DEEP GEOLOGIC

REPOSITORY

FOR OPG's LOW & INTERMEDIATE LEVEL WASTE

Postclosure Safety Assessment (V1): Analysis of Human Intrusion and Other Disruptive Scenarios

July 2009

Prepared by:
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NWMO DGR-TR-2009-03

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

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July 2009

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DOCUMENT HISTORY

Title:	Postclosure Safety Assessment (V1): Analysis of Human Intrusion and Other Disruptive Scenarios		
Report Number:	NWMO DGR-TR-2009-03		
Revision:	0	**Date:**	6th July 2009
Notes:	Initial release		
Prepared by:	J Penfold and R Little		
Reviewed by:	J Pickens (interim version) L Limer (final version)		
Approved by:	R Little Project Manager Quintessa Limited		

EXECUTIVE SUMMARY

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 iteration of the safety assessment that will support the final EIS and PSR.

This report presents an analysis of disruptive events that could potentially affect the DGR and its environment. These are events that are unlikely to occur, but if they did occur, they would disrupt or bypass many of the repository barriers. The analysis, therefore, seeks to understand the consequences of these events, and the robustness of the repository to them.

The following Disruptive Scenarios have been identified through the use of a systematic approach:

- unintentional intrusion into the repository as a result of an exploration borehole, leading to release of contaminated materials from the repository to the surface environment and to the Shallow Bedrock Groundwater Zone (the **Human Intrusion Scenario**);
- the unexpected poor performance of the shaft seals (the **Severe Shaft Seal Failure Scenario**);
- the potential for a poorly sealed site investigation/monitoring borehole near the repository, resulting in an enhanced permeability path through the geological barrier (the **Open Borehole Scenario**); and
- an extreme earthquake that is assumed to reactivate a hypothetical fault in the vicinity of the DGR (the **Extreme Earthquake Scenario**).

Other disruptive events have been identified in the assessment of the DGR. However, these are not considered in this report because: they are addressed in other reports (i.e., ice-sheets in the Normal Evolution Scenario); or they are not plausible over the timescales of the assessment (e.g., volcanoes); or they have no effect on the DGR (e.g., plane crashes).

Any one of the events that could initiate the disruptive scenarios considered in this report is very unlikely to occur in any given year. 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. The likelihood of the Human Intrusion Scenario can only be judged on the basis of the current level of technology and societal development, which is impossible to extrapolate to long timescales. Nevertheless, for context, the current rate of drilling of deep boreholes would indicate a probability of striking a DGR emplacement room of approximately one in 200,000 years. The Severe Shaft Seal Failure Scenario and Open Borehole Scenario would also require unlikely conditions that result in the poor performance of shaft and borehole seal materials. Very large earthquakes in the vicinity of the DGR are unlikely - approximately one in 10^6 years under present conditions. One or more might occur at some point in the assessment timeframe; however, there is no evidence for any previous significant permeable pathway near the site between the repository horizon and the near surface that might be reopened by these or other events.

Since these are unlikely or "what if" scenarios, they are assessed using stylised conceptual models, based on simple but conservative assumptions. The consequences can be compared with a public dose criterion of 1 mSv a^{-1} for disruptive events, and as well as a risk benchmark of 10^{-5} a^{-1}. The calculation cases for the Disruptive Scenarios are based on the base case (BC) geosphere model, which uses low host rock permeabilities inferred from the DGR-1 and DGR-2 site investigation boreholes and documented in the Phase 1 geosynthesis reports.

The **Human Intrusion Scenario** could in principle result in contaminated slurry (water and some suspended particles), gas and/or undiluted (borehole core) waste to be released to the surface. The materials released at any given time would, however, depend on the conditions in the repository, in particular, the state of repository resaturation. Conservative assessment calculations have considered the potential exposure of the drill crew and site workers to these materials. The assessment did not take account of good practice and many standard operating procedures that would reduce the likelihood of the scenario. The calculated peak annual dose of about 6 mSv is to a person occupying the site and farming on land contaminated with drilling mud from the borehole. Ingestion of plants contaminated with C-14 is the key pathway. The drilling crew could also receive an exposure about 2 mSv, if exposure occurred for a significant period of time (around a month of drilling shifts). Both these cases, however, are very unlikely. Calculated peak annual doses to other potentially exposed groups after the intrusion are at least an order of magnitude lower, beneath the dose criterion for Disruptive Scenarios. If it is further assumed that the borehole is poorly sealed, thereby providing an increased permeability pathway from the repository to the Shallow Bedrock Groundwater Zone, an adult member of a local exposure group could receive a dose of around 0.002 mSv a^{-1}.

The **Shaft Seal Failure Scenario** demonstrates that even with extreme assumptions concerning the performance of the shaft seals, the DGR system can meet the relevant dose criterion. A peak dose of 0.02 mSv a^{-1} is calculated to the local exposure group assumed to be living on the site after about 10 ka. The main contaminant is C-14, initially dissolved in groundwater, but volatilised when the groundwater is used for irrigation. It should be emphasised that the assessment of the scenario is highly cautious and should be regarded as a "what if" calculation.

The **Open Borehole Scenario** considers a monitoring borehole near to the site that is poorly sealed and provides an enhanced permeability pathway up through the geosphere. The calculations show that it has a very minor influence on the performance of the system, and calculated doses are similar to those of the Normal Evolution Scenario. This is a consequence of the distance and the low host rock permeability between the repository and the borehole.

The only natural disruptive event that has been identified as being of potential significance is an **extreme earthquake** that causes the reactivation of a fault in the vicinity of the DGR. Although there is no geological evidence of such faults in the vicinity of the DGR site, a cautious "what if" calculation has considered the activation of a fault. It is conservatively assumed to occur immediately after closure and provide a permeable fault zone that can transmit contaminants to the Shallow Bedrock Groundwater Zone. The assessment calculations show the calculated doses are similar to those calculated for the Normal Evolution Scenario.

Calculations have been undertaken to assess the impact of radionuclides on non-human biota and the impact of non-radioactive species in the waste on humans and other biota.

The results indicate that potential impacts of radionuclides are below the relevant criteria for all the scenarios assessed with the exception of the Human Intrusion Scenario. In this case, no-effect concentrations could be exceeded by up to a factor of 60 for soil contaminated by the slurry. 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 farming immediately after the intrusion event. Furthermore, the model is conservative as the contaminated slurry is dispersed in a relatively small area of soil.

For the non-radioactive species, Environmental Quality Standards would also be met in most cases. The exception is that well water concentrations could exceed Environmental Quality Standards for groundwater by up to a factor of 50 for some elements (i.e., Cd, Cr, Cu and Pb) for the Human Intrusion and Severe Shaft Seal Failure Scenarios due to the enhanced permeability route directly from the repository to the Shallow Bedrock Groundwater Zone via a poorly sealed borehole intruding into the repository, or the severely degraded shaft seals. However, these situations are very unlikely, and moreover the calculation cases have cautiously ignored any solubility limitation and sorption of the species in the repository, shaft and geosphere.

Overall, the isolation afforded by the location and design of the DGR limits the likelihood of disruptive events potentially able to bypass the natural barriers to a small number of situations with very low probability. Even if these events were to occur, the analysis shows that the 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, even with conservative assessment modelling assumptions. However, the potential release of contaminated water, particles and gas via an exploration borehole drilled into the repository could result in exposures that exceed the 1 mSv dose criterion. The assessment is highly unlikely, however, since human intrusion is unlikely, and furthermore drilling practice is to contain and limit the release of material from boreholes.

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. Thus, the results presented in this report should be seen as being generally conservative and overestimates of impacts.

Further work on disruptive events analysis will seek to enhance overall confidence in the outcomes of this analysis, and further investigate the issues identified above in light of results from other DGR programmes such as waste characterisation, repository design and geosynthesis.

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1. INTRODUCTION

Ontario Power Generation (OPG) is proposing to build a Deep Geologic Repository (DGR) for Low and Intermediate Level Waste (L&ILW) near the existing Western Waste Management Facility (WWMF) at the Bruce site in the Municipality of Kincardine, Ontario (Figure 1-1). 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 a basis for a future version of the safety assessment that will support the final EIS and PSR.

The Version 1 work is building upon a preliminary SA conducted by Quintessa in 2002 and 2003 (Penfold et al. 2003) and is being 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.

This report (Human Intrusion and Other Disruptive Events) is one of a suite of documents that presents the Version 1 SA studies (Figure 1-2), which also includes the Postclosure SA main report (Quintessa et al. 2009), the Normal Evolution Scenario Analysis report (Walke et al. 2009a), 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).

A high-level description of the DGR system is provided below. More details are provided in the System and its Evolution report (Little et al. 2009) and the Data report (Walke et al. 2009b).

Waste:	Approximately 160,000 m^3 of stored L&ILW, representing a disposal volume of about 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 2062, the earliest potential closure date, 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 (Table 1-1).
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 (Figure 1-1). The South Panel (footprint 114,400 m^2) contains most of the LLW, while the East Panel (footprint 99,450 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).
Geosphere:	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 (with 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 towards Lake Huron.

Biosphere: 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 around 9 °C with an average precipitation rate of 0.98 m a^{-1}. Land uses on the Bruce Site are presently restricted to those associated with the nuclear operations and support activities. The region around the Bruce Site is mainly used for agriculture (arable and livestock), recreation and some residential development. Groundwater is used for municipal and domestic water in this region. The lake provides water for larger communities, and is used for fishing.

1.1 PURPOSE AND SCOPE

A range of possible future evolutions of the DGR system has been identified in the System and its Evolution report (Little et al. 2009). The Normal Evolution Scenario describes the expected evolution of the DGR system and its degradation (gradual loss of barrier function) with time. Four other scenarios (Disruptive Scenarios) have also been identified that examine the impacts of unlikely events that lead to the disruption or abnormal degradation of barriers and the associated loss of containment. These Disruptive Scenarios have a low probability of occurrence (with some being on the limits of plausibility); however, they have an important role in demonstrating the robustness of the DGR's performance in unexpected situations. They comprise:

- the **Human Intrusion Scenario**, which investigates the impact of an exploration borehole being unintentionally drilled down into the DGR;
- the **Severe Shaft Seal Failure Scenario**, which considers rapid and extensive degradation of the engineered seals in the shafts;
- the **Open Borehole Scenario**, which considers the consequences of a site investigation borehole in the vicinity of the DGR being poorly sealed; and
- the **Extreme Earthquake Scenario**, which investigates the impact of a high magnitude earthquake causing the reactivation of a fault in the vicinity of the DGR.

Other disruptive events have been identified in the assessment of the DGR. However, these are not considered in this report, because either they are addressed in other reports (i.e., ice-sheets in the Normal Evolution Scenario Analysis report, Walke et al. 2009a), or they are not plausible over the timescales of the assessment (e.g., volcanoes) or they have no effect on the DGR (e.g., plane crashes). These implausible and low consequence disruptive events are discussed and screened out from further consideration in the Features, Events and Processes report (Garisto et al. 2009).

The purpose of the current report is to provide an analysis of the four selected Disruptive Scenarios. It describes the scenarios and the associated conceptual models, outlines the development of the mathematical models and their implementation in software tools, and presents the results obtained and the uncertainties identified. A comparable analysis of the Normal Evolution Scenario is provided in Normal Evolution Scenario Analysis report (Walke et al. 2009a).

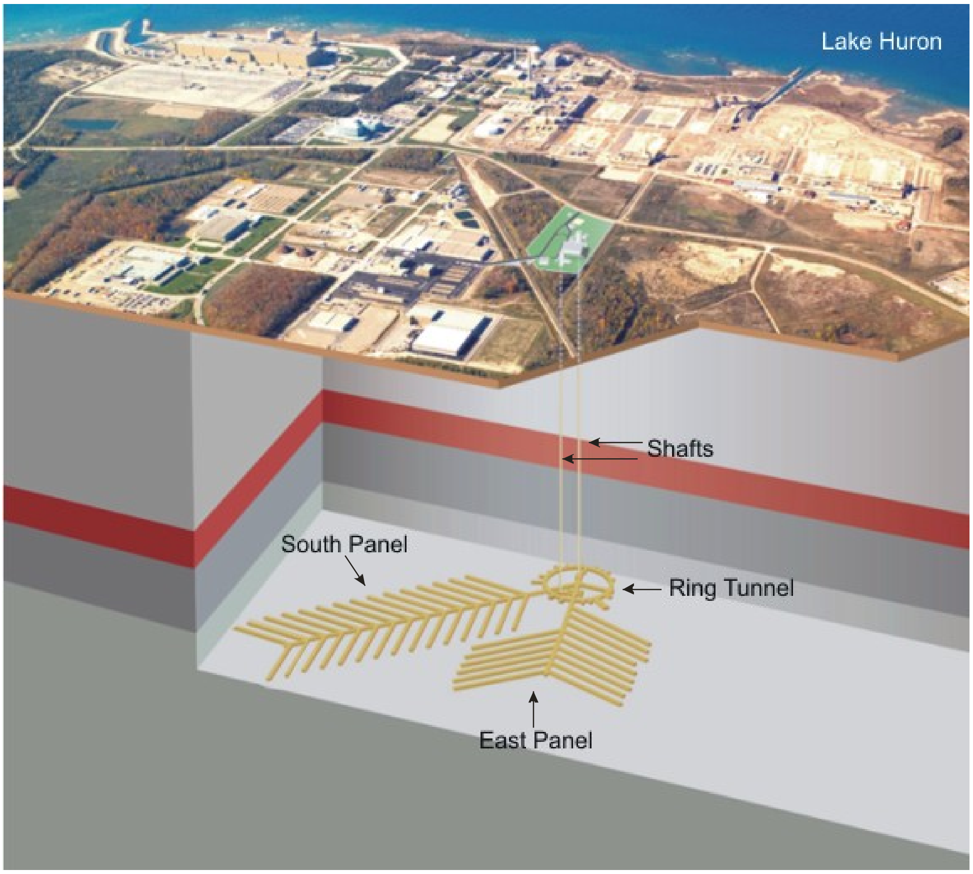

Figure 1-1: The DGR Concept at the Bruce Site

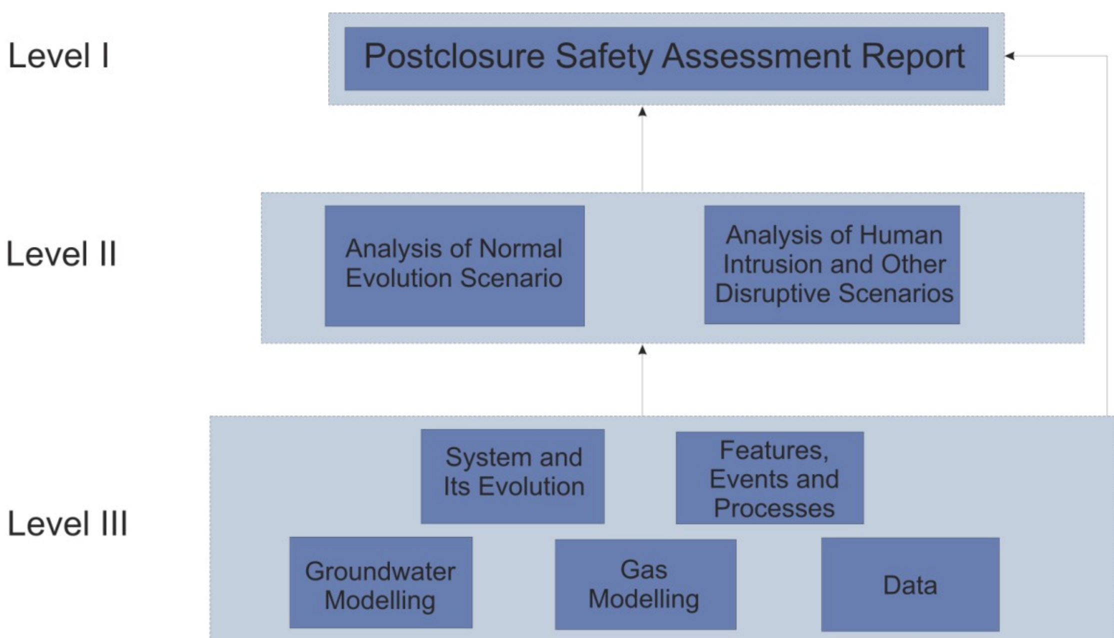

Figure 1-2: Document Structure for the Version 1 Postclosure Safety Assessment

Table 1-1: 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)		
	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.
* Inventories for U-232, U-233, Am-242m and Cm-243 has been derived from scaling to inventory data on the mass of uranium disposed.

1.2 REPORT OUTLINE

Each of the four disruptive scenarios is considered in turn in Sections 2 to 5. The following structure, which reflects the approach used to develop the models for assessment (Appendix A), is used in each section:

- overview of the scenario and development of the conceptual model;
- identification of the calculation cases;
- overview of the mathematical models, software implementation and data; and
- summary of the results.

A consideration of uncertainties and issues for further work is provided in Section 6, and summary and conclusions are provided in Section 7.

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.

2. HUMAN INTRUSION SCENARIO

2.1 SCENARIO OVERVIEW

The natural barriers around the repository might be breached in the future by human actions. Of particular interest is inadvertent intrusion, in which the investigators are unaware of the presence (or content) of the repository, and therefore may not take precautions to limit exposure of the investigators and to prevent contamination of the area. As indicated in the Assessment Context (Quintessa et al. 2009), intentional intrusion into the repository has not been assessed, in line with regulatory guidance (CNSC 2006).

Given the depth of the DGR, the type of human activity that might directly impact the closed repository is a deep borehole, unintentionally drilled into the repository as part of a future geological exploration programme (Little et al. 2009). Even this situation is highly unlikely because of the low resource potential of the rocks and the small footprint of the DGR. Such intrusion could only occur after all institutional control of the site was lost and societal memory or markers had become ineffective. The probability may be estimated as 5×10^{-6} a^{-1} using an emplacement room area of 52,400 m^2 (Walke et al. 2009b) and a rate of deep borehole drilling of 10^{-10} m^{-2} a^{-1} - e.g., resurveying a 10 x 10 km^2 area once every 100 years[1]. Nevertheless, the possibility of inadvertent human intrusion by this method cannot be ruled out over the long timescales of interest to the safety assessment[2].

Intrusion into the DGR from drilling for water is not credible at the site, because the groundwaters are not potable below about 100 m. Intrusion from other underground activities is unlikely at site because the geology is uniform across a large area and so there is nothing unique at this site.

If the scenario were to occur, however, the borehole could provide a direct pathway from the repository to the surface environment and the potential for direct exposure to waste inadvertently retrieved in the borehole core. The scenario that represents these conditions is referred to as the **Human Intrusion Scenario**.

This scenario represents the evolution of DGR system in the same way as the Normal Evolution Scenario with the only difference being that human intrusion into the repository can occur at some time after control of the site is no longer effective.

In this scenario, an exploration borehole is drilled down through the geosphere. Upon encountering the repository, the drilling crew registers a loss of drill fluid to the repository void if the repository pressure is less than the drill fluid pressure, or, if the repository pressure is greater than the drill fluid pressure, a surge of gas and/or slurry (water and some suspended waste) from the repository up the borehole. 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 any significant upflow from the repository (e.g. “blowout preventers” are standard

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[1] See Section 2.5.3 for further discussions on likelihood.

[2] 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.

practice in sedimentary rocks where one may encounter natural gas and are used on all the DGR site characterisation deep boreholes).

The investigators would most likely collect samples or conduct measurements at the repository level, because of its unusual properties relative to the surrounding rock. This would readily lead to the identification of any unexpected levels of radioactivity. 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.

However the scenario analysed considers the “what if” case of material from the borehole being released around the drill site. Further, the scenario also considers the long-term consequences of borehole being poorly sealed, resulting in the creation of a pathway for contaminants into permeable geosphere horizons above the repository.

For this scenario, therefore, contaminants could 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 the permeable geosphere horizons via the exploration borehole.

These releases could result in the exposure of the drilling 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.

The scenario is illustrated in Figure 2-1 and Figure 2-2.

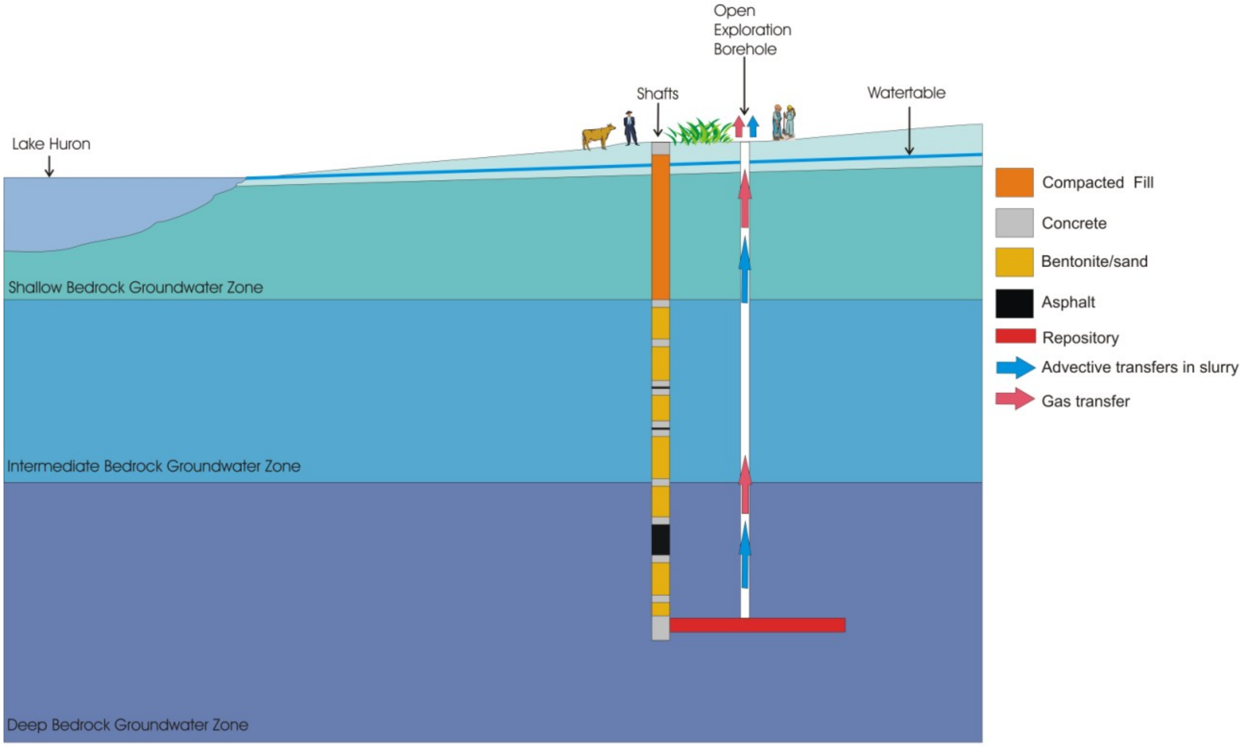


Figure 2-1: Human Intrusion: Schematic Representation of Short-term Gas and Slurry Releases

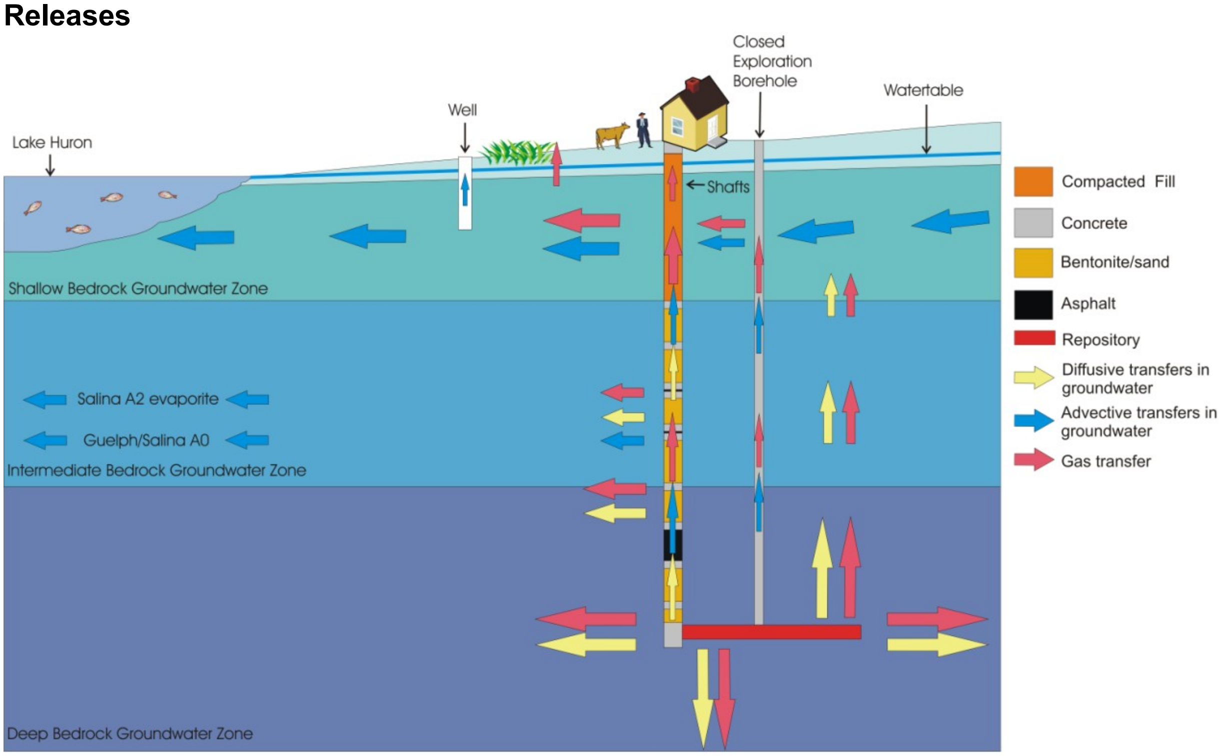


Figure 2-2: Human Intrusion Scenario: Schematic Representation of Long-term Groundwater Release

2.2 CONCEPTUAL MODEL

2.2.1 Key Features

The conceptual model for the Human Intrusion Scenario has been developed by first identifying the key features of the scenario. In the context of the safety assessment, "features" are distinct physical elements of the repository system – the waste, engineered components, rock, and parts of the surface environment such as soil and air. Features that require assessment include those media in which contaminants of interest may be present in the greatest concentrations during the evolution of the scenario. These can generally be grouped together as features relating to the source(s) of the contaminants, the pathway(s) by which the contaminants migrate from the repository and reach the surface environment, and the receptor(s) of the contaminants in the surface environment.

The **sources** of contaminants for the scenario are the repository media that can be transported to the surface environment via the exploration borehole. These are:

- solid waste;
- repository water that contains dissolved contaminants and particles of waste and other contaminated material such as C-14 labelled siderite ($FeCO_3$), corrosion product; and
- repository gas containing contaminants (mostly C-14) that have been released through volatilisation, corrosion and degradation of the wastes.

The borehole itself is considered to act as a **pathway** by which contaminated materials from the repository can be transported directly to the biosphere (i.e., the surface environment), or into the geosphere and then into the biosphere via discharge to the lake and potentially via a well. Any direct release to the biosphere would be relatively short in duration at the time of intrusion, whereas a release to the geosphere could persist for many thousands of years as the borehole could remain as a small but relatively permeable path (see the Groundwater Modelling report, Avis et al. 2009).

The **receptors** reside in the biosphere. Because of the inherent uncertainties associated with the Human Intrusion Scenario, it is appropriate to adopt a stylised treatment of the biosphere which recognises the uncertainty associated with the timing and character of the intrusion event. For this reason, a range of basic biosphere features have been identified consistent with describing the materials that could contain the highest concentrations of contaminants released via the borehole, and to which people could be exposed. For example, surface water features have not been explicitly considered, as they result in further dilution of any contaminated water released via the exploration borehole.

The key features for the Human Intrusion Scenario are summarised in Table 2-1 and described in greater detail in Appendix B.

Table 2-1: Summary of Key Features for the Human Intrusion Scenario

Waste and Repository Features	Geosphere Features	Biosphere Features
• Wasteforms (22 types) • Water (South Panel (LLW) emplacement rooms, East Panel (ILW and some LLW) emplacement rooms, and access/ring tunnels) • Gas (South Panel (LLW) emplacement rooms, East Panel (ILW and some LLW) emplacement rooms, and access/ring tunnels) • Engineered Structures (sealing walls, concrete monolith, and shaft seals and backfill)	• Borehole • Shallow Bedrock Groundwater Zone[1]	• Soil • Lake[2] • Biota • Atmosphere

Notes
(1) The basis for selecting the Shallow Bedrock Groundwater Zone as a point of discharge is discussed in Section 2.2.2.3.
(2) Only occurs when a release of contaminants via the borehole into groundwater is considered, as discussed in Section 2.2.2.3.

2.2.2 Description of the Conceptual Model

The conceptual model is formulated by combining the identified features, processes and events in a manner that describes the Human Intrusion Scenario. The resulting conceptual model is described in the following sections as a narrative, which also highlights some key characteristics of the model. Box 1 summarises the main aspects of the Human Intrusion Scenario, considering the surface and groundwater release pathways.

Box 1: Key Aspects of the Conceptual Model for the Human Intrusion 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).
- Consideration of sorption of some contaminants (C, Zr, Ni, Nb, U and Np) on concrete monoliths and solubility limitation for C and U only, consistent with the Normal Evolution Scenario (Walke et al. 2009a).
- Contaminants released into water via instant, diffusive and congruent release processes, consistent with the Normal Evolution Scenario (Walke et al. 2009a).
- H-3, C-14, Cl-36, Se-79, I-129 and Rn-222 also enter the gas phase as a result of metal corrosion, organic degradation, radioactive decay and/or volatilisation, consistent with the Normal Evolution Scenario (Walke et al. 2009a).
- Resaturation of repository before intrusion is determined by water inflow/outflow rate, gas generation rate and gas pressure.
- Resaturation of the repository is rapid after borehole intrusion occurs.
- Intrusion directly into East Panel (ILW and some LLW) in which contaminants are assumed to be uniformly mixed.
- Rockfall occurs progressively until a stable equilibrium is reached, consistent with the Normal Evolution Scenario (Walke et al. 2009a).

Geosphere and Shafts:

- Groundwater flow in the Deep and Intermediate Bedrock Groundwater Zones is upwards since the measured +140 m hydraulic head in the Cambrian sandstone is conservatively assumed to support indefinitely a steady-state vertical upwards hydraulic gradient and the observed underpressures in the Ordovician are assumed quickly dissipated (consistent with the Normal Evolution Scenario, Walke et al. 2009a) [3].
- Groundwater flow in the Guelph, Salina A0 and Salina A2 evaporite formations is horizontal[3].
- Groundwater flow in the Shallow Bedrock Groundwater Zone is horizontal towards Lake Huron[3].
- Contaminants in groundwater migrate through the geosphere, shafts and along the borehole by diffusion and advection[3].
- Sorption of some contaminants (C, Zr, Ni, Nb, U and Np) in geosphere and shaft but not in the backfilled site investigation borehole.

Biosphere:

- 300 year site control period (see main postclosure SA report, Quintessa et al. 2009).
- Constant temperate climate conditions (consistent with the base case calculations for the Normal Evolution Scenario, Walke et al. 2009a).
- 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.
- Gas release via the borehole is limited by blow-out preventers, but depressurisation allowed to be completed within a few weeks.
- Retrieval of an intact sample of waste in borehole core.
- Drill slurry / mud not contained, but spilled over drilling site.
- Drill crew and residents considered for the potential direct surface release via the exploration borehole (see Section 2.2.2.4). Residents are 100 m from the drill site.
- Laboratory technician is the exposure group considered for solid releases (see Section 2.2.2.4).
- 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 and concrete seal are no longer effective (see Section 2.2.2.3).
- Groundwater is pumped from a well in the Shallow Bedrock Groundwater Zone for domestic and farming use, including irrigation (consistent with the Normal Evolution Scenario, Walke et al. 2009a).
- Contaminants can also discharge from the Shallow Bedrock Groundwater Zone into the near shore lake bed sediments (consistent with the Normal Evolution Scenario, Walke et al. 2009a).
- Local exposure group considered for the release of contamination to the Shallow Bedrock Groundwater Zone into the biosphere (see Section 2.2.2.5).

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

2.2.2.1 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 the upper and intermediate formations (Shallow Bedrock Groundwater Zone and Intermediate Bedrock Groundwater Zone). It would only 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 Ordovician shales and limestones (collectively termed the Deep Bedrock Groundwater Zone), a narrower diameter borehole is drilled (15.24 cm or 6 inch), consistent with typical drilling practice of reducing borehole diameter with depth.

The likelihood of such a borehole encountering the repository is discussed in the analysis of results (Section 2.5).

2.2.2.2 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 (see Data report, Walke et al. 2009b).

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 are assumed 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[4] generated during the degradation of

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

waste (**slurry**). Measures to control the rate of groundwater release would be expected – in particular it is noted that drilling mud is typically stored and recycled on site. The volume and character of ejected water and slurry would be dependent on the pressurization 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 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.

2.2.2.3 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.

