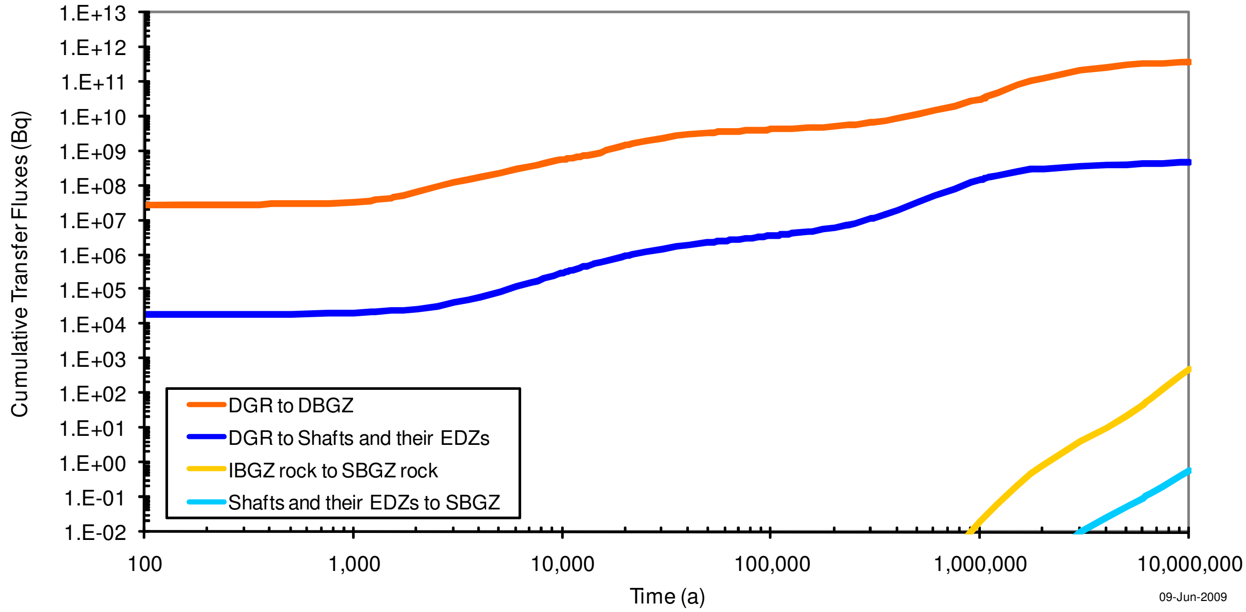

Figure 7-29: Cumulative Groundwater Fluxes through the Shafts/EDZs and Geosphere with Distance from the DGR for the NE-UG-BC-A Case

Figure 7-30 and Figure 7-31 summarise and illustrate the amounts in different parts of the system at different times for the NE-BC-A and NE-UG-BC-A cases, respectively. They show that over all times, the rocks act as a significant barrier to the migration of contaminants so that the majority of the activity present in the system is retained in the repository. For both cases, the containment in the repository and geosphere is such that no activity has reached the surface environment by 10 ka and, although some activity has reach the surface by 100 ka for the NE-BC-A case, it is negligible (only around 10 Bq - 15 order of magnitude less than the activity disposed). For the NE-UG-BC-A case, the activity that has reached the surface environment by 1 Ma is less than 100 Bq (14 order of magnitude less than the activity disposed and less than the natural radioactivity found in 1kg of shale from the Bruce site). Even after 10 Ma, the activity in the surface environment is 8 and 10 orders of magnitude less than that disposed for the NE-BC-A and NE-UG-BC-A cases, respectively.

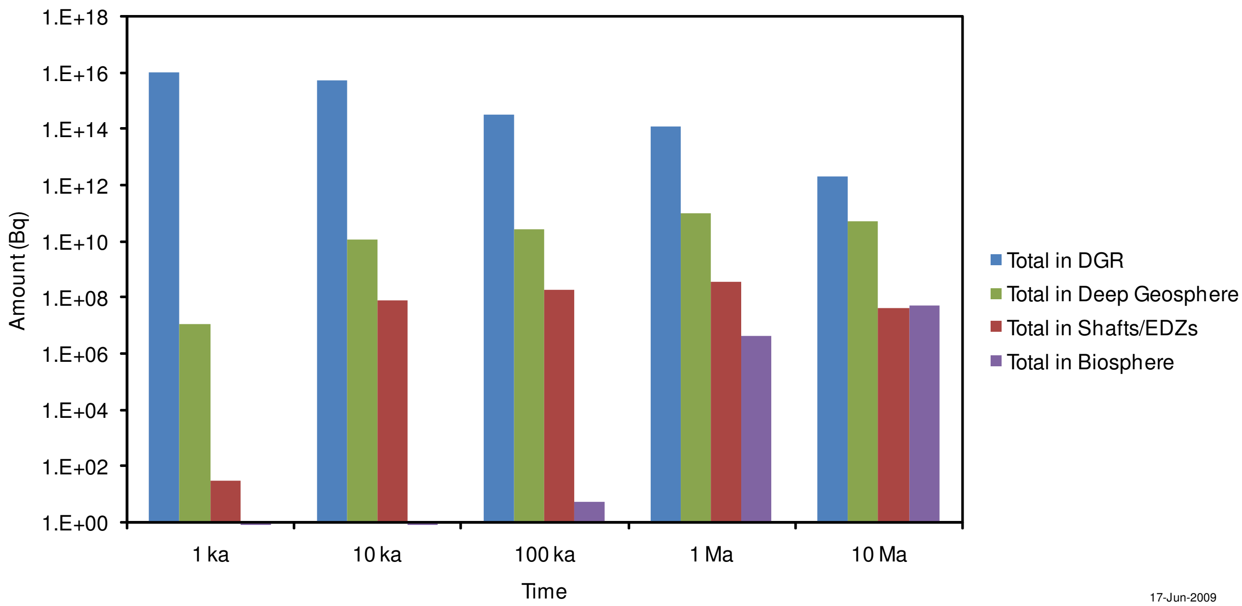

Figure 7-30: Distribution of Activity in System at Different Times for the NE-BC-A Case

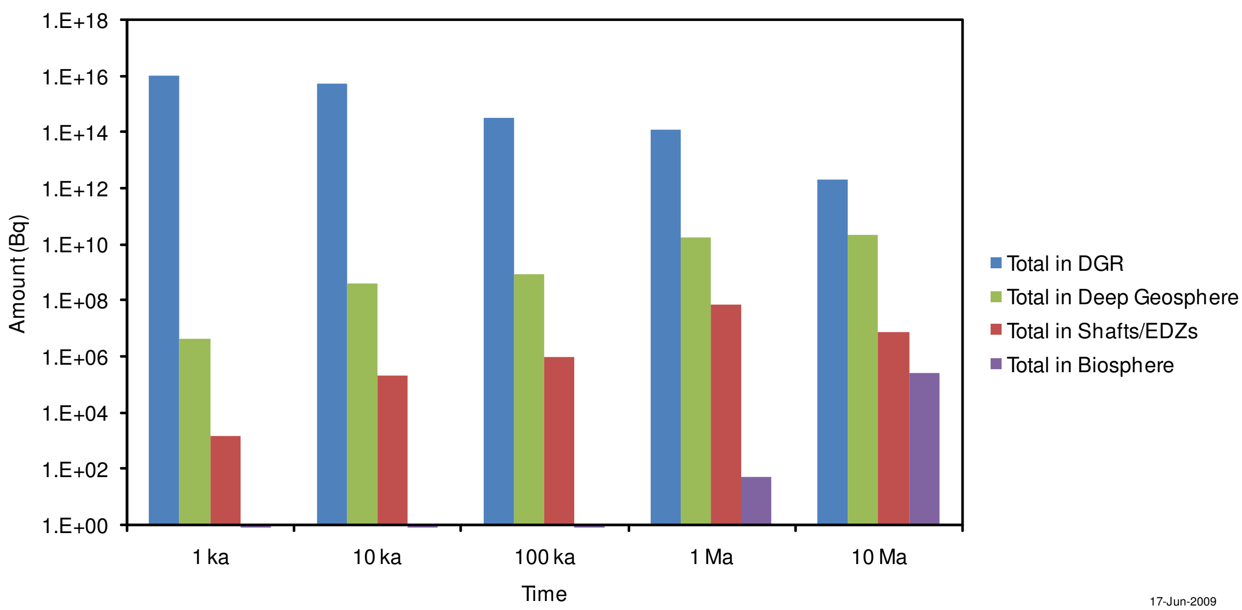

Figure 7-31: Distribution of Activity in System at Different Times for the NE-UG-BC-A Case

7.3.3 Mass transport is Diffusion-dominated

Figure 7-32 shows the "figure of merit" (FOM) for the BC-UG-NE-F3 case. The figure shows the spatial distribution of the dominant transport process (advection or diffusion). The FOM variable is the ratio given by:

$$FOM = \frac{\alpha V}{D_p} \qquad (1)$$

where

α = longitudinal dispersivity (m)
V = advective velocity (m s^{-1})
D_p = pore water diffusion coefficient (m^2 s^{-1})

For FOM < 0.1, diffusion is the dominant transport mechanism. For FOM > 10, advection dominates.

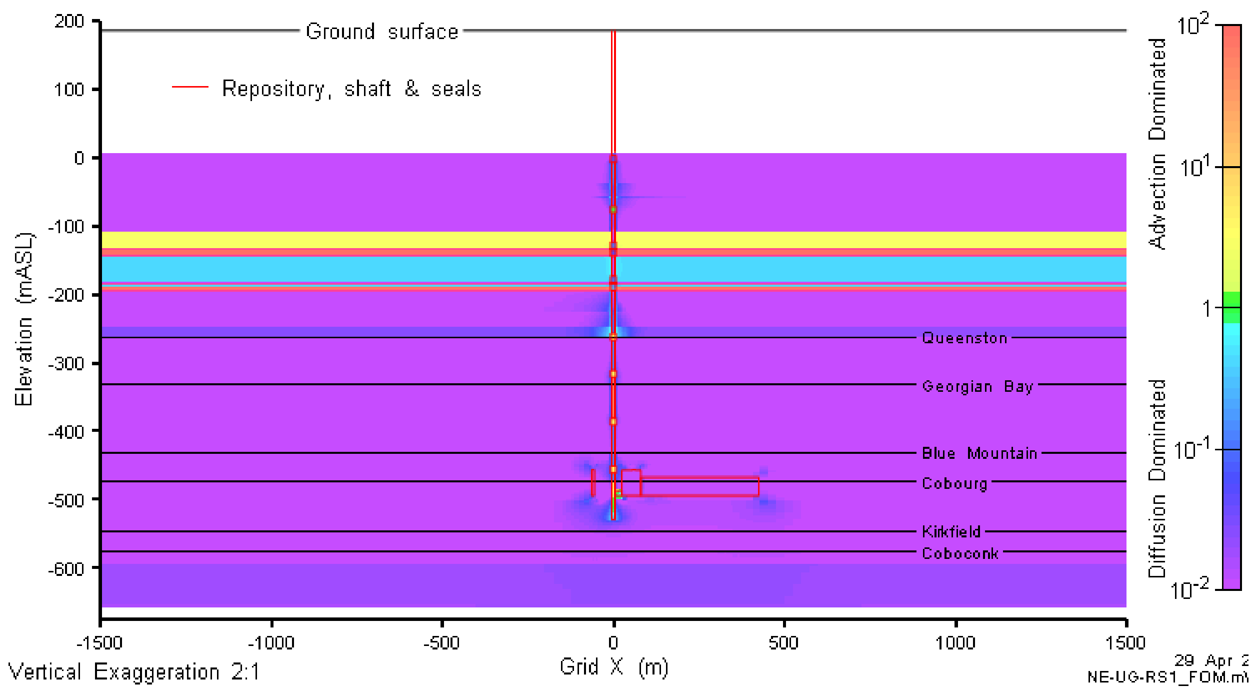

Figure 7-32: Figure of Merit for the NE-UG-BC-F3 Case

It is clear from Figure 7-32 that transport in the transport in the rock mass in the Deep and Intermediate Bedrock Groundwater Zones is diffusion dominated, with the exception of the higher permeability horizons (i.e., the Guelph, Salina A0 and Salina A2 evaporite) and the shafts and their EDZs. The dominance of diffusion for the NE-UG-BC-F3 case is also well illustrated by Figure 7-27.

7.3.4 Hydrogeochemical Conditions Limit Contaminant Mobility

The host rock environment provides a stable chemical environment that further tends to limit contaminant migration. It does this through a number of mechanisms.

- The high salinity in the porewater at depth provides a stabilising effect on groundwater movement. It also provides the possibility of salt precipitation in places, which could plug small pores or cracks.
- The host rocks have some capacity to chemically sorb radionuclides, especially the argillaceous component of the limestone, and the shales.
- The large volume of limestone host rock (calcium carbonate) provides a significant chemical buffering capacity, which will tend to maintain conditions within the repository around approximately neutral chemical conditions.

These processes have not been analysed in detail within this safety assessment. Simple sorption estimates have been included for several key elements for which there is strong evidence that it will be an important process even in highly saline conditions (see Table 6-6). Whilst sorption and precipitation of other elements will undoubtedly occur, it has conservatively been ignored in the assessment. Figure 7-33 shows the calculated total radionuclide transfer fluxes to the biosphere via the groundwater pathway with (NE-RS1-A) and without (NE-RT-A) sorption onto engineering materials and rock. Zirconium is one of the elements for which sorption is represented in the base case. The figure shows that sorption effectively prevents Zr-93 from reaching the surface environment, emphasising the significant chemical barrier that sorption in the shaft and geosphere provides in limiting contaminant mobility.

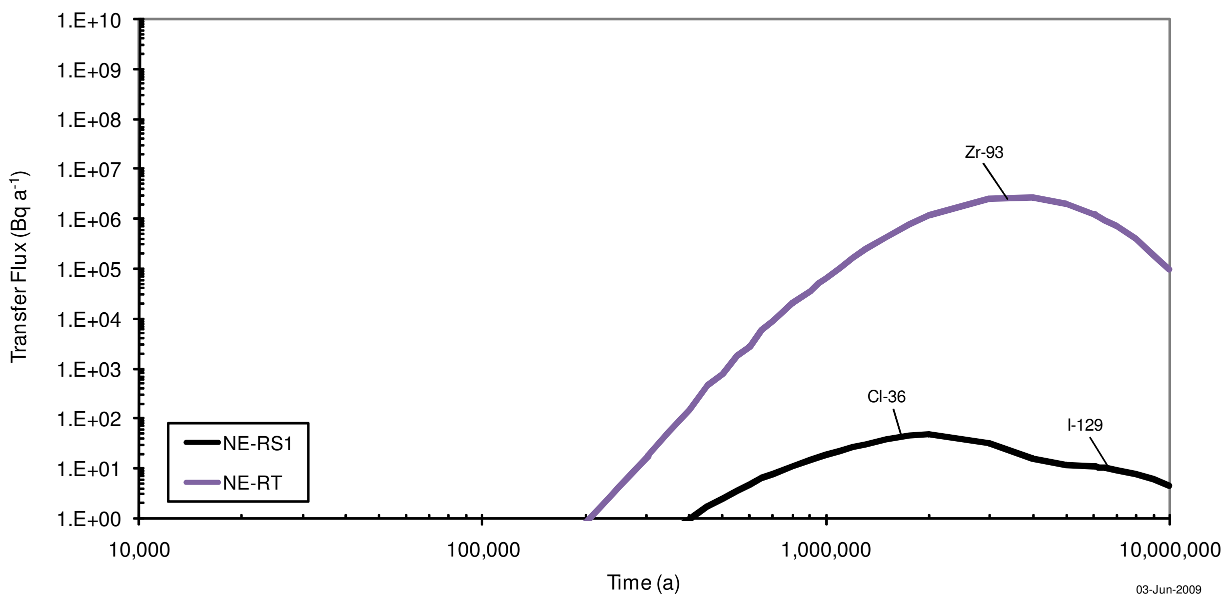

Figure 7-33: Calculated Radionuclide Transfer Fluxes to the Biosphere for Instant Repository Resaturation Cases with (NE-RS1-A) and without (NE-RT-A) Sorption for the Normal Evolution Scenario

As noted in Section 4.3.3, the Deep and Intermediate Bedrock Groundwater Zones contain dense brines that are expected to limit contaminant migration due to density effects. Detailed groundwater and gas modelling has not explicitly represented the effect of salinity gradients (see discussion in Avis et al. 2009 and Calder et al. 2009). Modelling of salinity is important in systems with topography, as increases in density with depth tend to decrease the depth of penetration of topographic induced heads and consequently moderates horizontal gradients, thus reducing transport. However, in the current local site system, where flow is conservatively assumed to be vertical due to the Cambrian overpressure, environmental head gradients are already effectively incorporated into the salinity profile.

7.3.5 Slow Resaturation of the Repository

The porewater in the rock around the repository will start to seep back into the repository on closure. The rate of resaturation is slow because of the rock properties and the gas generation within the repository.

Figure 7-34 and Figure 7-35 show the repository water saturation history for all calculation cases for the Phase 1 and decreased geosphere permeabilities, respectively (Calder et al. 2009). For the base case geosphere (Figure 7-34), all cases undergo early water saturation, and show an initial peak at around 1 ka of between 20 and 90% saturation before gas pressure in the repository develops sufficiently to force water out of the DGR. With time, the average repository pressure drops to below the geosphere pressures in the host rock and the DGR starts to slowly resaturate from around 100 ka. The rate of resaturation is slow and it is expected that complete resaturation of the repository could take over 1 Ma. Without the build up of gas pressure, in the base case geosphere, the repository would be resaturated by 10 ka.

In contrast, in the updated geosphere (Figure 7-35), the resaturation rate is naturally slow because of the very low permeability of the rock, with the exception of the Severe Shaft Seal Failure Scenario.

In either case, this delay in resaturation limits the releases from the waste to groundwater in the repository and the subsequent migration into porewater in the geosphere.

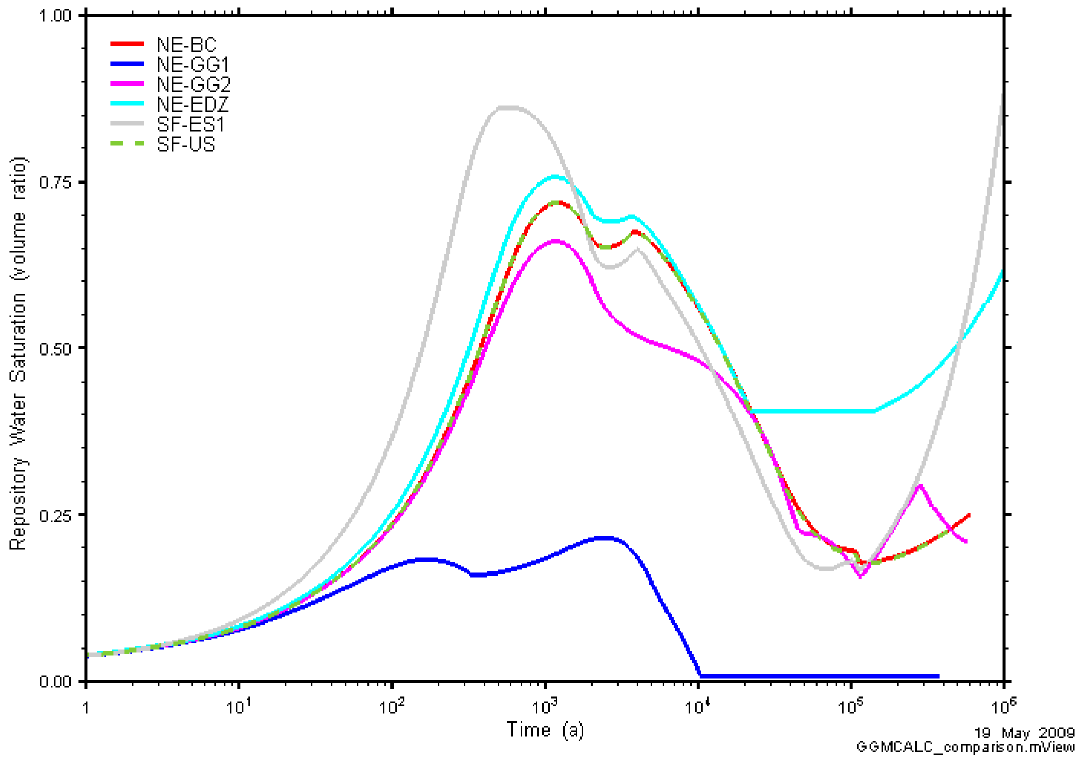

Figure 7-34: Repository Water Saturation for all Calculation Cases based on the Phase 1 Geosphere Permeabilities

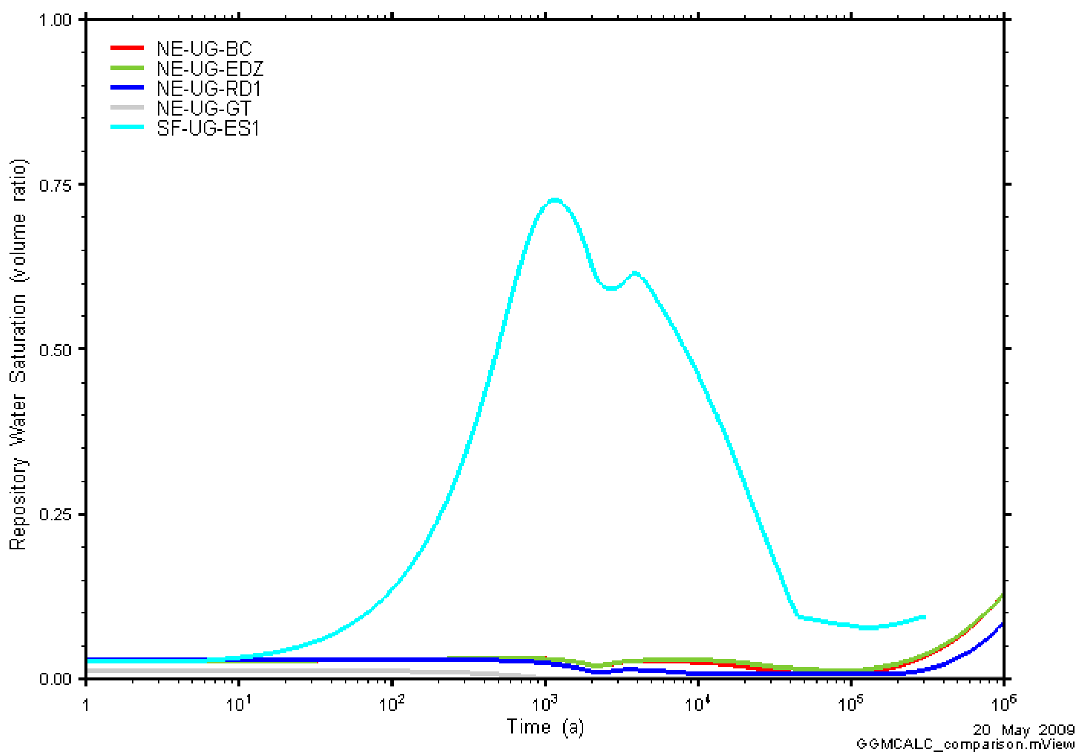

Figure 7-35: Repository Water Saturation for all Calculation Cases based on the Decreased Geosphere Permeabilities

7.3.6 Impacts are Likely to be Below Natural Background Dose Rates

The results presented in Section 7.1 and summarised in Figure 7-36 show that the peak doses for the Normal Evolution Scenario base calculation cases (NE-BC and NE-UG-BC) are well below the 0.3 mSv a^{-1} criterion and the dose from natural background radiation (2 mSv a^{-1}). Calculated peak annual doses occur well beyond 1 Ma. The NE-BC case is almost nine orders of magnitude below the 0.3 mSv a^{-1} dose criterion. The updated geosphere case is even lower, about 13 orders of magnitude below the dose criteria.

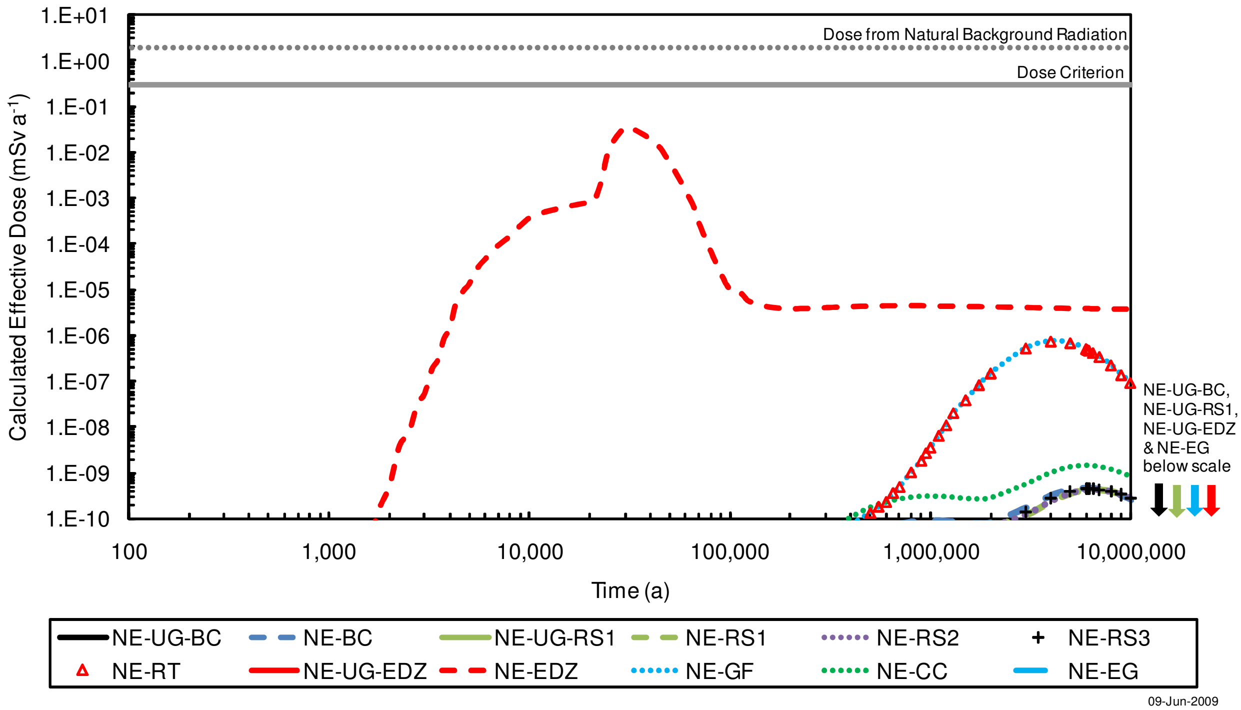

Figure 7-36: Calculated Doses for the Normal Evolution Scenario's Calculation Cases

Results for most of the variant calculation cases are similar to the base cases, with peak annual doses typically less than 10^{-6} mSv a^{-1}. The single exception is the EDZ case based on the base case geosphere that considers much faster contaminant migration through the shaft EDZs. The peak annual dose for this EDZ case is 0.04 mSv a^{-1} at around 30 ka after closure resulting from the release of C-14 gas into the shallow groundwater system and the surface environment. Doses after 100 ka are dominated by Ra-226, Pb-210 and Po-210 ingrown from the decay of Pu-238, U-238 and U-234. Using the updated geosphere model, the dose impact is reduced by more than ten orders of magnitude due to its lower permeabilities resulting in the decay of C-14 and Ra-226 and its progeny in the geosphere.

The analysis of potential events that could lead to possible penetration of barriers and abnormal degradation and loss of containment 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 (see Section 5.2). Even if these events were to occur, the vast majority of the contaminants in the waste will continue to be contained effectively by the DGR system such that, as discussed in Section 7.2 and summarised in Figure 7-37, safety criteria are met in almost all circumstances, even with conservative assessment modelling assumptions.