In the longer term, since the borehole is assumed to be poorly sealed, it provides an enhanced permeability pathway for release into the geosphere, conducting contaminants at a rate determined by the pressure difference between the point of release and the repository, and the effectiveness of the borehole sealing. Groundwater flow modelling (Avis et al., 2009) indicates that there will be inflow of water along most of the length of the borehole. There is inflow of water in the Guelph and Salina A0, which could lead to some dilution of the water released from the repository (perhaps up to a factor of 3 reduction in concentrations).

Model results (Avis et al., 2009) indicate that around 50% of the flow could be released at the Salina A2 evaporite, with the rest released as the borehole passes through the Salina G. The assessment adopts a cautious assumption that (a) there is no dilution of contaminated water during its transit up the borehole, and (b) all the contaminated water is released in the Salina G (closer to the surface than the Salina A2 evaporite).

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 and is described fully in the Normal Evolution Scenario Analysis report (Walke et al. 2009a).

2.2.2.4 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 (borehole core) waste.

Slurry

The conceptual model for exposure by slurry released from the borehole is shown in Figure 2-3 and Figure 2-4. Consideration of the potential exposure pathways, with allowance for the scenario definition, indicates that two potential exposure groups should be assessed:

- those directly exposed to contaminated slurry at the point of release (i.e., the drill crew) (Figure 2-3); and
- those exposed for a longer duration to contamination in the soil (e.g., a site resident using the contaminated site for growing food and grazing animals after the completion of drilling) (Figure 2-4).

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 **site resident** could use the contaminated drill site for farming 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 site resident are the same as defined for the local exposure group in the Normal Evolution Scenario (Walke et al. 2009a). This case conservatively assesses exposures to the contamination of soil used for growing food and grazing animals. Farming practices would mix the contamination into the top soil. The conceptual model for the local exposure group is described in full in the Normal Evolution Scenario Analysis report (Walke et al. 2009a). The main exposure routes of relevance are external irradiation from the soil and volatilised gas, inadvertent soil ingestion, consumption of animals and vegetables, and inhalation of volatilised contaminants and radon.

In addition to the human exposure groups, plants and animals could be exposed through uptake from contaminated soil.

Gas

The conceptual model for exposure following a gas release is shown in Figure 2-5. 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).

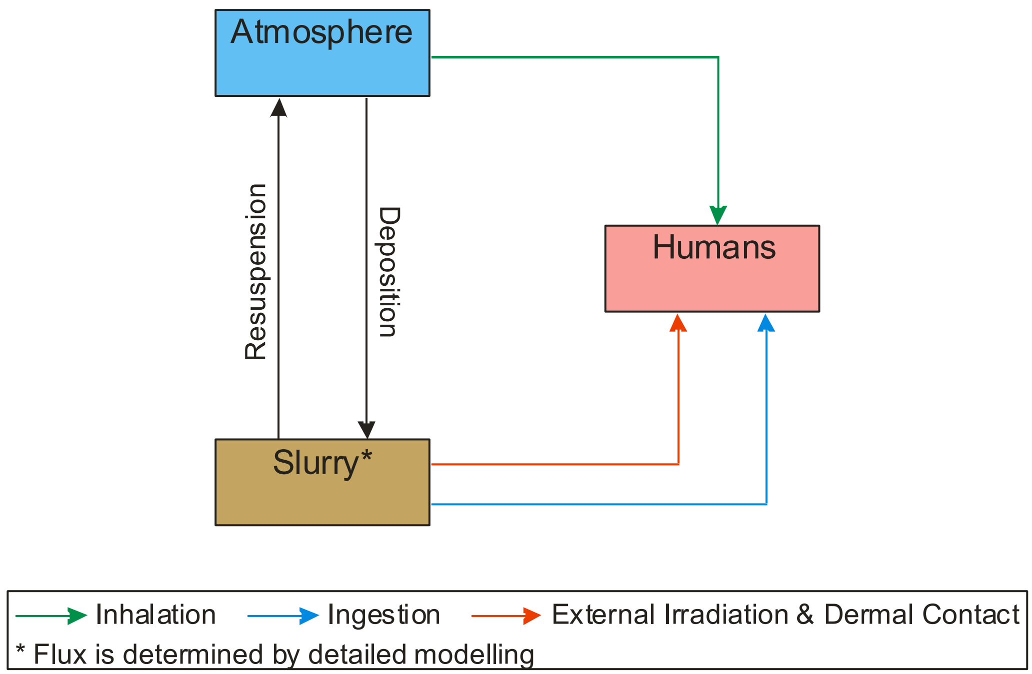


Figure 2-3: Human Intrusion Scenario: Conceptual Model for Exposure of the Drill Crew During the Slurry Release

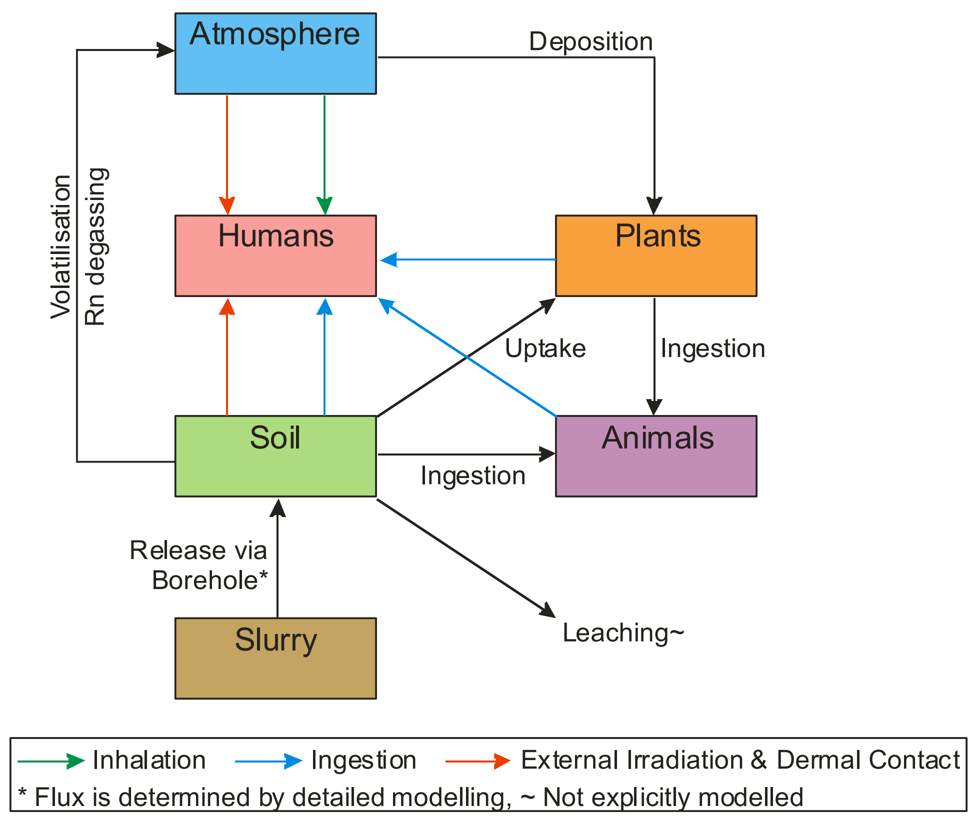
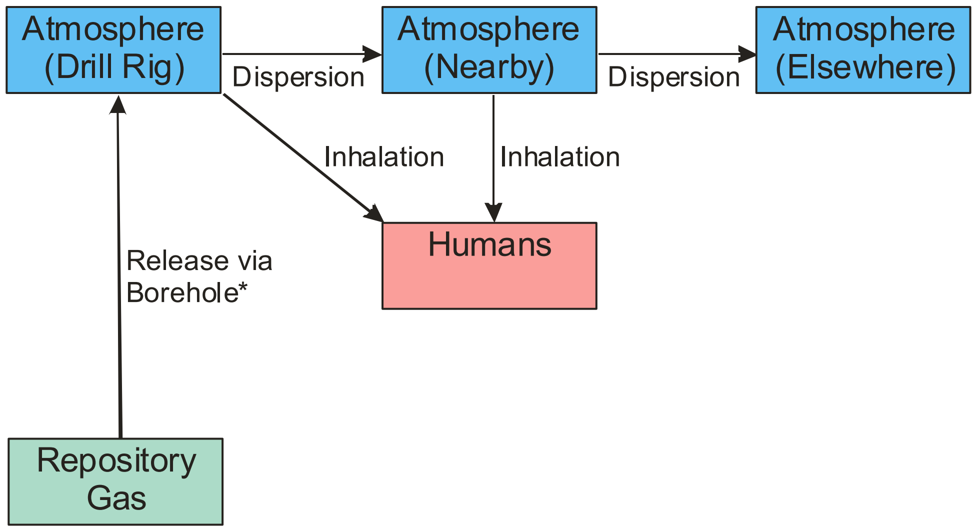


Figure 2-4: Human Intrusion Scenario: Conceptual Model for Exposure of the Site Resident to Soil Contaminated by Slurry



* Flux is determined by detailed modelling

Figure 2-5: Human Intrusion Scenario: Conceptual Model for Gas Release

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

Potential Exposure to Solid (Borehole Core) 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 2-6.

2.2.2.5 Receptors for the Shallow Bedrock Groundwater Zone Release Pathway

Detailed modelling (Avis et al. 2009) shows that releases to the Shallow Bedrock Groundwater Zone via a borehole would occur. It is therefore reasonable to adopt for this case the conceptual model of the biosphere and associated receptors as considered for the groundwater release in the Normal Evolution Scenario.

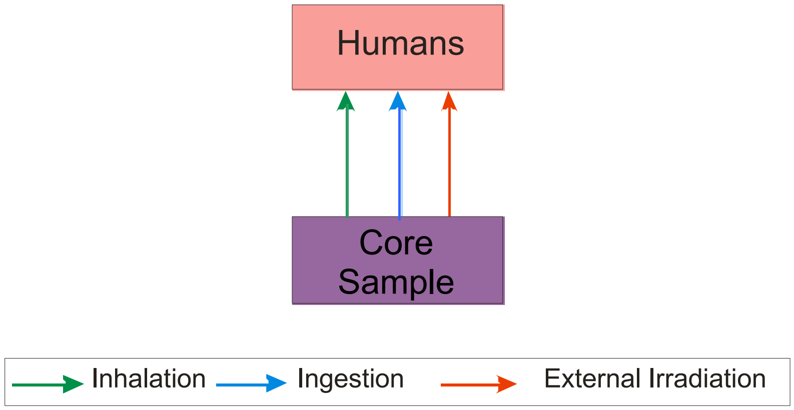


Figure 2-6: Human Intrusion Scenario: Conceptual Model for Core Retrieval

The model assesses releases of contaminated groundwater via a shallow well, and also to Lake Huron. The relevant potential exposure group is a **local exposure group** that makes use of local resources. The group lives on a self-sufficient farm and abstracts 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 hunt locally for deer and rabbits, obtain fish from a stream and from Lake Huron, and consume local honey. They swim recreationally in the lake. Further details of the biosphere conceptual model and associated potential exposure group are included in Normal Evolution Scenario Analysis report (Walke et al. 2009a).

2.2.3 FEP Audit

The features, events and processes considered in the conceptual model, have been audited against the DGR FEP list documented in Garisto et al. (2009). The FEP list is reproduced in Appendix C and an entry is made against each FEP to indicate its inclusion or exclusion from the conceptual model and the reasoning for inclusion or exclusion.

2.2.4 Key Conceptual Model Uncertainties

The nature of the Human Intrusion Scenario is that it is inherently uncertain. The timing of the intrusion event (if it ever occurs) is the subject of future uncertainty, and the precise conditions in which people are exposed also can only be resolved in very broad terms. For this reason, the conceptual model considers a small number of conservatively determined stylised situations centred on exposure when the intrusion occurs immediately (the drill rig crew) and subsequently (a stylised residential case). This approach recognises that all aspects of the postulated exposure (duration of exposure, ingestion rate and potential for inhalation of contamination and external exposure) are subject to significant uncertainty.

Nevertheless, some aspects of the conceptual model are subject to uncertainty that is, to a degree, tractable. These uncertainties are primarily related to the quantity of gas, liquid or solid that could be released at a given time. These attributes of the scenario are in turn dependent on the details of the repository conditions at a given time. The conceptual model uncertainties are, therefore, dealt with and discussed in the context of the repository conceptual model, which is described in detail in the Normal Evolution Scenario Analysis report (Walke et al. 2009a). For this scenario, the key uncertainties are:

- repository resaturation – the resaturation profile determines the potential for either gas or groundwater discharge via the borehole;
- waste degradation and contaminant release – which, together with resaturation, determine the distribution of contaminants between gas, water, suspended particulate and waste at a given time; and
- mixing between the different parts of the repository – which determines the contaminant concentrations in gas and water in the repository.

Other important uncertainties are associated with the repository design and engineering options, most significantly:

- the possibility for grouting waste and backfilling the repository; and
- uncertainty in the contaminant inventory.

2.3 CALCULATION CASES

Three primary calculation cases can be identified from consideration of the conceptual model and uncertainties described in Section 2.2:

- a case that considers the surface release pathway (and its slurry, gas and solid releases) for the reference resaturation profile for the DGR, which following initial partial resaturation, includes an extended period of unsaturated conditions beyond 1 Ma;
- an equivalent case that considers the slurry releases and a hypothetical instantaneous and permanent resaturation profile (to provide a perspective on possible impacts of contaminants in repository water during the period in which the previous case assumes the repository to be desaturated); and
- a case that considers the Shallow Bedrock Groundwater Zone release pathway.

In addition, two cases need to be considered for the non-radioactive species; one for the release to the surface from a saturated repository, the other for the release to the Shallow Bedrock Groundwater Zone. These five cases are summarised in Table 2-2.

Given the commonality of many aspects of the conceptual model with that developed for the Normal Evolution Scenario, calculation cases identified above have been derived with reference to those considered in the Normal Evolution Scenario (see the Normal Evolution Scenario Analysis report, Walke et al. 2009a, for more details).

For the Surface Release Pathway, the impacts of drilling the borehole at different times are evaluated in order to identify the time of peak impacts. For the Shallow Bedrock Groundwater Zone Release Pathway, a fixed time of intrusion is necessary to consider due to the need to model contaminant migration dynamically in the Shallow Bedrock Groundwater Zone. The time at which controls are no longer effective (300 years after DGR closure – see Quintessa et al. 2009) is adopted as the most conservative time for intrusion since, at this time, little contaminant migration has occurred from the repository and limited decay has occurred and so contaminant concentrations in the repository are at or near their highest.

The conceptual model described in Section 2.2.2 requires no modification to implement these calculation cases.

Table 2-2: Calculation Cases for the Human Intrusion Scenario

Case ID	Brief Description	Associated Detailed Modelling Cases
HI-SR1-A	As for the Normal Evolution Scenario case NE-BC-A (slow saturation) but an exploration borehole drilled from surface down to the repository at 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.	-

Notes:
HI – Human Intrusion Scenario; NE- Normal Evolution Scenario; SR – surface release; NR – non-radioactive species; GR – groundwater release; BC - base case; RS – repository saturation; A – AMBER; F3 – FRAC3DVS 3DS model

2.4 MATHEMATICAL MODELS, SOFTWARE IMPLEMENTATION AND DATA

2.4.1 Mathematical Models

In order to maintain consistency in approach, the Human Intrusion Scenario adopts the same mathematical models as the Normal Evolution Scenario in respect to the representation of most aspects of the conceptual models. The mathematical models specific to the Human Intrusion Scenario are therefore developed in addition to, and alongside, those relating to the Normal Evolution Scenario described in Section 4.1 of the Normal Evolution Scenario Analysis report (Walke et al. 2009a). These include a full description of:

- the spatial discretisation of the repository, geosphere and biosphere: the repository includes distinct components to represent the saturated and unsaturated components of each of the 22 distinct wastes, which reflect OPGs LLW and ILW waste categories; the geosphere includes distinct components to represent the groundwater zones, each discretised into a series of components that are spatially compatible with the repository design and location, as well as being sufficiently discretised to represent appropriately diffusive, advective and dispersive transport processes; and the biosphere represents distinct surface features explicitly, such as soils, streams and the lake;
- fundamental physical properties of media (including density, porosity, tortuosity, saturation and hydraulic conductivity) and chemical properties of media (including consequential effects such as capacity for sorption and elemental solubility of some contaminants);

- general contaminant processes including decay and degradation, sorption, advection (of water and gas), dispersion and diffusion;
- repository-specific processes, primarily related to wasteform saturation as a result of repository resaturation, and contaminant release – including instant release, delayed release, diffusive release, congruent release and the precipitation of C-14 in siderite (corrosion byproduct);
- diffusion, advection and dispersion in the geosphere and shafts;
- biosphere processes associated with contaminant transport in surface water, soils and atmosphere; and
- exposure models, considering external irradiation, inhalation (gas and dust), and ingestion (soil, water, plants, animal products and fish).

Additional mathematical models have been developed for the Human Intrusion Scenario:

- to calculate contaminant concentrations in:
    - the ejected slurry;
    - the soil contaminated by ejected slurry;
    - the concentration of contaminants in the gas released into the biosphere;
    - the borehole core;
- to evaluate the impacts of exposure (via ingestion, inhalation, and external irradiation) to undiluted slurry, slurry diluted in soil and contaminated core.

These are specified in Appendix D.

2.4.2 Software Implementation

In common with the Normal Evolution Scenario, the mathematical model for the Human Intrusion Scenario has been implemented in AMBER Version 5.2 (Enviros and Quintessa 2008a, b).

The human intrusion model has been integrated into the same AMBER assessment model as the Normal Evolution Scenario (see Section 4.2 of the Normal Evolution Scenario Analysis report, Walke et al. 2009a). The Human Intrusion Scenario is activated by multiplying mathematical model expressions by a scenario-dependent parameter, taking a value of 1 when the scenario is to be considered, and 0 otherwise.

The individual wasteforms in the repository are modelled explicitly in terms of unsaturated and saturated compartments and the released contaminants enter water and gas, which is distinguished between South Panel emplacement rooms, East Panel emplacement rooms and the access and ring tunnels. Precipitation of C-14 in siderite, formed under the geochemical conditions in the emplacement rooms, is also modelled. A proportion of the precipitate (10%) is taken to be suspended in any repository water that is present, with the rest adhered to surfaces or sediment on the floor of the repository (see Section 2.4.3.1).

The contaminant concentrations used in the Human Intrusion calculations for the surface release of contaminated slurry, gas and retrieval of core are derived directly from the calculated concentrations of contaminants in the repository using the equations specified in Appendix D.1.1. Dose calculations for the exposure groups are implemented using equations based on those specified in Appendix D.1.2.

The release of contaminated water to the Shallow Bedrock Groundwater Zone is represented in a different manner. The conceptual model involves a transfer of contaminated water up the borehole to the Shallow Bedrock Groundwater Zone. This is represented directly with an additional model transfer derived from the results of FRAC3DVS code (see below) between the repository water compartments and the Shallow Bedrock Groundwater Zone compartment overlying the point of intrusion. This transfer provides a limited “short-cut” for contaminant releases to the Shallow Bedrock Groundwater Zone. All other aspects of the model are identical to the Normal Evolution Scenario (including dose calculations for the local exposure group).

In addition, supporting models have been implemented in the FRAC3DVS code to allow the derivation of certain input data for the assessment calculations. The implementation of these models is described in Section 4.3 of the Groundwater Modelling report (Avis et al. 2009) (FRAC3DVS).

2.4.3 Data

A data report has been developed to support the postclosure safety assessment (Walke et al. 2009b). This comprises reference data (including commentary on parameter uncertainties) that describe the wastes, repository, geosphere and biosphere for the Normal Evolution Scenario’s base case. For context, these data are summarised in Table 2-3.

Table 2-3: Key Parameter Values for the Normal Evolution Scenario's Base Case that are used in the Human Intrusion 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 Data report (Walke et al. 2009b)
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 (waste packages and engineering)	1.3×10^8 kg
Total mass of metals (waste packages and engineering)	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 Section 2.3)
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.
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. Concrete bulkheads keyed across the inner EDZ. Asphalt water stops keyed across inner and outer EDZ.
Backfill/seal vertical and horizontal 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}
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}

PARAMETER	VALUE(S)
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
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.
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 standstone 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 Formations. 0 in all other horizons
Shallow Bedrock Groundwater Zone:	
horizontal hydraulic conductivity	1.0×10^{-7} to 1.0×10^{-4} 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
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 via Shallow Bedrock Groundwater Zone) 3) Sediments in Central Basin of Lake Huron (for discharge from Guelph, Salina A0 and Salina A2 evaporite)
Gas release	Soils and house located above repository
Landuse	Agriculture, recreation, forestry
Potential exposure groups	Local group making use of land for farming, fishing, recreation and dwelling (habit data provided in Data report, Walke et al. 2009b)

Where the reference data are available and suitable to the Human Intrusion Scenario and its calculation cases, these data have been used. However, some scenario-specific data are necessary, in order to reflect specific considerations and issues relevant only to the Human Intrusion Scenario, and are described below. Exposure pathway data specific to the Human Intrusion Scenario have been chosen to be a reasonable and consistent representation of the potential exposure conditions envisaged for the scenario. Other data have been adopted with reference to detailed groundwater and gas modelling and other sources of information where possible.

2.4.3.1 Surface Release of Contaminated Slurry and Gas

Quantities of Contaminated Media Released

The repository resaturation profile is used to determine the availability of slurry and/or gas for release to the surface via the borehole. The resaturation characteristics are the same as assumed for the Normal Evolution Scenario base case, and are illustrated in Figure 2-7. In order to give an indication of the sensitivity of the results to resaturation assumptions, a case is also considered in which the repository is instantaneously resaturated at closure, and remains 100% filled with water throughout the entire assessment timeframe.

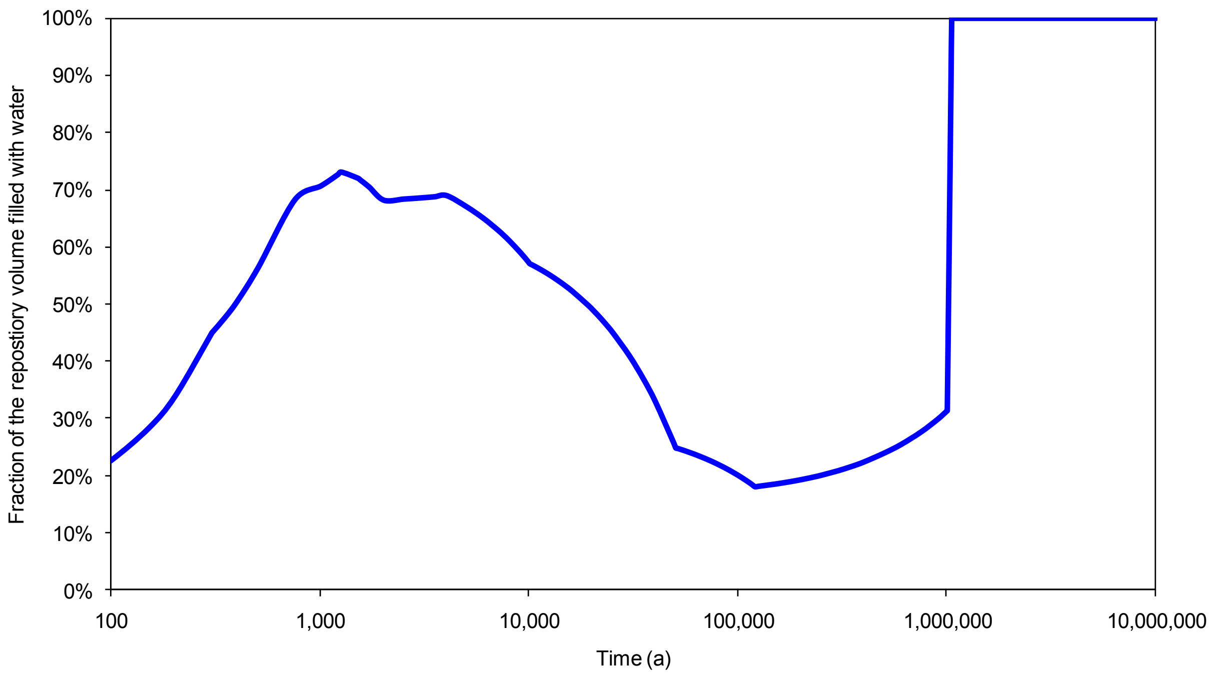


Figure 2-7: The Reference Resaturation Profile Used in the Human Intrusion Surface Release Scenario

The volume of contaminated water ejected from the borehole is 159 m^3, and water is only released if there is a sufficient amount present in the repository, taking account of resaturation. This value is derived conservatively by taking the entire repository void volume of 3.3 x 10^5 m^3

to be full of water at a pressure of 1.2 MPa[5], and a fluid compressibility of 4×10^{-10} Pa^{-1}. This value is based on a release from a saturated repository. A partially saturated repository could be at a higher pressure; however, the material release in such a case would be dominated by gas, with water being entrained in the gas flow. In such circumstances the rate of release would be limited by blowout preventors and, therefore, the total quantity of water entrained would be limited.

The ejected material is taken to be repository water with suspended particles of waste at a mass loading of 0.1 kg m^{-3}. No data could be obtained for this parameter; therefore, an estimate has been made of the value that is expected to be conservative. However, it is noted that it is a significant source of uncertainty. For comparison, the total mass of waste that could be extracted from the repository by a 6-inch diameter borehole is 100-300 kg; the mass of sediment assumed to be released is 5-15% (159 m^3 x 0.1 kg m^{-3}) of this extreme estimate. In calculating radionuclide concentrations in the slurry, the average activity concentration in water is assumed, and the suspended particles of waste are assumed to have the average concentration of contaminants of all wastes in the East Panel. This is a cautious approach, as some of the higher activity wastes, such as retube wastes, will corrode very slowly.

Siderite formed in the repository, which may contain C-14, may also be suspended in the water which is released via the borehole. Under the repository conditions, siderite may be present as a film on corroding materials; however, it is also possible that an amorphous, non-adherent form may arise. This latter form could be present in suspension in repository water. At present there is limited information on the form of siderite; however, it is expected that much of the corrosion product will be immobile. On this basis, it is assumed that 10% of all the C-14 in siderite is in suspension in repository water, and available for release to the surface via the borehole.

The drill crew are immediately exposed to the ejected slurry in undiluted form. In calculating the potential exposure of the drill crew after the immediate release, the contaminants released from the borehole in the liquid and particulate forms are mixed into an area of soil 100 m x 100 m and to a depth of 0.3 m. This is an intentionally conservative assumption, and would not be permitted under current regulations. Standard drilling practice is to collect slurry for disposal to a regulated facility.

The gas release would be inhibited by a blow-out prevention device (a “BOP”), routinely used in deep drilling operations. The scenario cautiously assesses the managed release of the gas by the drillers, via a BOP. A good example of the operation of the BOP is the practice that would be applied at the investigation boreholes drilled in conjunction with the DGR. Here, any gas can be vented from the BOP through a 2-inch diameter pipe, which runs 50 m to a flare pit (stacks are generally required where sour gas is present, but this is not the case at the DGR site). The flow of gas would be physically limited by the pipe. Scoping calculations show that, at the maximum gas pressure of 8.5 MPa, the peak gas release rate would correspond to a flow rate of 1 – 10 m^3 s^{-1} at the surface (atmospheric pressure).

For perspective, typical landfill gas flares operate at a gas flux of about 1 m^3 s^{-1} or less at atmospheric pressure. This value is therefore adopted for the assessment. Neglecting change

[5] 1.2 MPa is the difference between hydrostatic in the borehole (no gradient) and the initial steady state pressure at the repository horizon due to the Cambrian boundary condition (+140 m). The assumption is that the repository will vent fluid through the borehole until the pressure equalises to the weight of the standing column of fluid in the borehole, so 1.2 MPa represents the hydrostatic pressure in the borehole - not in the rock.

in temperature and taking the volume of gas to equal the repository void and the peak gas pressure (8.5 MPa), it can be estimated that the gas release would continue for about a year or more if the borehole were not sealed.

A minimal amount of atmospheric dispersion is assumed associated with the initial release of gas, and a time integrated air dispersion factor of 0.003 s m^{-3} is used in the calculations, calculated using a simple Gaussian dispersion model and assuming a short-term release at a distance of 50 m from the flare pit, on the plume centre-line (Clarke 1979). A time integrated air dispersion factor of 2.1×10^{-4} s m^{-3} is used for the chronic release. This value is smaller than the corresponding value for the short-term release, as consideration is given to varying wind direction and atmospheric conditions.

Drill Crew

The drill crew is initially exposed to undiluted slurry and gas for a period of 4 hours over one shift, and they then continue to work in the contaminated area for 12 hours a day over 30 days prior to the sealing of the borehole. The drill crew is exposed to an elevated dust level of 5.9×10^{-7} kg m^{-3} (i.e., ten times the ambient level given in the Data report, Walke et al. 2009b), to reflect dusty drilling conditions, at the same inhalation rate assumed for the adult in the local exposure group (8400 m^3 a^{-1}). The inadvertent ingestion rate for the contaminated material of 0.33 g d^{-1} is also consistent with the value for adults in the Data report (Walke et al. 2009b).

Nearby Resident

For the gas release, a nearby resident lives 100 m from the point of gas release via the borehole. They are cautiously assumed to inhale contaminated gas continuously for 30 days (prior to the sealing of the borehole) at a gas release rate of 1 m^3 s^{-1} at atmospheric pressure.

Adopting a Gaussian dispersion model indicates that time integrated air dispersion factor for a long-term ground-level release is 6.0×10^{-5} s m^{-3} at this distance (Clarke 1979). The person's inhalation rate is the same as that assumed for the adult of the local exposure group (8400 m^3 a^{-1}, Walke et al. 2009b).

Site Resident

For the long-term exposure to slurry diluted in soil, the site resident farms the land contaminated with contaminants in the ejected slurry. It is conservatively assumed that the contaminants become mixed with soil, but are not leached from it. Half of the activity is assumed to be present in land used for growing crops and half in land used for raising animals. The habits of the exposed people are the same as adopted for the local exposure group assessed in the Normal Evolution Scenario (see Walke et al. 2009b).

2.4.3.2 Retrieval of Contaminated Core

The laboratory technician closely examines a sample of core (a mass of 5 kg is adopted, corresponding to a length of about 60 cm) for a duration of 4 hours. The core contains undiluted waste. The concentration of the waste would be dependent upon the specific contents of the waste package intercepted by the borehole; for this analysis, the average concentration of all waste in the East Panel is used.

The examination of the core is assumed to lead to inadvertent ingestion and inhalation of dust (e.g. as a result of any grinding, etc). An enhanced dust concentration of 5.9 x 10^{-7} kg m^{-3} (approximately 10 times ambient concentrations given in the Data report, Walke et al. 2009b), with inhalation and inadvertent ingestion rates consistent with those considered for the Normal Evolution Scenario (8400 m^3 a^{-1} and 0.33 g d^{-1}, respectively). To take account of the limited size of the sample, external irradiation is calculated with the assumption of point-source geometry and exposure at a distance of 1 m.

2.4.3.3 Shallow Bedrock Groundwater Zone Pathway

The rate of release of contaminated water to the Shallow Bedrock Groundwater Zone via a borehole into the repository has been calculated by detailed groundwater release analysis. A rate of transfer of approximately 10^{-5} a^{-1} is applied based on the analysis presented in the Groundwater Modelling report (Avis et al. 2009) which shows a peak flux of (unsorbed) Cl-36 at the top of the Salina F unit of 0.016 g a^{-1} after around 2700 years, for an initial inventory of 926 g of the radionuclide. This approach takes into account the poorly sealed nature of the borehole (the borehole is assumed to have a hydraulic conductivity of 10^{-4} m s^{-1}). It cautiously ignores the sorption of radionuclides on the sealing material.

The discharge is cautiously taken to commence immediately after control is no longer effective (300 years after repository closure). This is the earliest plausible time at which inadvertent intrusion could occur, and results in a conservative estimate of dose. It is assumed to result in the (relatively) rapid resaturation of the repository. The DGR is therefore assumed to be filled with water from 300 year onwards in this case.

All other data considered for the Shallow Bedrock Groundwater Zone Release Pathway calculations, including the description of potential exposure group, are the same as the base case for the Normal Evolution Scenario documented in the Data report (Walke et al. 2009b).

2.5 RESULTS

2.5.1 Release of Contaminants via the Borehole

The magnitude of potential exposures associated with the human intrusion scenario is dependent on the concentrations of contaminants in the materials that are released – slurry, gas and waste in the case of the Surface Release Pathway, and groundwater in the case of the Shallow Bedrock Groundwater Zone Pathway. The concentrations are calculated by a model identical to that adopted for the Normal Evolution Scenario, except that transport in the borehole from repository to the surface or Shallow Bedrock Groundwater Zone is included.

2.5.1.1 Surface Release Pathway – Reference Resaturation Profile

Amounts of radionuclides in the repository reduce over time due to radioactive decay and by migration into the geosphere and shafts. Decay is dominant, and the migration component is relatively small until very long times because the repository does not completely resaturate[6] until after 1 Ma in this calculation case. Table 2-4 shows how the average activity concentration in wastes changes with time. It can be seen that for some LLW streams there is an appreciable

[6] It is possible that the poor sealing of an intrusion borehole might lead to rapid resaturation of the repository, and this case is considered in Section 2.5.1.3.

reduction over the first few hundred years. A decrease in activity concentration of more than two orders of magnitude after 300 years (the end of control) occurs for compacted wastes, drums and “other” non-processible wastes, and ALW sludges. The benefits of control are, however, limited for other waste streams. Concentrations in most wastes, particularly the ILW streams, decrease slowly as they are dominated by longer-lived radionuclides. Even if it were possible to guarantee control for 1000 years or more it would bring little additional benefit in terms of the reduction in concentrations in most waste streams.