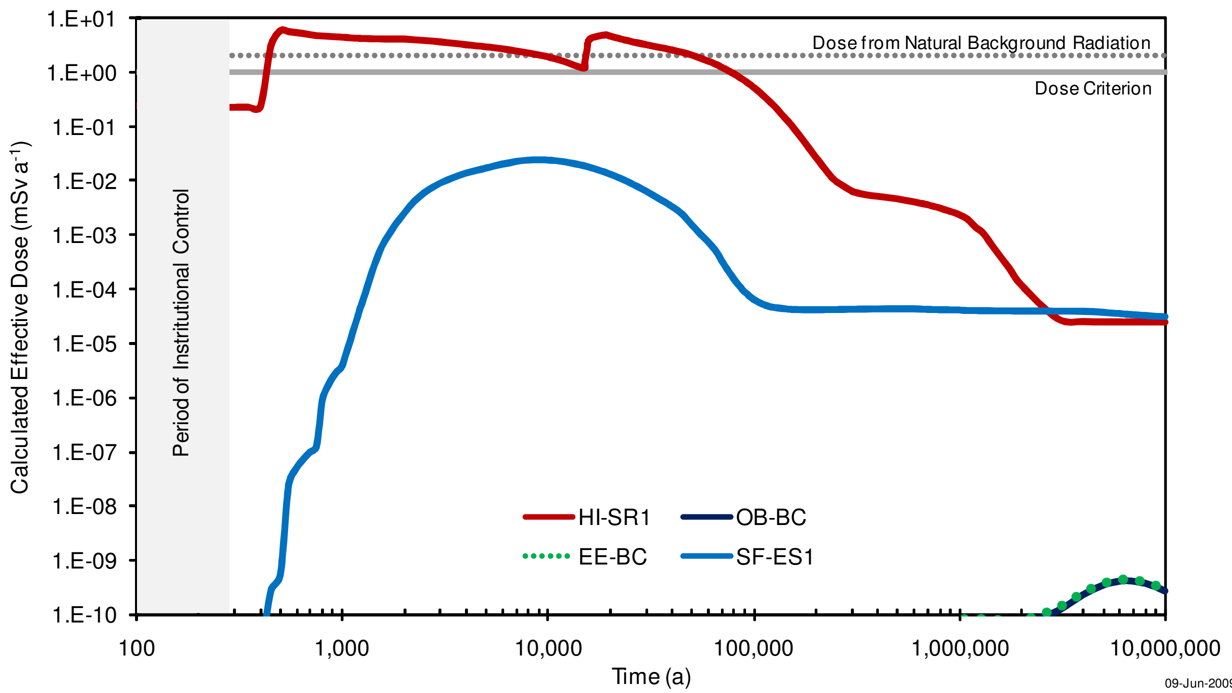

Figure 7-37: Calculated Doses for the Disruptive Scenarios

Although the potential release of contaminated water, particles and gas via an exploration borehole drilled into the repository could result in exposures that marginally exceed the 1 mSv criterion and the dose from natural background radiation (2 mSv a^{-1}), the assessment is highly conservative. Drilling practice is to carefully contain and limit the release of such material from boreholes. Any material released could be expected to be collected for disposal as waste (or vented, in the case of gases) rather than allowed to be released in an uncontrolled manner into the surface environment.

7.3.7 Radioactivity Reduces with Time due to Radioactive Decay

There is an order of magnitude reduction in the amount of radioactivity present in the south panel in the first hundred years after repository closure due to the decay of short-lived radionuclides such as H-3. Thereafter, the rate of decrease is more gradual, as the remaining inventory becomes dominated by longer-lived radionuclides. Nevertheless, the average concentration in wastes continues to decrease in both the south and east panels, as shown in Figure 7-38. Figure 7-39 shows that the activity in the waste decreases below the activity of naturally occurring radionuclides in the rocks above the DGR after 100 ka. Figure 7-38 and Figure 7-39 only consider losses due to radioactive decay; losses to groundwater and gas are not considered.

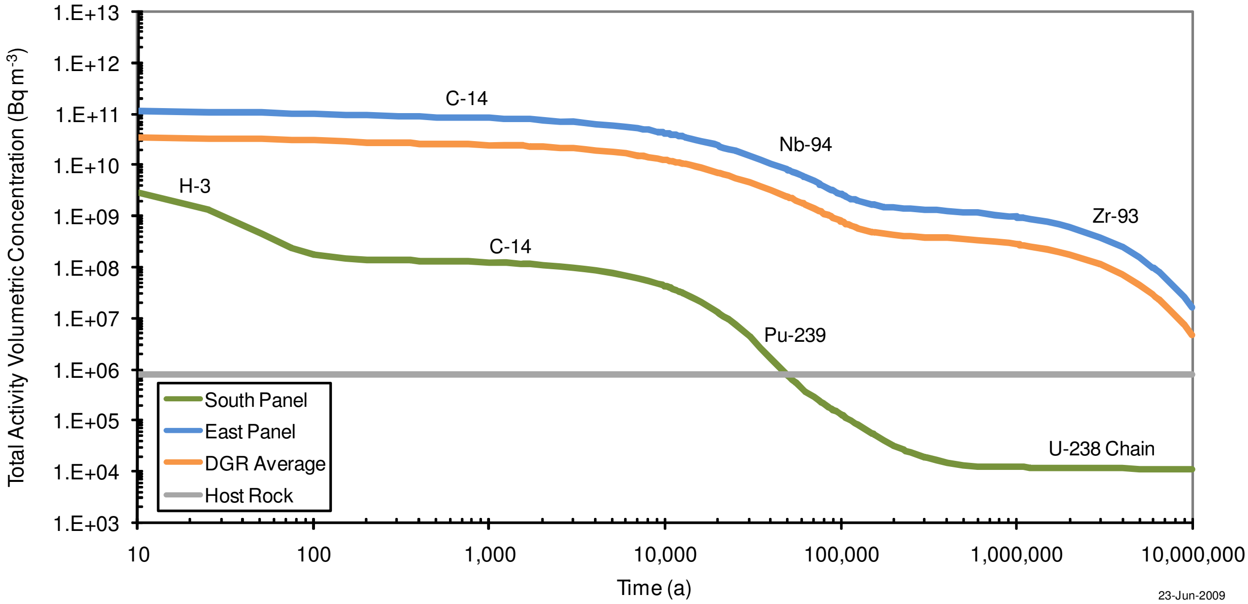

Figure 7-38: Long-term Reduction in the Activity Concentration of LLW and ILW

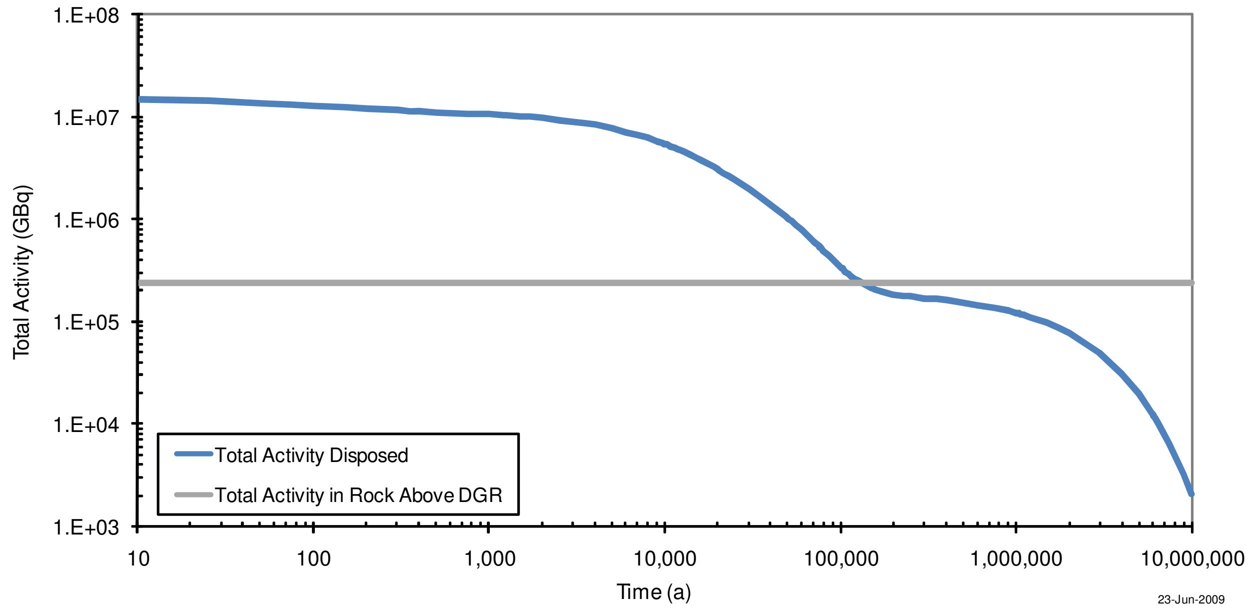

Figure 7-39: Total Activity Disposed in Comparison to Total Activity in Rock above DGR

7.4 ANALYSIS OF DESIGN VARIANTS

The reference design (Section 4.2, Figure 4-1 and Figure 4-2) assessed comprises:

- waste emplacement rooms excavated at 680 m depth in two panels and joined to a central ring tunnel via access tunnels;
- no grouting of wastes;
- no backfilling of the repository;
- a concrete monolith at the base of each shaft;
- a sequence of 11 concrete bulkheads in each shaft; and
- a sequence of backfill materials between the concrete bulkheads (bentonite/sand, asphalt and engineered fill) in each shaft.

The results for this reference design for the Normal Evolution Scenario base cases (NE-BC and NE-UG-BC) show that the calculated peak dose for the base case is almost nine orders of magnitude lower than the dose criterion of 0.3 mSv a^{-1}, and, in the case of the low permeability base case, is a further four orders of magnitude lower.

A number of detailed and assessment-level calculations have been undertaken to assess alternative repository design and shaft performance assumptions. In addition, calculations have been undertaken for a “what if” scenario that assumes that the shaft seals and the shaft EDZs have the physical and chemical properties of crushed rock from the time of closure of the repository (see Sections 5.2.2.2 and 6.2.3). Details of these cases are provided in Appendix A. Associated results are summarised in Table 7-7.

Table 7-7: Calculated Impacts of Design Variants

Design Variant	Relevant Cases	Calculated Peak Dose to an Adult (mSv a^{-1})	Cumulative Flux into Shallow Bedrock Groundwater Zone: Cl-36 in Groundwater at 1 Ma (g)	Cumulative Flux into Shallow Bedrock Groundwater Zone: Bulk and Dissolved Gas at 500 ka (kg)
Base case	NE-BC NE-UG-BC	4.6E-10 4.2E-14	1.4E-04* 4.1E-14*	4.3E+02 3.0E+00
Backfill of tunnels only with concrete	NE-UG-RD1	-	1.4E-15	3.0E+00
High Shaft EDZ permeability [33]	NE-EDZ NE-UG-EDZ	3.5E-02 4.5E-12	6.1E+02 7.0E-02	9.3E+06 3.7E+01
Severe shaft seal failure	SF-ES1 SF-UG-ES1 SF-US	2.4E-02 - 7.6E-08	8.9E+02 4.9E+00 8.4E+00	1.3E+07 2.6E+05 3.5E+04**

*Values for NE-RS1-F3 and NE-UG-RS1-F3 cases
** At 250 ka.

The backfilling of the repository tunnels (NE-UG-RD1) limits rockfall in the repository, although rockfall could still occur in the emplacement rooms. This backfilling delays and limits the groundwater flux of Cl-36 to the Shallow Bedrock Groundwater Zone by a factor of 30 over the 1 Ma calculation period. In contrast, there is no effect on the gas flux, although the reduced void volume in the repository does cause an increase in repository gas pressure from 6.9 MPa

[33] Hydraulic conductivity for shaft inner and outer EDZs assumed to be four and two orders of magnitude greater than the surrounding rock mass, respectively. Interruption of shaft inner EDZ by concrete bulkheads and asphalt waterstops is assumed to be ineffective.

for the NE-UG-BC case to 7.5 MPa for the NE-UG-RD1 case. Although not assessed in the Version 1 SA, it is expected that, based on these results, the backfilling of the emplacement rooms would decrease groundwater fluxes, but increase gas fluxes.

Differing assumptions concerning the performance of shaft seals and shaft EDZ can cause groundwater fluxes to vary by at least six orders of magnitude and gas fluxes by at least four orders of magnitude (NE-EDZ case). The calculated peak doses are more than eight orders of magnitude higher than the equivalent base cases due to the earlier and greater flux of contaminants (specifically C-14) released via the shafts and their associated EDZs. Nevertheless, they remain below the relevant dose criterion even under the conservative assumptions adopted (e.g., no Ordovician underpressure and constant Cambrian overpressure). Using the updated geosphere model, the dose impact for the NE-UG-EDZ case is ten orders of magnitude lower than that for NE-EDZ case due to its lower permeabilities resulting in the decay of C-14 and uranium progeny in the geosphere.

The above results indicate that there appears to be no major benefit to be gained from backfilling the repository. They also emphasise the importance of the shaft seals in limiting contaminant fluxes up through the shafts and the associated EDZ. The keying of the seals into the shaft EDZ is important, as are assumptions concerning the extent and permeability of the EDZ.

Given the importance of the geosphere and shaft seals in limiting the release of contaminants to the surface environment, it is expected that modifying the design of the repository in terms of its orientation, its depth (within a range of a few tens of metres), and the configuration of emplacement rooms will have limited effect on calculated impacts.

7.5 ASSESSMENT OF UNCERTAINTIES

As noted in Section 3.7.1, uncertainties can be considered in three categories.

- **Future or scenario uncertainty** – uncertainty in the evolution of the disposal 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 disposal system. This has been investigated through the use of detailed and assessment-level models, which use differing representations of the system, and in variant calculation cases.
- **Data uncertainty** – uncertainty in the parameters used as input in the modelling. This has been investigated through variant calculation cases.

The results from the calculation cases identified in Section 6.3 and Table 6-4 can be used to assess the relative impact of these three categories of uncertainty and their associated sources of uncertainty.

7.5.1 Scenario Uncertainty

A Normal Evolution Scenario and four Disruptive Scenarios (Human Intrusion, Severe Shaft Seal Failure, Open Borehole and Extreme Earthquake) 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 of these calculation cases are shown in Table 7-8. Very low contaminant release to the Shallow Bedrock Groundwater Zone and very low peak annual dose (about 9-13 orders of magnitude below the dose criteria of 0.3 mSv a^{-1}) are calculated for the Normal Evolution Scenario.