Table 2-4: Change in Average Activity Concentration of Wastes with Time since Closure in 2062

	Average activity concentration (Bq/kg)						
Waste Stream	0 a	100 a	300 a	1000 a	10 ka	100 ka	1 Ma
Bottom Ash	5.9E+04	1.9E+04	4.9E+03	2.0E+03	471	1.0	<0.1
Baghouse Ash	2.4E+04	2.6E+03	488	58	6.4	0.1	<0.1
Compacted Boxed	1.5E+07	1.0E+04	5.1E+03	4.0E+03	904	4.5	<0.1
Compacted Bales	8.5E+05	3.9E+03	3.2E+03	2.5E+03	589	1.4	<0.1
Non-pro. Drums	6.2E+07	1.8E+04	1.5E+04	1.2E+04	3.0E+03	<0.1	<0.1
Non-pro. Boxes	9.8E+06	7.6E+05	6.1E+05	5.0E+05	1.1E+05	75	<0.1
Non-pro. Other	1.7E+06	5.8E+03	1.9E+03	1.5E+03	368	0.4	<0.1
LLW Resins	4.8E+07	9.8E+06	8.6E+06	7.2E+06	1.7E+06	1	<0.1
ALW Resins	2.3E+04	4.7E+03	4.0E+03	3.4E+03	802	<0.1	<0.1
ALW Sludges	9.7E+04	533	439	366	87	<0.1	<0.1
Steam Gens.	1.7E+05	1.1E+05	8.0E+04	4.7E+04	7.9E+03	<0.1	<0.1
CANDECON Resins	8.0E+06	8.6E+05	1.8E+05	4.8E+04	1.1E+04	<0.1	<0.1
Moderator Resins	1.3E+09	1.3E+09	1.2E+09	9.7E+08	3.2E+08	350	<0.1
PHT Resins	5.7E+07	4.2E+07	4.0E+07	3.1E+07	7.5E+06	4	<0.1
Misc. Resins	3.2E+07	7.8E+06	7.0E+06	5.3E+06	1.3E+06	1	<0.1
Core Hardware	2.5E+08	1.3E+08	4.8E+07	2.2E+07	1.2E+07	5.2E+06	<0.1
Filters and Elements	2.4E+06	2.2E+06	2.0E+06	1.7E+06	4.4E+05	126	<0.1
IX Columns	2.3E+07	1.7E+07	1.6E+07	1.4E+07	3.4E+06	39	<0.1
Pressure Tubes	1.2E+09	1.2E+09	1.2E+09	1.1E+09	8.0E+08	6.2E+07	<0.1
End Fittings	2.0E+08	1.0E+08	2.9E+07	5.9E+06	2.2E+06	1.1E+05	<0.1
Calandria Tubes	5.2E+08	2.7E+08	1.0E+08	5.1E+07	3.9E+07	3.0E+07	<0.1
Calandria Tube Inserts	7.2E+08	3.6E+08	1.0E+08	1.9E+07	5.5E+06	1	<0.1

The calculated average concentrations of the ten radionuclides present with highest concentrations at closure in waste, plus the two of the most significant actinides (Pu-240 and Am-241), in the East Panel (the point of intrusion assessed by the scenario) are presented in Figure 2-8. Here, the time axis is the time at which the intrusion is assumed to occur, after closure. The notable drop in the average Ni-59 concentrations at 15 ka is attributed to the occurrence of a rock collapse, which crushes containers in the repository, permitting instant release of contaminants from certain waste streams. This effect is not seen for Zr-93 and Nb-94 because these radionuclides are released more slowly due to their corrosion resistant form compared with the Ni-59, which is mainly present in more rapidly corroding steel end fittings.

C-14 and Cl-36 are also unaffected due to the specific wasteform release mechanisms. The variations in waste form concentration in the first few thousand years relate to the points at which resaturation results in a water level that permits releases from specific waste packages.

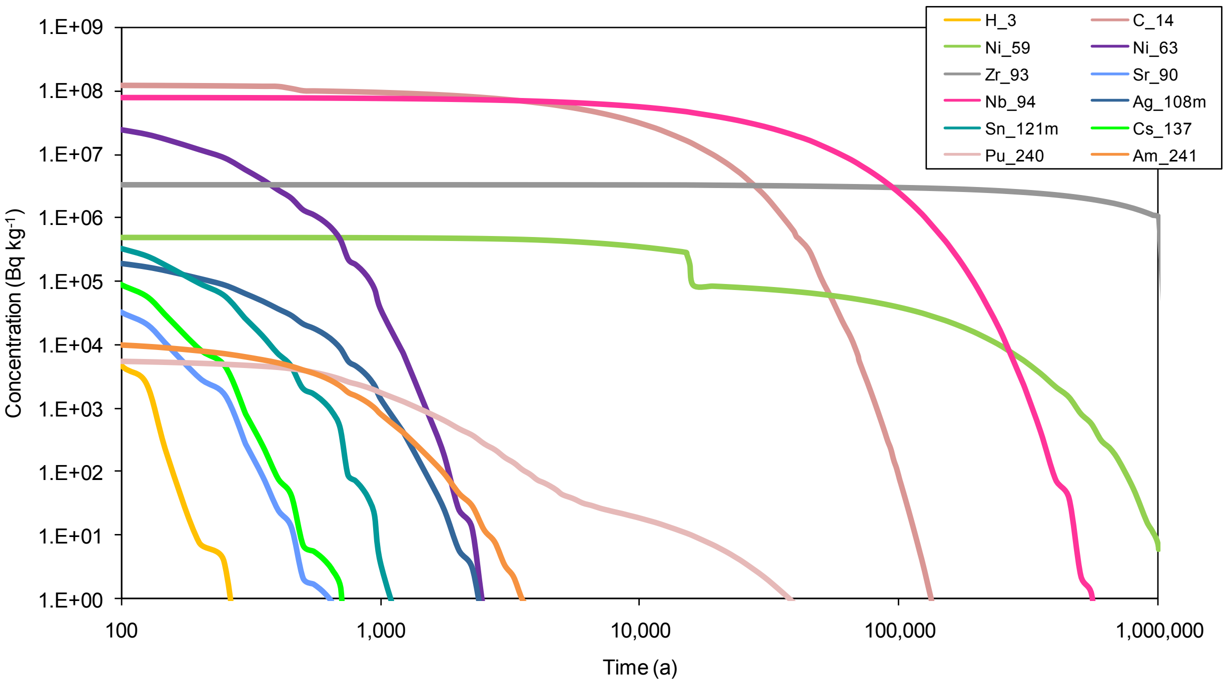


Figure 2-8: Calculated Average Concentrations of Radionuclides in Wastes in the East Panel, as a Function of the Time of Intrusion (Decay and transport)

Whilst the majority of the activity remains in the wastes, certain contaminants are released to repository water and gas, some to a significant degree. Figure 2-9 shows the calculated concentrations in repository water and suspended particulate (both particles of corroded waste and also siderite containing C-14) for the five most significant contaminants in water and the five most significant in suspended particulate. The sharp changes in concentration in the water correspond to the timings of the release of wastes, for example the sharp increase in C-14 in suspended siderite at 500 years corresponds to the time at which corrosion of containers results in the release of radionuclides from moderator resins. The sharp increases in concentrations of Zr-93, Nb-94 and Ni-59 in water correspond to the crushing of containers by a rock collapse at 15 ka.

Figure 2-9 shows that initially the contaminants in suspended waste particulate and siderite tend to dominate compared to the activity in water. Between around 400 a and 4 ka C-14 in siderite is present with about 100 times the activity of any other contaminant, and remains the dominant contributor to activity until a rockfall causes the release of contaminants such as Zr-93, Nb-94, and Ni-59 from resilient containers at 15 ka. As contaminants are released by dissolution, the concentrations in water become more significant. For longer-lived contaminants, the concentrations in water can be seen to increase substantially (by factors of 1000 or more) over the first 10 ka. It is also notable that generally the same contaminants are present in high concentrations in both water and suspended particulate. The only notable differences are H-3 in water and Cs-137 in suspended particulate. Changes in the relative significance of contaminants in water and particulate are a result of the waste form release models which are specific to each waste stream, and the amount of the particular radionuclides in the waste stream. Sorption is not a significant factor, as it has been conservatively neglected for wastes and packaging materials in the model, although releases can be limited by elemental solubility and sorption onto concrete repository structures (e.g., concrete monolith).

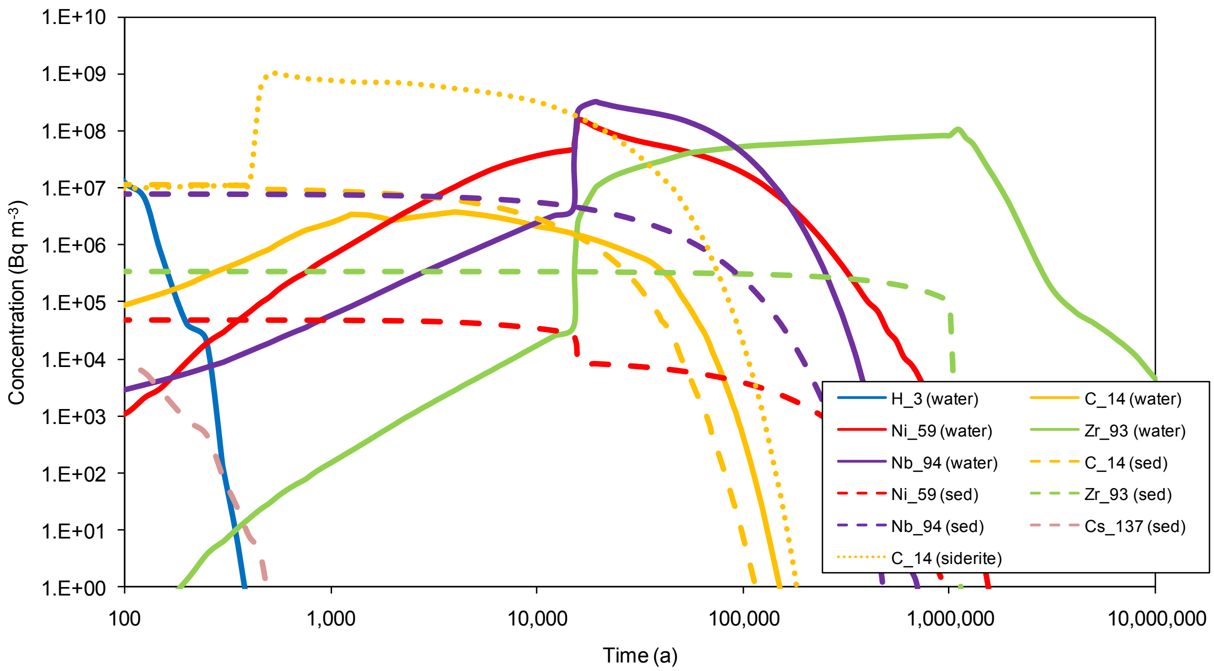


Figure 2-9: Calculated Concentrations of Radionuclides in Repository Water and Suspended Particulate in the East Panel, as a Function of the Time of Intrusion, assuming the Reference Resaturation Profile

Slurry released to the surface in drilling mud is conservatively assumed to be left at the drilling site. This would not be permitted under current regulations, but has been assessed in order to provide perspective on potential exposures through the long-term contamination of the surface environment by the slurry. Over time, it could become mixed with soil and used by people. In the present analysis, the site is used immediately after the intrusion. The slurry is assumed to be present in soil both used for crops and grazing by the potential exposure group assessed in the Normal Evolution Scenario (NES). The calculated concentrations, shown in Figure 2-10, are many orders of magnitude higher than in the NES. C-14 is the dominant radionuclide up to 15 ka (mainly associated with siderite as Fe(C-14)O_3), when the rock collapse results in increased releases of Ni-59, Nb-94 and Zr-93. However, the concentrations relating to intrusion have only a very low probability of occurring at any given time.

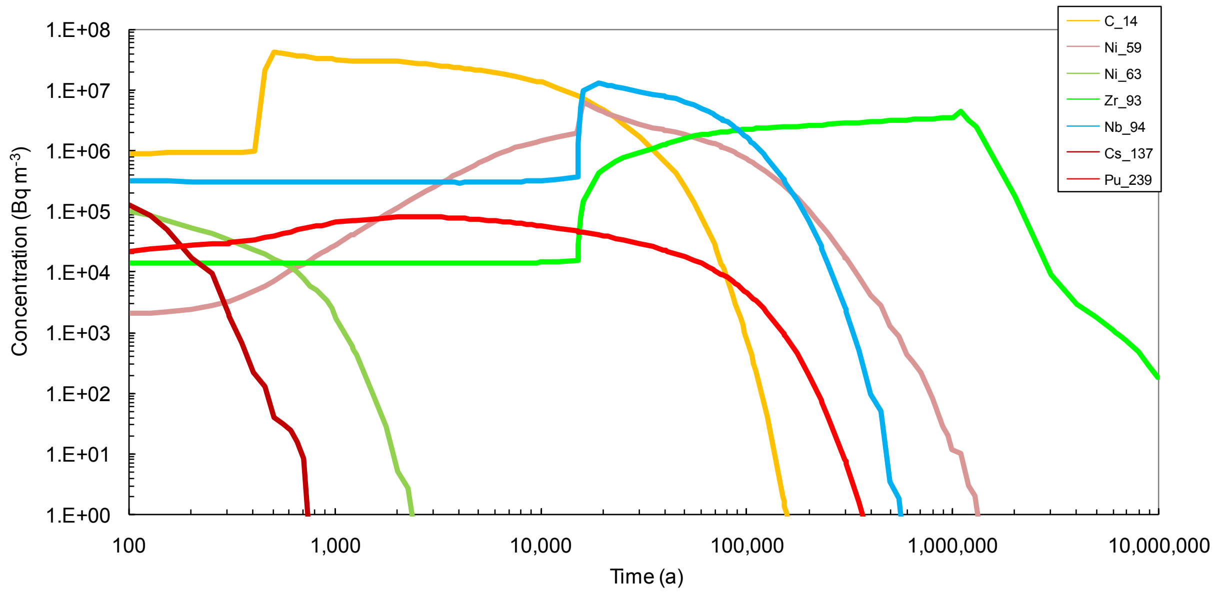


Figure 2-10: Calculated Concentrations of Radionuclides in Soil at the Drill Site if Slurry is Released, as a Function of Time of Intrusion, Assuming the Reference Resaturation Profile

Calculated concentrations of non-radioactive contaminants in soil and water have only been assessed for the instantaneous resaturation case (as this is cautious) described in Section 2.5.1.2.

The calculated concentrations of contaminants in repository gas are presented in Figure 2-11. Gas is assumed to mix throughout the repository, so the concentrations reflect the overall average. C-14, released through biodegradation of plastic and cellulosic wastes in saturated and unsaturated conditions, is present with the greatest activity. The peak concentration reaches 5 x 10^8 Bq m^{-3} after 3000 years. Tritium is present initially but decays with a half-life of 12.3 years. Gaseous Cl-36, Se-79 and I-129 arise by volatilisation, but the concentrations are not significant, being lower than 1 Bq m^{-3}. Rn-222 is associated with the ingrowth of Ra-226 from disposed uranium. There is no Ra-226 in the disposed inventory, so Rn-222 is not present initially. The long half-life of the Th-230 parent of Ra-226 results in the gradual increase in Rn-222. It becomes the most significant gaseous contaminant after about 150 ka, and concentrations persist to 1 Ma when the repository entirely resaturates.

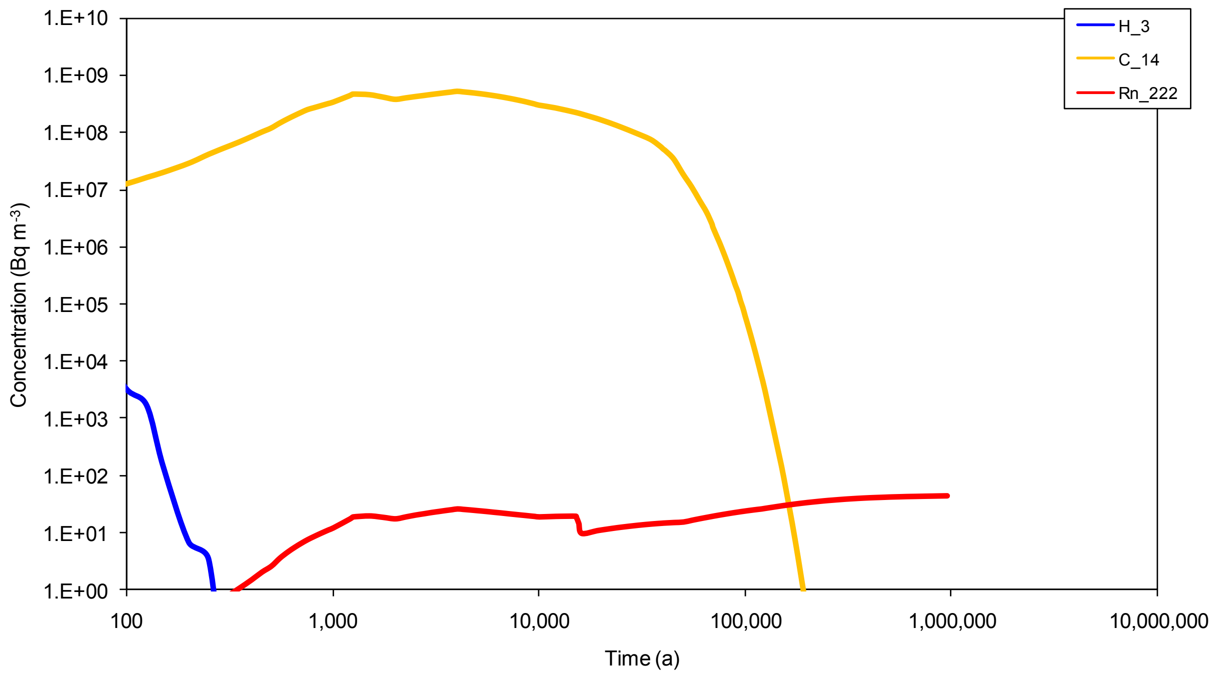


Figure 2-11: Calculated Concentrations of Radionuclides in Repository Gas in the East Panel, as a Function of the Time of Intrusion

2.5.1.2 Surface Release Pathway – Instantaneous Resaturation Profile

The base case resaturation profile represents the most likely pattern of evolution of the repository, based on detailed modelling. Complete resaturation of the repository on an early timescale is very unlikely to occur, owing to the combination of very impermeable host rock and gas pressurization. Nevertheless, a hypothetical case has been assessed in which the repository is instantaneously resaturated at closure. This case has been evaluated in the Human Intrusion calculations primarily to show the possible consequences of a greater potential release of contaminated water and sediment in the period up to 1 Ma. It should be interpreted as a “what if” calculation as such early resaturation is entirely speculative and does not result from processes identified in the normal evolution scenario.

The calculated concentrations in slurry are shown in Figure 2-12 below. Initially, the highest concentrations are associated with suspended particles (primarily C-14 in siderite, with a minor contribution from suspended particles of corroded waste). Unsurprisingly, concentrations in water can be seen to gradually increase, as contaminants are released from wastes. A step change is notable after 15 ka, corresponding to a hypothetical failure of the DGR roof. This event is assumed to result in the crushing of packages and the rapid release of contaminants from wastes into the water. A rapid decrease in the concentrations in suspended waste particulate is also notable at 1 Ma, when metal corrosion is complete and concentrations reduce as the contaminants migrate in groundwater. The concentrations that could occur in soil, if the slurry were to be dumped on site against current regulations, are shown in Figure 2-13.

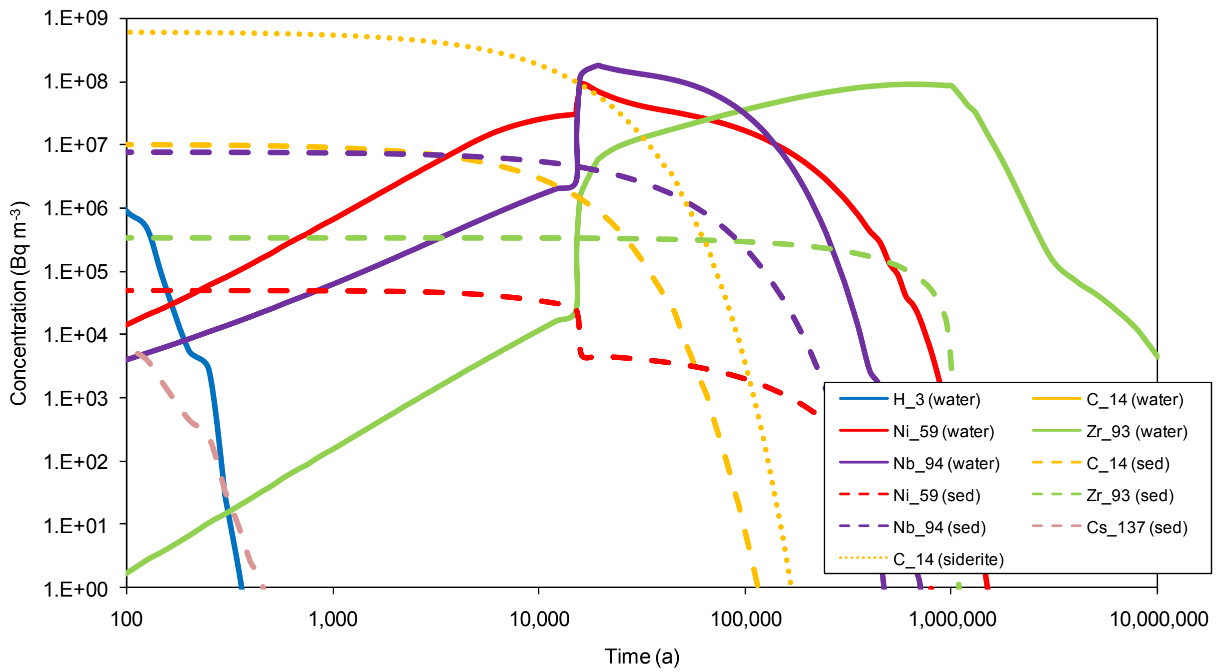


Figure 2-12: Calculated Concentrations of Radionuclides in Repository Water and Suspended Particulate in the East Panel, as a Function of the Time of Intrusion, assuming the Instantaneous Resaturation on Closure

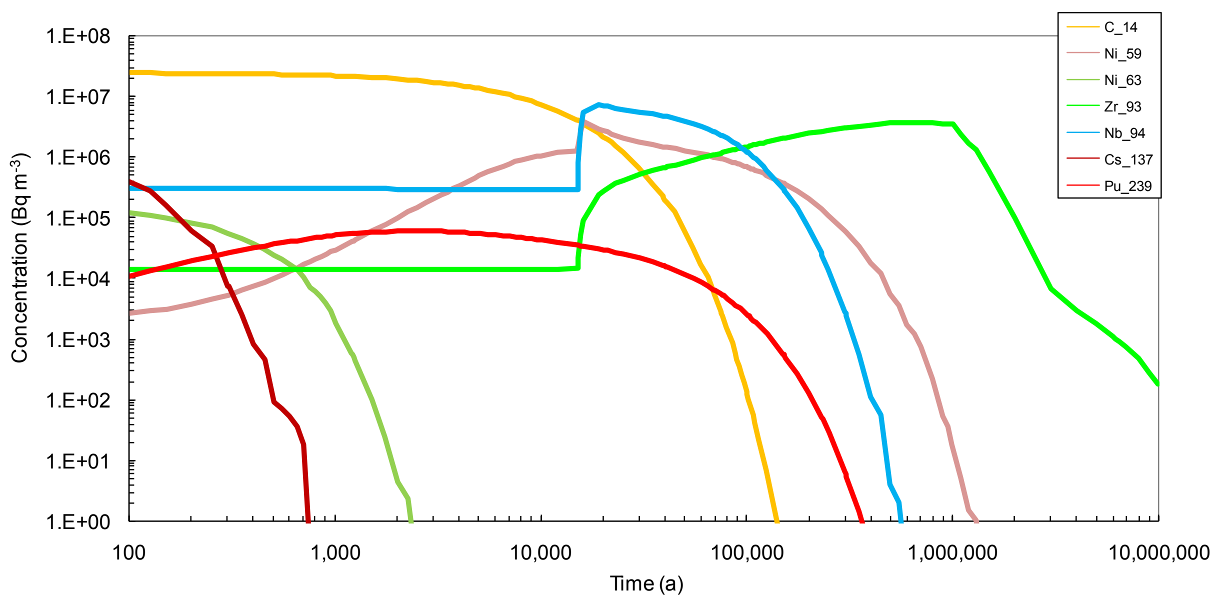


Figure 2-13: Calculated Concentrations of Radionuclides in Soil at the Drill Site if Slurry is Released, as a Function of the Time of Intrusion, assuming the Instantaneous Resaturation on Closure

Comparison of calculated concentrations of non-radioactive contaminants in soil contaminated with slurry against Environmental Quality Standards (EQS) for soil indicate that all the EQS values would be exceeded for all non-radioactive contaminants assessed except thallium. However, this comparison is highly conservative as slurry would be contained and safely disposed according to current practice and regulations. Calculations for radionuclides show that concentrations in soil contaminated with slurry exceed the no-effect concentrations for a variety of contaminants including 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.

Radionuclides are not present in gas for this case, as there is not assumed to be any gas present in the repository and any radionuclides evolved as gas are assumed to be rapidly dissolved into the water.

2.5.1.3 Shallow Bedrock Groundwater Zone Pathway

If the borehole were not sealed properly, it would remain as an enhanced permeability pathway after investigations cease. Under such circumstances, contaminants would continue to be released from the repository, through the borehole. The calculation case conservatively considers a release to the Shallow Bedrock Groundwater Zone following a borehole drilled 300 years after closure that remains poorly sealed.

The calculated fluxes of contaminants through the borehole are presented in Figure 2-14. The rate of release, driven by the pressure differential between the water at repository depth and in the Shallow Bedrock Groundwater Zone, is many orders of magnitude greater than is calculated for release through the shaft and geosphere in the Normal Evolution Scenario. Contaminants are also released to the Shallow Bedrock Groundwater Zone very much earlier, with peak releases for some contaminants occurring only a few thousand years after the intrusion event. It should be noted that, cautiously, sorption of contaminants in the borehole is not modelled. For this case, shorter-lived radionuclides can be released to the Shallow Bedrock Groundwater Zone due to the relatively rapid transport from the repository, and dominate over those longer-lived radionuclides identified as being of significance in the Normal Evolution Scenario.

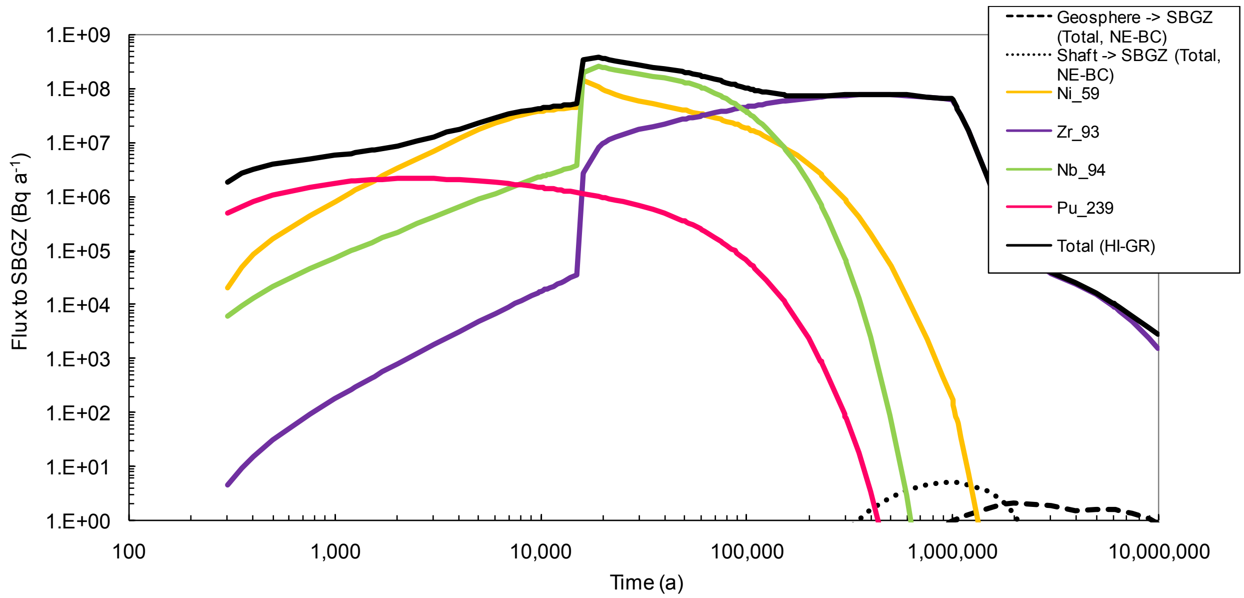


Figure 2-14: Flux of Contaminants Released via an Intrusion Borehole Drilled 300 years after Repository Closure

The figure also illustrates the potential significance of the roof failure (modelled at 15 ka). This event is assumed to result in the crushing of packages and the rapid release of contaminants from wastes into the water. The sharp decline in fluxes around 1 Ma corresponds to the end of the corrosion release of zirconium and niobium and the fully resaturation of the repository and subsequent release of contaminants into groundwater.

The result of the borehole pathway is that higher concentrations occur in the Shallow Bedrock Groundwater Zone than calculated for the Normal Evolution Scenario. This is because the borehole provides a rapid (but limited capacity) pathway that bypasses the Guelph, Salina A0 and Salina A2 evaporite formations. Calculated doses are primarily related to the release of contaminants in groundwater via a well rather than groundwater discharge to Lake Huron. Figure 2-15 shows that substantially higher concentrations of contaminants are present in well water than occurs in the Normal Evolution Scenario, and concentrations peak very much earlier at 8.5 ka rather than 1 Ma. The concentrations of the dominant contaminants in irrigated soil are shown in Figure 2-16.

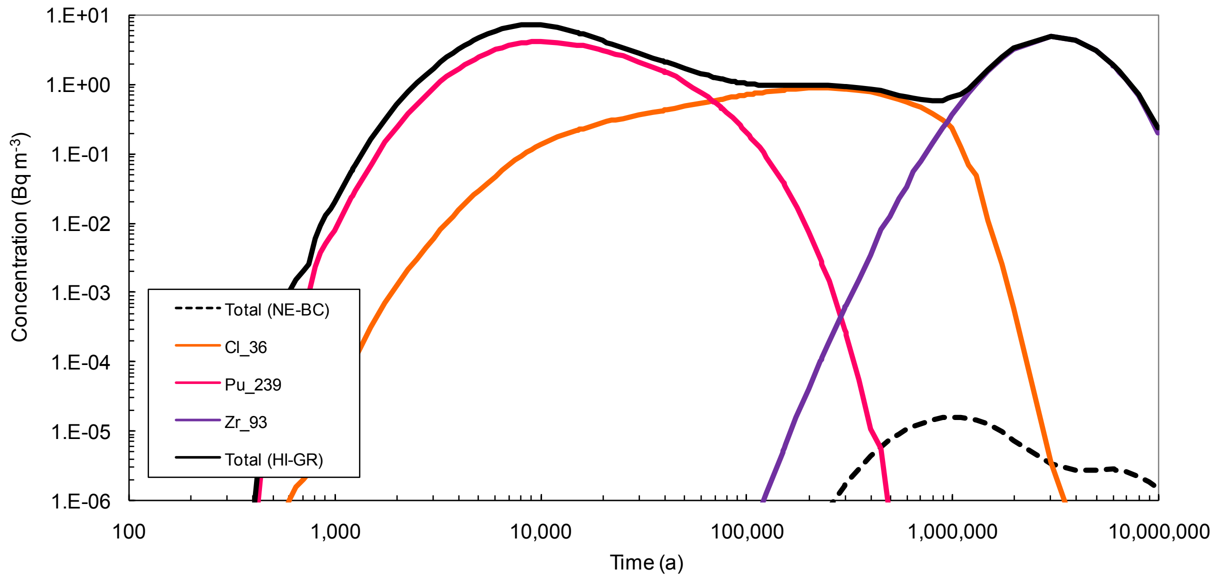


Figure 2-15: Calculated Concentration of Contaminants in Well Water, Assuming an Intrusion Borehole Provides a Pathway from the Repository to the Shallow Bedrock Groundwater Zone

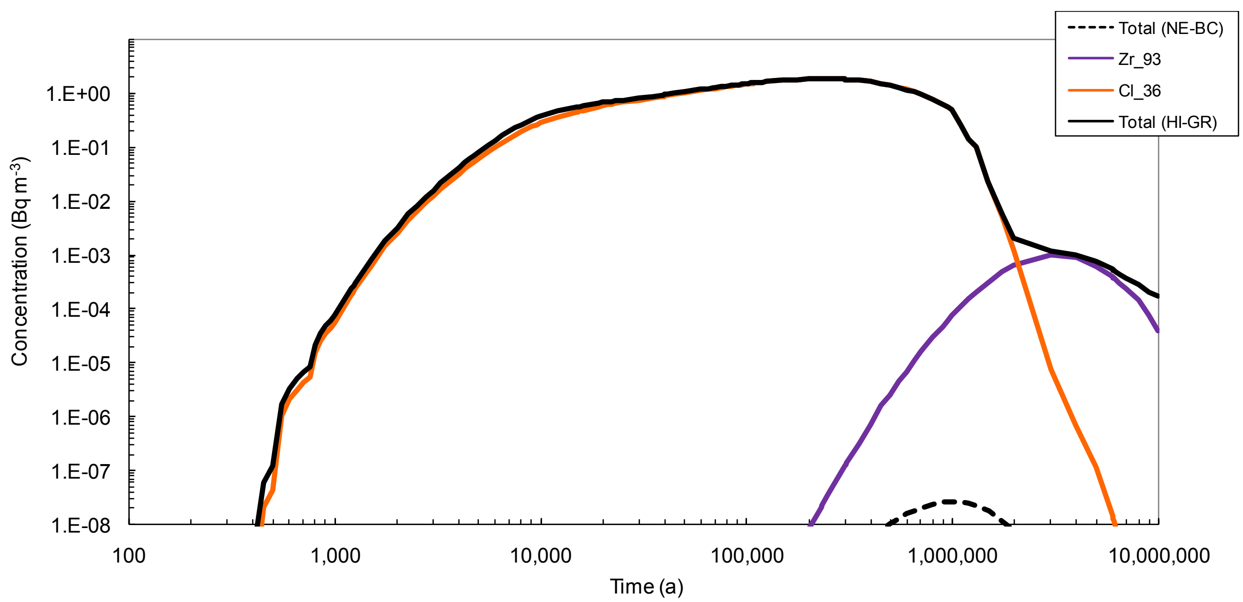


Figure 2-16: Calculated Concentrations Irrigated Soil, Assuming an Intrusion Borehole Provides a Pathway from the Repository to the Shallow Bedrock Groundwater Zone

The concentrations of radionuclides in environmental media are far below the no-effect concentrations.

Calculated concentrations of non-radioactive contaminants in soil remain below the relevant EQS criteria for all non-radioactive species (Table 2-5). For most contaminants, the calculated concentrations in well water do not exceed the relevant EQS, except for Cu and Pb (by up to a factor of 6). 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.

Table 2-5: Ratio of Peak Calculated Concentration of Non-radioactive Species against Environmental Quality Standards for the Human Intrusion Scenario Groundwater Release

Group	Species	Groundwater[1]	Soil[2]	Sediment[3]
Elements	Ag	6.5E-05	2.4E-07	1.5E-06
	As	3.0E-04	1.7E-05	1.4E-07
	B	1.5E-05	1.6E-03	-
	Ba	1.4E-04	2.0E-06	-
	Be	6.9E-04	5.1E-08	-
	Cd	1.7E-01	7.7E-05	2.0E-03
	Co	1.7E-03	3.0E-07	1.4E-06
	Cr	8.7E-01	4.6E-05	4.5E-03
	Cu	**5.9E+00**	3.7E-04	1.6E-01
	Hg	4.9E-03	2.1E-05	7.4E-06
	Mo	6.5E-04	4.0E-05	-
	Ni	2.3E-02	6.4E-06	7.5E-04
	Pb	**2.9E+00**	1.1E-04	8.9E-03
	Sb	1.6E-02	4.9E-05	-
	Tl	1.2E-05	1.7E-05	-
	U	1.7E-09	2.2E-11	-
	V	3.6E-03	2.6E-07	-
	Zn	7.6E-03	8.4E-07	3.8E-04
Organic Species	Chlorobenzenes and Chlorophenols	6.4E-03	3.1E-06	6.1E-04
	Dioxins and Furans	6.4E-02	6.6E-05	-
	PAH	2.6E-04	2.5E-07	2.2E-05
	PCB	1.2E-05	5.9E-09	6.5E-06

Notes:
1 Well water abstracted from the Shallow Bedrock Groundwater Zone.
2 Cropped soil, which receives potentially contaminated irrigation water.
3 Sediment associated with surface water (concentrations are highest in the Lake Shore sediment).

2.5.2 Calculated Radiation Doses

2.5.2.1 Surface Release Pathway – Reference Resaturation Profile

The peak calculated doses to the various exposure groups assessed for the Surface Release Pathway, assuming the reference resaturation profile, are summarised in Table 2-6. The local resident, exposed to soil contaminated with slurry, receives the highest calculated dose of 5.8 mSv a^{-1}. The dose is dominated by C-14, assumed to be present in soil as a result of the slurry, and taken up via plants that are eaten. Other groups are exposed for less time and by fewer pathways, and hence the dose received is considerably lower. The doses to those involved with the drilling activities are dominated by Nb-94, via external irradiation. The nearby resident is assumed to live close to the drilling site and be exposed to any releases of contaminated gas (0.12 mSv). C-14 is present in significant concentrations in gas and dominates their exposure.

Table 2-6: Summary of Peak Calculated Doses for the Human Intrusion Surface Release Pathway, Showing Time of Peak, Dominant Pathway and Radionuclide

	Drill crew (instant)	Drill crew (chronic)	Lab worker	Nearby resident	Site resident
Peak dose	0.17 mSv	1.6 mSv	0.35 mSv	0.12 mSv	5.8 mSv a^{-1}
Duration of exposure (h a^{-1})	4	360	4	720	8766
Time (a)	19000	19000	300	4000	500
Dominant pathway	External (soil and sediment)	External (soil and sediment)	External (point source)	Inhalation (gas)	Ingestion (plant)
Dominant radionuclide	Nb-94	Nb-94	Nb-94	C-14	C-14

Impacts to non-human biota have also been assessed and the environmental concentrations lie well below relevant criteria.

As, for this calculation case, the intrusion event is not constrained to occur at any particular time, it is of value to examine how the potential dose varies with time of intrusion. The results, shown in Figure 2-17, reflect the calculated concentrations presented in Section 2.5.1. Calculated doses can be seen not to be significantly higher if no control was applied and intrusion occurred before 300 y.

The criterion of 1 mSv a^{-1} is exceeded in the case of the drill crew (exposed chronically, over an assumed period of 30 days during which they are assumed to be on-site for 12 h per day) and local resident, who is assumed to live on and farm soil contaminated with slurry from the repository. For the drill crew, exposure to C-14 in gas is most important up to 15 ka, with external irradiation from Nb-94 being dominant thereafter. For the local resident, the release of C-14 in slurry (dominated by the suspended siderite) is the most important pathway in the first 15 ka. The concentration of siderite in repository water has been identified as a significant uncertainty in the assessment calculations. After 15 ka, Nb-94 (present in solution in the water released from the repository) is the most important contributor to dose, via external irradiation from soil or sediment.

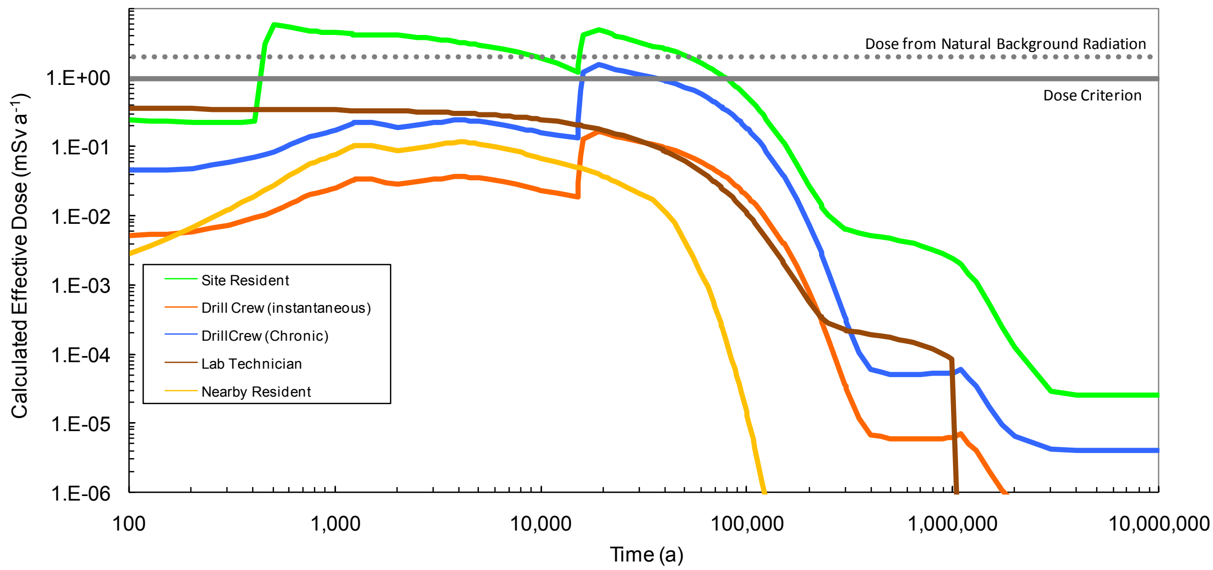


Figure 2-17: Calculated Effective Doses from Human Intrusion Surface Release, as a Function of the Time of Intrusion, assuming the Reference Resaturation Profile

The calculated exposure of the site resident provides an indication of the potential long-term consequences of ground contamination with material from the repository, although the calculation of doses conservatively does not take account of radioactive decay or leaching of the contaminants from soil over the period in which the exposure is assessed (assumed to be one year, immediately following the intrusion). Furthermore, the assumption that the repository is pressurised, as a result of the Cambrian[7], is conservative and current estimates of head in the repository horizon suggest that there would be no excess pressure and hence no release of water via the borehole. The exposure group is assumed to have the same habits and characteristics as the adult of the local exposure group considered for the Normal Evolution Scenario.

2.5.2.2 Surface Release Pathway – Instantaneous Resaturation Profile

The instantaneous resaturation calculation case is intended to illustrate the potential consequences of a much longer period in which there could be contaminant release in water than occurs when the reference resaturation profile is considered. Because the repository is fully saturated, no contaminants are released in gas.

The calculated doses are shown in Figure 2-18, which shows that potential doses exceed 1 mSv a^{-1} for the site resident, with doses to other exposure groups remaining below the criterion. The peak doses to a hypothetical site resident who uses soil contaminated by the slurry for agricultural purposes is 3.5 mSv a^{-1}, arises after about 300 years, from C-14 in plants. The sharp increase at 15 ka is associated with the hypothetical rockfall event and after this time the dose is dominated by external irradiation by Nb-94.

[7] There may be excess gas pressure too, however there would be a rapid discharge of the gas. The head space is assumed to vent before it could force water up the borehole.

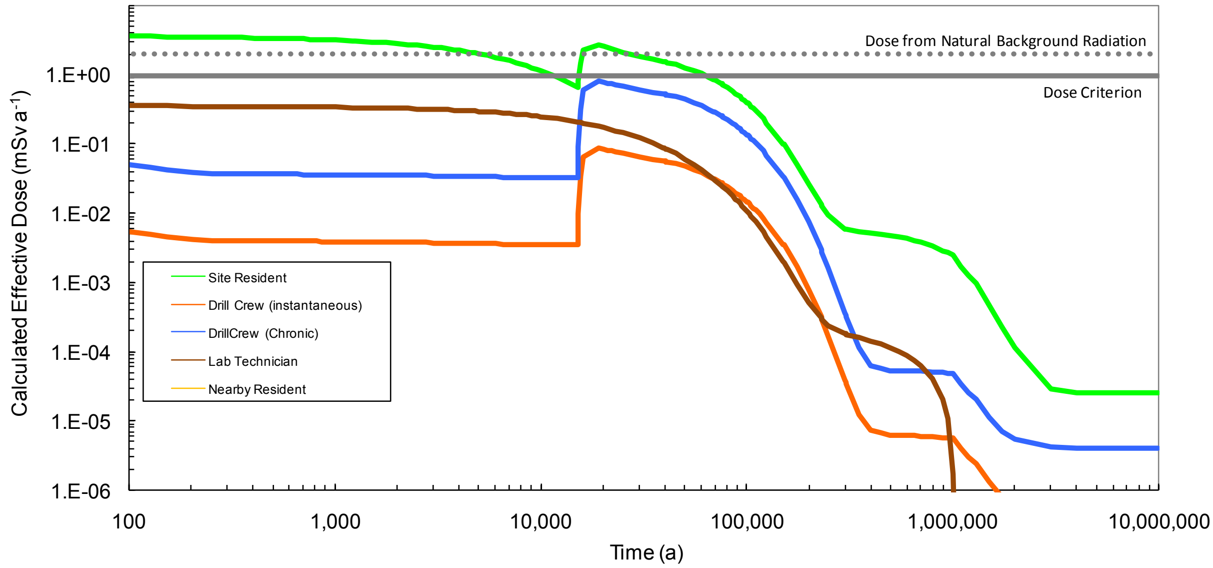


Figure 2-18: Calculated Effective Doses from Human Intrusion Surface Release, as a Function of the Time of Intrusion, assuming the Instantaneous Resaturation on Closure

Finally, it is noted that whilst the concentrations of contaminants in slurry are different in this case, the concentration in waste of key radionuclides does not differ greatly from the reference resaturation case, so the exposure of the lab technician to retrieved core is similar for both cases. The sharp decline in dose at 1 Ma corresponds to repository resaturation and the completion of metal corrosion, so therefore a stop in the release of zirconium and niobium (Figure 2-12).

2.5.2.3 Shallow Bedrock Groundwater Zone Release Pathway

The Shallow Bedrock Groundwater Zone Release Pathway evaluates the potential effects of a long-term release of contaminated water from the repository through a borehole that has not been properly sealed. The potential exposures arising from the Shallow Bedrock Groundwater Zone Release Pathway are assessed for the same local exposure group as the Normal Evolution Scenario, a resident that uses the land at the site for agricultural purposes. The main source of contamination is well water obtained from the Shallow Bedrock Groundwater Zone. The figures presented in Section 2.5.1.3 show that the concentrations in well water and irrigated soil are far higher than calculated for the Normal Evolution Scenario. Figure 2-19 shows that consequently, the doses are substantially greater than those calculated for the Normal Evolution Scenario, peaking at approximately 1 x 10^{-3} mSv a^{-1} after 8.5 ka. However, this level of dose remains well below the dose criterion. The dominant contaminants are Pu-239 and Pu-240 and the dominant pathway is the ingestion of contaminated water. These radionuclides are dominant in this case, because the pathway permits them to be released directly via the investigation borehole to the Shallow Bedrock Groundwater Zone, before they have decayed substantially (Pu-239 and Pu-240 have half-lives of 24 and 6.5 ka respectively). In the Normal Evolution Scenario it is only very long-lived (and mobile) contaminants such as I-129 that remain on timescales in which the plume reaches the Shallow Bedrock Groundwater Zone.

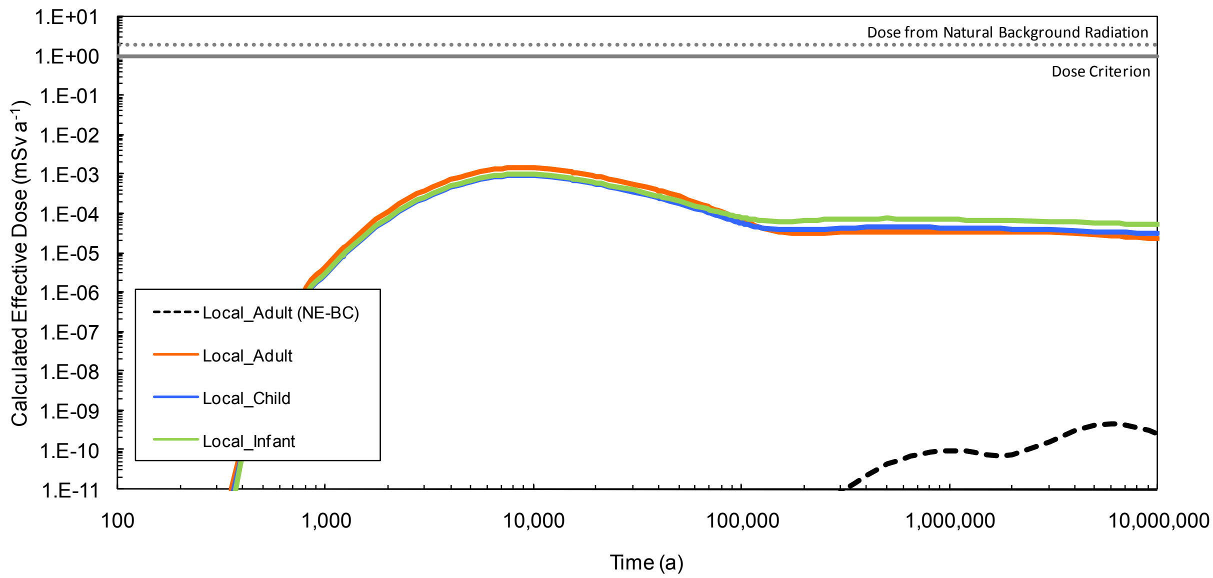


Figure 2-19: Calculated Effective Dose to the Local Exposure Group, for the Groundwater Release Variant of the Human Intrusion Scenario

2.5.3 Likelihood

The calculated doses presented in Section 2.5.2 would obviously only arise if the intrusion event actually occurs, clearly unlikely in any given year. Reported estimates of the probability of intrusion by deep borehole have been obtained from records of actual drilling frequency and more conceptual approaches.

Records of the areal frequency of deep borehole drilling indicate a reasonably broad range, depending on the nature of exploration and the resource potential of the area being investigated. A value of 1 x 10^{-10} m^{-2} a^{-1} (Gierszewski et al. 2004) is a reasonable estimate for the DGR site, taking into account its limited resource potential.

This estimate is supported by the following conceptual argument. If a geological region of interest is re-surveyed every 100 years (approximately three generations), and a representative survey area covered by a single deep borehole is 10 km x 10 km, the areal frequency of deep boreholes would be 1 x 10^{-10} m^{-2} a^{-1}.

The footprint of the repository is 214,000 m^2 (Walke et al. 2009b) which implies a likelihood of intrusion of 2 x 10^{-5} a^{-1}; however, it is noted that the actual plan area of waste emplacement rooms is lower at 52,400 m^2, implying a likelihood of intrusion of 5 x 10^{-6} a^{-1}. Furthermore, the calculations presented in this section correspond to intrusion into the East Panel, in which the highest activity concentration wastes are intended to be emplaced. The likelihood of intrusion into this part of the repository is 2 x 10^{-6} a^{-1} (based on an area of 20,500 m^2 for the East Panel– Walke et al. 2009b).

It is important to emphasise that the measure of likelihood is uncertain. It is based upon the assumption that the level of technological development remains as it is today throughout the assessment timeframe (consistent with ICRP 2000). In practice, it might increase or decrease, and so intrusion likelihood should therefore be recognised as being dependent on future societal developments.

These estimates of likelihood can be interpreted in two ways:

- as a measure of the likelihood that an individual is exposed in a given year; and
- as a measure of the likelihood that intrusion occurs during the assessment timeframe.

In relation to the first point, using an estimate of the likelihood of intrusion into the emplacement rooms of 5×10^{-6} a^{-1} and a risk conversion factor of 0.073 Sv^{-1} (CNSC 2006), 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), much less than the risk benchmark of 10^{-5} a^{-1}.

The second point relates to the integral of the annual probability of intrusion over the whole assessment timeframe. Over the timescales under consideration in the assessment (in excess of 1 Ma), the estimate of likelihood implies an increasing probability that intrusion will occur. However, it is important to recognise that the probability of the actual scenarios occurring is lower than that of intrusion occurring since the scenarios makes additional conservative assumptions as discussed below. Furthermore, if the intrusion event occurs after 80 ka, Figure 2-18 shows that the calculated doses for all exposure groups are below the dose criterion, even with the conservative assumptions adopted.

The human intrusion model assumes that the repository is overpressurised (due to the influence of the pressurised Cambrian). This assumption creates a pressure-driven release of water from the repository. However, current information (Avis et al. 2009) indicates that the host formation is actually underpressurised, such that water would be drawn in via an intrusion borehole, rather than be released.

In addition, 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. Some of the most important conservatisms are:

- **Drill Crew** – the gas is assumed to be released at a relatively high rate and there is conservative parameterisation of exposure pathways (e.g., inadvertent ingestion and inhalation of contaminated slurry);
- **Laboratory Technician** – the assumption that intact core could be retrieved from the waste (most wastes are not of a form that would permit this), and conservative parameterisation of exposure pathways, such as the assumed high dust loading and lack of dust mask;
- **Nearby Resident** – the gas is assumed to be released at a relatively high rate and the nearest resident to the drilling site would probably be more than 100 m away; and
- **Site Resident** – drilling slurry would not be permitted to be dumped on site, as has been assumed, under current practices, and the parameterisation of the exposure group is conservative.

3. SEVERE SHAFT SEAL FAILURE SCENARIO

3.1 SCENARIO OVERVIEW

Another scenario in which the containment offered by the DGR system might be degraded is concerned with the performance of the shaft seals. The shafts provide a potential pathway for the migration of contaminated water and gas from the repository through the geosphere. To limit the release of contaminants, seals are installed in the shaft at closure. The Normal Evolution Scenario takes account of the role of these engineered barriers and assumes their performance meets design specifications. It also includes an expected degree of degradation of shaft seal properties with time.

However, an alternative scenario is considered in which the shaft seal does not meet design expectations (Little et al. 2009). This could be because the shaft seal materials are not fabricated or installed appropriately (and not detected by DGR quality control procedures), or the long-term performance of the seal materials may deviate 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**. Given the simple materials used, and the quality control measures that will be applied to the DGR project, the scenario is very unlikely and should be seen as a hypothetical "what if" scenario that is designed to investigate the robustness of the DGR system.

The Severe Shaft Seal Failure Scenario represents the evolution of DGR system in the same way as the Normal Evolution Scenario with the only difference being that there is more rapid and more extensive seal degradation in the shafts.

The scenario is illustrated in Figure 3-1.

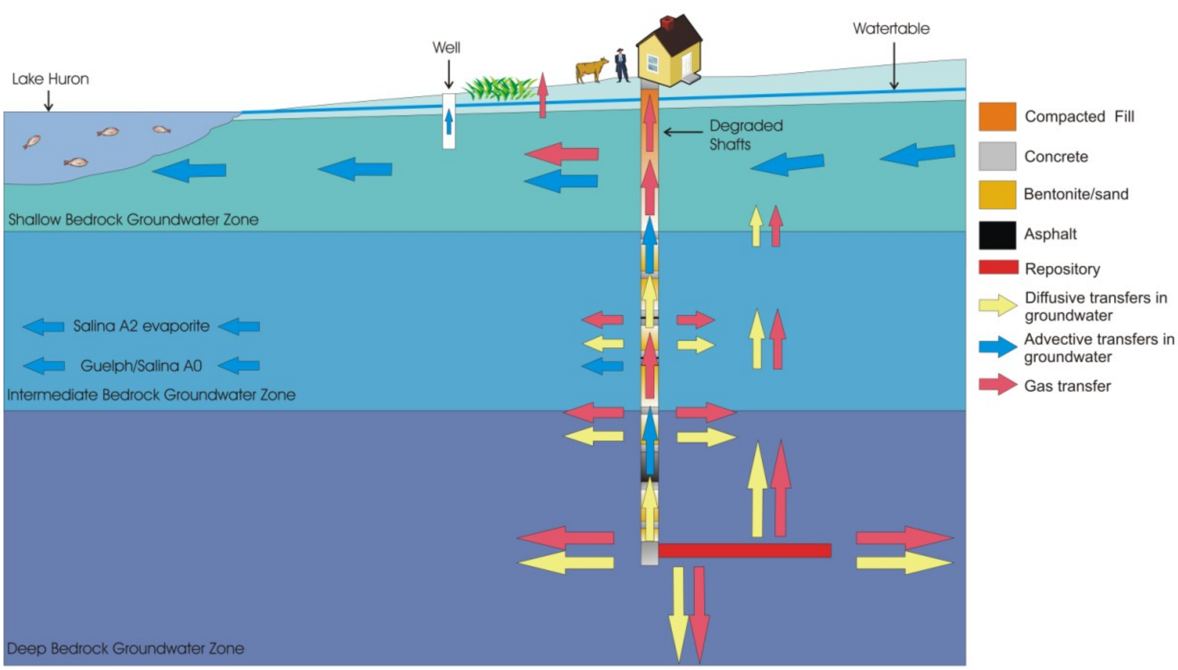


Figure 3-1: Severe Shaft Seal Failure Scenario

3.2 CONCEPTUAL MODEL

3.2.1 Key Features, Processes and Events

The internal features, processes and events considered for the Severe Shaft Seal Failure Scenario are the same as for the Normal Evolution Scenario (as described in the Normal Evolution Scenario Analysis report, Walke et al. 2009a) with the exception that the concrete monoliths, the shaft seals and backfill do not function as planned. This could be due to human factors (i.e., the shafts are not sealed and backfilled to the required specification), or natural factors (i.e., chemical and/or physical conditions in the geosphere cause the backfill to degrade more rapidly than anticipated). The key features are summarised in Table 3-1 and the key processes and events in Table 3-2.

Table 3-1: Summary of Key Features for the Severe Shaft Seal Failure Scenario

Waste and Repository Features	Geosphere Features	Biosphere Features
• Wasteforms (22 types) • Water (South Panel (LLW) emplacement rooms, East Panel (ILW and some LLW) emplacement rooms, and access/ring tunnels) • Gas (South Panel (LLW) emplacement rooms, East Panel (ILW and some LLW) emplacement rooms, and access/ring tunnels) • Engineered Structures (sealing walls, concrete monoliths, and shaft seals and backfill)	• Excavation Damaged Zone • Deep Bedrock Groundwater Zone • Intermediate Bedrock Groundwater Zone • Shallow Bedrock Groundwater Zone	• Well Water • Surface Water (stream and wetland) • Surface Water Sediment (stream and wetland) • Lake Water • Lake Sediment • Soil • Biota • Houses and Buildings • Atmosphere

3.2.2 Description of the Conceptual Model

The conceptual model is the same as for the Normal Evolution Scenario (as described in the Normal Evolution Scenario Analysis report, Walke et al. 2009a), 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 due to Cambrian overpressure (see discussion in Groundwater and Gas Modelling reports, Avis et al. 2009 and Calder et al. 2009). The changed properties of the shaft also result in a different resaturation profile to that determined for the base case. The key aspects of the conceptual model for releases from the repository are summarised in Box 2.

Table 3-2: Summary of Key Processes and Events for the Severe Shaft Seal Failure Scenario

Processes Internal to Features	Processes Resulting in Transport of Contaminants between Features	Events and Processes Changing Features with Time
• Decay of contaminants • Degradation of contaminants • Gas generation • Sorption • Elemental solubility • Chemical effects that result in changes to the properties of engineered materials • Radiation dosimetry	• Gas release from saturated and unsaturated wasteforms • Gas transport in the repository, geosphere and biosphere. • Gas dissolution in water • Gas volatilisation • Resaturation of the repository • Aqueous release from the saturated wasteform types (instant release, delayed instant release, congruent release and diffusive release) • Groundwater transport (advection, dispersion and diffusion) • Surface water transport • Infiltration • Interflow • Bioturbation • Resuspension and sedimentation • Erosion and deposition • Water pumping • Uptake by biota • Human ingestion, inhalation, external irradiation and dermal adsorption of contaminated media	• Physical and chemical degradation of wasteforms • Severe physical and chemical degradation of engineered structures and backfill on closure • Climate change due to glacial/interglacial cycling • Land use change

Box 2:
Key Aspects of the Conceptual Model for the Severe Shaft Seal Failure 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).
- Consideration of sorption of some contaminants (C, Zr. Ni, Nb, U and Np) on concrete monoliths and solubility limitation on C and U only, consistent with the Normal Evolution Scenario (Walke et al. 2009a).
- Contaminants released into water via instant, diffusive and congruent release processes, consistent with the Normal Evolution Scenario (Walke et al. 2009a).
- 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, consistent with the Normal Evolution Scenario (Walke et al. 2009a).
- Resaturation of repository determined by water inflow/outflow rate, gas generation rate and gas pressure (see Section 3.4.3).
- Contaminants migrate into the host rock and shafts by diffusion and advection (driven by the pressure head in the Cambrian)[8] or by gas permeation (driven by repository gas pressure relative to the porewater pressure) or by gas dissolution into groundwater[9].
- The concrete monolith at the base of each shaft is degraded from closure[10].
- Rockfall occurs progressively until a stable equilibrium is reached, consistent with the Normal Evolution Scenario (Walke et al. 2009a).

Shafts:

- Migration up the shafts occurs by both advection and diffusion through the shaft cores and EDZs[8].
- The shaft seals and backfill are physically and chemically degraded from the time of closure[9].
- The shaft seals do not penetrate the shaft EDZ[10].
- The inner EDZ has increased permeability[10].
- Reduce sorption of some contaminants (C, Zr, Ni, Nb, U and Np) on shaft materials (concrete and bentonite/sand).
- Gas breakthrough time of 1,500 years and travel time from repository to surface of 750 years[11].

Geosphere:

- Groundwater flow in the Deep and Intermediate Bedrock Groundwater Zones is upwards since the measured +140 m hydraulic head in the Cambrian sandstone is conservatively assumed to support indefinitely a steady-state vertical upwards hydraulic gradient and the observed underpressures in the Ordovician are assumed quickly dissipated (consistent with the Normal Evolution Scenario, Walke et al. 2009a)[8].
- Groundwater flow in the Guelph, Salina A0 and Salina A2 evaporite Formations is horizontal[8].
- Groundwater flow in the Shallow Bedrock Groundwater Zone is horizontal towards Lake Huron[8].
- Contaminants migrate through the geosphere by diffusion and advection in groundwater[8] or gas permeation through the shaft or excavation damaged zones (EDZs)[9].
- Sorption of some contaminants (C, Zr, Ni, Nb, U and Np) is considered in geosphere.
- There is no breakthrough of bulk gas from repository to surface via the geosphere[9].

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[8] Based on findings presented in the Groundwater Modelling Report (Avis et al. 2009).
[9] Based on findings presented in the Gas Modelling Report (Calder et al. 2009).
[10] Conservative assumption adopted for the scenario to investigate the importance of this feature.
[11] The travel time for the shafts is based on findings presented in the Gas Modelling Report (Calder et al. 2009). The breakthrough time is the time of the first release of free-phase gas at the surface via the shafts. The travel time is the time taken for free-phase gas to travel from repository to surface via the shafts once the initial breakthrough has been achieved. Further details are provided in Appendix D of the Normal Evolution Scenario Analysis report (Walke et al. 2009a).

Box 2 (cont.):
Key Aspects of the Conceptual Model for the Severe Shaft Seal Failure Scenario

Biosphere:
- 300 year site control period (see postclosure SA main report, Quintessa et al. 2009).
- Constant temperate climate conditions (consistent with the base case calculations for the Normal Evolution Scenario, Walke et al. 2009a).
- Groundwater is pumped from a well in the Shallow Bedrock Groundwater Zone for domestic and farming use, including irrigation (consistent with the Normal Evolution Scenario, Walke et al. 2009a).
- 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 (consistent with the Normal Evolution Scenario, Walke et al. 2009a).
- Possible release of gaseous contaminants from shafts and geosphere to house and soil due to gas permeation and volatilisation from groundwater with subsequent atmospheric dispersion of gas.
- Surface media become contaminated following release of contaminants via shafts, well, and groundwater discharge to lake.
- Potential impacts estimated based on assuming a self-sufficient family farm located on the repository site and using groundwater from well and lake (consistent with the Normal Evolution Scenario, Walke et al. 2009a).

3.2.3 FEP Audit

As noted in Section 3.2.2, the conceptual model for the Severe Shaft Seal Failure Scenario is broadly the same as the Normal Evolution Scenario (as described in the Normal Evolution Scenario analysis report, Walke et al. 2009a) with only differences relating to parameters describing the performance of the seals, backfill and EDZ (Section 3.2.2). Thus, the only internal FEPs that differ in the Severe Shaft Seal Failure Scenario relate to the seals, backfill and EDZ; these are itemised below.

- FEP 2.1.05 (Shaft characteristics) – concrete monoliths, and the shaft seals and backfill have degraded physical and chemical characteristics from the time of closure due to the human/natural factors discussed in Section 3.2.1.
- FEP 2.1.06 (Mechanical processes and conditions in shafts) – mechanical fracturing occurs in shaft materials from the time of closure.
- FEP 2.1.07 (Hydraulic/hydrogeological processes and conditions in shafts) – enhanced water and gas flow from the time of closure due to physically and chemically degraded state of shafts.
- FEP 2.1.08 (Chemical/geochemical processes and conditions in shafts) – promote enhanced degradation of the shaft materials from time of closure.
- FEP 2.1.09 (Biological/biochemical processes and conditions in shafts) – promote enhanced degradation of the shaft materials from time of closure.
- FEP 2.2.03.02 (Disturbed Zone (in geosphere): Shafts) – no keying of shaft seals into EDZ. Enhanced permeability in inner EDZ.