Table 7-8: Calculated Peak Doses and Cumulative Fluxes for the Assessed Scenarios

Scenario	**Calculated Peak Dose to an Adult (mSv a^{-1})**	**Cumulative Flux into Shallow Bedrock Groundwater Zone**	
		Cl-36 in Groundwater (g) at 1 Ma	**Bulk and Dissolved Gas (kg) at 500 ka**
Normal Evolution	4.6E-10 (4.2E-14)	1.4E-04* (4.1E-14)*	4.3E+02 (3.0E+00)
Human Intrusion - surface release - groundwater release	 5.8E+00 1.5E-03	 - 3.7E+02	 - -
Severe Shaft Seal Failure	2.4E-02 (-)	8.9E+02 (4.9E+00)	1.3E+07 (2.6E+05)
Open Borehole	4.3E-10	2.2E-04	-
Extreme Earthquake	4.4E-10	3.0E-03	-

Notes:
*Values for NE-RS1-F3 and NE-UG-RS1-F3 cases
Values in brackets are for the very low permeability (UG) base case.
- No calculation case

Even with the Disruptive Scenarios, the highest dose is 6 mSv for the Human Intrusion Scenario, which considers “what if” the repository is intruded directly via an exploration borehole and current drilling standards (which would prevent much of the release from the borehole) are neglected. The Severe Shaft Seal Failure Scenario gives a lower dose (0.02 mSv a^{-1}) than the Human Intrusion Scenario. The impacts of the Open Borehole and Extreme Earthquake Scenarios are broadly comparable with the Normal Evolution Scenario (i.e., within a factor of two).

7.5.2 Model Uncertainty

7.5.2.1 Alternative Modelling Approaches

Two detailed computer models developed using the FRAC3DVS finite-element code have been used to evaluate groundwater flow and transport in the Deep and Intermediate Bedrock Groundwater Zones; a 2D radial (2DR) model and a 3D simple (3DS) model, both of which can be linked to a 3DSU model of the Shallow Bedrock Groundwater Zone (Avis et al. 2009.

Uncertainties with the associated modelling assumptions and approaches (e.g., the assumption of instantaneous resaturation and contaminant release) are presented in the Groundwater Modelling report (Avis et al. 2009).

In addition to the groundwater models developed in FRAC3DVS, an assessment-level model has been developed using the AMBER compartment-model code. The 2DR, 3DS and AMBER models represent three different modelling conceptualisations of the DGR system and enable associated uncertainties to be considered.

Figure 7-40 provides a comparison of the cumulative fluxes at the top of the Deep Bedrock Groundwater Zone calculated for the two FRAC3DVS models (NE-NHG-F3 and NE-NHG-F2) and the comparable AMBER case (NE-RT-A)[34] (see Appendix A for details of the three cases). The AMBER model shows an order of magnitude agreement with the 2DR and 3DR models in respect of the flux via the geosphere (shown as Rock in Figure 7-40), and the shafts and their EDZs (shown as Shafts in Figure 7-40) with the AMBER model erring on the conservative side (i.e., with the AMBER model calculating higher and earlier cumulative fluxes).

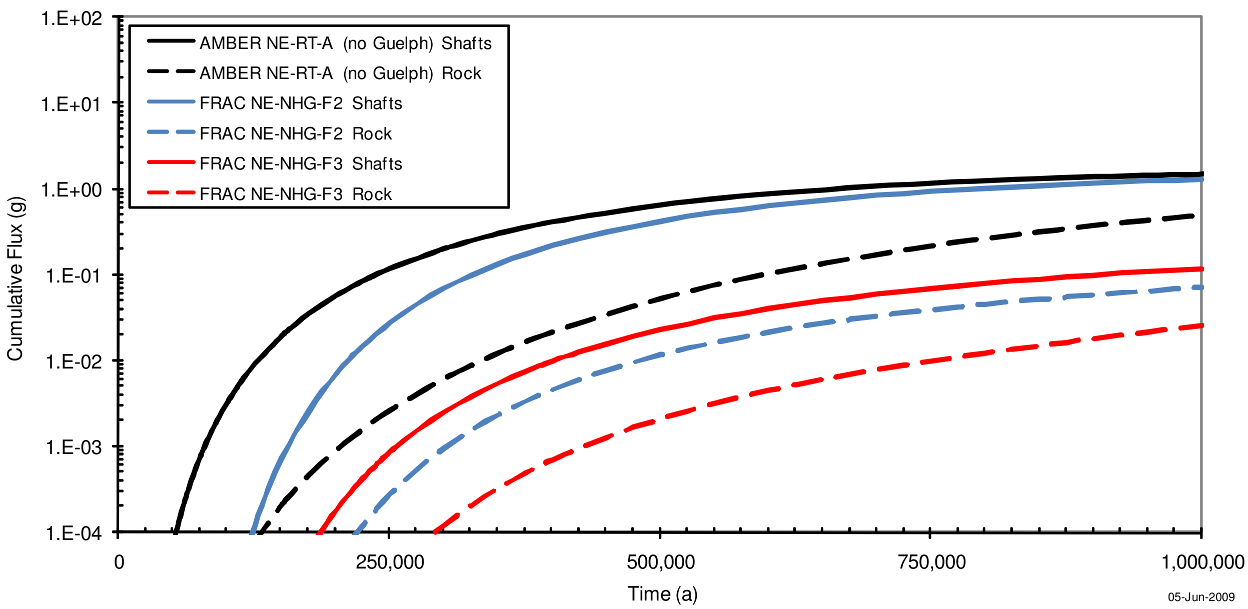

Figure 7-40: Cumulative Cl-36 Flux Across the Top of the Deep Bedrock Groundwater Zone

Figure 7-41 shows the comparison of the cumulative fluxes at the top of the Intermediate Bedrock Groundwater Zone. The fluxes calculated by AMBER remain higher than the FRAC3DVS fluxes and there is still an order of magnitude agreement between the 2DR and AMBER models in respect of the flux via the shafts and their EDZs, and the geosphere.

[34] Two versions of this case were evaluated: one with horizontal flow in the Guelph, Salina A0 and Salina A2 evaporite formations (directly comparable with NE-RS1-F3); and one with no horizontal flow in the Guelph, Salina A0 and Salina A2 evaporite formations (directly comparable with NE-NHG-F2 and NE-NHG-F2). The results shown in Figure 7-40 and Figure 7-41 are for the version with no horizontal flow, whilst those in Figure 7-42 are for the version with horizontal flow.

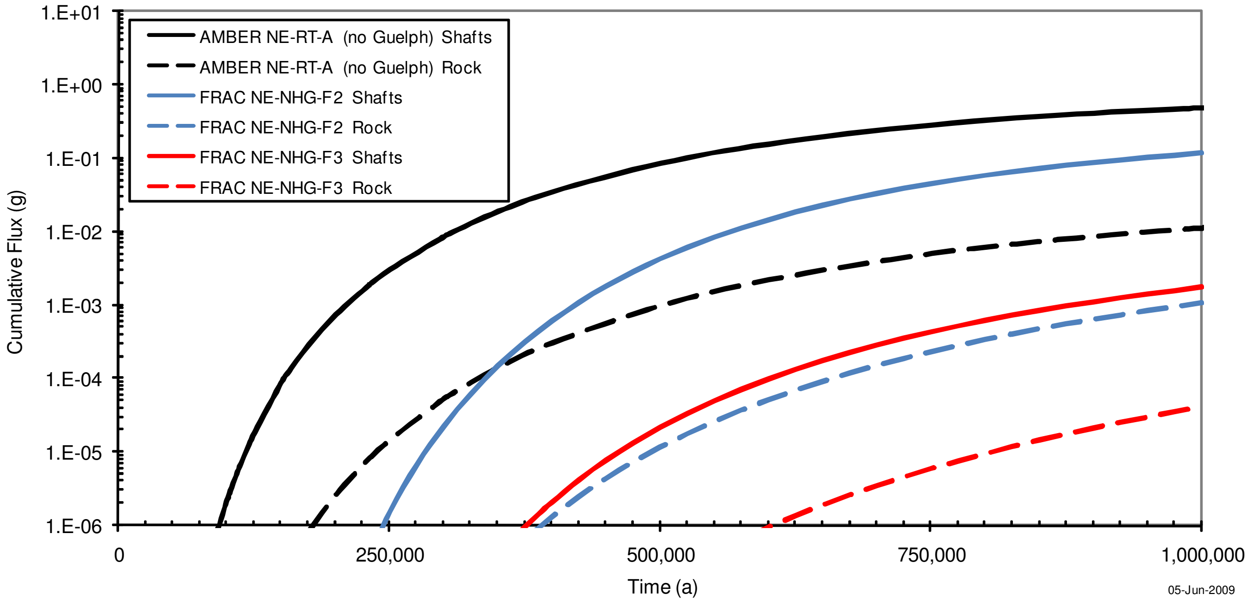

Figure 7-41: Cumulative Cl-36 Flux Across the Top of the Intermediate Bedrock Groundwater Zone

A comparison was also undertaken of a FRAC3DVS case and an AMBER case that consider horizontal flow in the Guelph, Salina A0 and Salina A2 evaporite formations (i.e., the NE-RS1-F3 and the NE-RT-A[32] cases). The results are shown on Figure 7-42 and indicate an order of magnitude agreement between the cumulative fluxes along the Guelph/Salina A0 pathway and the Salina A2 evaporite pathway, with AMBER calculating the higher fluxes for both pathways.

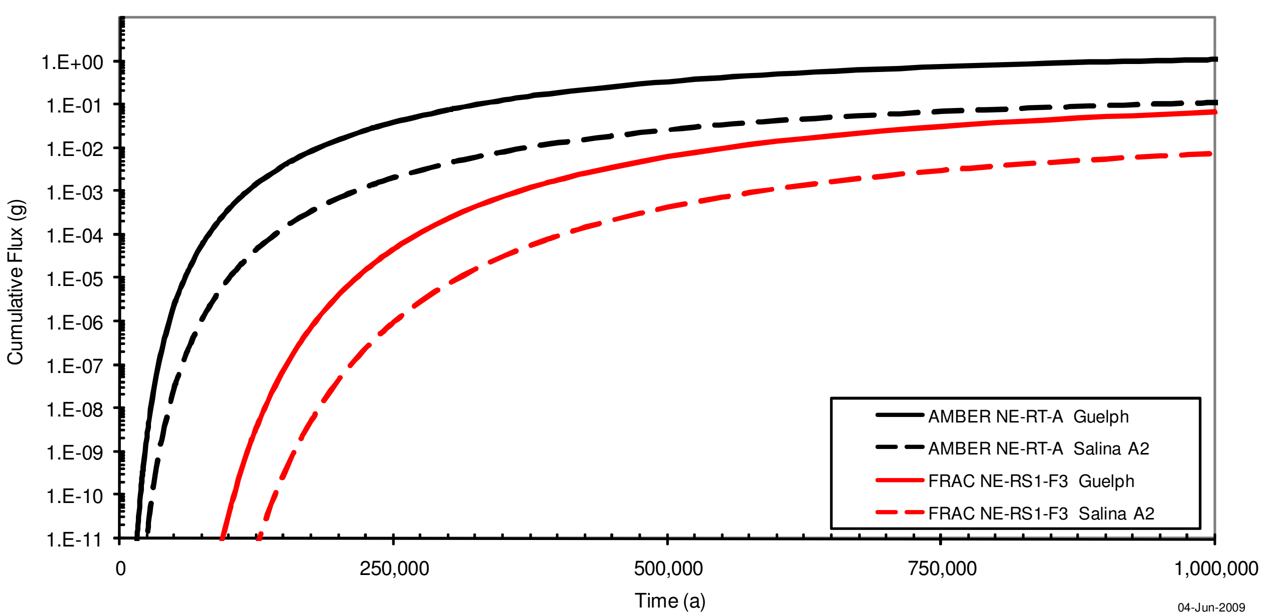

Figure 7-42: Cumulative Cl-36 Flux via the Guelph and Salina A2 Evaporite Formations

The AMBER and FRAC3DVS results were also compared for the drinking water well pathway and the Shallow Bedrock Groundwater Zone pathway to the Lake (i.e., for the same release from geosphere into this zone, and excluding the Guelph, Salina A0 and Salina A2 evaporite pathways) (Figure 7-43). The FRAC3DVS 3DSU model only considers the Shallow Bedrock Groundwater Zone. The AMBER model is conservative in that it calculates slightly higher and earlier fluxes to the biosphere compared with the FRAC3DVS 3DSU model.

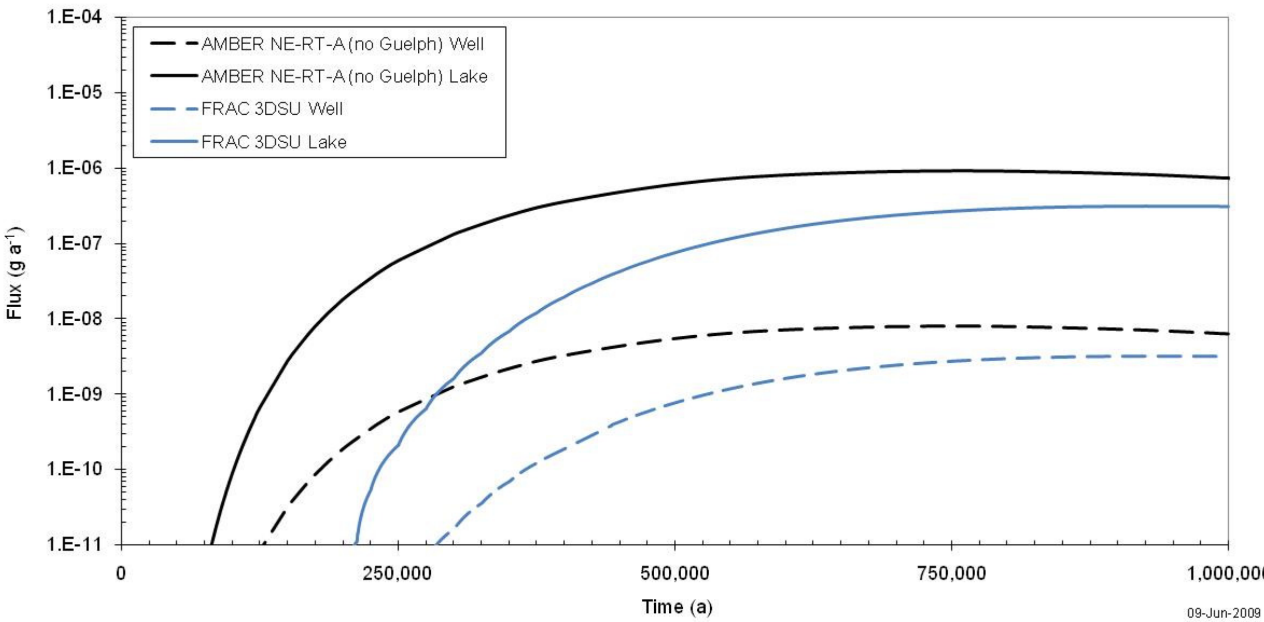

Figure 7-43: Cl-36 Flux in the Shallow Bedrock Groundwater Zone to the Well and Lake

Overall, the trends in the AMBER results are sufficiently similar to the FRAC3DVS model to build confidence in the safety assessment results, noting that the AMBER cumulative fluxes are typically more than an order of magnitude higher than the 3D model results.

Bulk gas flows and saturations from the detailed gas model (T2GGM) are used to inform the contaminant transport calculations undertaken by AMBER. The Gas Modelling report (Calder et al. 2009) has highlighted several uncertainties and issues related to the modelling approach (such as the differentiation of the flux of uncontaminated and contaminated gases, the representation of the migration of individual gas rather than bulk air, and the development of a 3D gas model rather than the 2D model used for the Version 1 SA calculations). Work has been identified by Calder et al. (2009) that could be undertaken to confirm the treatment of these uncertainties in the Version 1 SA is conservative.

Both the groundwater and gas modelling has been undertaken assuming constant density and so has not explicitly represented the effect of salinity gradients identified in Section 4.3.3. As explained in Section 7.3.4 and the detailed groundwater and gas modelling reports (Avis et al. 2009 and Calder et al. 2009), it is considered that the current approach is appropriate and does not give rise to significant uncertainties. Again, future work could be undertaken to confirm the conservative nature of the Version 1 SA calculations with regard to the representation of the salinity profile and its impact on contaminant migration.

7.5.2.2 Alternative Conceptual Models

Impact of future climate change on the DGR system

Although glacial/interglacial cycling will have a significant impact on the surface and near-surface systems, its impact is expected not to be as significant in the intermediate and deep geosphere (Section 5.1). Nevertheless, it is recognised 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 a range of the calculation cases assessed can be used to provide an initial evaluation of each of these potential impacts (Table 7-9). They are all below the dose criterion of 0.3 mSv a^{-1}. It is important to recognise that the current calculation cases do not explicitly represent the effects of climate change on the intermediate and deep geosphere. Nevertheless, the cases provide a preliminary indication of potential effects.

Table 7-9: Potential Impacts of Climate Change on the Intermediate and Deep Geosphere

Consequence of Climate Change	Relevant Cases	Calculated Peak Dose to an Adult (mSv a^{-1})	Cumulative Flux into Shallow Bedrock Groundwater Zone	
			Cl-36 in Groundwater at 1 Ma (g)	Bulk and Dissolved Gas at 500 ka (kg)
Base case	NE-BC NE-UG-BC	4.6E-10 4.2E-14	1.4E-04* 4.1E-14*	4.3E+02 3.0E+00
Degraded shaft EDZ performance	NE-EDZ NE-UG-EDZ	3.5E-02 4.5E-12	6.1E+02 7.0E-02	9.3E+06 3.7E+01
Alternative resaturation and rockfall assumptions	NE-RS1 NE-UG-RS1 NE-RS2 NE-RS3 NE-UG-RD1	4.3E-10 4.8E-14 4.3E-10 4.3E-10 -	- - - - 1.4E-15	- - - - 3.0E+00
Disequilibrium in heads in Ordovician and Cambrian	NE-UG-NHG	-	2.2E-16	-

*Values for NE-RS1-F3 and NE-UG-RS1-F3 cases

FRAC3DVS results show that different assumptions concerning the performance of the shaft seals and the associated EDZ have a significant (more than six orders of magnitude) effect on the calculated fluxes, whilst T2GGM result show up to five orders of magnitude effect. There is also an increase in dose impacts of up to nine orders of magnitude, although calculated peak doses remain below the dose criterion. The difference in doses (compared to fluxes) arises due to the differences in the timing of the peak flux and hence the relative importance of radionuclides such as Pu-239 and C-14.

The impacts of different resaturation times, rockfall and disequilibrium head assumptions are less significant with variations of a factor of 30 or less.

The impact of glacial/interglacial cycling on the surface environment and the nature of the discharge of contaminants from the geosphere has been evaluated in the current assessment through the use of a 'Reference Biosphere' approach, presented in the System and its Evolution report (Little et al. 2009). Rather than explicitly considering the sequence of climate states that would affect the Bruce site, the base case for the Normal Evolution Scenario considers stylised, constant temperate conditions which are broadly comparable with those presently found at the site. An alternative case considers release of contaminants to a tundra system; the calculated peak dose is a factor of three greater than for the temperate system. The results show that the overall impact of glacial/interglacial cycling on doses is limited, consistent with the findings of Lum and Garisto (2008).

Over/Underpressures

Site characterisation work has identified that the Cambrian sandstones are overpressured, whilst the Ordovician sediments are underpressured (Figure 4-7). There are several possible origins of these over/underpressures, and the likely cause(s) as well as their evolution are currently being investigated - see discussion in the Phase I Geosynthesis report (Gartner Lee 2008c) and the System and its Evolution report (Little et al. 2009).

In the analyses presented in this report, this uncertainty was conservatively treated by assuming that the underpressures quickly dissipated after closure, and that the high pressure in the Cambrian formation remained 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 persists in the Ordovician units as prevailing liquid gradients will be downward at all points above the repository horizon, including the shaft and EDZ system.

One case however considered the effect of the Ordovician underpressures, the NEUG-NHG-F2 case. In this transient case, the initial hydraulic pressures included the current measured profile, which were allowed to dissipate naturally according to the permeability and storativity of the rock mass. In this case with very low permeable (UG) geosphere the underpressures persist for well in excess of 1 Ma. This reduced transport into the Shallow Bedrock Groundwater Zone by more than two orders of magnitude compared with the NE-UG-RS1-F3 case. Part of this reduction is due to the less conservative nature of the 3DS cases (see the Groundwater Modelling report, Avis et al. 2009), but the impact of the Ordovician underpressures can also be expected to contribute to some of the reduction.

One potential cause for the Ordovician underpressures is the presence of gas in the rocks. Site characterisation suggests that there might be some initial gas saturation, although its extent is uncertain. The NE-UG-GT case assumes an initial value of 10% gas saturation in the Ordovician compared to the base case value of 0%. Gas modelling results show that gas from the repository does not migrate into the rock mass for these cases, due to gas pressure gradients towards the repository. Although gas from the repository does migrate into the shaft, it does not migrate above 260 m below ground surface over the calculation period of 1 Ma. Thus the base case of no initial gas saturation in the Ordovician can be seen to be conservative.

Evolution of repository and shafts

The evolution of the repository, its EDZ and their effect on contaminant release and migration can be evaluated through analysis of a number of calculation cases. In particular, uncertainties arise due to complex interactions between chemical conditions, the amount and types of microbes in the repository and surrounding host rock, corrosion, gas generation rates and resaturation rates and their impact on the resaturation profile of the DGR.

Table 7-10 summarises results for cases that consider alternative conditions for:

- release mechanisms and sorption/solubility conditions;
- resaturation profiles; and
- rockfall.

The NE-RT-A case with instant resaturation and instant release (i.e., no account is taken for waste packaging delaying the release of contaminants into groundwater) and no sorption shows an increase in the calculated peak dose of more than three orders of magnitude compared to the base case, although the calculated peak dose is still more than five orders below the dose criterion. As discussed under the impact of future climate change on the DGR system, the impact of different resaturation and rockfall assumptions is a factor of 30 or less.

Table 7-10: Calculated Impacts of Differing Repository Conditions

Condition	Relevant Cases	Calculated Peak Dose to an Adult (mSv a^{-1})	Cumulative Flux into Shallow Bedrock Groundwater Zone	
			Cl-36 in Groundwater at 1 Ma (g)	Bulk and Dissolved Gas at 500 ka (kg)
Base case	NE-BC NE-UG-BC	4.6E-10 4.2E-14	1.4E-04* 4.1E-14*	4.3E+02 3.0E+00
Instant resaturation and release to porewater, and no sorption or solubility limitation	NE-RT	7.5E-07	-	-
Alternative resaturation assumptions	NE-RS1 NE-UG-RS1 NE-RS2 NE-RS3	4.3E-10 4.8E-14 4.3E-10 4.3E-10	- - - -	- - - -
Alternative rockfall assumptions	NE-UG-RD1	-	1.4E-15	3.0E+00

*Values for NE-RS1-F3 and NE-UG-RS1-F3 cases

7.5.3 Data Uncertainty

7.5.3.1 Partitioning of Contaminants between Phases

A number of AMBER calculation cases have been analysed to investigate the impact of assumptions relating to the partitioning of contaminants. Comparison of the NE-BC-A case (C-14, Cl-36, Se-79 and I-129 partitioned between gas and groundwater) and the NE-RS1-A case (all C-14, Cl-36, Se-79 and I-129 assumed to be in groundwater) indicates that calculated peak dose differs by less than a factor of two. The variation in doses between the equivalent UG cases is a factor of three.

In contrast, comparison of the NE-RS1-A case (which includes sorption of certain radionuclides in the repository, shaft and geosphere) with the NE-RT-A (which includes no sorption) shows that calculated peak doses occur earlier (4 Ma vs. 6 Ma) and are three orders of magnitude higher for the NE-RT-A case due to the instantaneous release of contaminants and the absence of sorption. Nevertheless, the calculated peak dose is still more than five orders of magnitude below the dose criterion.

7.5.3.2 Shaft Sealing Material and EDZ Characteristics

As discussed in Section 7.5.2.2, the calculation cases assessed show that the uncertainties (be they related to the conceptual model and/or the data) associated with shaft sealing material and EDZ characteristics and their variation with time have a significant (orders of magnitude) effect on the calculated impacts, although impacts for all cases remain below the relevant criteria.

7.5.3.3 Hydraulic Characteristics of the Guelph, Salina A0 and Salina A2 Evaporite Formations

The Guelph and the adjacent Salina A0 Formations and the Salina A2 evaporite Formation are the main permeable units in the Intermediate Bedrock Groundwater Zone and could intercept contaminated groundwater transported from below through either the shaft or the rock mass. However, their effect on transport depends entirely on their hydraulic characteristics (gradient and environmental head), which are currently being determined as part of the site characterisation programme. The base case for the 3DS FRAC3DVS calculations assumes that there is a horizontal gradient in these formations of 0.002 based on the results of regional groundwater modelling (see Table 6-5). Assuming no horizontal gradient in these formations increases the Cl-36 flux in groundwater to the Shallow Bedrock Groundwater Zone by about an order of magnitude.

There is also uncertainty over the discharge points of these formations. The NE-RT-A case assumes pathlengths of 5 km to discharge points under Lake Huron, and the NE-GF-A case assumes longer pathlengths of 80 km. Figure 7-44 shows later (due to the longer travel time through the geosphere) and slightly reduced doses (due to additional decay resulting from the longer travel time) to a downstream exposure group for the NE-GF-A case. Figure 7-44 also shows that the calculated dose to the Local Exposure Group is unchanged compared with the NE-RT-A case, since the dose is unaffected by fluxes from the Guelph, Salina A0 and Salina A2 evaporite (dose is dominated by fluxes from the Shallow Bedrock Groundwater Zone). All calculated doses are at least five orders of magnitude below the dose criterion.

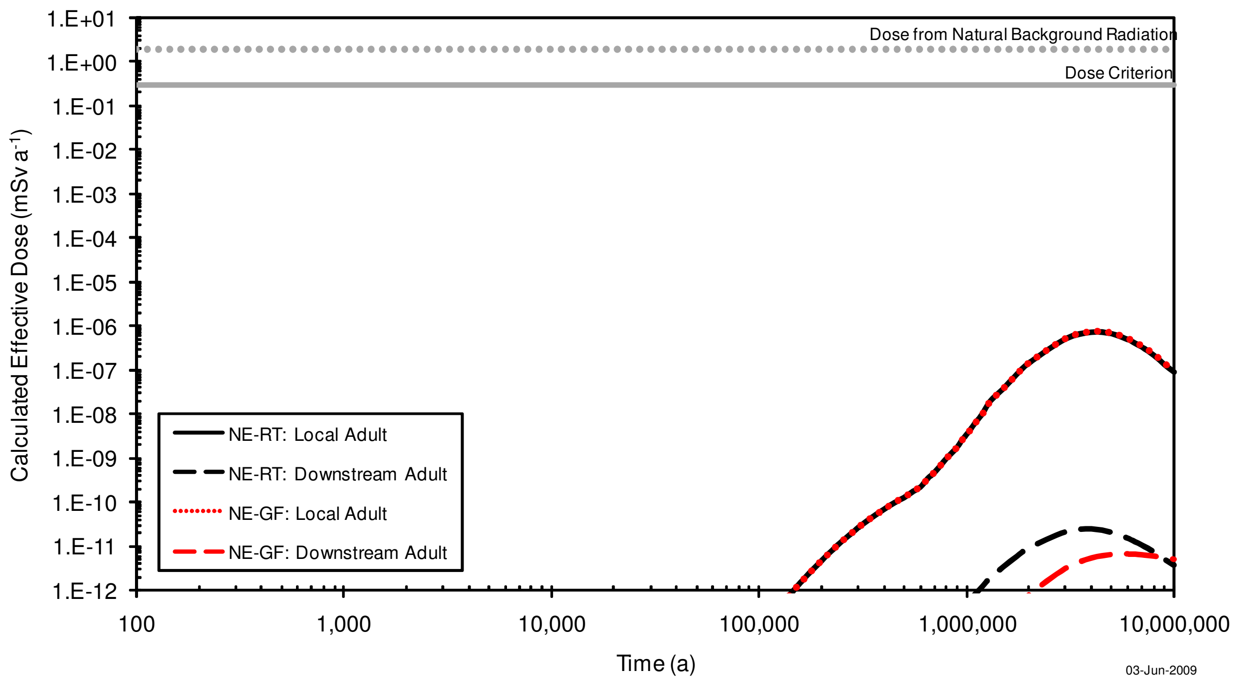

Figure 7-44: Total Calculated Effective Dose to Adults for the NE-RT-A and NE-GF-A Cases

7.5.3.4 Geosphere Permeabilities

The associated hydraulic conductivities derived from the Phase 1 site data from DGR-1 and DGR-2 are documented in the Data report (Walke et al. 2009b) and summarised in Table 6-5. Initial Phase 2 site investigation data made available in early 2009 (DGR 2009) indicates that the Phase 1 values are over-estimates and lower hydraulic conductivity values should be adopted for Ordovician and Silurian sediments. Therefore groundwater, gas and assessment calculation cases have been undertaken using both sets of values (Table 7-11), The lower permeabilities limit the migration of contaminants and therefore result in reduced fluxes and doses (Table 7-11). The impact is greatest on groundwater fluxes (almost ten orders of magnitude over the 1 Ma calculation period), and is much less significant for gas fluxes (an order of magnitude over the 1 Ma calculation period). The reduced fluxes into the Shallow Bedrock Groundwater Zone reduce the magnitude (by more than four orders of magnitude) and extends the time of maximum calculated dose to beyond 10 Ma (Figure 7-17).