3.2.4 Key Conceptual Model Uncertainties

Since the Severe Shaft Seal Failure Scenario and the Normal Evolution Scenario have essentially the same conceptual models, the conceptual model uncertainties are also the same. These are discussed in the Normal Evolution Scenario analysis report (Walke et al. 2009a) and so are not replicated here. However, it should be noted that one of the motivations behind considering the Severe Shaft Seal Failure Scenario is specifically to examine the effects of uncertainties relating to the performance of the shaft seals and the shaft EDZ (a key conceptual model uncertainty for the Normal Evolution Scenario). The Severe Shaft Seal Failure Scenario investigates these uncertainties by considering an extreme ("what if") treatment of the performance of the shafts.

3.3 CALCULATION CASES

Three calculation cases can be identified from consideration of the conceptual model developed in Section 3.2, which considers the release of radioactive and non-radioactive contaminants (Table 3-3).

Table 3-3: Calculation Cases for the Severe Shaft Seal Failure Scenario

Case ID	Brief Description	Associated Detailed Modelling Cases
SF-ES1-A	As for the Normal Evolution Scenario case NE-BC-A but hydraulic properties of all seals, backfill and inner EDZ set to extreme degraded values from t=0, all seals not keyed into 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 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.	-

Notes:
SF – Severe Shaft Seal Failure Scenario; NE- Normal Evolution Scenario; ES – entire shaft failed; US – upper shaft failed; NR – non-radioactive contaminants; BC - base case; A – AMBER; F2 – FRAC3DVS 2DR model; T – T2GGM

Given the commonality of many aspects of the conceptual model with that developed for the Normal Evolution Scenario, calculation cases identified above have been derived with reference to those considered in the base case for the Normal Evolution Scenario (see the Normal Evolution Scenario Analysis report, Walke et al. 2009a, for more details). The only modifications for SF-ES1-A and SF-NR-A cases are:

- the hydraulic properties of shaft seals, shaft backfill and shaft inner EDZ are set to extreme degraded values from closure;
- the seals are not keyed into the EDZ;
- more rapid transfers of gas and groundwater through the shafts are specified (based on detailed groundwater and gas modelling of the scenario, Avis et al. 2009 and Calder et al. 2009); and
- a modified resaturation profile (see Figure 3-2).

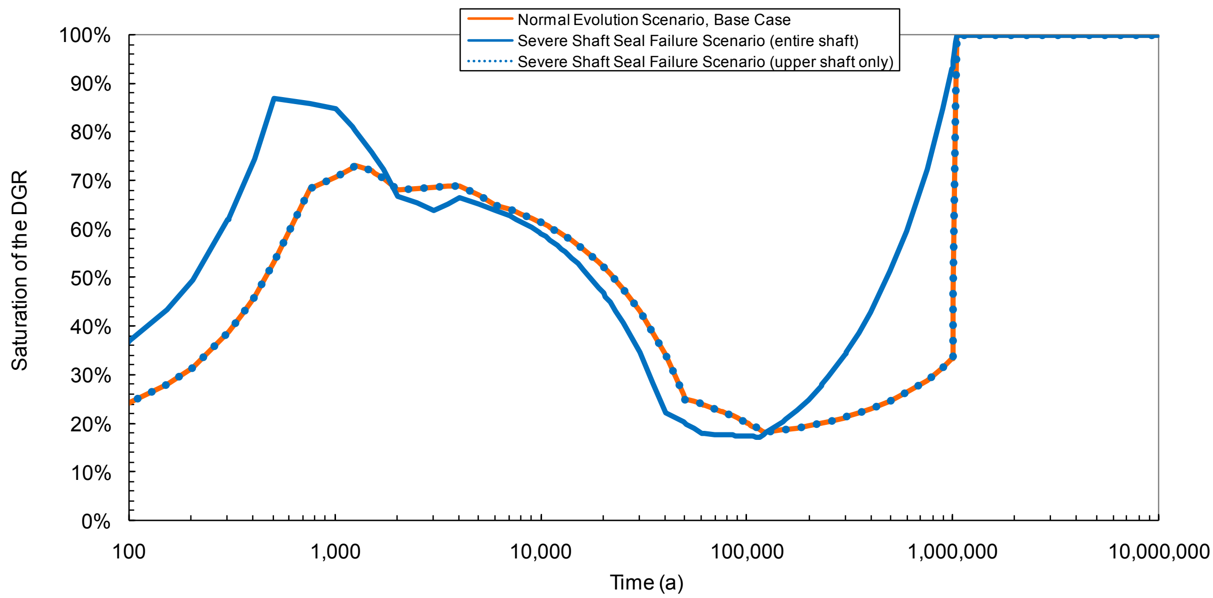

Figure 3-2: Repository Resaturation Profiles Assessed for the Severe Shaft Seal Failure Scenario

The SF-US-A case is a variant that considers that the shafts and their EDZs in the Shallow and Intermediate Bedrock Groundwater Zones (Devonian and Silurian) are degraded, whilst the characteristics of the shafts and EDZs in the Deep Bedrock Groundwater Zone (Ordovician) remain the same as the Normal Evolution Scenario. For this scenario, the resaturation profile is essentially the same as that of the Normal Evolution Scenario Base Case since flow into the repository is mostly from the geosphere rather than from shafts (Avis et al 2009).

The modifications required for the three calculation cases can be represented in model parameters, and no changes are necessary to the conceptual model presented in Section 3.2.

3.4 MATHEMATICAL MODELS, SOFTWARE IMPLEMENTATION AND DATA

3.4.1 Mathematical Models

The Severe Shaft Seal Failure Scenario adopts the same general mathematical models as the Normal Evolution Scenario. There is no need to modify any aspects of the mathematical models, since the scenario can be represented by simply modifying the properties of the shaft seal materials and the shaft EDZs. The mathematical models used are described in detail in Section 4.1 of the Normal Evolution Scenario Analysis report (Walke et al. 2009a).

3.4.2 Software Implementation

The scenario is implemented in AMBER Version 5.2 (Enviros and Quintessa 2008a, b). The scenario-specific data are implemented as alternative parameter values that can be selected by defining model run settings with a scenario-dependent parameter taking a value of 1 when the scenario is to be considered, and 0 otherwise. The scenario-dependent parameter is also used to change the characteristics of the seals in the EDZ to be the same as the EDZ, thereby effectively removing the seals from the EDZ (consistent with the conceptual model).

In addition, models have been implemented in the FRAC3DVS and T2GGM codes to allow the derivation of certain input data for the assessment calculations. The implementation of these models is described in Section 4.3 of the Groundwater Modelling report (Avis et al. 2009) (FRAC3DVS) and Section 4.3 of the Gas Modelling report (Calder et al. 2009) (T2GGM).

3.4.3 Data

The Severe Shaft Seal Failure Scenario adopts the same parameter values as for the Normal Evolution Scenario (summarised in Table 2-3) with the exception that pessimistic values are adopted for the engineered materials in the shaft and the associated EDZ.

3.4.3.1 SF-ES1-A and SF-NR-A

The pessimistic values for the engineered materials in the shaft and the associated EDZ are cautiously assigned to the model from closure onwards. The hydraulic conductivities, porosities, densities and diffusion coefficients are summarised in Table 3-4. The sorption values are presented in Table 3-5 and are an order of magnitude lower than the reference values given in the Data report (Walke et al. 2009b). It is assumed that the hydraulic conductivity of the inner EDZ is four orders of magnitude greater than the rock mass (rather than the two orders of magnitude assumed for the Normal Evolution Scenario). The advective velocities that are used in the AMBER model are derived from the results of groundwater modelling (Figure 3-3) (Avis et al. 2009).

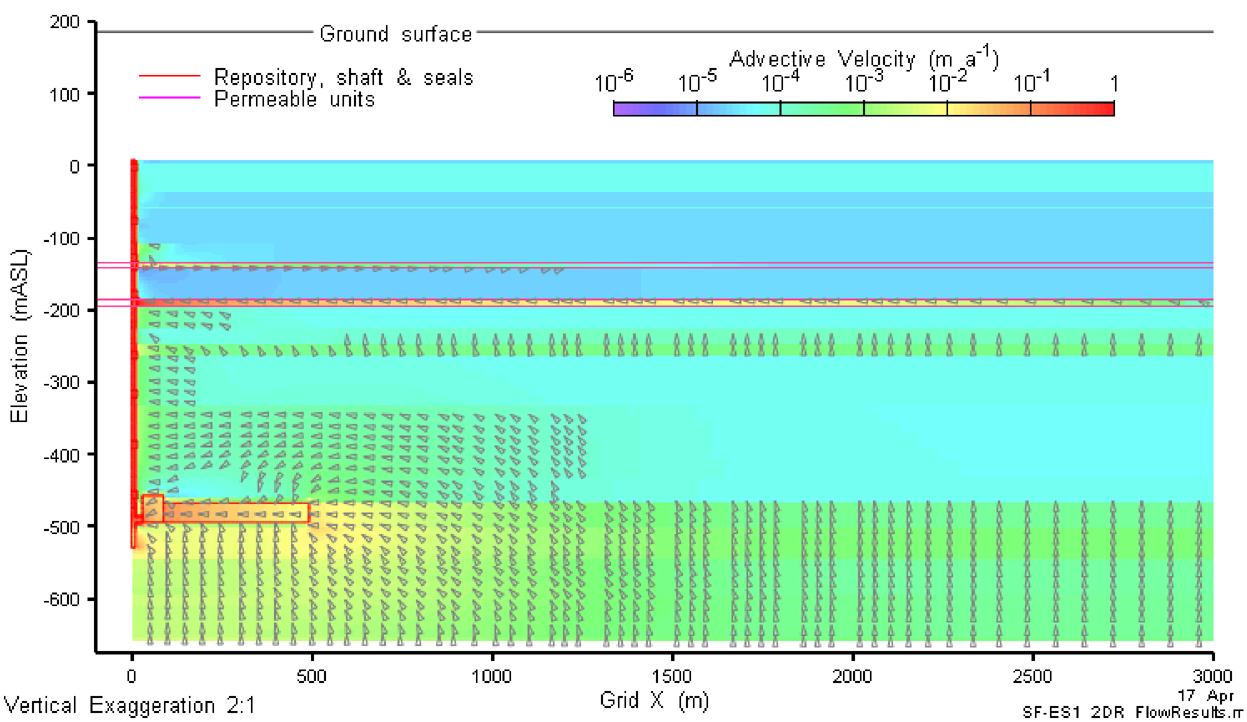

Figure 3-3: Advective Velocities for the Severe Shaft Seal Failure Scenario SF-ES1-F2 Case

Table 3-4: Hydraulic Conductivities, Porosities, Densities and Diffusion Coefficients for Shaft Sealing Materials for the Severe Shaft Seal Failure Scenario's SF-ES1-A and SF-NR-A Calculation Cases

Parameter	Shaft Sealing Material	Deep and Intermediate Bedrock Groundwater Zones	Shallow Bedrock Groundwater Zone
Vertical and Horizontal Hydraulic Conductivity ($m\ s^{-1}$) (1)	Concrete (3)	1E-7 (4)	1E-7 (4)
	Bentonite/sand	1E-7 (4)	
	Asphalt	1E-7 (4)	
	Engineered Fill	1E-4 (5)	
Diffusion and Transport Porosities (-) (2)	Concrete (3)	0.25 (6)	0.35 (6)
	Bentonite/sand	0.4 (6)	
	Asphalt	0.15 (6)	
	Engineered Fill	0.4 (6)	
Grain Density ($kg\ m^{-3}$) (7)	Concrete	2430	
	Bentonite/Sand	2720	
	Asphalt	2400	
	Engineered Fill	2650	
Dry Bulk Density ($kg\ m^{-3}$) (8)	Concrete	1825	1580
	Bentonite/Sand	1630	
	Asphalt	2040	
	Engineered Fill	1590	
Horizontal and Vertical Effective Diffusion Coefficient ($m^2\ s^{-1}$)	Concrete (9)	2.5E-11	1.25E-9
	Bentonite/Sand (9)	1E-9	
	Asphalt (9)	1E-12	
	Engineered Fill (10)	1.25E-9	
Horizontal and Vertical Pore Water Diffusion Coefficient ($m^2\ s^{-1}$) (11)	Concrete	1E-10	3.6E-9
	Bentonite/Sand	2.5E-9	
	Asphalt	6.7E-12	

Notes:

1. Values for freshwater. Slightly lower values (less than a factor of two) can be expected for saline conditions due to greater density and viscosity of water. However the Data report (Walke et al. 2009b) adopts freshwater values for all conditions.
2. The transport (effective) porosity values are taken to be the same as the diffusion (accessible) porosity values for all materials.
3. Value for structural and low permeability cement and is for all concrete in repository rooms, tunnels and shafts (including shaft monoliths).
4. Upper limit given in the Data report (Walke et al. 2009b) for degraded concrete adopted for all shaft materials other than the engineering fill.
5. Mid point of range given in Freeze and Cherry (1979) for sand.
6. Taken to be 0.05 higher than the upper end of range given in the Data report (Walke et al. 2009b) due to increased degradation of concrete.
7. Taken from the Data report (Walke et al. 2009b).
8. Calculated using porosity values.
9. Taken to be an order of magnitude higher than reference value given in the Data report (Walke et al. 2009b) due to increased degradation of concrete.
10. Taken to be the same as degraded concrete in Shallow Bedrock Groundwater Zone.
11. Calculated by dividing effective diffusion coefficient by diffusion porosity.

Table 3-5: Sorption Coefficients for Shaft Sealing Materials for the Severe Shaft Seal Failure Scenario's SF-ES1-A and SF-NR-A Calculation Cases (m3 kg-1)

Element	Concrete	Bentonite/ Sand	Asphalt	Engineered Fill
C	0.0001	0	0	0
Ni	0.001	0.01	0	0
Zr	0.1	0.01	0	0
Nb	0.01	0.01	0	0
U	0.1	0.05	0	0
Np	0.1	0.05	0	0
All other elements	0	0	0	0

The resaturation profile used is based on detailed model results (Calder et al. 2009) and is illustrated in Figure 3-2. Resaturation reaches 87% after 500 years, and decreases to 17% after 115,000 years. The repository is then assumed to completely resaturate by 1.05 Ma.

3.4.3.2 SF-US-A

The case-specific considerations are:

- the hydraulic and sorption properties of the Silurian and Devonian seals, backfill and inner EDZ are set to the values used for the SF-ES1-A calculation case from closure (see Section 3.4.3.1);
- the Silurian and Devonian seals are not keyed into the shaft EDZs; and
- the hydraulic and sorption properties of the Ordovician seals, backfill and inner EDZs are as for the Normal Evolution Scenario (including those at the Silurian-Ordovician boundary) (see Data report, Walke et al. 2009b).

The advective velocities that are used in the AMBER model are derived from the results of groundwater modelling (Figure 3-4) (Avis et al. 2009).

The resaturation profile used is based on detailed model results (Calder et al. 2009) and is illustrated in Figure 3-2, and is exactly the same as the base case for the Normal Evolution Scenario (Walke et al. 2009a). Resaturation reaches 73% after 1200 years, and decreases to 18% after 120,000 years. The repository subsequently slowly but steadily resaturates, and is assumed to completely resaturate shortly after 1 Ma.

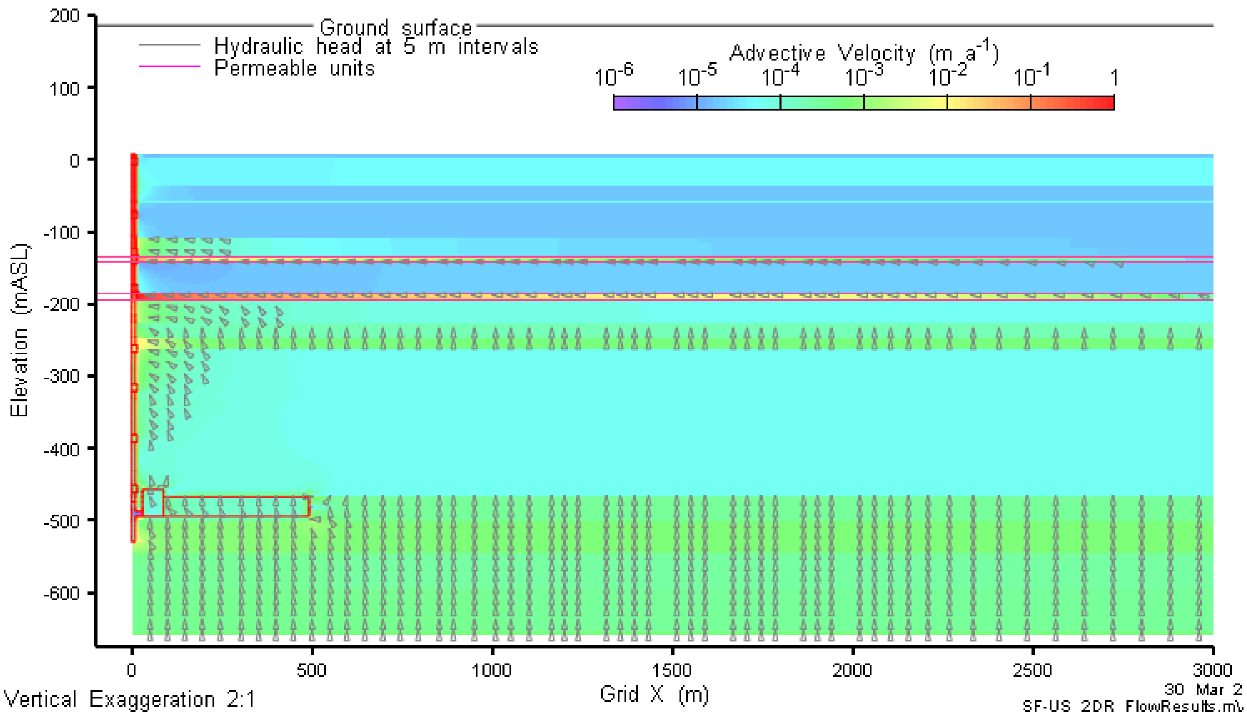

Figure 3-4: Advective Velocities for the Severe Shaft Seal Failure Scenario SF-US-F2 Case

3.5 RESULTS

3.5.1 Release of Contaminants via the Degraded Shaft

The primary effect of the assumption of instantaneously degraded shaft seal materials is to permit very much greater flows through the shafts, resulting in an earlier release and greater fluxes of contaminants to the Shallow Bedrock Groundwater Zone than found in the calculations for the Normal Evolution Scenario (Walke et al. 2009a).

Calculated fluxes of contaminants in groundwater are illustrated in Figure 3-5 for the case in which the whole shaft seal system is severely degraded. In the Normal Evolution Scenario, the key radionuclides are C-14 (up to 12500 a), Ni-59 and Nb-94 (12.5 ka to 100 ka), and Zr-93 (thereafter). For the severe shaft seal failure case, the greater advective velocities that are permitted by the degraded materials enable shorter lived contaminants such as C-14 to be transported to the Shallow Bedrock Groundwater Zone in significant amounts (C-14 is primarily in gas, although this is assumed to dissolve into the groundwater upon reaching the Shallow Bedrock Groundwater Zone). Other contaminants emerge in the Shallow Bedrock Groundwater Zone much earlier. For example, the peak release of Ni-59 in groundwater occurs after about 35 ka in this case, compared with more than 1 Ma in the Normal Evolution Scenario. As a consequence, many contaminants that decay to trivial levels before they are released in the Normal Evolution Scenario are significant in this case. The dominant pathway through the shaft is via the severely degraded shaft seals rather than the EDZ, except for a period between 2 ka and 13 ka and after 1.2 Ma.

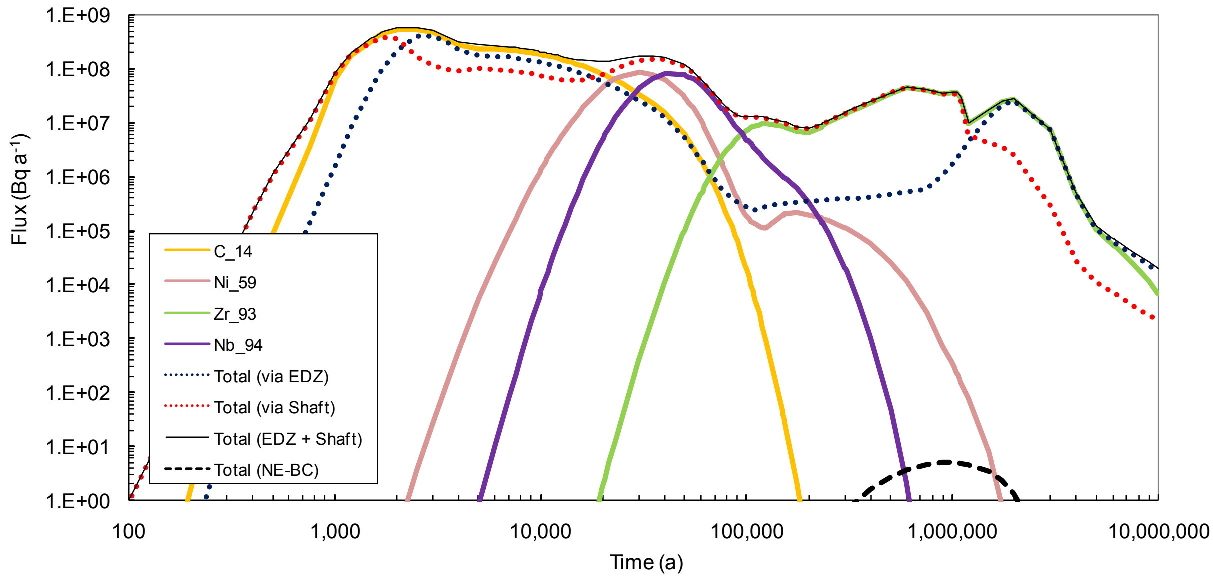

Figure 3-5: Calculated Fluxes of Contaminants in Groundwater through the Shaft for the Severe Shaft Seal Failure Scenario (Degradation of Entire Shaft), Compared with Results for the Normal Evolution Scenario

Even if the shaft seals are only degraded in the upper shaft, greater releases occur than observed for the Normal Evolution Scenario, the peak flux being about 100 times greater. Figure 3-6 shows that this case results in later breakthrough than if the entire shaft seal system has been degraded, but the fluxes still occur much earlier than for the Normal Evolution Scenario. The peak flux occurs after about 400 ka rather than 1 Ma. (The small peak seen just after 1 Ma corresponds to the time at which the repository completely resaturates and all contaminants are completely released to groundwater.) In this case, the continuing function of the lower shaft seals acts to limit the very early releases of contaminants; however, once they have diffused through this region and reached the degraded shaft, contaminants are transported relatively rapidly to the Shallow Bedrock Groundwater Zone. Nevertheless, the function of the lower shaft is sufficient to mean that shorter-lived contaminants are retained as they decay, and different contaminants dominate for this case.

The greater fluxes to the Shallow Bedrock Groundwater Zone result in increased concentrations in groundwater, and subsequently greater releases via the hypothetical well considered for the local exposure group. Contaminant concentrations in the well are shown in Figure 3-7 for the case in which the whole shaft seal system is severely degraded. It is notable that releases to the surface are calculated to occur very much sooner than in the Normal Evolution Scenario, such that appreciable quantities of C-14 may be released before the contaminant has decayed to a significant degree. The long period of essentially constant concentrations of Cl-36 are a consequence of the congruent release mechanism used for the waste streams containing the largest amounts of Cl-36, coupled with its relatively high mobility once released. Zr-93 is also released slowly with a congruent release model, but the element is effectively sorbed, delaying its release to the shallow groundwaters.

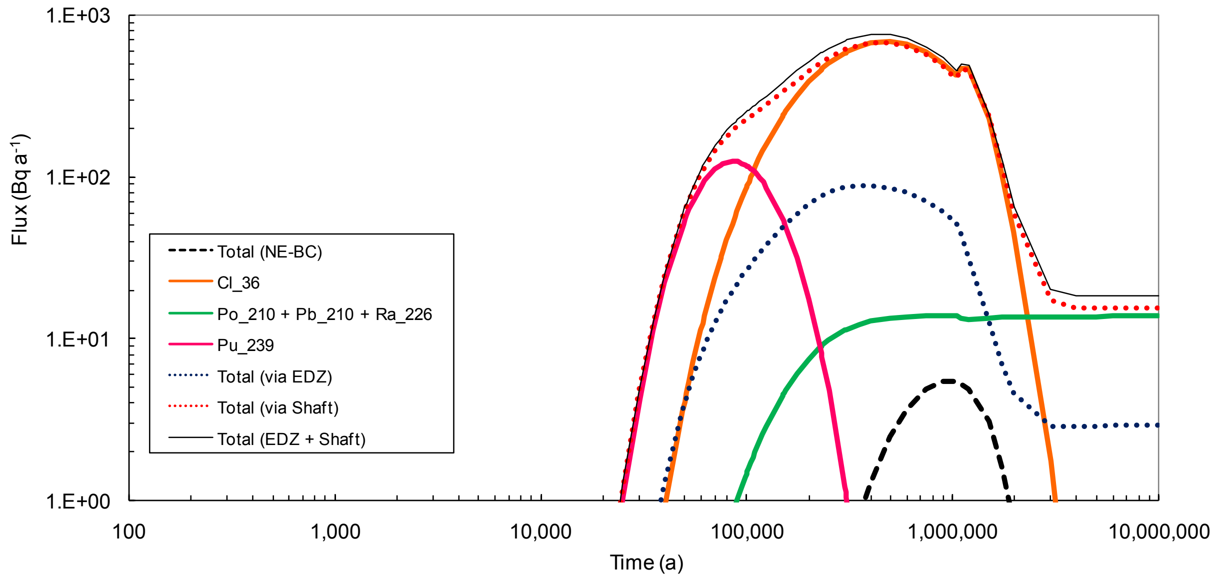

Figure 3-6: Calculated Fluxes of Contaminants in Groundwater through the Shaft for the Severe Shaft Seal Failure Scenario (Degradation of Upper Shaft Only), Compared with Results for the Normal Evolution Scenario

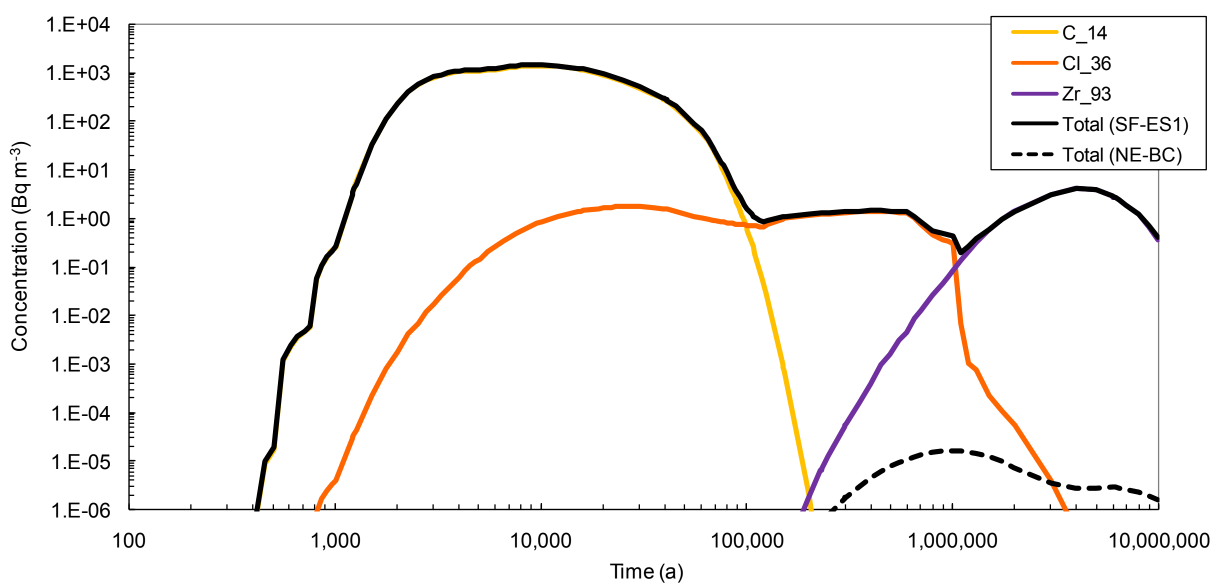

Figure 3-7: Calculated Concentration of Contaminants in Well Water, for the Severe Shaft Seal Failure Scenario (Degradation of Entire Shaft), Compared with Results for the Normal Evolution Scenario

Concentrations in soil are shown in Figure 3-8, which shows similarity with the well water concentrations, except that Cl-36 is relatively more significant and Zr-93 less so. This is due to the more effective retention of chlorine by organic soils compared with zirconium. The concentrations of radionuclides in environmental media lie well below the no-effect concentrations.

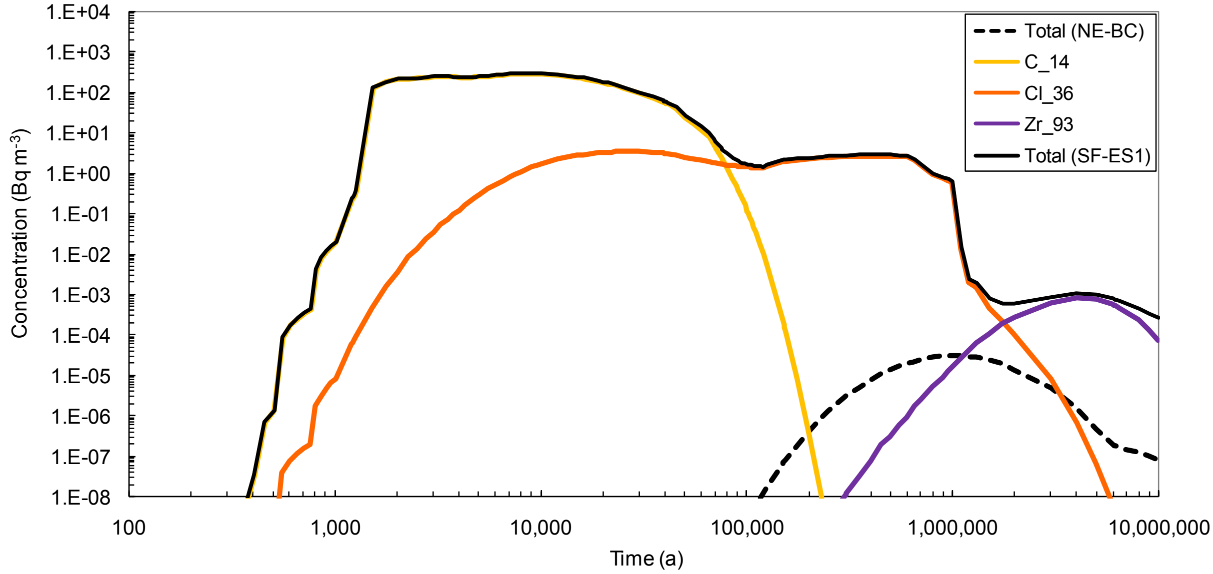

Figure 3-8: Calculated Concentration of Contaminants in Irrigated Soil, for the Severe Shaft Seal Failure Scenario (Degradation of Entire Shaft), Compared with Results for the Normal Evolution Scenario

Failure of the upper shaft only also leads to higher concentrations in water and soil than those calculated for the Normal Evolution Scenario, although the margin is considerably less than if the entire shaft system degrades. Figure 3-9 shows the concentrations are increased by about a factor of 100. The dominant radionuclides are those released into the Shallow Bedrock Groundwater Zone with the greatest fluxes.

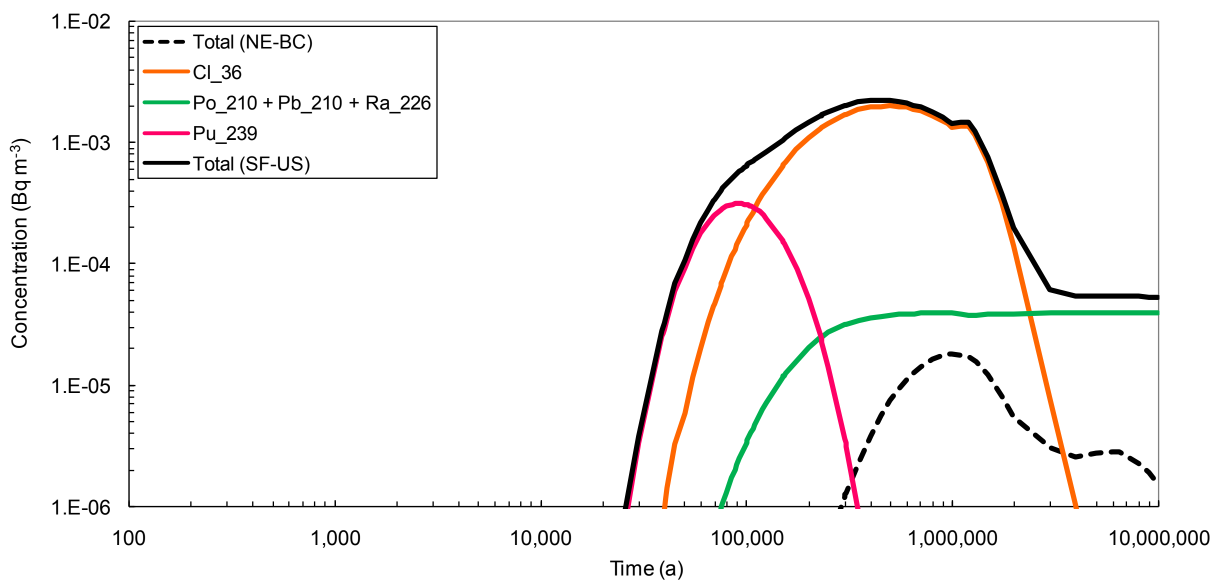

Figure 3-9: Calculated Concentration of Contaminants in Well Water, for the Severe Shaft Seal Failure Scenario (Degradation of Upper Shaft Only), Compared with Results for the Normal Evolution Scenario

The concentrations in well water of four non-radioactive species (Cd, Cr, Cu and Pb) are calculated to exceed the relevant EQS by up to a factor of 50 (Table 3-6). Contaminant concentrations in soil and sediment remain below the relevant criteria for all non-radioactive species except Cu, which marginally exceeds the EQS for sediment. However, the scenario is unlikely, and the calculation is conservative because it ignores solubility and sorption in the repository and geosphere for these elements.

Table 3-6: Ratio of Peak Calculated Concentration of Non-radioactive Species against Environmental Quality Standards for the Severe Shaft Seal Failure Scenario

Group	Species	Groundwater[1]	Soil[2]	Sediment[3]
Elements	Ag	5.3E-04	2.0E-06	1.1E-05
	As	2.3E-03	1.3E-04	1.0E-06
	B	1.2E-04	1.3E-02	-
	Ba	1.1E-03	1.6E-05	-
	Be	4.1E-03	3.1E-07	-
	Cd	**1.4E+00**	6.4E-04	1.5E-02
	Co	1.2E-02	2.1E-06	9.3E-06
	Cr	**6.3E+00**	3.3E-04	3.0E-02
	Cu	**4.9E+01**	3.1E-03	**1.2E+00**
	Hg	4.0E-02	1.8E-04	5.6E-05
	Mo	4.0E-03	2.5E-04	-
	Ni	2.1E-02	5.8E-06	6.0E-04
	Pb	**2.4E+01**	8.8E-04	6.7E-02
	Sb	1.4E-01	4.1E-04	-
	Tl	9.5E-05	1.3E-04	-
	U	5.4E-10	4.8E-12	-
	V	2.1E-02	1.5E-06	-
	Zn	6.3E-02	7.0E-06	2.9E-03
Organic Species	Chlorobenzenes and Chlorophenols	5.3E-02	2.6E-05	4.6E-03
	Dioxins and Furans	5.3E-01	5.5E-04	-
	PAH	2.1E-03	2.1E-06	1.7E-04
	PCB	1.0E-04	4.8E-08	4.9E-05

Notes:
1 Well water abstracted from the Shallow Bedrock Groundwater Zone.
2 Cropped soil, which receives potentially contaminated irrigation water.
3 Sediment associated with surface water (concentrations are highest in the Lake Shore sediment).

3.5.2 Calculated Radiation Doses

The degradation of the entire shaft seal results in calculated doses to the local exposure group that are more than seven orders of magnitude higher than calculated for the Normal Evolution Scenario. The peak value reaches 0.02 mSv a^{-1} after 10 ka for adults (Figure 3-10). The peak at 10 ka corresponds to the inhalation of C-14 gas that has volatilised from groundwater in the Shallow Bedrock Groundwater Zone that has been contaminated by releases via the shaft. (Detailed calculations indicate that any gas released via the shafts will be dissolved in groundwater on reaching the Shallow Bedrock Groundwater Zone.) The largely constant dose beyond 100 ka relates to progeny in the U-238 decay chain (primarily Po-210).

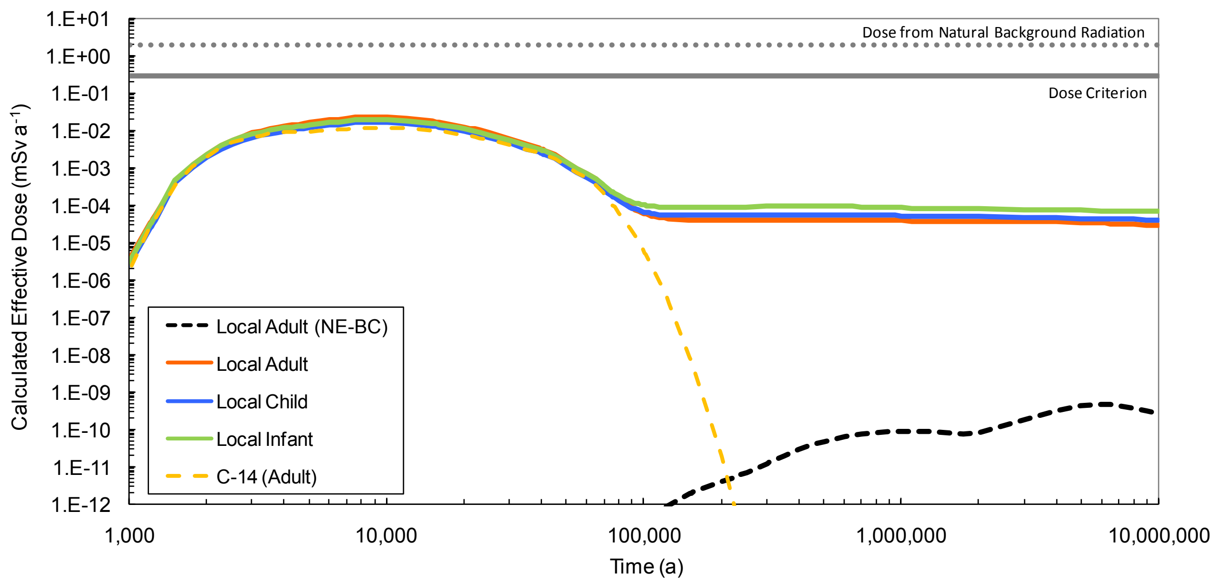

Figure 3-10: Calculated Effective Doses to the Local Exposure Group for the Severe Shaft Seal Failure Scenario (Degradation of the Entire Shaft) and Normal Evolution Scenario (NES)

The key contaminants are shown in Figure 3-11. In addition to C-14, isotopes of plutonium, and decay products in the U-238 chain, most significantly Po-210, are most important in relation to human exposure (in contrast with the Normal Evolution Scenario). This is because the shaft seal failure permits these shorter-lived and comparatively radiotoxic contaminants to reach the surface environment well within the assessment timeframe (and before radioactive decay has reduced concentrations substantially). These contaminants are also sorbed in soil. As a result, these radionuclides are present in the surface environment on a timescale at which they are significant, and hence result in the increased doses compared with the Normal Evolution Scenario.

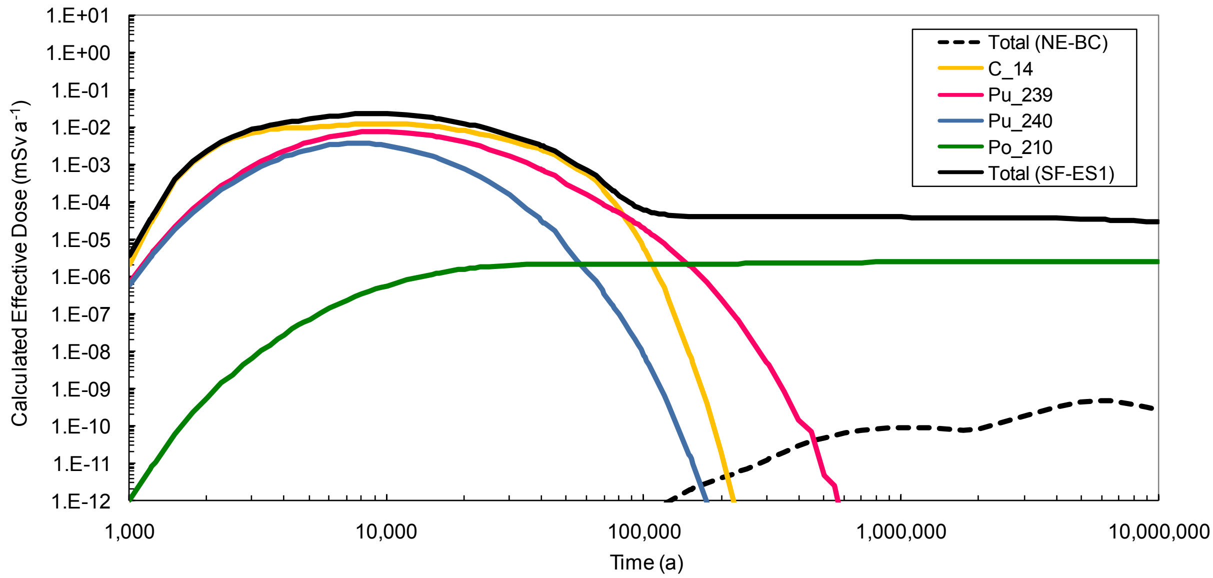

Figure 3-11: Severe Shaft Seal Failure Scenario (Degradation of the Entire Shaft): Dominant Contaminants in the Calculated Exposure of an Adult Member of the Local Exposure Group

Degradation of the upper shaft only results in much smaller changes compared with the Normal Evolution Scenario, although the peak dose is still increased by more than 200 times to 1.6×10^{-7} mSv a^{-1}, peaking at 650 ka (Figure 3-12). However, this level of dose is more than six orders of magnitude below the criterion. The peak doses are associated with U-238 series progeny (e.g., Ra-226, Pb-210 and Po-210).

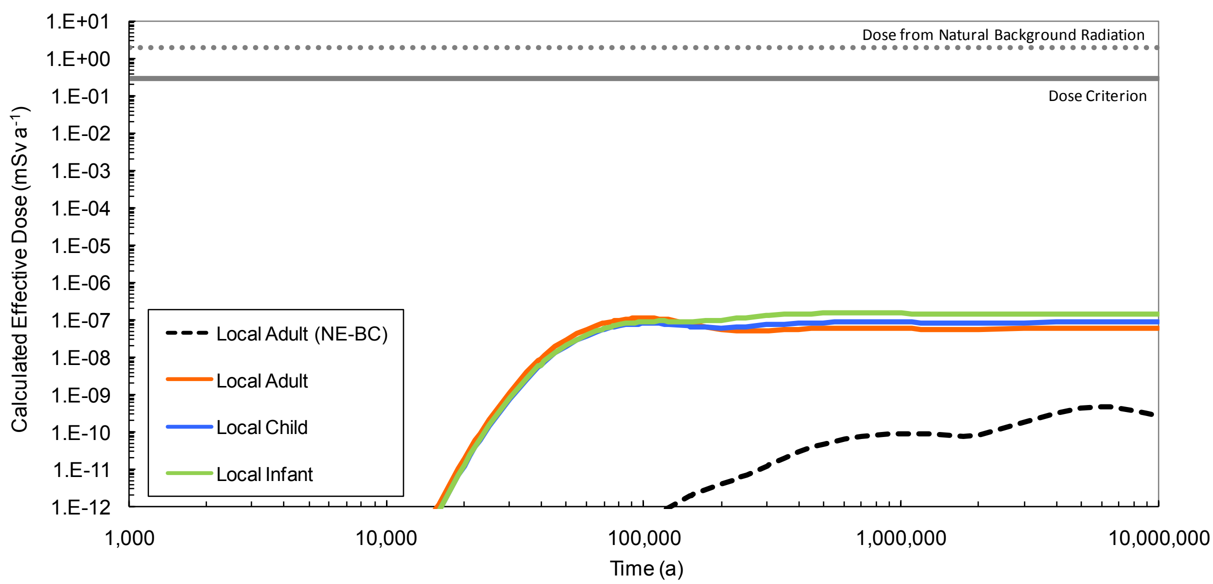

Figure 3-12: Calculated Effective Doses to the Local Exposure Group for the Severe Shaft Seal Failure Scenario (Degradation of the Upper Shaft Only) and Normal Evolution Scenario (NES)

The results demonstrate the importance of the shaft seal in the overall performance of the DGR system. However, even with the extreme assumptions concerning the performance of the seals, the calculated doses remain below the criteria that are applied to the Disruptive Scenarios. This outcome demonstrates the robustness of the DGR system.

3.5.3 Likelihood

The Shaft Seal Failure Scenario represents an extremely conservative assessment of the performance of the repository. It is not possible to gauge the likelihood of the scenario in any meaningful way.

The representation of the shaft is deliberately speculative and assumes the failure of future societies to properly close the DGR. Such a situation is on the limits of plausibility, and the scenario is considered as a “what if” calculation. It is intended to test the robustness of the system and determine the bounds of performance of the DGR. In these terms, the results presented in Sections 3.5.1 and 3.5.2 show that even with severely degraded shaft seals, the calculated doses for the DGR system are below the safety criteria that are applied to the Disruptive Scenarios, demonstrating its robustness.

Although the Shaft Seal Failure Scenario is initially derived from consideration of future human actions, it also illustrates the consequences of unexpectedly poor performance of the Shaft Seal as a result of other factors. This could include, for example, a change in geochemical conditions that may cause more rapid degradation of materials than are anticipated in the Normal Evolution Scenario.

4. OPEN BOREHOLE SCENARIO

4.1 SCENARIO OVERVIEW

A third scenario in which the DGR containment barrier might be breached is through a site investigation/monitoring borehole in the vicinity of the repository not being properly sealed (Little et al. 2009).

The DGR site will have several deep boreholes around the repository, used for site characterisation initially and for monitoring during and after operation. These boreholes will not intersect the repository itself, but will be some distance away. 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 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 the 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**. In common with the Severe Shaft Seal Scenario, it is difficult to assign a probability to the Open Borehole Scenario. However, as noted, it would be expected to be very unlikely.

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 geological barrier to contaminant migration from the DGR. The subsequent exposure pathways and groups are the same as those considered in the Normal Evolution Scenario (Walke et al. 2009a).

The scenario is illustrated in Figure 4-1.

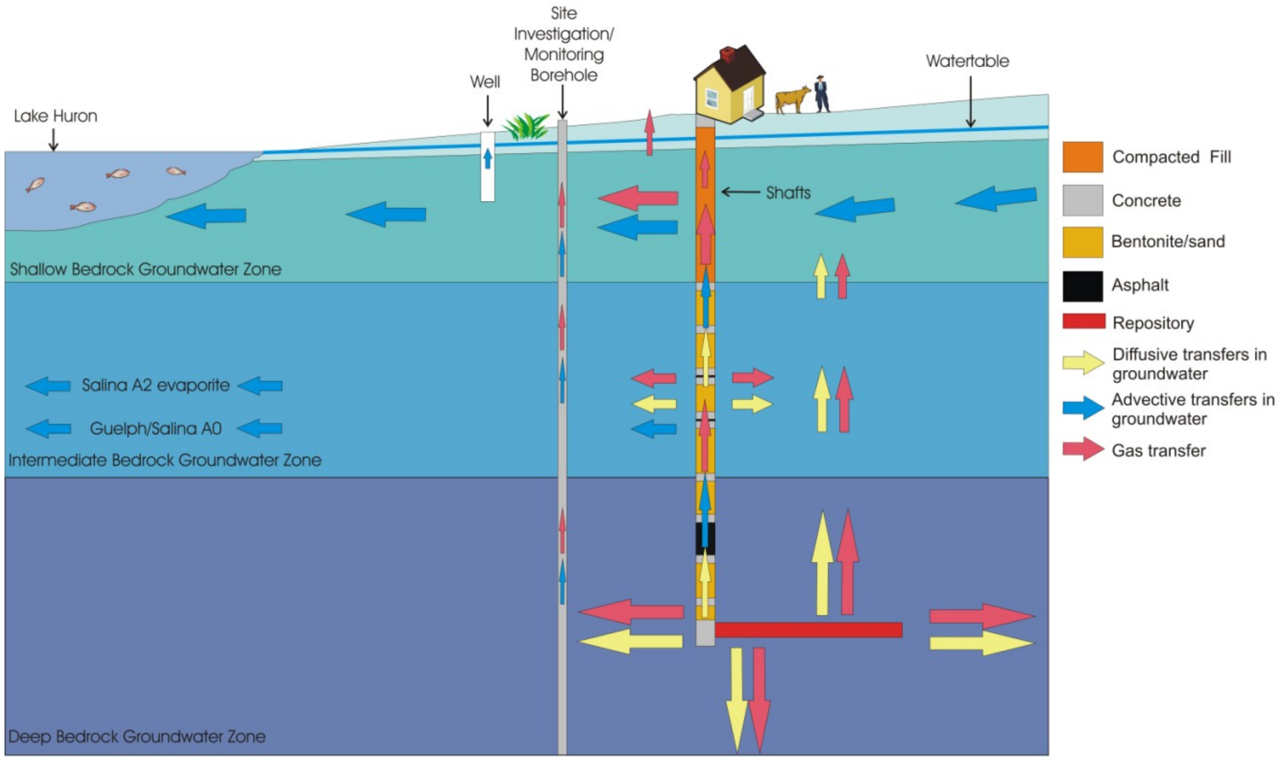

Figure 4-1: Open Borehole Scenario

4.2 CONCEPTUAL MODEL

4.2.1 Key Features, Processes and Events

The internal features, processes and events considered for the Borehole Scenario are the same as for the Normal Evolution Scenario (as described in the Normal Evolution Scenario Analysis report, Walke et al. 2009a) with the exception that the DGR-3 site investigation borehole is poorly sealed. The borehole provides an enhanced permeability connection between the geosphere in the vicinity of the repository, the overlying groundwater zones and the biosphere. (DGR-3 was selected as it was the closest of the existing and planned boreholes to the repository footprint.)

The key features are summarised in Table 4-1 and the key processes and events in Table 4-2.

Table 4-1: Summary of Key Features for the Open Borehole Scenario

Waste and Repository Features	Geosphere Features	Biosphere Features
• Wasteforms (22 types) • Water (South Panel (LLW) emplacement rooms, East Panel (ILW and some LLW) emplacement rooms, and access/ring tunnels) • Gas (South Panel (LLW) emplacement rooms, East Panel (ILW and some LLW) emplacement rooms, and access/ring tunnels) • Engineered Structures (sealing walls, concrete monoliths, and shaft seals and backfill) • Poorly sealed borehole	• Excavation Damaged Zone • Deep Bedrock Groundwater Zone • Intermediate Bedrock Groundwater Zone • Shallow Bedrock Groundwater Zone	• Well Water • Surface Water (stream and wetland) • Surface Water Sediment (stream and wetland) • Lake Water • Lake Sediment • Soil • Biota • Houses and Buildings • Atmosphere

Table 4-2: Summary of Key Processes and Events for the Open Borehole Scenario

Processes Internal to Features	Processes Resulting in Transport of Contaminants between Features	Events and Processes Changing Features with Time
• Decay of contaminants • Degradation of contaminants • Gas generation • Sorption • Elemental solubility • Chemical effects that result in changes to the properties of engineered materials • Radiation dosimetry	• Gas release from saturated and unsaturated wasteforms • Gas transport in the repository, geosphere and biosphere. • Gas dissolution in water • Gas volatilisation • Resaturation of the repository • Aqueous release from the saturated wasteform types (instant release, delayed instant release, congruent release and diffusive release) • Groundwater transport (advection, dispersion and diffusion) • Surface water transport • Infiltration • Interflow • Bioturbation • Resuspension and sedimentation • Erosion and deposition • Water pumping • Uptake by biota • Human ingestion, inhalation, external irradiation and dermal adsorption of contaminated media	• Physical and chemical degradation of wasteforms • Physical and chemical degradation of engineered structures and backfill on closure • Climate change due to glacial/interglacial cycling • Land use change

4.2.2 Description of the Conceptual Model

The conceptual model is the same as for the Normal Evolution Scenario (as described in the Normal Evolution Scenario Analysis report, Walke et al. 2009a) 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. However, Avis et al. (2009) show that the flow rates from the repository horizontally towards the borehole 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 aspects of the conceptual model for releases from the repository are summarised in Box 3.

Box 3:
Key Aspects of the Conceptual Model for the Open Borehole 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).
- Consideration of sorption of some contaminants (C, Zr, Ni, Nb, U and Np) on concrete monoliths, and solubility limitation for C and U only, consistent with the Normal Evolution Scenario (Walke et al. 2009a).
- Contaminants released into water via instant, diffusive and congruent release processes, consistent with the Normal Evolution Scenario (Walke et al. 2009a).
- 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, consistent with the Normal Evolution Scenario (Walke et al. 2009a).
- Resaturation profile consistent with the instantaneous resaturation case of the Normal Evolution Scenario (Walke et al. 2009a) (i.e., completely saturated from closure onwards). This is chosen conservatively to maximise the release of contaminants into groundwater that may subsequently migrate via the borehole.
- Contaminants in water migrate into the host rock and shafts by diffusion and advection (driven by the pressure head in the Cambrian)[12].
- Rockfall occurs progressively until a stable equilibrium is reached, consistent with the Normal Evolution Scenario (Walke et al. 2009a).

Geosphere and Shafts:

- Poorly sealed site investigation/monitoring borehole located 400 m from western edge of South Panel. Borehole extends from surface down to Pre-Cambrian.
- Groundwater flow in the Deep and Intermediate Bedrock Groundwater Zones is upwards since the measured +140 m hydraulic head in the Cambrian sandstone is conservatively assumed to support indefinitely a steady-state vertical upwards hydraulic gradient and the observed underpressures in the Ordovician are assumed quickly dissipated (consistent with the Normal Evolution Scenario, Walke et al. 2009a)[12].
- Groundwater flow in the Guelph, Salina A0 and Salina A2 evaporite Formations is horizontal[12].
- Groundwater flow in the Shallow Bedrock Groundwater Zone is horizontal towards Lake Huron[12].
- Contaminants in groundwater migrate through the geosphere, shafts and along the borehole by diffusion and advection[12].
- Sorption of some contaminants (C, Zr, Ni, Nb, U and Np) is considered in the geosphere and shafts.

Biosphere:

- 300 year site control period (see postclosure SA main report, Quintessa et al. 2009).
- Constant temperate climate conditions (consistent with the base case calculations for the Normal Evolution Scenario, Walke et al. 2009a).
- Groundwater is pumped from a shallow well for domestic and farming use, including irrigation (consistent with the Normal Evolution Scenario, Walke et al. 2009a).
- 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 (consistent with the Normal Evolution Scenario, Walke et al. 2009a).
- Possible release of gaseous contaminants into biosphere via shafts and geosphere to house and soil due to volatilisation from groundwater with subsequent atmospheric dispersion of gas.
- Surface media become contaminated following release of contaminants via shafts, well and groundwater discharge to lake.
- Potential impacts estimated based on assuming a self-sufficient family farm located on the repository site and using groundwater from well and lake (consistent with the Normal Evolution Scenario, Walke et al. 2009a).

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

4.2.3 FEP Audit

As noted in Section 4.2.2, the conceptual model for the Open Borehole Scenario is broadly the same as the Normal Evolution Scenario (as described in the Normal Evolution Scenario analysis report, Walke et al. 2009a) with only differences relating to presence of the poorly sealed site investigation/monitoring borehole. The borehole can be seen to be part of the Engineered System and can be treated in a similar manner to the shaft. Therefore, the only internal FEPs that differ are:

- FEP 2.1.05 (Shaft characteristics) – the borehole is poorly backfill when it is closed; and
- FEP 2.1.07 (Hydraulic/hydrogeological processes and conditions in shafts) – enhanced water and gas flow from the time of closure due to poor sealing of borehole.

4.2.4 Key Conceptual Model Uncertainties

Since the Open Borehole Scenario and the Normal Evolution Scenario have essentially the same conceptual models, the conceptual model uncertainties are also the same. These are discussed in the Normal Evolution Scenario analysis report (Walke et al. 2009a) and so are not replicated here. One of the motivations behind considering the Open Borehole Scenario is specifically to examine the effects of uncertainties relating to the performance of the site investigation/monitoring borehole seals. The scenario investigates these uncertainties by considering an extreme (‘what if’) treatment of the performance of the borehole sealing material.

4.3 CALCULATION CASES

Two calculation cases can be identified from consideration of the conceptual model developed in Section 4.2 that consider the release of radioactive and non-radioactive contaminants (Table 4-3).

Table 4-3: Calculation Cases for the Open Borehole Scenario

Case ID	Brief Description	Associated Detailed Modelling Cases
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.	-

Notes:
OB – Open Borehole Scenario; NE- Normal Evolution Scenario; RS1 – instant repository resaturation variant; NR – non-radioactive contaminants; BC - base case; A – AMBER; F3 – FRAC3DVS 3DS model

Given the commonality of many aspects of the conceptual model with that developed for the Normal Evolution Scenario, calculation cases identified above have been derived with reference to those considered in the instant resaturation case for the Normal Evolution Scenario (see the

Normal Evolution Scenario Analysis report, Walke et al. 2009a, for more details). This is chosen conservatively to maximise the release of contaminants into groundwater that may subsequently migrate via the borehole. The only modification for the OB-BC-A and OB-NR-A cases is the introduction of the poorly sealed borehole that provides an enhanced permeability connection between the level of the repository, the overlying groundwater zones and the biosphere.

4.4 MATHEMATICAL MODELS, SOFTWARE IMPLEMENTATION AND DATA

4.4.1 Mathematical Models

The Open Borehole Scenario adopts the same general mathematical models as the Normal Evolution Scenario. The models used are described in detail in Section 4.1 of the Normal Evolution Scenario Analysis report (Walke et al. 2009a). The exception is the incorporation of a specific pathway to represent the more rapid transport of contaminants in the borehole.

4.4.2 Software Implementation

The scenario is implemented in AMBER Version 5.2 (Enviros and Quintessa 2008a, b). The scenario can be selected by defining model run settings with a scenario-dependent parameter, taking a value of 1 when the scenario is to be considered, and 0 otherwise.

The release of contaminated water to the Shallow Bedrock Groundwater Zone via the borehole is represented with a transfer derived from the results of FRAC3DVS code (see below) between the compartments that represent the Deep Bedrock Groundwater and the Shallow Bedrock Groundwater Zones. This transfer provides a “short-cut” for contaminant releases to the Shallow Bedrock Groundwater Zone. The approach is similar to that adopted for the groundwater release calculation case for the Human Intrusion scenario (see Section 2.4). All other aspects of the model are identical to the Normal Evolution Scenario (including dose calculations for the local exposure group).

A T2GGM model has not been developed for the Open Borehole Scenario. This is because the representation of the scenario would require the development of 3D model and so cannot be represent in the 2D radial gas transport model that has been developed for the current assessment (Calder et al. 2009). Due to the absence of T2GGM results, the AMBER model does not consider the impact of the borehole on gas transport. Nevertheless, it is expected the impacts would be several orders of magnitude less than those associated with the Severe Shaft Failure Scenario presented in Section 3 due to the additional 400 m lateral travel distance for gas through the geosphere to the borehole and the significantly smaller diameter.

4.4.3 Data

The borehole is located 400 m from the western edge of the South Panel. The rate of transfer of contaminated water from the Deep to the Shallow Bedrock Groundwater Zones via a borehole has been calculated by detailed groundwater release analysis. The method used to determine the transfer rate up the intrusion borehole (see Section 2.4.3) cannot be used in this instance. This is because the Cl-36 flux calculated by FRAC3DVS represents the flux along the whole pathway from the repository to the Shallow Bedrock Groundwater Zone and Salina A2 evaporite. The value required for the model is just related to the flow up the borehole itself. Consequently, the approach used has been to use the calculated volumetric flow rates through the borehole to the key points of release. The FRAC3DVS results indicate a total flow rate from the repository horizon via the borehole of 17.5 m^3 a^{-1}, with:

- 10 m^3 a^{-1} discharging to the Salina A2 evaporite; and
- 7.5 m^3 a^{-1} discharging to the Salina F.

This approach takes into account the poorly sealed nature of the borehole (the borehole is assumed to have a hydraulic conductivity of 10^{-4} m s^{-1}). It cautiously ignores the sorption of radionuclides on the sealing material. The pathway is taken to be active immediately after closure of the repository.

All other data considered for the calculations, including the description of potential exposure group, are the same as the base case for the Normal Evolution Scenario documented in the Data report (Walke et al. 2009b).

4.5 RESULTS

4.5.1 Release of Contaminants via the Open Borehole

The poorly sealed borehole provides an additional pathway for contaminants from the rock in the vicinity of the repository to be transported to the Shallow Bedrock Groundwater Zone. Although the fluxes of water are relatively small (17.5 m^3 a^{-1} via the borehole), they are not insignificant in the context of the transport of contaminants through the DGR geosphere. However, the calculated fluxes via the borehole are substantially lower than the flux that occurs via the shaft and geosphere for the case where no poorly sealed borehole is present, as can be seen from Figure 4-2. The initial peak, at 1 Ma, relates to Cl-36, whilst I-129 is dominant for times after 4 Ma.

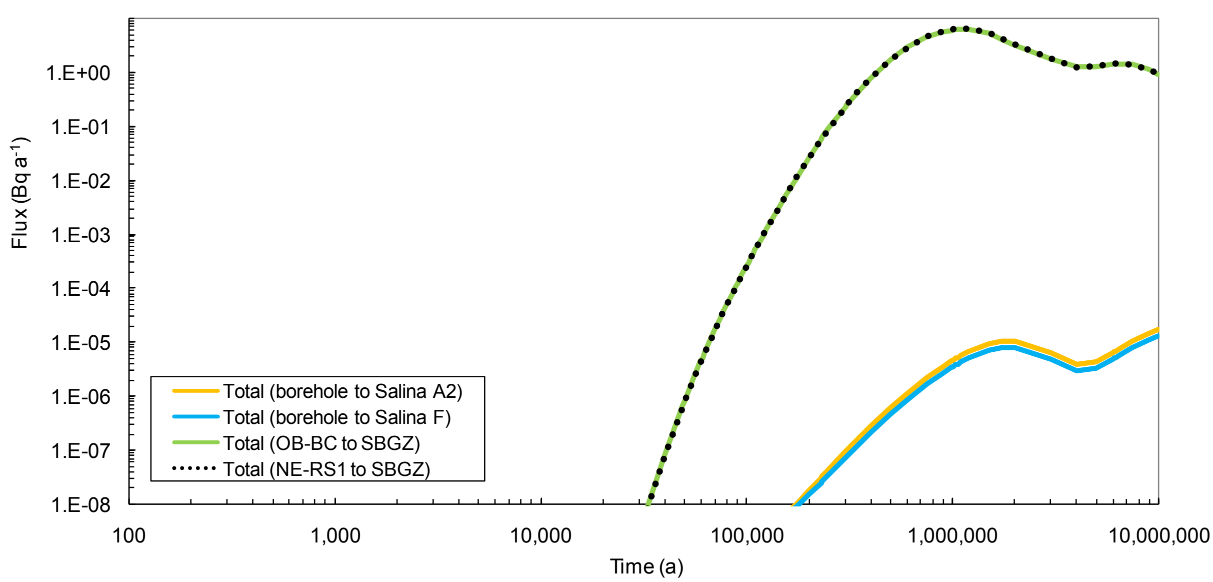

Figure 4-2: Calculated Fluxes of Contaminants in the Borehole, Compared with the total Flux into the Shallow Bedrock Groundwater Zone for the Normal Evolution Scenario

The results illustrate that the enhanced permeability pathway has limited influence on the overall performance of the DGR system. This is because contaminants must diffuse through 400 m of the very low permeability host rocks around the DGR before the borehole is reached. This is not greatly less than the distance over which contaminants are transported vertically upwards in the geosphere and shaft. The permeability is sufficiently low that only a very small advective flow is set up as a result of the head gradient. In addition, the geometry of the system is such that only a small effective area of the south panel is involved in transport towards the borehole.

Because the fluxes to the Shallow Bedrock Groundwater Zone are dominated by transport through the shaft and geosphere, the resultant concentrations in media that could expose people are not affected by the presence of the poorly sealed borehole. The calculations for the open borehole case show the results to be only 0.01% different at the time of the peak concentration in well water (2 x 10^{-5} Bq m^{-3} after 1.1 Ma). The concentrations of non-radioactive contaminants in well water, soil and sediment are well below the relevant EQS (Table 4-4) and the concentrations of radionuclides in environmental media lie well below the no-effect concentrations.