Table 7-11: Calculated Impacts of Differing Geosphere Permeabilities

Condition	Relevant Cases	Calculated Peak Dose to an Adult (mSv a^{-1})	Cumulative Flux into Shallow Bedrock Groundwater Zone	
			Cl-36 in Groundwater at 1 Ma (g)	Bulk and Dissolved Gas at 500 ka (kg)
Higher permeabilities	NE-BC	4.6E-10	1.4E-04*	4.3E+02
Lower permeabilities	NE-UG-BC	4.2E-14	4.1E-14*	3.0E+00

*Values for NE-RS1-F3 and NE-UG-RS1-F3 cases

7.5.3.5 Gas Flow Parameters for the Silurian

Capillary pressure curves are particularly important in defining conditions for cases with initial gas saturation, such as the NE-UG-GT case, as initial gas pressures in the rock are not known. For units above the Queenston, data to support the values for these parameters did not exist, and values have been assumed or calculated based on the Davies relationship (Davies 1991), as discussed in the Data report (Walke et al. 2009b). Additional site characterisation data and analyses from the Phase 2 investigation are expected to provide these data and, ahead of these data becoming available, no variant calculations have been undertaken to assess the sensitivity of the model to these parameter values.

7.5.3.6 Repository Gas Generation Parameters

The sensitivity of gas pressure and fluxes was investigated using two calculation cases.

First, a calculation case (NE-GG1-T, higher gas generation) was evaluated, which considered the effect of increased metallic waste inventories due to additional overpacking of carbon and stainless steel wastes, increased corrosion rates and degradation rates. The total mass of metals is increased to 7.3×10^7 kg from 5.8×10^7 kg and the corrosion and degradation rates are increased by an order of magnitude (compared to those given in Table 6-5). This resulted in an increase in the gas flux to the Shallow Bedrock Groundwater Zone by less than a factor of two. Peak repository gas pressure is marginally increased from 8.5 MPa at 2 ka (NE-BC-T case) to 8.6 MPa at 11 ka.

A second calculation case (NE-GG2-T, lower gas generation) has been assessed in which the corrosion and degradation rates for the base case are reduced by an order of magnitude and the hydrogen consumption rate for methanogenic reaction is lowered from 1 a^{-1} to 0.01 a^{-1}. This results in a slight increase in peak repository gas pressure (8.8 MPa [35] at 2.2 ka) and a small (less than a factor of two) increase in gas fluxes.

Thus gas pressure and fluxes appear to be only marginally affected by these changes in gas generation parameters and so the impacts on humans and the environment will be minimal.

7.5.3.7 Alternative Lifestyles and Receptor Locations

Doses have been evaluated for exposure groups that are local to the site for all scenarios. The food consumption rates for exposures are based on the conservative recommendations of CSA (2008), which typically uses 90th percentile rates (see Data report, Walke et al. 2009b). In addition, a case has been evaluated, based on the NE-RS1-A case, in which dose to a "downstream" exposure group is evaluated. The group is exposed via consumption of lake fish and water from the South Basin of Lake Huron. The fish consumption rate for adults is taken to be 100 g d^{-1} – a value which is five times the value for the Local Exposure Group given in the Data report (Walke et al. 2009b) and twice the maximum value given in the survey of fish consumption by the Chippewas of Nawash (Nawash Fishes 2002). The drinking water consumption rate for adults is the same as that for the Local Exposure Group, i.e., 2.3 L d^{-1} (Walke et al. 2009b). Despite the significantly increased fish consumption rate, the calculated

[35] The slower degradation results in slower production of carbon dioxide. Thus there is less carbon dioxide available for the hydrogen consuming methane generation reaction, which also proceeds at a slower rate than for the base case. This results in hydrogen, rather than methane, being the dominant gas in the repository and in higher gas pressures.

peak dose to the Downstream Exposure Group is more than four orders of magnitude lower than the calculated peak dose to the Local Exposure Group (Figure 7-45) due to the significant dilution and dispersion of radionuclides in the lake.

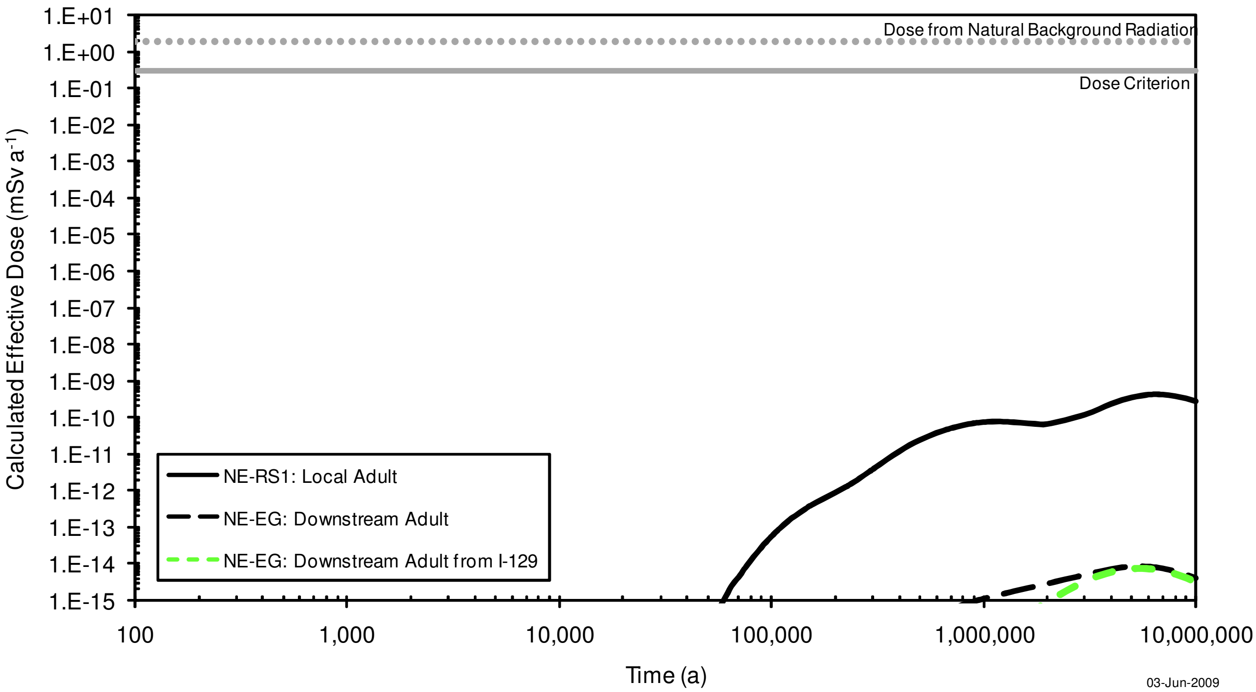

Figure 7-45: Calculated Effective Dose to Adult Member of Exposure Groups for the NE-RS1-A and NE-EG-A Cases

7.6 CONFIDENCE BUILDING MEASURES

As noted in Section3.7.3, it is important to develop confidence in the safety assessment and its results. A range of measures can be used to develop confidence both in terms of establishing confidence within each stage of the assessment process and in the overall process. As the assessment of a repository progresses through a series of iterations, it can be expected that the level of confidence will increase as uncertainties are identified and reduced.

Evidence of the measures that have been used in the current assessment of the DGR are summarised in Table 7-12 and Table 7-13. As discussed in Section 7.5, the current assessment has a range of associated uncertainties. These will be addressed by the future programme of work outlined in Section 8 and, as a consequence, further confidence will be developed in the subsequent iterations of the assessment.

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 7-14, together with a commentary on how they have been considered in the current assessment.

Table 7-12: 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 Section 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 disposal system (repository, geological setting and surface environment) and associated uncertainties. • Linkage to geosynthesis, site characterisation, waste characterisation, and repository design.	Section 4 provides a summary of the system description. A more detailed description is provided in the System and its Evolution report (Little et al. 2009) in which the current understanding of the DGR system and its wastes is summarised and the associated uncertainties discussed. Information from the on-going geosynthesis, site characterisation, waste characterisation and repository design programmes has been used in the current assessment (see start of Section 4).
Scenarios	• The set of scenarios is 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 characterisation, waste characterisation and repository design.	The approach used to identify and justify the scenarios is summarised in Section 5 and described in detail in the System and its Evolution report (Little et al. 2009). A wide range of external (or scenario generating) 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, Table 5-3 and Table 5-4). 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 5-5).
Models	• The conceptual models and associated data are consistent with the assessment context, disposal 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 characterisation, waste characterisation and repository design.	The process used for developing the conceptual models for the scenarios is described in Section 6.1 and its application summarised in Section 6.2 and described in the Normal Evolution and Disruptive Scenarios Analysis reports (Walke et al. 2009a; Penfold and Little 2009). The assessment context, disposal 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 B). The Gas Generation Model (GGM) component of the T2GGM code has been developed specifically for the DGR assessment and has an associated set of documentation to demonstrate its applicability to the DGR (Calder et al. 2009; Suckling et al. 2009). 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).

Assessment Stage	Confidence Building Measures	Evidence of Use in the Safety Assessment
Analysis of Results	• Key assumptions are documented and justified • Uncertainties are adequately addressed. • Compliance with regulatory requirements and recommendations is analysed. • Key areas for further work are identified.	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, Little et al. 2009); model assumptions in the Normal Evolution and Disruptive Scenarios Analyses reports, Walke et al. 2009a, Penfold and Little 2009; data assumptions in the Data report, Walke et al. 2009b). As noted in the assessment context (Section 3.7.2), 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, but physically plausible, 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 (Little et al. 2009), the Data report (Walke et al. 2009b), and the Normal Evolution and Disruptive Scenarios reports (Walke et al. 2009a; Penfold and Little 2009). They are assessed in Section 7.5 of the current report and a programme of future work designed to reduce/manage them further is identified in Section 8. Compliance with regulatory requirements and recommendations is summarised in Sections 7.1.3 and 7.2 for the Normal Evolution and Disruptive Scenarios, respectively. Recommendations for further work are provided in Section 8. Their aim is to reduce uncertainties and build further confidence in the assessment of the DGR.
Review and Modification	• Modifications are implemented in a structured and well-documented manner. • Work is specified with the aim of ensuring that key uncertainties will be reduced or better understood.	The assessment results have been subject to a process of internal (QIS Partnership) and external (OPG and NWMO) review and revision since 2008, when initial results were produced for the Version 1 SA. This review process has been documented and an audit trail of review comments and responses produced. It is expected that the current assessment will form the basis of future assessments. The uncertainties that have been identified during the assessment are summarised in Section 7.5. It is envisaged that these will be investigated in a subsequent assessment in light of the current results and the on-going programme of geosynthesis, site investigation, waste characterisation and repository design work identified in Section 8.

Table 7-13: 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 Assessment
Use of a systematic approach	An approach based on the IAEA's ISAM methodology (see Section 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 disposal system and its uncertainties	As discussed in Section 7.5, there are a number of key uncertainties associated with the understanding of the DGR system and its evolution (e.g., the evolution of repository conditions, the hydrogeological conditions). These uncertainties have been explored in the current assessment using variant calculations. This information informs on the significance of the uncertainties, and guides the priority areas for further investigation and, if possible, reduction during future assessments.
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 exposure 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 Section 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 1-3). 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 (2009). It is in accordance with the requirements of the International Standard ISO 9001:2000. A number of project-specific procedures have been developed, for example for the peer review and verification of deliverables (documents, calculation files and software tools), and the storage of project records and deliverables.
Peer review of the assessment	In addition to being reviewed by OPG and NWMO staff, the assessment documents have been reviewed by specialists in the QIS Partnership and their comments have been addressed in the final versions of the documents. International peer review of V1 postclosure SA is planned by NWMO.
Involvement of stakeholders in the development of the assessment	As noted in Section 3.2, the assessment has been undertaken primarily to inform the DGR Project Team, who will use the knowledge gained to help inform the DGR EIS and Preliminary Safety Report and the associated programme of work (including inventory characterisation, site characterisation, geosynthesis, and design). OPG and NWMO staff have been heavily involved in the development of the assessment through the specification of the work programme, attendance at technical meetings, and the review of the project output.

Table 7-14: Addressing the EIS Guidelines for the DGR in the Version 1 Safety Assessment

Issue	Guidance	Consideration in the Version 1 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 scenarios	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.	Systematic, transparent and traceable approach has been used to identify and develop scenarios (Section 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 5-5).
	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 expert judgment (including a scenario workshop in April 2008), 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 waste disposal system (Section 6.2.1). It is recognised 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 stylised, 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).
	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), conceptualised (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 Section 5.