Table 4-4: Ratio of Peak Calculated Concentration of Non-radioactive Species against Environmental Quality Standards for the Open Borehole Scenario

Group	Species	Groundwater[1]	Soil[2]	Sediment[3]
Elements	Ag	2.9E-07	1.1E-09	1.3E-08
	As	1.1E-06	6.2E-08	1.0E-09
	B	5.8E-08	6.2E-06	-
	Ba	5.6E-07	8.2E-09	-
	Be	1.8E-06	1.3E-10	-
	Cd	7.1E-04	3.2E-07	1.5E-05
	Co	5.8E-06	1.0E-09	9.2E-09
	Cr	3.0E-03	1.6E-07	2.9E-05
	Cu	2.4E-02	1.5E-06	1.2E-03
	Hg	2.0E-05	8.8E-08	5.7E-08
	Mo	1.9E-06	1.2E-07	-
	Ni	7.0E-22	1.9E-25	3.8E-21
	Pb	1.2E-02	4.4E-07	6.8E-05
	Sb	6.8E-05	2.0E-07	-
	Tl	4.5E-08	6.3E-08	-
	U	1.0E-33	1.3E-35	-
	V	9.9E-06	7.2E-10	-
	Zn	3.1E-05	3.5E-09	2.9E-06
Organic Species	Chlorobenzenes and Chlorophenols	2.7E-05	1.3E-08	4.6E-06
	Dioxins and Furans	2.6E-04	2.7E-07	-
	PAH	1.1E-06	1.0E-09	1.7E-07
	PCB	5.0E-08	2.4E-11	5.0E-08

Notes:
1 Well water abstracted from the Shallow Bedrock Groundwater Zone.
2 Cropped soil, which receives potentially contaminated irrigation water.
3 Sediment associated with surface water (concentrations are highest in the Lake Shore sediment).

4.5.2 Calculated Radiation Doses

The calculated radiation doses for the Open Borehole scenario do not differ to any significant degree from those calculated with the equivalent Normal Evolution Scenario case, as the fluxes in both cases are dominated by transport through the geosphere and shaft. Figure 4-3 demonstrates that the results are unaffected by the presence of a poorly sealed borehole. The peak dose remains at 6.5 x 10^{-10} mSv a^{-1} at 6.5 Ma.

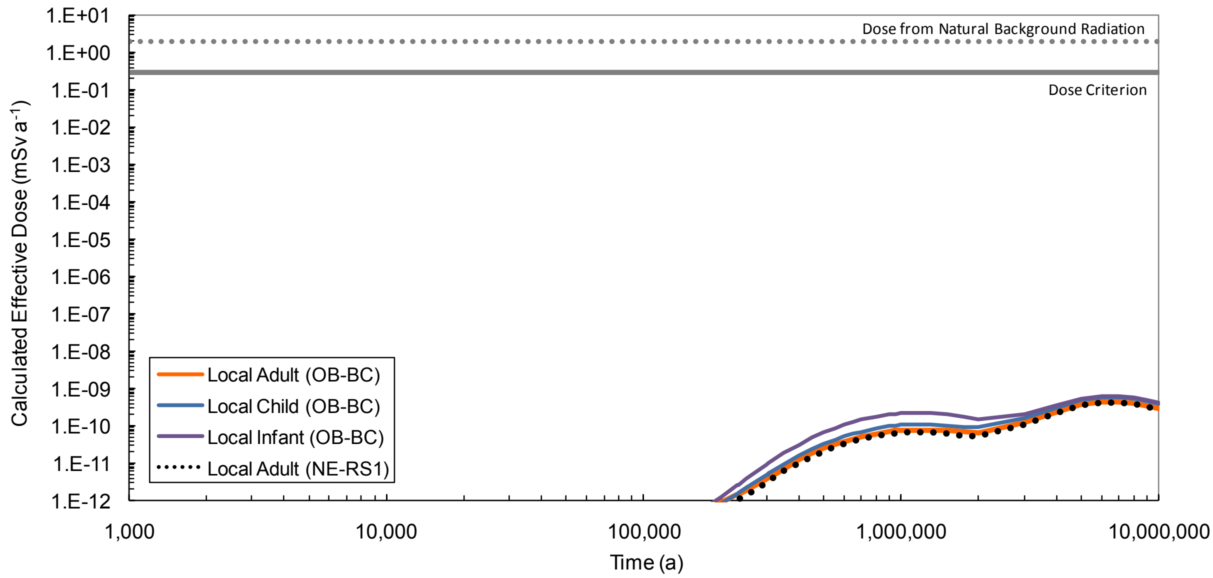

Figure 4-3: Calculated Effective Doses to the Local Exposure Group for the Open Borehole Scenario and Normal Evolution Scenario (NES)

4.5.3 Likelihood

The Open Borehole scenario is deliberately speculative and assumes the failure of future societies to properly seal a borehole close to the DGR. Such a situation is on the limits of plausibility. The “what if” calculation is primarily intended to test the robustness of the system and determine the bounds of performance of the DGR. The results show that the presence of such a feature does not affect in any significant way the performance of the system. This is because the very low permeability of the host rocks limits the influence of the low head introduced by the borehole. Specifically, in order to reach the borehole, and a fast route to the Shallow Bedrock Groundwater System, contaminants must diffuse similar distance to that taken through rock mass when diffusing vertically upwards.

5. EXTREME EARTHQUAKE SCENARIO

5.1 SCENARIO OVERVIEW

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[13] **M** ≥ 6 may occur, even though its annual probability of occurrence within a 20 km radius of the DGR is around 10^{-6} (Atkinson 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 (Little et al. 2009). Because the event 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**.

The evolution of the system is similar to the Normal Evolution Scenario, except that the earthquake with a moment magnitude of **M** ≥ 6 occurs in the region around the Bruce site at some time following the closure of the repository. The potential impact on the failure of the shaft seals is bounded by 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. Therefore the combination of a large earthquake near the site, the existence of an undetected closed fault, and its reactivation due to the earthquake, is very unlikely. Nevertheless, the Extreme Earthquake Scenario considers the hypothetical case of “what if” there is a vertical fault in the vicinity of the repository, and that it 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.

The scenario is illustrated in Figure 5-1.

[13] 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).

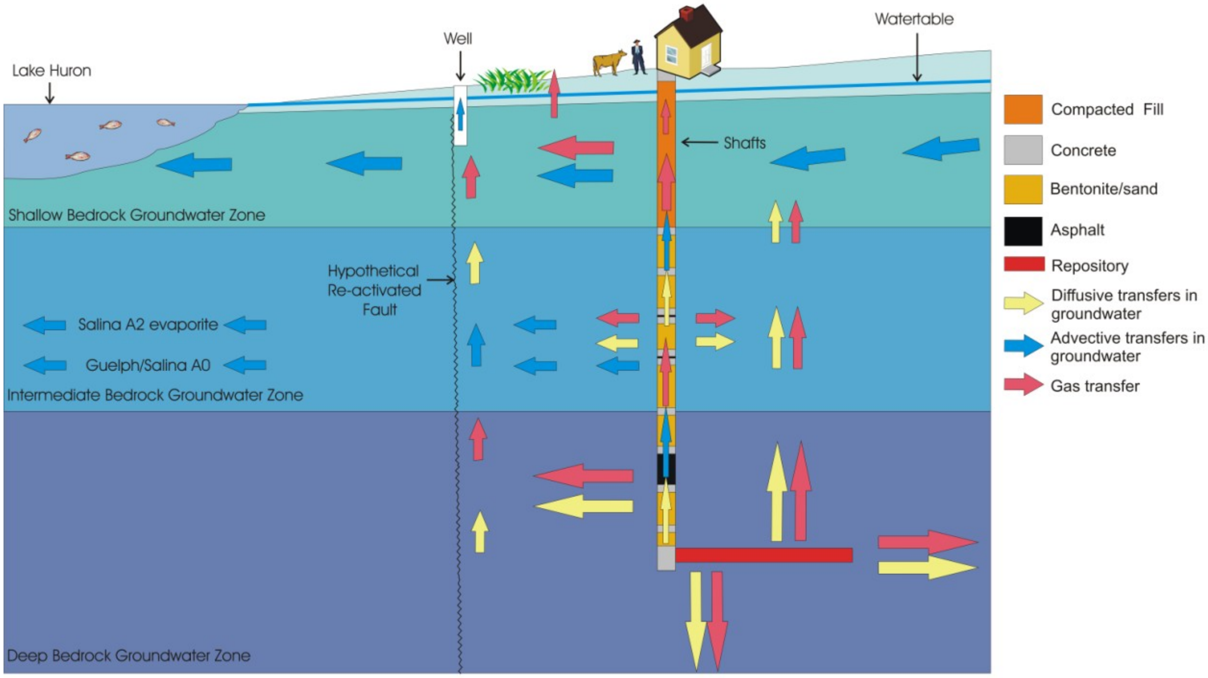

Figure 5-1: Extreme Earthquake Scenario

5.2 CONCEPTUAL MODEL

5.2.1 Key Features, Processes and Events

The internal features, processes and events considered for the Extreme Earthquake Scenario are the same as for the Normal Evolution Scenario (as described in the Normal Evolution Scenario Analysis report, Walke et al. 2009a) with the exception that a hypothetical fault down gradient of the repository, which extends from the Cambrian into the Shallow Bedrock Groundwater Zone, is reactivated by a high magnitude earthquake. The key features are summarised in Table 5-1 and the key processes and events in Table 5-2.

Table 5-1: Summary of Key Features for the Extreme Earthquake Scenario

Waste and Repository Features	Geosphere Features	Biosphere Features
• Wasteforms (22 types) • Water (South Panel (LLW) emplacement rooms, East Panel (ILW and some LLW) emplacement rooms, and access/ring tunnels) • Gas (South Panel (LLW) emplacement rooms, East Panel (ILW and some LLW) emplacement rooms, and access/ring tunnels) • Engineered Structures (sealing walls, concrete monoliths, and shaft seals and backfill)	• Excavation Damaged Zone • Deep Bedrock Groundwater Zone • Intermediate Bedrock Groundwater Zone • Shallow Bedrock Groundwater Zone • Reactivated Fault	• Well Water • Surface Water (stream and wetland) • Surface Water Sediment (stream and wetland) • Lake Water • Lake Sediment • Soil • Biota • Houses and Buildings • Atmosphere

Table 5-2: Summary of Key Processes and Events for the Extreme Earthquake Scenario

Processes Internal to Features	Processes Resulting in Transport of Contaminants between Features	Events and Processes Changing Features with Time
• Decay of contaminants • Degradation of contaminants • Gas generation • Sorption • Elemental solubility • Chemical effects that result in changes to the properties of engineered materials • Radiation dosimetry	• Gas release from saturated and unsaturated wasteforms • Gas transport in the repository, geosphere and biosphere. • Gas dissolution in water • Gas volatilisation • Resaturation of the repository • Aqueous release from the saturated wasteform types (instant release, delayed instant release, congruent release and diffusive release) • Groundwater transport (advection, dispersion and diffusion) • Reactivation of fault due to extreme earthquake • Surface water transport • Infiltration • Interflow • Bioturbation • Resuspension and sedimentation • Erosion and deposition • Water pumping • Uptake by biota • Human ingestion, inhalation, external irradiation and dermal adsorption of contaminated media	• Physical and chemical degradation of wasteforms • Physical and chemical degradation of engineered structures and backfill, especially the concrete monoliths and shaft seals and backfill • Climate change due to glacial/interglacial cycling • Land use change

5.2.2 Description of the Conceptual Model

The conceptual model is the same as for the Normal Evolution Scenario (as described in the Normal Evolution Scenario Analysis report, Walke et al. 2009a), since the status of the FEPs is broadly the same. The only difference is that, due to the activation 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 aspects of the conceptual model for releases from the repository are summarised in Box 4. In the conceptual model, the Cambrian overpressured hydraulic head is assumed to be unaffected, despite being connected by a permeable path to the surface.

5.2.3 FEP Audit

The conceptual model for the Extreme Earthquake Scenario is broadly the same as the Normal Evolution Scenario (as described in the Normal Evolution Scenario analysis report, Walke et al. 2009a) with only differences relating to the hypothetical fault and its reactivation. Thus, only two internal FEPs differ, both of which relate to the fault:

- FEP 2.2.04.01 (Large-scale discontinuities (in geosphere): faults and shear zones) – the vertical fault is reactivated by extreme earthquake at closure; and
- FEP 2.2.12 (Undetected features in geosphere) – a vertical fault is present that is not detected during site characterisation.

5.2.4 Key Conceptual Model Uncertainties

There are various uncertainties associated with the Extreme Earthquake Scenario, additional to those associated with the Normal Evolution Scenario (discussed in the Normal Evolution Scenario Analysis report, Walke et al. 2009a). These relate to the likelihood and impacts of extreme earthquakes on the DGR system, especially in terms of repository room/tunnel stability and shaft/geosphere integrity. To demonstrate the robustness of the DGR, a cautious approach has been taken that includes pessimistic assumptions to assess the potential impacts of an extreme earthquake on repository safety.

Box 4:
Key Aspects of the Conceptual Model for the Extreme Earthquake 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).
- Consideration of sorption of some contaminants (C, Zr, Ni, Nb, U and Np) on concrete monoliths, and solubility limitation for C and U only, consistent with the Normal Evolution Scenario (Walke et al. 2009a).
- Contaminants released into water via instant, diffusive and congruent release processes, consistent with the Normal Evolution Scenario (Walke et al. 2009a).
- 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, consistent with the Normal Evolution Scenario (Walke et al. 2009a).
- Resaturation profile consistent with the instantaneous resaturation case of the Normal Evolution Scenario (Walke et al. 2009a) (i.e., completely saturated from closure onwards). This is chosen conservatively to maximise the release of contaminants into groundwater that may subsequently migrate via the fault.
- Contaminants in water migrate into the host rock and shafts by diffusion and advection (driven by the pressure head in the Cambrian)[14].
- Rockfall occurs progressively until a stable equilibrium is reached, consistent with the Normal Evolution Scenario (Walke et al. 2009a).

Geosphere and Shafts:

- Hypothetical vertical fault reactivated at repository closure by extreme earthquake. Fault extends from Cambrian to Shallow Bedrock Groundwater Zone.
- Groundwater flow in the Deep and Intermediate Bedrock Groundwater Zones is upwards since the measured +140 m hydraulic head in the Cambrian sandstone is conservatively assumed to support indefinitely a steady-state vertical upwards hydraulic gradient and the observed underpressures in the Ordovician are assumed quickly dissipated (consistent with the Normal Evolution Scenario, Walke et al. 2009a)[14].
- Groundwater flow in the Guelph, Salina A0 and Salina A2 evaporite Formations is horizontal[14].
- Groundwater flow in the Shallow Bedrock Groundwater Zone is horizontal towards Lake Huron[14].
- Contaminants in groundwater migrate through the geosphere, shafts and along the fault by diffusion and advection[14].
- Sorption of some contaminants (C, Zr, Ni, Nb, U and Np) is considered in the shafts and geosphere (including the fault).

Biosphere:

- 300 year site control period (see postclosure SA main report, Quintessa et al. 2009).
- Constant temperate climate conditions (consistent with the base case calculations for the Normal Evolution Scenario, Walke et al. 2009a).
- Groundwater is pumped from a shallow well for domestic and farming use, including irrigation (consistent with the Normal Evolution Scenario, Walke et al. 2009a).
- 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 (consistent with the Normal Evolution Scenario, Walke et al. 2009a).
- Possible release of gaseous contaminants into biosphere via shafts and geosphere to house and soil due to volatilisation from groundwater with subsequent atmospheric dispersion of gas.
- Surface media become contaminated following release of contaminants via shafts, well and groundwater discharge to lake.
- Potential impacts estimated based on assuming a self-sufficient family farm located on the repository site and using groundwater from well and lake (consistent with the Normal Evolution Scenario, Walke et al. 2009a).

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

5.3 CALCULATION CASES

Two calculation cases can be identified from consideration of the conceptual model developed in Section 5.2 that considers the release of contaminants in groundwater (Table 5-3).

Given the commonality of many aspects of the conceptual model with the model developed for the Normal Evolution Scenario, the calculation case has been derived with reference to the base case for the Normal Evolution Scenario (see the Normal Evolution Scenario Analysis report, Walke et al. 2009a, for more details). The only modification is that a hypothetical reactivated fault is positioned 500 m down gradient from the repository extending from the Cambrian into the Shallow Bedrock Groundwater Zone, thereby providing an enhanced permeability connection between the level of the repository, the overlying groundwater zones and the biosphere.

Table 5-3: Calculation Cases for the Extreme Earthquake Scenario

Case ID	Brief Description	Associated Detailed Modelling Cases
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.	-

Notes:
EE – Extreme Earthquake Scenario; NE- Normal Evolution Scenario; RS1 – instant repository resaturation variant; NR – non-radioactive contaminants; BC - base case; A – AMBER; F3 – FRAC3DVS 3DS model

5.4 MATHEMATICAL MODELS, SOFTWARE IMPLEMENTATION AND DATA

5.4.1 Mathematical Models

The Extreme Earthquake Scenario adopts the same basic mathematical model as used for the Normal Evolution Scenario due to the commonality of the associated conceptual models. The models used are described in detail in Section 4.1 of the Normal Evolution Scenario Analysis report (Walke et al. 2009a). The exception is the incorporation of a specific pathway to represent the more rapid transport of contaminants in the fault zone.

Detailed groundwater flow modelling shows that the fault only has an influence on contaminant transport in the region of the Guelph and the overlying geology, as a result of the distribution of pressure in the geosphere. Specifically, the main connections occur between the Guelph, Salina A0 and Salina A2 evaporite Formations. A portion of the contaminants in these more permeable layers can be transported to the Shallow Bedrock Groundwater Zone via the fault.

Based on the observations of the detailed groundwater modelling, the fault is only represented as a pathway between the Guelph, Salina A0 and Salina A2 evaporite Formations and the Shallow Bedrock Groundwater Zone.

5.4.2 Software Implementation

The scenario is implemented in AMBER Version 5.2 (Enviros and Quintessa 2008a, b). The modified Normal Evolution Scenario model requires the fault zone to be explicitly represented with model compartments. The compartments are discretised in the vertical direction in the same manner as the other geosphere units; however, each represents a sub-vertical planar feature with the width of the fault zone, and enhanced permeability. Adjective and diffusive transfers are then assigned to represent the near-vertical transport along the fault, with the rate being determined by the head difference between each layer and the base of the Shallow Bedrock Groundwater Zone (where groundwater flow from the fault is discharged). As noted above, it is only necessary to represent the fault, as it passes through the geosphere between the Salina F and Guelph Formations.

The calculation case for the scenario is selected with an appropriate scenario-dependent parameter. This parameter is used to activate the transfer used to represent the fault that is reactivated by the earthquake.

In addition, a model has been implemented in the FRAC3DVS code to allow the derivation of the input for the assessment calculations, in particular the calculated heads that drive flow up the fault. The implementation is described in Section 4.3 of the Groundwater Modelling report (Avis et al. 2009) (FRAC3DVS).

A T2GGM model has not been developed for the Extreme Earthquake Scenario. This is because the representation of the scenario would require the development of 3D model and so cannot be represent in the 2D radial gas transport model that has been developed for the current assessment (Calder et al. 2009). Due to the absence of T2GGM results, the AMBER model does not consider the impact of the fault on gas transport. Nevertheless, it is expected the impacts would be several orders of magnitude less than those associated with the Severe Shaft Failure Scenario presented in Section 3 due to the additional 500 m lateral travel distance for gas through the geosphere to the reactivated fault.

5.4.3 Data

The Extreme Earthquake Scenario adopts the same parameter values as for the Normal Evolution Scenario (summarised in Table 2-3) with the exception that a hypothetical vertical fault, reactivated following an extreme earthquake immediately following the closure of the DGR, is taken to be 500 m down gradient of the repository (i.e., beyond the area considered in the site investigation programme) and it extends from the Cambrian up into the Shallow Bedrock Groundwater Zone. The fault zone is 1 m wide, with permeability enhanced by three orders of magnitude compared with the surrounding rock. The fault's other flow and transport characteristics are the same as the surrounding rock. The advective velocities that are used in the AMBER model are derived from the results of groundwater modelling (Figure 5-2) (Avis et al. 2009).

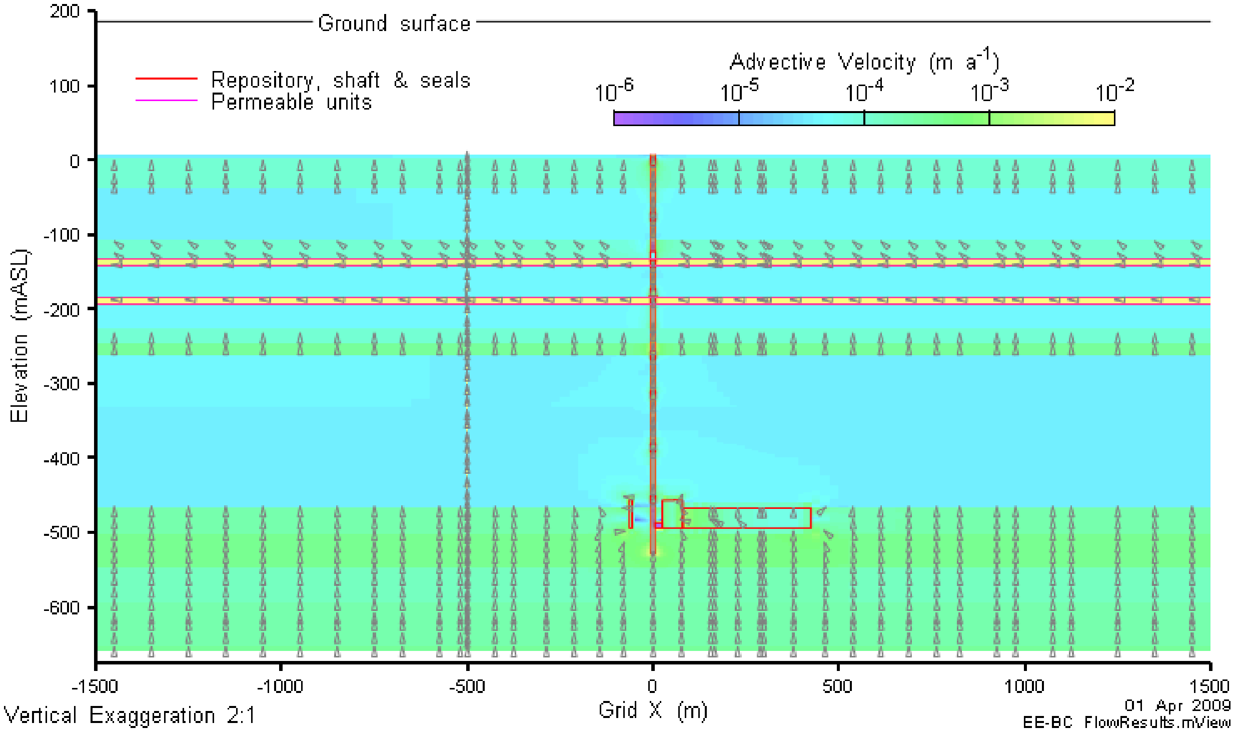

Figure 5-2: Advective Velocities for the Extreme Earthquake Scenario EE-BC-F3 Case

5.5 RESULTS

5.5.1 Release of Contaminants via the Fault

The primary difference from the Normal Evolution Scenario (instant resaturation case) is the presence of an additional pathway between the Guelph, Salina A0 and Salina A2 evaporite Formations and Shallow Bedrock Groundwater Zone that is more permeable than the surrounding geosphere. A measure of the comparative significance of this pathway is given in Figure 5-3. This shows that the fault transmits significantly greater amounts of activity than is the case for either the shaft or geosphere in the Normal Evolution Scenario. The peak flux, of 100 Bq a^{-1} is about 20 times greater than the peak release in the Normal Evolution Scenario, although slightly later (at 1.75 Ma compared with 1 Ma).

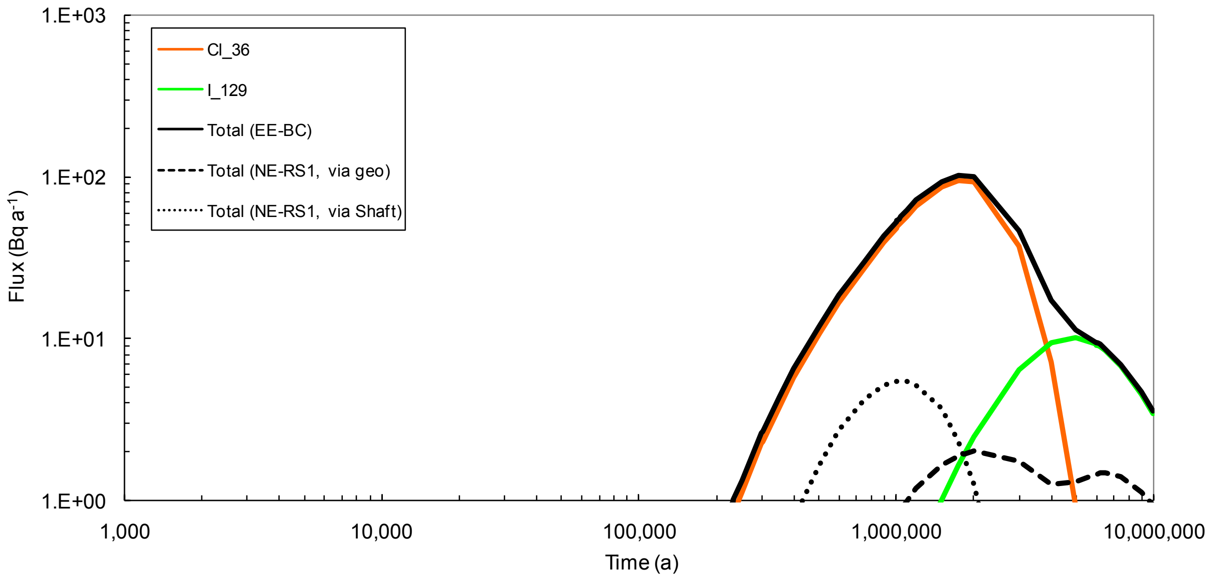

Figure 5-3: Calculated Fluxes of Contaminants in Groundwater from the Fault into the Shallow Bedrock Groundwater Zone, Compared with Results for the Normal Evolution Scenario (instant resaturation)

The contaminants released with highest flux in both the Extreme Earthquake and Normal Evolution Scenario are Cl-36 and I-129.

These contaminants are present with the highest concentrations in water drawn via a hypothetical water well by the local exposure group. It is notable that the diffusion of contaminants into the geosphere, coupled with the dispersion in the shallow geosphere, result in little difference between the Extreme Earthquake and Normal Evolution Scenarios. Figure 5-4 shows that the concentrations peak in a similar way. The peak concentration in the Extreme Earthquake Scenario is 1.79×10^{-5} Bq m^{-3} compared with 1.75×10^{-5} Bq m^{-3} for the Normal Evolution Scenario. In both cases the peak concentration occurs after about 1.1 Ma and is associated with Cl-36. The similarity occurs because, although there are greater fluxes from the fault in the Extreme Earthquake Scenario, the point of discharge is close to, but a substantial depth beneath, the well.

The same pattern is also carried through to the calculated concentrations in soil, in which Cl-36 (retained in organic soils) results in the highest concentrations at about 4×10^{-5} Bq m^{-3} after 1.1 Ma. Calculated concentrations of radionuclides in water and soil are also well below the criteria applied for the protection of non-human biota. The calculated concentrations of non-radioactive contaminants lie well below their relevant EQS (Table 5-4).

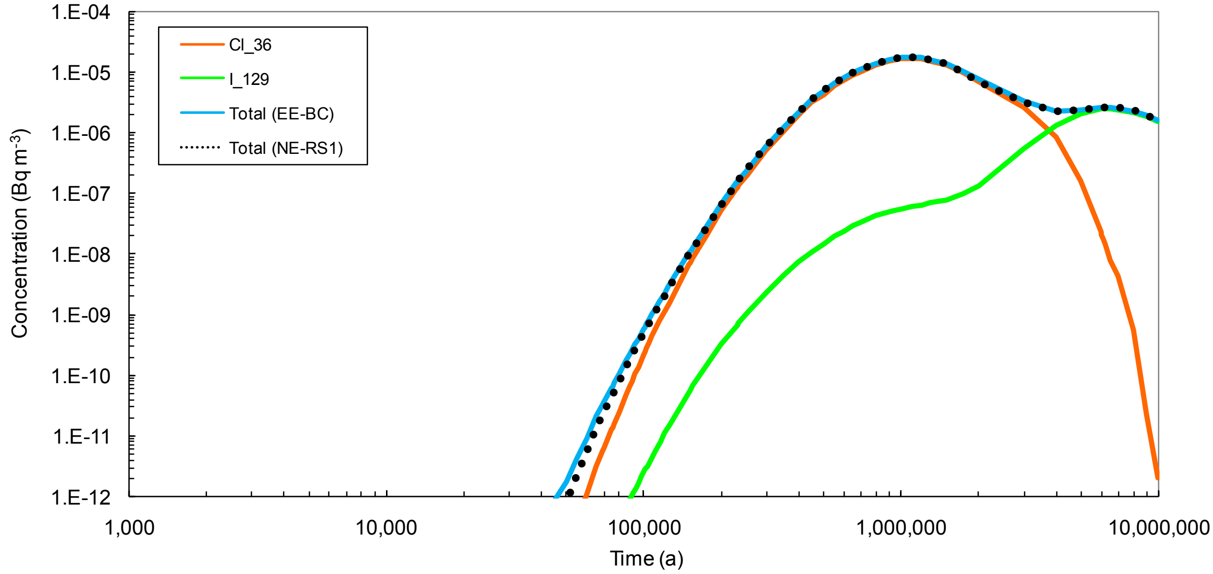

Figure 5-4: Calculated Concentration of Contaminants in Well Water, for the Extreme Earthquake Scenario, Compared with Results for the Normal Evolution Scenario

Table 5-4: Ratio of Peak Calculated Concentration of Non-radioactive Species against Environmental Quality Standards for the Extreme Earthquake Scenario

Groups	Species	Groundwater[1]	Soil[2]	Sediment[3]
Elements	Ag	2.9E-07	1.1E-09	6.2E-08
	As	1.1E-06	6.2E-08	4.9E-09
	B	5.8E-08	6.2E-06	-
	Ba	5.7E-07	8.2E-09	-
	Be	1.8E-06	1.4E-10	-
	Cd	7.2E-04	3.2E-07	7.5E-05
	Co	5.8E-06	1.0E-09	4.5E-08
	Cr	3.0E-03	1.6E-07	1.4E-04
	Cu	2.4E-02	1.5E-06	5.7E-03
	Hg	2.0E-05	8.9E-08	2.8E-07
	Mo	1.9E-06	1.2E-07	-
	Ni	7.2E-22	2.0E-25	1.3E-19
	Pb	1.2E-02	4.4E-07	3.3E-04
	Sb	6.8E-05	2.1E-07	-
	Tl	4.5E-08	6.3E-08	-
	U	5.9E-40	7.4E-42	-
	V	1.0E-05	7.3E-10	-
	Zn	3.1E-05	3.5E-09	1.4E-05
Organic Species	Chlorobenzenes and Chlorophenols	2.7E-05	1.3E-08	2.3E-05
	Dioxins and Furans	2.7E-04	2.8E-07	-
	PAH	1.1E-06	1.0E-09	8.3E-07
	PCB	5.0E-08	2.4E-11	2.4E-07

Notes:
1 Well water abstracted from the Shallow Bedrock Groundwater Zone.
2 Cropped soil, which receives potentially contaminated irrigation water.
3 Sediment associated with surface water (concentrations are highest in the Lake Shore sediment).

5.5.2 Calculated Radiation Doses

The calculated radiation doses for the Extreme Earthquake Scenario 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 (see Figure 5-5). As a guide, the peak calculated dose to a local adult is 4.38×10^{-10} mSv a^{1}, compared with 4.28×10^{-10} mSv a^{-1} calculated for the equivalent case of instant resaturation for the Normal Evolution Scenario. The peak value is also very far below the relevant dose criterion.

The key pathways and contaminants are also very similar. Both the Extreme Earthquake and Normal Evolution Scenarios are dominated by the ingestion of animal foodstuffs, although the ingestion of plants is significant. The key radionuclides are Cl-36 and I-129.

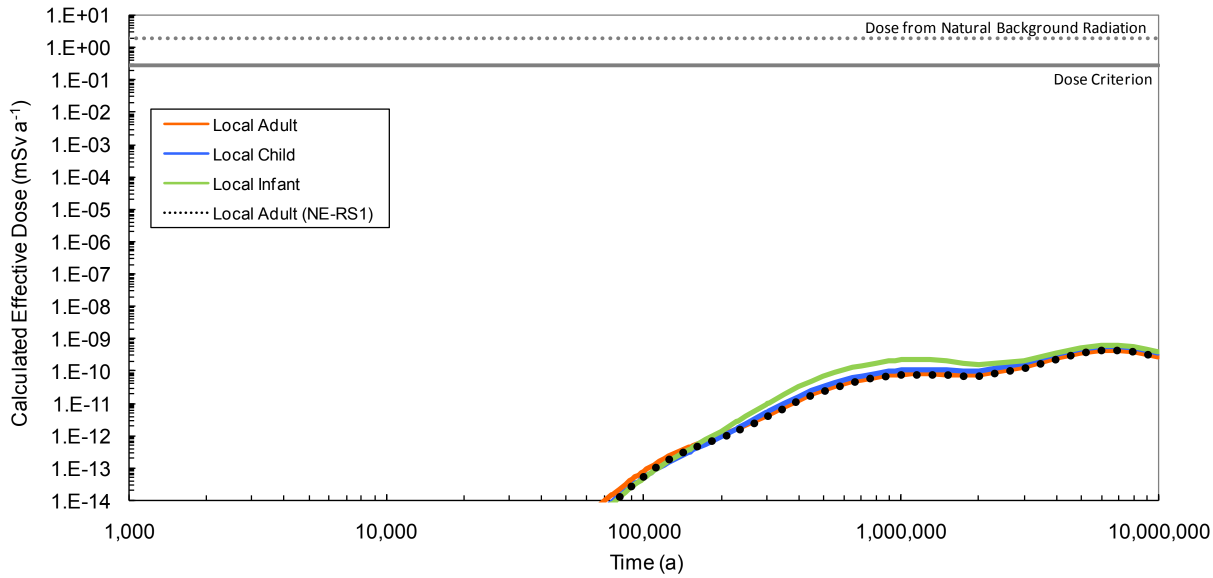

Figure 5-5: Calculated Effective Dose to the Local Exposure Group, Assuming an Extreme Earthquake Activates a Fault

5.5.3 Likelihood

The probability of a high magnitude earthquake is very low. As noted in the introduction to the scenario, the location is relatively stable and does not have a history of substantial earthquakes. The geological stability of the region has been assessed as part of the geosynthesis programme. It concludes that **M** ≥ 6 events have a frequency of <0.001 a^{-1} per 10^6 km^2 in the Central Canadian craton, with a variability of about a factor of three (Atkinson 2007). This suggests that an event of **M** ≥ 6 would be expected somewhere within a 20 km radius of the Bruce Site roughly once in every 800,000 years (with an uncertainty of a factor of 3 on this return period). The rate could potentially be altered under future glaciation cycles, but the rate is clearly very low in any case.