Issue	**Guidance**	**Consideration in the Version 1 Safety Assessment**
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: • scoping calculations, e.g., to identify the contaminants for assessment (see Data report, Walke et al. 2009b) and the extent of rockfall in the repository (see Appendix A of the System and its Evolution report, Little et al. 2009); • detailed groundwater and gas calculations (see associated reports, Avis et al. 2009, and Calder et al. 2009); and • assessment calculations (see Normal Evolution and Disruptive Scenarios reports, Walke et al. 2009a, and Penfold and Little 2009). The current assessment uses multiple deterministic calculations. Probabilistic calculations will be used in future assessments.
	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 and 7.3 show that the system maintains its safety functions under the Disruptive Scenarios assessed.
	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: waste dissolution rates (e.g., Figure 7-1 and Figure 7-2); groundwater age and travel time (Section 7.1.2); fluxes of contaminants (e.g. Figure 7-12 and Figure 7-13); concentrations of contaminants in specific environmental media (e.g., Figure 7-16, Figure 7-18).
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: • scoping calculations, e.g., to identify the contaminants for assessment (see Data report, Walke et al. 2009b) and the extent of rockfall in the repository (see Appendix A of the System and its Evolution report, Little et al. 2009); • detailed groundwater and gas calculations (see associated reports, Avis et al. 2009, and Calder et al. 2009); and • assessment calculations (see Normal Evolution and Disruptive Scenarios reports, Walke et al. 2009a, and Penfold and Little 2009). The current assessment uses multiple deterministic calculations. Probabilistic calculations will be used in future assessments.

Issue	Guidance	Consideration in the Version 1 Safety Assessment
Demonstration of confidence in mathematical models (cont.)	Demonstrating consistency amongst the results of the long-term assessment model and complementary scoping and bounding assessments.	Key contaminants identified in the scoping calculations described in Data report (Walke et al. 2009b) are comparable to those identified in the Normal Evolution and Disruptive Scenarios reports (Walke et al. 2009a, and Penfold and Little 2009). Scoping calculations for repository gas pressure are presented in Appendix B of the Gas Modelling report (Calder et al. 2009) and build confidence in the gas pressures calculated using T2GGM.
	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.	Not undertaken for the current assessment.
	Performing model intercomparison studies of benchmark problems	The assessment code used (AMBER) has been extensively applied to benchmark problems from international studies including those of the IAEA and NEA (Enviros and Quintessa 2008b).
	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 B. Further details, including code verification and validation information, are provided in the Groundwater Modelling report (Avis et al. 2009), Gas Modelling report (Calder et al. 2009) and the Normal Evolution Scenario Analysis report (Walke et al. 2009a). The review of calculations is documented as part of the quality management system applied to the project (Quintessa 2009).
	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 codes used have been used in a wide number of studies, and have associated, peer-reviewed, open-literature publications (Appendix B). Further details are provided in the Groundwater Modelling report (Avis et al. 2009), Gas Modelling report (Calder et al. 2009) and the Normal Evolution Scenario Analysis report (Walke et al. 2009a).

Issue	Guidance	Consideration in the Version 1 Safety Assessment
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 analysed.	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 7.5.
	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 Section 7. More detailed analysis and interpretation is provided in the following supporting reports: Normal Evolution Scenario Analysis (Walke et al. 2009); Human Intrusion and Other Disruptive Scenarios Analysis (Penfold and Little 2009); Groundwater Modelling report (Avis et al. 2009); and Gas Modelling report (Calder et al. 2009). These analyses identify the key processes that control 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 characterisation 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 7.5. Uncertainties are evaluated arising from scenarios (Section 7.5.1), mathematical models (Section 7.5.2.1), conceptual models (Section 7.5.2.2) and data (Section 7.5.3).
	For the uncertainties, which have important impact on long-term safety, follow-up field and laboratory investigation programmes in combination with refinement of mathematical models should be proposed.	A programme of work has been identified to address the identified uncertainties (Section 8).

8. IMPLICATIONS FOR DGR WORK PROGRAMMES

The results presented in Section 7.1 indicate that the DGR system provides effective containment of the disposed radionuclides for a long period of time (many hundreds of thousands of years) for the Normal Evolution Scenario. 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, and the embedded nature of contamination in the higher activity zircaloy metal wastes means that they are released slowly as the wastes corrode over time. The low permeability of geosphere and the engineered barriers in the shaft further limit the migration of contaminants in groundwater or as bulk gas. The amount of contaminants reaching the surface is small, such that the calculated peak doses for the base case is almost nine orders of magnitude below the 0.3 mSv a^{-1} dose criterion. Calculations have also been undertaken to assess the impact of radionuclides on non-human biota and the impact of non-radioactive species on humans and the environment. The results indicate that potential impacts are well below the relevant criteria.

In addition, consideration has been given to disruptive events that, although unlikely to occur, could disrupt or bypass many of the repository barriers. The analysis 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 almost all circumstances (Section 7.2).

As noted in Section 3.7.2, 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, but physically plausible, 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 overestimates of impacts. For example the base case calculations for the Normal Evolution Scenario do not account for the potential impact of Ordovician underpressures in limiting contaminant migration and conservatively assume a constant vertical hydraulic head gradient due to the Cambrian overpressure.

It is important to recognise that there is a range of uncertainties associated with the current assessment. These uncertainties and their effects on calculated impacts have been evaluated in Section 7.5. This evaluation has highlighted a number of issues for further analysis in the next iteration of the safety assessment (Section 8.1). In addition, it is recognised that studies could be undertaken under the other DGR work programmes to help support the assessment of these issues in future assessments (see Section 8.2).

8.1 POSTCLOSURE SAFETY ASSESSMENT WORK PROGRAMME

Analysis of the results obtained for the current assessment and the associated uncertainties has highlighted the following two main areas of key uncertainties to be addressed in the next iteration of the postclosure safety assessment.

1. **Characterisation of shaft and EDZ properties** and their physical and chemical evolution with time, including further review of whether there are any significant effects from glaciation, and seismic and gas loadings that would cause the seals to degrade

faster than currently expected in the Normal Evolution Scenario. Various calculation cases have shown the significant variation (more than nine orders of magnitude at the extreme) in calculated impacts arising from differing assumptions relating to the characteristics and evolution of the shafts and their EDZs. Although this is an important source of uncertainty that needs to be addressed further (see Sections 8.2.2 and 8.2.4), it should be recognised that the calculated peak doses for all calculation cases remain below the relevant dose criterion.

2. **Understanding and representing the geosphere system**. As noted in Section 7.5, both conceptual and parameter uncertainties exist relating to the geosphere that result in variations in impacts of more than four orders of magnitude. In particular:
   - the geosphere permeability, especially in the Deep and Intermediate Bedrock Groundwater Zones (i.e., low or very low);
   - the origin and evolution of the hydraulic head distribution in the geosphere (especially under conditions of glacial/interglacial cycling);
   - the flow characteristics of the Guelph, Salina A0 and Salina A2 evaporite formations; and
   - gas flow parameters, especially in the formations above the Ordovician.

   Of these, calculations have shown that the variations in permeability considered in the assessment have the greatest impact on calculated peak doses, with a range of more than four orders of magnitude. Nevertheless, doses remain many orders of magnitude below the dose criterion even for the higher permeability geosphere.

Further improvements to the postclosure safety assessment will help improve our understanding of the DGR processes.

1. Building confidence in the detailed and assessment calculations through using different safety assessment strategies: e.g., using a combination of approaches such as scoping and bounding calculations, deterministic and probabilistic approaches (as recommended in the EIA guidelines for the DGR). As noted in Table 7-14, there is scope for the next iteration of the assessment to undertake probabilistic, as well as deterministic calculations, and to compare the results obtained using the detailed and assessment calculations with those obtained from simplified scoping models.
2. Enhancement of models used to represent the DGR system, its evolution and the migration of contaminants through it. Such improvements could include: geochemical models and more detailed 3 dimensional groundwater models and 3 dimensional gas models; the modelling of individual gases (rather than bulk gases); the explicit representation of the salinity profile in groundwater and gas calculations; and the improved integration of detailed groundwater and gas calculations. Analysis of modelling approaches adopted for the Version 1 SA has demonstrated the conservative nature of the AMBER and 2D FRAC3DVS calculations when compared to the 3D FRAC3DVS calculations which calculate one to two orders of magnitude lower impacts.
3. Partitioning of contaminants between phases (gas-solid, liquid-gas and liquid-solid) in the DGR system. For example assumptions concerning the sorption of contaminants (i.e., liquid-solid partitioning) can affect calculated impacts and the relative importance of contaminants by up to three orders of magnitude (compare peak calculated dose for NE-RS1-A (sorption of certain radionuclides), 4.3×10^{-10} mSv a^{-1}, and NE-RT-A (no sorption), 7.7×10^{-7} mSv a^{-1}). There could be scope to undertake a literature review to determine appropriate geosphere sorption coefficients for certain elements, such as Pu and Pb, that are currently considered to be non-sorbed.

8.2 OTHER DGR WORK PROGRAMMES

The next postclosure safety assessment will take account of developments arising from the on-going waste characterisation, repository design, site characterisation and geosynthesis programmes. However, it is recognised that these programmes should, in turn, be informed by the results of the Version 1 SA. This will allow relevant work to be undertaken by the other DGR work programmes to support the evaluation of the postclosure safety assessment issues identified in Section 8.1.

8.2.1 Waste Characterisation

Assessment calculation results are ultimately dependent on the estimated amount of contaminants (radioactive and non-radioactive) that are present in the waste. Most aspects of the waste inventory are not subject to a significant degree of uncertainty (i.e., uncertainties are typically less than an order of magnitude) or the uncertainty is not important to the assessment – see discussion in Section 4.5.1. Nevertheless, the waste inventories, including the inventory of non-radioactive species in wastes, should be updated periodically so they are consistent with current storage and projections.

8.2.2 Repository Design

The design of the shaft seal evaluated in the current assessment differs from that presented in the May 2008 version of the DGR conceptual design developed by Hatch (Hatch 2008). After discussion and agreement with NWMO in February 2009, the following modifications were made:

- the asphalt waterstops have been repositioned around the permeable Guelph formation; and
- the rock around the shaft is not reamed out in an effort to remove the Inner EDZ.

There is a need to ensure that the next revision of the conceptual design takes into account the results of the assessment of this modified shaft design, particularly the need to ensure that seals penetrate the shaft EDZ and the need to take measures to minimise the extent of the EDZ and its impact on the performance of the host rock.

Calculation cases have shown no significant benefit to be gained from backfilling the access and ring tunnels (see Section 7.4).

8.2.3 Site Characterisation

It is expected that the on-going programme of site characterisation (Intera 2008) will yield improved site-specific information, which will reduce certain key data uncertainties discussed in Section 7.5.3. In particular, further information to that available for the Version 1 SA on the following data items would be of value to the next iteration of the safety assessment:

- the permeability of formations, particularly in the Ordovician and Silurian;
- the flow characteristics (e.g., gradient, hydraulic conductivity and porosity) of the Guelph, Salina A0 and Salina A2 evaporite formations;
- gas capillary pressure and relative permeability parameters, especially for the formations above the Queenston; and

- the geochemical characteristics of the pore water and rocks, especially for the Cobourg formation, which could be used to support the development of geochemical models of repository and shaft conditions and their evolution.

8.2.4 Geosynthesis

The current assessment has highlighted the need for supporting information from the geosynthesis programme:

- to characterise the rock EDZ properties, and their evolution with time;
- to understand the origins and future evolution of the current hydraulic head distribution; and
- to demonstrate that the effects of glacial/interglacial cycling, seismic events and gas loading will be limited in the repository and deep and intermediate geosphere.

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APPENDIX A: CALCULATION CASES

A.1 ASSESSMENT MODEL CALCULATION CASES

A total of 13 deterministic parameter and conceptual model sensitivity cases have been developed to assess the impact of different parameterisations of the DGR system for the Normal Evolution Scenario (Table A-1). A further 12 calculation cases are considered for the Disruptive Scenarios (Table A-2).

Table A-1: Assessment Modelling Cases for the Normal Evolution Scenario

Case ID	Case Description	Associated Detailed Modelling Cases	Uncertainties which case can be used to addressed
NE-BC-A	Based on detailed groundwater and gas modelling reference cases but considers: • final resaturation from 1.0 Ma to 1.05 Ma (cautious assumption, T2GGM calculations suggest a longer timescale); • only dissolved gas release to Shallow Bedrock Groundwater Zone (i.e., no bulk gas release) (based on T2GGM calculations); • source terms with release for certain radionuclides partitioned between gas and groundwater; • sorption and potential solubility limitation of certain radionuclides; • additional time-dependent processes (e.g., rockfall) but no explicit consideration of climate change See Table 6-5 for summary of data.	NE-BC-T NE-RS1-F3	Base case for radioactive contaminants
NE-UG-BC-A	As NE-BC-A but with updated preliminary geosphere data from DGR-3 and DGR-4.	NE-UG-BC-T	• Alternative permeabilities in geosphere • Alternative resaturation profile
Repository Resaturation			
NE-RS1-A	As NE-BC-A but with: • immediate water resaturation of repository; • no gas generation in repository; and • no degassing from groundwater.	NE-RS1-F3	• Timing of resaturation of repository (instant resaturation) • Partitioning of contaminants between groundwater and gas (all in groundwater)
NE-UG-RS1-A	As NE-RS1-A but with updated preliminary geosphere data from DGR-3 and DGR-4.	NE-UG-RS1-F3	• Alternative permeabilities in geosphere • Timing of resaturation of repository (instant resaturation) • Partitioning of contaminants between groundwater and gas (all in groundwater)

Case ID	Case Description	Associated Detailed Modelling Cases	Uncertainties which case can be used to addressed
NE-RS2-A	As NE-BC-A but with final water resaturation between 10 ka to 20 ka due to internal repository processes resulting in faster gas release from repository.	-	• Timing of resaturation (much earlier than base case)
NE-RS3-A	As NE-BC-A but with final water resaturation between 50 ka and 60 ka.	-	• Timing of resaturation (much earlier than base case)
Groundwater Release and Transport Model			
NE-RT-A	As NE-RS1-A but with: • instantaneous release of radionuclides to groundwater; and • no radionuclides sorbed or solubility limited in repository or geosphere. Case allows direct comparison with NE-RS1-F3 Also consider version with no horizontal flow in the Guelph, Salina A0 and Salina A2 evaporite formations (directly comparable with NE-NHG-F2 and NE-NHG-F2).	NE-RS1-F3, NE-NHG-F2 & F3	• Timing of resaturation (instant resaturation) • Partitioning of contaminants between groundwater and gas (all in groundwater) • Contaminant release and migration (instantaneous release and no sorption/solubility limitation)
Excavation Damaged Zone			
NE-EDZ-A	As NE-BC-A but hydraulic conductivity for shaft inner EDZ assumed to be four orders of magnitude greater than intact geosphere, and hydraulic conductivity for shaft outer EDZ assumed to be two orders of magnitude greater than intact geosphere. Interruption of shaft inner EDZ by concrete bulkheads and asphalt waterstops is assumed to be ineffective.	NE-EDZ-F2 NE-EDZ-T	• The evolution of the shafts and their EDZs, and their impact on contaminant migration • The gas and groundwater flow and transport characteristics of the shaft sealing materials and the shaft EDZ
Geosphere			
NE-GF-A	As NE-RT-A, but with 80 km pathlength in the Guelph Formation leading to discharge into the Central Basin of Lake Huron.	GW-G3-F GAS-G2-T	• Hydrogeological conditions in the geosphere and the associated processes and properties • Hydraulic characteristics of the Guelph, Salina A0 and Salina A2 evaporite Formations

Case ID	**Case Description**	**Associated Detailed Modelling Cases**	**Uncertainties which case can be used to addressed**
Climate Change			
NE-CC-A	As NE-BC-A, but with alternative constant state biosphere (i.e., tundra rather than temperate)	-	• Biosphere evolution • Alternative geosphere-biosphere interface • Human consumption rates
Exposure Group			
NE-EG-A	As NE-RS1-A, but with dose to “downstream” exposure group evaluated. The group is exposed via consumption of lake fish and water from the South Basin of Lake Huron.	NE-RS1-F3	• Human consumption rates
Non-radioactive contaminants			
NE-NR-A	As NE-RS1-A, but with non-radioactive species identified in Table 4-4.	NE-RS1-F3	• Base case for non-radioactive species

Table A-2: Assessment Modelling Cases for the Disruptive Scenarios

Case ID	Case Description	Associated Detailed Modelling Cases
HI-SR1-A	As for the Normal Evolution Scenario case NE-BC-A (slow saturation) but with an exploration borehole drilled from surface down to the repository sometime after controls are no longer effective. Borehole terminated at repository depth. Case considers the consequences of surface release immediately following intrusion.	-
HI-SR2-A	As HI-SR1-A, but based on the Normal Evolution Scenario case NE-RS1-A (immediate resaturation)	HI-GR-F3
HI-NR1-A	As for HI-SR2-A, but assesses the consequences of a release of non-radioactive species.	--
HI-GR-A	As HI-SR1-A but considers long-term release of radionuclides from the repository to the Shallow Bedrock Groundwater Zone through an exploration borehole drilled at 300 years. The repository vents any gases and fully resaturates through the exploration borehole.	HI-GR-F3
HI-NR2-A	As for HI-GR-A, but assesses the release of non-radioactive species.	-
SF-ES1-A	As for the Normal Evolution Scenario case NE-BC-A but hydraulic properties of all seals, backfill and shaft inner EDZ set to extreme degraded values from t=0, all seals not keyed into shaft EDZ, and reduced sorption on shaft materials. Gas flows derived from detailed gas modelling case.	SF-ES1-F2 and SF-ES1-T
SF-US-A	Failure of the upper shaft seals only. As for SF-ES1-A but characteristics of the Ordovician seals, backfill and inner shaft EDZ (including those at the Silurian-Ordovician boundary) as for NE-BC-A.	SF-US-F2 and SF-US-T
SF-NR-A	As SF-ES1-A, but assesses consequences of non-radioactive species.	-
OB-BC-A	As for the Normal Evolution Scenario case with instant resaturation (NE-RS1-A) but with poorly sealed borehole from surface down to Pre-Cambrian located 400 m from the western edge of the South Panel. Characteristics of borehole and associated flow conditions to be the same as used for detailed groundwater case OB-BC-F3	OB-BC-F3
OB-NR-A	As for OB-BC-A but with the inventory of non-radioactive species disposed in the repository.	-
EE-BC-A	As for the Normal Evolution Scenario case with instant resaturation (NE-RS1-A) but with reactivated fault 500 m down gradient from the repository. Characteristics of fault and associated flow conditions to be the same as used for detailed groundwater case EE-BC-F3.	EE-BC-F3
EE-NR-A	As for EE-BC-A, but with the inventory of non-radioactive species disposed in the repository.	-

A.2 DETAILED GROUNDWATER MODELLING CALCULATION CASES

Seven parameter and conceptual model sensitivity cases for detailed groundwater modelling have been developed to assess the impact of different parameterisations of the geological and engineered barrier systems for the Normal Evolution Scenario (Table A-3).

The reference case is consistent with that summarised in Table 6-5 with the following additions/modifications:

- 1,000,000 year simulation period;
- no flow boundaries on all vertical model boundaries with the exception of a horizontal gradient of 0.002 in the Guelph, Salina A0 and Salina A2 evaporite formations achieved by fixed head boundaries at the elevation of the formations along the Y-axes;
- constant density water flow;
- repository resaturation and contaminant transport is assumed to start immediately after facility closure; and
- Cl-36 transport, initial concentration in repository based on instantaneous dissolution of the Cl-36 inventory given in Walke et al. (2009).

Table A-3: Detailed Groundwater Modelling Cases for the Normal Evolution Scenario

Case ID	Case Description
NE-RS1-F3	Reference case parameters for groundwater modelling based on V1 inventory, R1 repository conceptual design and Phase 1 site characterisation data, with immediate repository resaturation and no gas generation.
NE-UG-RS1-F3	NE-RS1 with updated geosphere data
NE-NHG-F2 & NE-NHG -F3	NE-RS1 with no horizontal gradients in permeable Silurian sediments (Guelph, Salina A0 and Salina A2 evaporite)
NE-UG-NHG-F2	NE-NHG with updated geosphere, transient flow from current pressure distribution
NE-EDZ-F2	As NE-NHG-F2, but hydraulic conductivity, K, for shaft inner EDZ assumed to be four orders of magnitude (OM) greater than intact geosphere, and K for shaft outer EDZ assumed to be two OM greater than intact geosphere. Interruption of shaft inner EDZ by concrete bulkheads and asphalt waterstops is assumed to be ineffective.
NE-UG-EDZ-F2	NE-EDZ with updated geosphere
NE-UG-RD1-F3	NE-UG-RS1 with ring and access tunnels sealed with concrete.

Six calculation cases are considered for Disruptive Scenarios (Table A-4).

Table A-4: Detailed Groundwater Modelling Cases for the Disruptive Scenarios

Case ID	Case Description
HI-GR-F3	As NE-RS1-F3 but with an exploration borehole drilled from surface down to the repository and then terminated at repository depth. The borehole was assumed to be sealed with a fill material.
SF-ES1-F2	As NE-NHG but with hydraulic properties of all seals, backfill and shaft inner EDZ set to extreme values and seals not keyed into shaft EDZ.
SF-UG-ES1-F2	As SF-ES1 with updated geosphere data
SF-US-F2	As SF-ES1 but with failure only for those seal system components located above the top of the Queenston shale.
EE-BC-F3	As NE-RS1 but with a single high permeability, reactivated fault 500 m down gradient from the repository.
OB-BC-F3	As NE-RS1 but with a poorly sealed site characterisation borehole located downgradient of the repository at the current location of site characterisation borehole DGR-3.

A.3 DETAILED GAS CALCULATION CASES

Eight modelling sensitivity cases for detailed gas modelling have been defined for the Normal Evolution Scenario (Table A-5). The base case is equivalent to the base case considered for the detailed groundwater modelling (Appendix A.2) with the following additions/modifications:

- no horizontal gradient in the Guelph, Salina A0 and Salina A2 evaporite formations (due to the limitations of a 2D radial model used for the T2GGM modelling);
- single bulk gas of air;
- initial gas saturation 98.3% in the repository (based on initial water content of waste), 50% in shaft, and 0% in intact rock; and
- initial inventory of metal mass is 5.8×10^7 kg and of organic mass is 2.2×10^7 kg.

Table A-5: Detailed Gas Modelling Cases for the Normal Evolution Scenario

Case ID	Case Description
NE-BC-T	Base case (BC) parameters.
NE-UG-BC-T	NE-BC with updated geosphere data from DGR3 and 4
NE-GG1-T	NE-BC except increased gas generation achieved by increasing the inventory (and hence surface area) of metals disposed in the repository and increased corrosion and degradation rates using the maximum values given in the V1b Data Report (Walke et al. 2009).
NE-GG2-T	NE-BC except use reduced degradation rates (i.e. minimum values from Version 1 data report (Walke et al. 2009) which for anaerobic conditions are an order of magnitude less than the best estimate values) and a lower hydrogen consumption rate (0.01/yr).
NE-EDZ-T	NE-BC except permeability for shaft inner EDZ assumed to be four orders of magnitude greater than intact geosphere, and permeability for shaft outer EDZ assumed to be two orders of magnitude greater than intact geosphere. Interruption of shaft inner EDZ by concrete bulkheads and asphalt waterstops is assumed to be ineffective. Reduced $1/\alpha$ values for the shaft EDZ calculated using the Davies relationship (Davies, 1991), which suggests that air-entry pressures are highly inversely correlated with permeability.
NE-UG-RD1-T	NE-UG-BC except backfill access tunnels and ring tunnels filled with low permeability concrete (rockfall only in emplacement rooms).
NE-UG-GT-T	NE-UG-BC except initial gas saturations in Ordovician sediments of 10% (consistent with site characterisation results).

The only disruptive scenario considered for the detailed gas modelling is the Severe Shaft Seal Failure Scenario; the associated calculation cases are listed in Table A-6. Other scenarios are not considered due to the limitations of the 2D radial gas transport model (i.e. features such as open boreholes or fractures, required by the Human Intrusion, Open Borehole and Extreme Earthquake Scenarios cannot be modelled with a 2D radial model; a 3D model would be required).

Table A-6: Detailed Gas Modelling Cases for the Severe Shaft Seal Failure Scenario

Case ID	Case Description
SF-ES1-T	As NE-BC but with hydraulic properties of all seals, backfill and shaft inner EDZ set to extreme values and seals not keyed into shaft EDZ.
SF-UG-ES1-T	SF-ES1 with updated geosphere data.
SF-US-T	As SF-ES1 but with failure only for those seal system components located above the top of the Queenston shale.

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APPENDIX B: OVERVIEW OF SOFTWARE TOOLS USED

B.1 AMBER

B.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 fast 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 (Enviros and Quintessa 2008a).

B.1.2 QUALITY ASSURANCE

AMBER is managed and developed under Quintessa's ISO 9001:2000 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., Walke et al. 2009a).

AMBER has a wide international user base, with over 70 organisations in more than 30 countries owning licences. There are in excess of 75 publications describing assessments in which AMBER has been applied (Enviros and Quintessa 2008b), including several international code intercomparison exercises.

Two DGR-specific models (AMBER_V1_NF&GEOv2 (for the repository, shafts and geosphere) and AMBER_V1_BIOv2 (for the biosphere)) have been implemented in the AMBER 5.2 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-radiological contaminants (AMBER_V1_NF&GEO_NRv2 and AMBER_V1_BIO_NRv2). The quality assurance of these models is discussed in Appendix H of the Normal Evolution Scenario Analysis report (Walke et al. 2009b).

B.2 FRAC3DVS

B.2.1 DESCRIPTION

FRAC3DVS solves the three-dimensional variably-saturated groundwater flow and solute transport equations in non-fractured or discretely-fractured media. Developed at the University of Waterloo by Therrien, Sudicky, and McLaren, FRAC3DVS provides a realistic representation of fracture connectivity, which can greatly influence the mass transport process by providing preferential pathways for rapid contaminant migration.

FRAC3DVS uses the control volume finite element approach to solve Richards' equation governing 3-D unsaturated/saturated subsurface flows, and the classical advection-dispersion equation for problems that also involve solute transport and chain decay.

FRAC3DVS provide several discretisation 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 ILU-preconditioned ORTHOMIN solution package and a Newton-Raphson linearisation package.

B.2.2 QUALITY ASSURANCE

Initially released in 1995, FRAC3DVS has enjoyed widespread acceptance with both academics and groundwater professionals. The flow and solute code has been verified against other numeric and analytic models. Verification cases are published in the FRAC3DVS documentation.

A version of FRAC3DVS (FRAC3DVS-OPG Version R622) has been documented for use on the DGR project (Therrien et al. 2007).

FRAC3DVS-OPG is currently undergoing qualification consistent with NWMO Software Quality requirements. Reports detailing the use of FRAC3DVS include Therrien and Sudicky (1996), Lacombe et al. (1995), Normani et al. (2004), Park et al. (2005) and Garisto et al. (2004).

B.3 T2GGM

B.3.1 DESCRIPTION

The postclosure safety assessment of the DGR requires the calculation of the generation and build-up 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 1.3). 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 Intera Engineering Ltd and is described in Suckling et al. (2009).

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 Suckling et al. (2009). Basically, 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 galvanised 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 includes 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 model for simulating the coupled transport of water, vapour, non-condensable gas, and heat in porous and fractured media in multi dimensions developed by the Earth Sciences Division of Lawrence Berkeley National Laboratory (Pruess et al. 1999). TOUGH2 includes the flexibility to handle different fluid mixtures (water, water with tracer; water, CO_2; water, air; water, air, with vapour pressure lowering; and water, hydrogen). 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 functions. The code includes Klinkenberg effects and binary diffusion in the gas phase, capillary and phase adsorption effects for the liquid phase. Heat transport occurs by means of conduction (with thermal conductivity dependent on water saturation), convection, and binary diffusion, which includes both sensible and latent heat.

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 coupling of GGM and TOUGH2 allows the interactions between gas generation (by corrosion and microbial degradation), gas pressure, and water saturation in the repository to be represented explicitly.

B.3.2 QUALITY ASSURANCE

Quality assurance documentation for **T2GGM** is provided in Suckling et al. (2009).

GGM has been developed under the DGR postclosure safety assessment project and so has been subject to the project's QA requirements (Quintessa 2009), 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, 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).

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