There is also compelling geological data to indicate that there is no significant vertical fault in the vicinity of the DGR. The calculation case has considered a very cautious set of assumptions that is appropriately designated a “what if” case. The results demonstrate that even if such a situation were to occur, the consequence would be very low.

The calculation case does not consider directly the possible degradation of the shaft seals by the shaking resulting from an earthquake. Detailed information on the possible consequences have not been established. However, they would not be as significant as assumed in the Severe Shaft Seal Failure Scenario, for which the consequences remained below 1 mSv a^{-1} despite the very cautious modelling assumptions.

6. UNCERTAINTIES AND ISSUES FOR FURTHER WORK

6.1 Uncertainties

All disruptive scenarios are influenced by uncertainties in the undisturbed performance of the system, described in the Normal Evolution Scenario assessment (Walke et al. 2009). Of particular significance is the uncertainty in the rate and character of resaturation of the repository. This determines the extent to which contaminants can be released at any given time in groundwater or (where relevant) gas. Two bounding assumptions have been adopted in the human intrusion assessment to illustrate the relative importance of resaturation times. The Severe Shaft Seal Failure Scenario adopts a specific set of assumptions for resaturation that are based on detailed modelling results. The Open Borehole and Extreme Earthquake Scenarios assume instantaneous resaturation of the repository, as the scenarios only consider groundwater releases.

The probability of occurrence, and nature of, natural disruptive events themselves can, to some degree, be gauged by careful examination of historical evidence. For example the assessment of potential effects of earthquakes draws on a broad base of information and it can be concluded that the site lies in an area that is unlikely to be subject to high magnitude earthquakes. However, whilst the probability of such an event is very low in any given year, the probability of its occurrence during the assessment timeframe is high. The main uncertainty, therefore, lies in the timing of such an event, and its specific consequences for the DGR region. The timing cannot be determined in advance, although some periods (such as immediately following a glaciation) are more likely to involve seismic events in response to the crustal flexing.

The consequences of earthquakes remain uncertain for the DGR. Some analyses of the effects of seismic shaking have been undertaken for the DGR rooms (Damjanac, 2008), and have been used to inform the assessment. However, the effects on the shaft seals have yet to be assessed. The severe shaft seal failure calculation case can be taken to bound the potential consequences of an earthquake in relation to the integrity of the shaft. It is highly unlikely that the shafts would be completely degraded, as envisaged in the Severe Shaft Seal Failure Scenario. Nevertheless, the results indicate that even dramatic and unexpected damage would not lead to a situation in which potential exposures exceeded safety criteria.

Disruptive scenarios related to human actions – such as human intrusion and the open borehole scenario – are distinct because their probability of occurrence cannot be determined in any meaningful fashion for the timescales of relevance to the safety assessment. This is because the likelihood is intrinsically linked to the character of human society and technology, which is not predictable. It is possible to make estimates, based on current behaviour, that inform on the overall likelihood. However, care is needed in interpreting these estimates. It is for this reason that the assessment outcomes are compared to a dose criterion first, and only if necessary to likelihood or risk criteria.

Taken as a whole, the assessment of disruptive events has shown that, even with conservatively defined exposure groups, the impacts of the events do not lead to calculated peak doses of greater than the dose criterion of 1 mSv a^{-1} in most cases assessed. The Human Intrusion Scenario, is, however, an exception. It is possible that a release of water containing C-14 could result in exposures that exceed this value for a local exposure group, whilst a conservative assessment of the exposure of the drill crew also yields a potential exposure of more that 1 mSv a^{-1} from external irradiation by Nb-94. Whilst the scenario is intended to be stylised and conservative, the key uncertainties are:

- the rate of release of C-14 in the repository, and the potential for it to be incorporated into suspended siderite, which could then be released through the borehole;
- the pressurisation of the repository (the pressures are based on the effect of the Cambrian; in practice the repository may actually be located in a zone of low head); and
- the characteristics of the release of contaminated water and slurry from the DGR.

Any one of these factors has the potential to affect the calculated doses associated with the pathway. Given their importance to results that lie near the 1 mSv a^{-1} dose criterion, these are regarded as the key uncertainties. However, the calculations have adopted cautious models and parameter values, therefore the results can reasonably be regarded as indicative of the highest exposures that could be conceived as a result of disruptive events.

The Severe Shaft Seal Failure Scenario results in calculated peak doses that lie well below the 1 mSv a^{-1} criterion, and the case takes extreme values to characterise the degraded shaft and so is clearly a bounding case. The Open Borehole and Extreme Earthquake scenarios only result in very minor changes in calculated impacts compared with the Normal Evolution Scenario, despite being both uncertain and cautiously defined.

Most non-radioactive species meet environmental quality standards in the Human Intrusion Scenario. Higher concentrations of non-radioactive species could occur in the Shallow Bedrock Groundwater Zone for the Human Intrusion Scenario case in which the borehole is assumed to be poorly sealed, and the Severe Shaft Seal Failure Scenario case in which the shaft seals are assumed to fail to function properly. In these cases, some non-radioactive contaminants could exceed environmental quality standards. However, the calculation have conservatively ignored any solubility limitation and sorption of the species in the repository, shaft or geosphere. There is no exceedance of environmental quality standards for the Open Borehole and Extreme Earthquake Scenarios.

6.2 Further Work

Additional studies are merited to explore a number of the areas of uncertainty discussed in Section 6.1, and build further confidence in the safety assessment.

As noted, the Human Intrusion Scenario is highly dependent on the resaturation and pressure characteristics of the repository, as they determine the potential for the release of contaminated media. Other modelling choices that relate to the potential surface release of the water, slurry and gas also merit review.

The Severe Shaft Seal Failure Scenario also has the potential to result in doses much higher than the Normal Evolution Scenario, although more than an order of magnitude below the relevant dose criterion. This is primarily because the scenario involves extreme assumptions. Nevertheless, it illustrates the key role of the shaft seals in the overall performance of the DGR system. The scenario does not consider the degradation of the barriers from a mechanistic point of view but instead assigns degraded characteristics to the materials. Whilst this is a reasonable approach for the purposes of determining the greatest potential consequences, it does not provide information on the specific circumstances by which the shaft seals could be degraded – e.g., enhanced chemical degradation or seismic shaking. There is merit in examining the performance of the shaft seals from this perspective in future safety assessment calculations.

The Extreme Earthquake Scenario provides an indication that seismic effects are very unlikely to be of major significance, unless they impact on the shaft. Analysis of the effects of ground shaking on the integrity of shaft sealing will add to the overall confidence in the performance of this critical element of the system.

The Open Borehole scenario provides further confidence in the overall safety of the system by demonstrating that enhanced permeability pathways, even relatively close to the DGR, have a very minor effect on performance because of the high degree of containment by the low-permeability rocks.

7. SUMMARY AND CONCLUSIONS

The analysis of human intrusion and other disruptive scenarios has considered the following scenarios:

- unintentional intrusion into the repository as a result of an exploration borehole, leading to release of contaminated materials from the repository to the surface environment and to the Shallow Bedrock Groundwater Zone (the **Human Intrusion Scenario**);
- the unexpected poor performance of the shaft seals (the **Severe Shaft Seal Failure Scenario**);
- the potential for a poorly sealed site investigation/monitoring borehole near the repository, resulting in an enhanced permeability path through the geological barrier (the **Open Borehole Scenario**); and
- an extreme earthquake that is assumed to reactivate a hypothetical fault in the vicinity of the DGR (the **Extreme Earthquake Scenario**).

Any one of the events that could initiate these scenarios is very unlikely to occur in any given year. 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. The likelihood of the Human Intrusion Scenario can only be judged on the basis of the current level of technology and societal development, which is impossible to extrapolate to long timescales. Nevertheless, for context, the current rate of drilling of deep boreholes would indicate a probability of striking a DGR emplacement room of approximately one in 200,000 years. The Severe Shaft Seal Failure Scenario and Open Borehole Scenario would also require unlikely conditions that result in the poor performance of shaft and borehole seal materials. Very large earthquakes in the vicinity of the DGR are unlikely - approximately one in 10^6 a under present conditions. One or more might occur at some point in the assessment timeframe; however, there is no evidence for any previous significant permeable pathway near the site between the repository horizon and the near surface that might be reopened by these or other events.

The Human Intrusion Scenario could in principle result in contaminated slurry (water and some suspended particles), gas and/or undiluted (borehole core) waste to be released to the surface. The materials released at any given time would, however, depend on the conditions in the repository, in particular, the state of repository resaturation. Conservative assessment calculations have considered the potential exposure of the drill crew and site workers to these materials. The assessment did not take account of good practice and many standard operating procedures that would reduce the likelihood of the scenario. The calculated peak dose of about 6 mSv is to a person occupying the site and farming on land contaminated with drilling mud from the borehole, after about 750 years, if it is assumed that drilling slurry contaminates the soil. Ingestion of plants contaminated with C-14 is the key pathway. The majority of the C-14 is released in the form of contaminated siderite ($FeCO_3$), a corrosion product. The drilling crew could also receive an exposure about 2 mSv, if exposure occurred for a significant period of time (around a month of drilling shifts). Both these cases, however, are very unlikely. Calculated peak annual doses to other potentially exposed groups after the intrusion are at least an order of magnitude lower, beneath the dose criterion for Disruptive Scenarios (1 mSv a^{-1}). If it is further assumed that the borehole is poorly sealed, thereby providing an increased permeability pathway from the repository to the Shallow Bedrock Groundwater Zone, an adult member of a local exposure group could receive a dose of around 0.002 mSv a^{-1}.

The Shaft Seal Failure Scenario demonstrates that even with extreme assumptions concerning the performance of the shaft seals, the DGR system can meet the relevant dose criterion. A peak dose of 0.02 mSv a^{-1} is calculated to the local exposure group assumed to be living on the site after about 10 ka. The main contaminant is C-14, initially dissolved groundwater, but volatilised when the groundwater is used for irrigation. It should be emphasised that the assessment of the scenario is highly cautious and should be regarded as a “what if” calculation.

The Open Borehole Scenario considers a monitoring borehole near to the site that is poorly sealed and provides an enhanced permeability pathway up through the geosphere. The calculations show that it has a minor influence on the performance of the system. This is a consequence of the distance and the low host rock permeability between the repository and the borehole.

The only natural disruptive event that has been identified as being of potential significance is an extreme earthquake that causes the reactivation of a fault in the vicinity of the DGR. Seismic assessments indicate that an event of **M** ≥ 6 within a 20 km radius of the Bruce Site is roughly once in 800,000 years (with an uncertainty of a factor of three on this return period). Although there is no geological evidence of such faults in the vicinity of the DGR site, a cautious “what if” calculation has considered the activation of a fault. It is conservatively assumed to occur immediately after closure and provide a permeable fault zone that can transmit contaminants to the Shallow Bedrock Groundwater Zone. The assessment calculations show the consequences are well below the dose criterion with the calculated peak dose of around 4×10^{-10} mSv a^{-1} to an adult local resident, assumed to be living on the site. The calculated doses are similar to those calculated for the Normal Evolution Scenario.

Calculations have been undertaken to assess the impact of radionuclides on non-human biota and the impact of non-radioactive species in the waste on humans and other biota.

The results indicate that potential impacts of radionuclides are below the relevant criteria for all the scenarios assessed with the exception of the Human Intrusion Scenario. In this case, no-effect concentrations could be exceeded by up to a factor of 60 for soil contaminated by the slurry. 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 farming immediately after the intrusion event. Furthermore, the model is conservative as the contaminated slurry is dispersed in a relatively small area of soil.

For the non-radioactive species, Environmental Quality Standards would also be met in most cases. The exception is that well water concentrations could exceed environmental quality standards for groundwater by up to a factor of 50 for some elements (i.e., Cd, Cr, Cu and Pb) for the Human Intrusion and Severe Shaft Seal Failure Scenarios due to the enhanced permeability route directly from the repository to the Shallow Bedrock Groundwater Zone via a poorly sealed borehole intruding into the repository, or the severely degraded shaft seals. However, these situations are very unlikely, and moreover the calculation cases have cautiously ignored any solubility limitation and sorption of the species in the repository, shaft and geosphere.

Overall, the isolation afforded by the location and design of the DGR limits the likelihood of disruptive events potentially able to bypass the natural barriers to a small number of situations with very low probability. Even if these events were to occur, the analysis shows that the 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, even with cautious assessment modelling assumptions. However, the potential release of contaminated water, particles and gas via a borehole could result in exposures that exceed the 1 mSv dose criterion. The assessment is highly unlikely, however, since human intrusion is unlikely, and furthermore drilling practice is to contain and limit the release of material from boreholes.

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.

Further work on disruptive events analysis will seek to enhance overall confidence in the outcomes of this analysis, and further investigate the issues identified above in light of results from other DGR programmes such as waste characterisation, repository design and geosynthesis.

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APPENDIX A: MODEL DEVELOPMENT APPROACH

The approached used for the development of conceptual and mathematical models is illustrated in Figure A-1 and described below.

First, the conceptual models are developed for each scenario using input from the assessment context (documented in Section 3 of the main report, Quintessa et al. 2009), the system description (documented in the System and Its Evolution report, Little et al. 2009), the DGR features, events and processes (FEP) list (documented in Garisto et al. 2009), and the scenarios for assessment (documented in the System and Its Evolution report, Little et al. 2009). 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 (a base case and variant 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 indicate 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 concentrations and doses as a function of space and time.

Learning from analysis of the implemented mathematical model may cause changes in understanding regarding the formulation of the conceptual model. 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.

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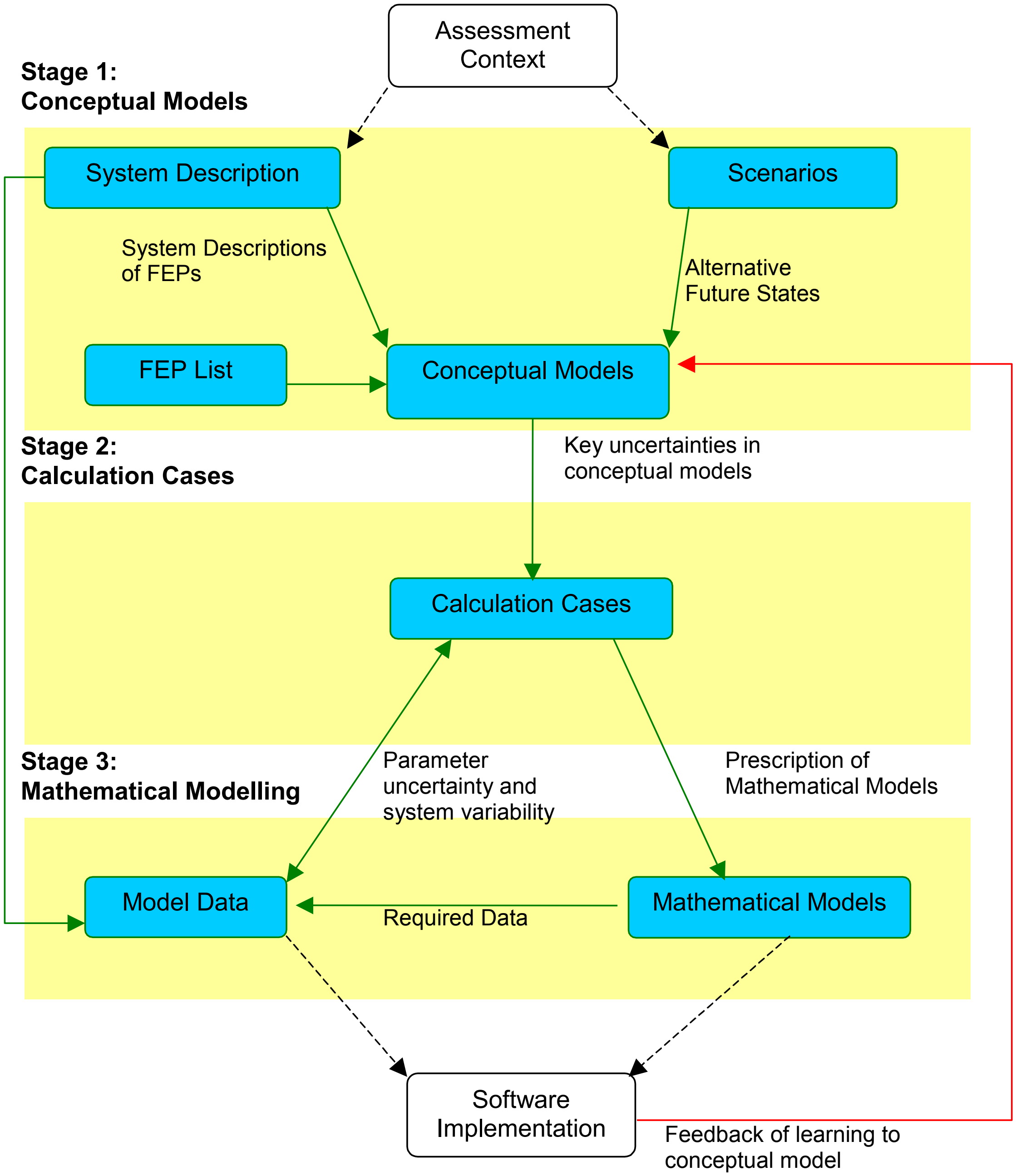

Figure A-1: Model Development Approach

APPENDIX B: FEATURES, EVENTS AND PROCESSES CONSIDERED IN THE CONCEPTUAL MODEL OF HUMAN INTRUSION

B.1 FEATURES

B.1.1 FEATURES COMMON TO THE HUMAN INTRUSION AND NORMAL EVOLUTION SCENARIO

The philosophy for the current assessment is to adopt a common set of features where reasonable, in order that the safety assessment is self-consistent, as far as possible. Consequently, the Human Intrusion Scenario adopts a representation of many of the features that is consistent with the Normal Evolution Scenario described in the Normal Evolution Scenario Analysis report (Walke et al. 2009).

The repository features considered in the Human Intrusion Scenario that are also considered in the Normal Evolution Scenario include:

- the wasteforms (22 types, corresponding to OPG waste streams);
- the repository water (distinguishing between the South Panel (LLW) emplacement rooms, the East Panel (ILW and some LLW) emplacement rooms and the associated access tunnels and ring tunnel);
- the engineered features (plugs etc. determine in part the rate of release from the repository and are therefore relevant); and
- the repository gas (distinguishing between the South Panel (LLW) emplacement rooms, the East Panel (ILW and some LLW) emplacement rooms and the associated access tunnels and ring tunnel).

The repository features described above are necessary to include in the conceptual model in order to describe the evolution of the repository and in particular the release of contaminants from waste into gas and water. Only a subset of these features could be released to the surface via the borehole: repository water, gas, and solid waste. The highest concentrations occur in the East Panel, therefore the conceptual model for the Human Intrusion Scenario evaluates the consequences of a borehole into this part of the repository. The concentrations of contaminants in waste and repository water released to the surface therefore relate to those calculated for the East Panel. Repository gas, however, will mix throughout the repository as vents at the top of emplacement rooms will allow gas to mix. Gas released from the repository would therefore be characteristic of the whole repository.

It is necessary to represent only a portion of the geosphere, as the borehole acts to bypass various of the geological barriers to contaminant migration. Detailed groundwater modelling presented in the Groundwater Modelling report (Avis et al. 2009) indicates that the Guelph, Salina A0, Salina A2 evaporite and Salina G formations would be receptors for releases of water from the repository via a borehole. It is conservative to assume that releases are to the formations closest to the surface, therefore the only geological features necessary to represent directly are the upper formations, collectively referred to as the Shallow Bedrock Groundwater Zone in the Normal Evolution Scenario.

The uncertain nature of the Human Intrusion Scenario means that it is appropriate to focus on a simplified set of key biosphere media that are likely to receive the greatest concentrations of contaminants from either releases of contaminants from the borehole to the surface environment, or from releases of contaminated water into the Shallow Bedrock Groundwater Zone. The key media are those into which contaminants are initially released. Some of the receptors are only relevant for releases to the Shallow Bedrock Groundwater Zone, and are indicated so.

- Soils;
- Biota;
- Atmosphere; and
- Well Water *(only relevant to Shallow Bedrock Groundwater Zone Release Pathway)*.

Whilst the drilling of exploration boreholes would be technically feasible in all four biosphere states (temperate, tundra, glacial and post-glacial) identified in the System and Its Evolution report (Little et al. 2009), drilling in the temperate state would present fewer technical and logistical difficulties due to the less extreme weather conditions. Therefore drilling can be expected to be less unlikely under such a state. In addition, the more favourable climatic conditions can be expected to result in longer exposure times for the site dwellers and hence great impacts. As a result, the temperate biosphere is taken as the reference state for the Human Intrusion Scenario.

B.1.2 FEATURES SPECIFIC TO THE HUMAN INTRUSION SCENARIO

The only feature that is specific to the Human Intrusion Scenario is the exploration borehole itself. The borehole provides the primary pathway of interest for the scenario. It is categorised as a geosphere feature although it has the potential to connect the repository and the biosphere directly. It can therefore be represented as a transfer of contaminants from one location to another. Contaminated water released from the repository through the borehole may either be discharged directly to the surface or enter the geosphere (the Shallow Bedrock Groundwater Zone, as discussed above).

B.2 KEY PROCESSES AND EVENTS

B.2.1 PROCESSES COMMON TO THE HUMAN INTRUSION AND NORMAL EVOLUTION SCENARIOS

The Human Intrusion Scenario considers many of the same processes as the Normal Evolution Scenario (described in detail in the Normal Evolution Scenario Analysis report (Walke et al. 2009).

The following processes are relevant to the conceptual model of the **repository** component of the DGR system for the Human Intrusion Scenario, and must be represented for both a surface release of contaminants and a release to the Shallow Bedrock Groundwater Zone. These processes are required to model the release of contaminants from the waste into the various media that could be released via the borehole, and include:

- decay and waste degradation;
- physical and chemical degradation of wasteforms;
- physical degradation of engineered structures such as concrete monoliths and shaft seals;
- chemical evolution of engineered structures;
- gas generation;
- resaturation of the repository;
- chemical effects (that can influence sorption);
- aqueous release from the saturated wasteform types (instant release, delayed instant release, congruent release and diffusive release);
- gas release from saturated and unsaturated wasteforms;

- aqueous mixing in the repository;
- gas transport;
- gas dissolution in water;
- elemental solubility; and
- the release of contaminants in water and gas from the repository into the geosphere.

It is also necessary to represent **geosphere** migration for the case of human intrusion that results in a release via the borehole to the Shallow Bedrock Groundwater Zone. The processes are the same as modelled in the Normal Evolution Scenario, but only those migration in the Shallow Bedrock Groundwater Zone is relevant to the Human Intrusion Scenario:

- groundwater transport by advection; and
- groundwater transport by dispersion.

Finally, human exposure in the **biosphere** must be assessedfor both the case of borehole release to the surface, and the case of release to the Shallow Bedrock Groundwater Zone. For the latter, the model is identical to biosphere model for the Normal Evolution Scenario., The processes modelled for the borehole release are more limited, consistent with the more limited range of exposure pathways relevant to drill crews and nearby residents, and include:

- sorption;
- gas transport in the biosphere;
- infiltration (modelled in a simplified manner, by simply mixing contaminants in a defined soil depth);
- suspension of contaminated dust;
- uptake by biota;
- human ingestion of contaminated media;
- human inhalation of contaminated media;
- external irradiation of humans by contaminated media; and
- radiation dosimetry.

B.2.2 EVENTS SPECIFIC TO THE HUMAN INTRUSION SCENARIO

The scenario-initiating event is the penetration of the repository by an exploratory borehole, which provides a pathway to either the Shallow Bedrock Groundwater Zone or the surface environment for wastes, repository gas and repository water. It is assumed that the borehole could occur at any time after control of the repository is no longer effective, although it is not certain to occur at any time. Other characteristics of the borehole intrusion event are described in greater detail in Section 2.2.2.1.

B.2.3 PROCESSES SPECIFIC TO THE HUMAN INTRUSION SCENARIO

Several processes are specific to the Human Intrusion Scenario as they are consequential to the scenario-initiating event. The processes of interest are related to the transport of contaminants via the borehole to either the surface environment or the Shallow Bedrock Groundwater Zone.

Water and Slurry Release via Borehole: Contaminated water and slurry may be released if the DGR has become pressurised. The volume discharged is dependent on the extent of pressurisation. Released water may re-enter the geosphere along the path of the borehole, however it is conservative to assess primary points of release at:

- the surface (prior to closure and sealing of the borehole); or
- the Shallow Bedrock Groundwater Zone (once the casing and seal are no longer effective).

Gas Release via Borehole: Contaminated gas in the repository will be released via the borehole, at a rate dependent on the pressure differential between the repository and surface, and the borehole size, until the pressure has equalised. The well would be expected to be fitted with blow-out protection that would limit the rate of gas release. The repository gas pressure, and hence gas flux, has been evaluated as part of the support gas analysis work that has been undertaken in the Gas Modelling report (Calder et al. 2009).

Solid Release via Borehole: Contaminated core might be retrieved, although this is unlikely as most wastes will be unconsolidated.

REFERENCES FOR APPENDIX B

Avis, J., N. Calder and R. Walsh. 2009. Postclosure Safety Assessment (V1): Groundwater Modelling. Nuclear Waste Management Organization (NWMO) Report DGR-TR-2009-06-R0. Toronto, Canada.

Calder, N., J. Avis, P. Humphreys, F. King, P. Suckling and R. Walsh. 2009. Postclosure Safety Assessment (V1): Gas Modelling. Nuclear Waste Management Organization (NWMO) Report DGR-TR-2009-07-R0. Toronto, Canada.

Little, R., A. Bath, P. Humphreys, F. King, R. Metcalfe, J. Penfold, D. Savage, G. Towler, and R. Walke. 2009. Postclosure Safety Assessment (V1): System and Its Evolution. Nuclear Waste Management Organization (NWMO) Report DGR-TR-2009-04-R0. Toronto, Canada.

Walke, R. L. Limer, R. Little, J. Penfold and G. Towler. 2009. Postclosure Safety Assessment (V1): Analysis of the Normal Evolution Scenario. Nuclear Waste Management Organization (NWMO) Report DGR-TR-2009-02-R0. Toronto, Canada.

APPENDIX C: FEP AUDIT OF CONCEPTUAL MODELS FOR THE HUMAN INTRUSION SCENARIO

The features, events and processes considered in the conceptual model for Human Intrusion and Disruptive Events, have been audited against the DGR FEP list documented in Garisto et al. (2009).

An entry is made against each FEP to indicate its inclusion or exclusion from the conceptual model. In the case of inclusion, the section of this document in which the process is discussed is identified and the FEP appears in **emboldened** font. In the case of exclusion, the reason for exclusion is documented.

It should be noted that the treatment of many FEPs is the same as for the Normal Evolution Scenario, as the Human Intrusion Scenario adopts a common modelling approach to, for example, the evolution of the wastes and repository. Common treatment of a FEP is noted with the phrase “*As Normal Evolution Scenario*”.

FEP				Included in Conceptual Model for Human Intrusion Scenario
2. REPOSITORY SYSTEM FACTORS				
2.1	Waste, Waste Form & Engineered System			
	2.1.01	Waste inventory		
		2.1.01.01	**Radionuclide content**	**Yes**, consider - see Table 2-5 of System and its Evolution report (Little et al. 2009). *As Normal Evolution Scenario*
		2.1.01.02	**Chemical content**	**Yes**, explicitly consider - see Table 2-5 of System and its Evolution report (Little et al. 2009). *As Normal Evolution Scenario*
	2.1.02	Waste-form characteristics		
		2.1.02.01	**Metallic wastes**	**Yes**, consider - see Tables 2-1, 2-2 and 2-6 of System and its Evolution report (Little et al. 2009). *As Normal Evolution Scenario*
		2.1.02.02	**Organic wastes**	**Yes**, consider - see Tables 2-1, 2-2 and 2-6 of System and its Evolution report (Little et al. 2009). *As Normal Evolution Scenario*
		2.1.02.03	**Non-metallic, inorganic wastes**	**Yes**, explicitly consider - see Tables 2-1, 2-2 and 2-6 of System and its Evolution report (Little et al. 2009). *As Normal Evolution Scenario*
	2.1.03	Waste-packaging characteristics		
		2.1.03.01	**Containers**	**Yes**, consider - see Table 2-3 of System and its Evolution report (Little et al. 2009) and Table 3-7 and 3-9 of Data report (Walke et al. 2009a). *As Normal Evolution Scenario*
		2.1.03.02	**Overpacks**	**Yes**, consider - see Table 2-3 of System and its Evolution report (Little et al. 2009) and Table 3-7 and 3-9 of Data report (Walke et al. 2009a). *As Normal Evolution Scenario*
	2.1.04	Emplacement room and access and ring tunnel characteristics		
		2.1.04.01	**Roofs and walls**	**Yes**, consider in calculation of mass of concrete and steel in the repository (see Tables 4-8 and 4-9 of Data report, Walke et al. 2009a). *As Normal Evolution Scenario*
		2.1.04.02	**Floors**	**Yes**, consider in calculation of mass of concrete and steel in the repository (see Tables 4-8 and 4-9 of Data report, Walke et al. 2009a). *As Normal Evolution Scenario*
		2.1.04.03	**Rock bolts**	**Yes**, consider in calculation of mass of steel in the repository (see Table 4-9 of Data report, Walke et al. 2009a). *As Normal Evolution Scenario*
		2.1.04.04	**Sealing walls**	**Yes**, but conservatively assume that have no impact on migration of contaminants - see Sections 2.3.1.1 and 2.3.1.3 of the Normal Evolution Scenario report (Walke et al. 2009b). However, included in calculation of mass of concrete and steel in the repository (see Tables 4-8 and 4-9 of Data report, Walke et al. 2009a). *As Normal Evolution Scenario*

FEP			Included in Conceptual Model for Human Intrusion Scenario
	2.1.04.05	Backfill	**No**, no backfill considered in the reference repository design - see Section 2.2.3 of System and its Evolution report (Little et al. 2009). Unlike Normal Evolution Scenario, no variant case is considered with backfill.
2.1.05	**Shaft characteristics**		
	2.1.05.01	**Lining**	**Yes**, consider but only for shafts in Shallow Bedrock Groundwater Zone since liner removed from repository level up to the start of this zone at closure (see Section 2.2.3.4 of the System and its Evolution report, Little et al. 2009). *As Normal Evolution Scenario*
	2.1.05.02	**Backfill**	**Yes**, consider backfill (bentonite/sand mix, asphalt and engineered fill) – see Section 2.2.3.4 of the System and its Evolution report, Little et al. 2009). *As Normal Evolution Scenario*
	2.1.05.03	**Plugs**	**Yes**, consider 11 concrete bulks (two with asphalt waterstops) – see Section 2.2.3.4 of the System and its Evolution report, Little et al. 2009). *As Normal Evolution Scenario*
	2.1.05.04	Rock bolts	**No**, the only rock bolts would be in the Shallow Bedrock Groundwater Zone since liner removed from repository level up to the start of this zone at closure (see Section 2.2.3.4 of the System and its Evolution report, Little et al. 2009). *As Normal Evolution Scenario*
2.1.06	Mechanical processes and conditions (in wastes and emplacement rooms, tunnels and shafts)		
	2.1.06.01	Packaging collapse	
		A **Steel failure**	**Yes**, consider failure of the steel packaging as a result of corrosion and rockfall (see Section 2.3.1.2 of the Normal Evolution Scenario report (Walke et al. 2009b). *As Normal Evolution Scenario*
		B **Concrete failure**	**Yes**, consider failure of the concrete packaging as a result of rockfall (see Section 2.3.1.2 of the Normal Evolution Scenario report (Walke et al. 2009b). *As Normal Evolution Scenario*
	2.1.06.02	Material volume changes	
		A **Concrete shrinkage/ expansion**	**Yes**, see discussion of concrete shrinkage/expansion in Section 4.2.3 of the System and its Evolution report (Little et al. 2009). *As Normal Evolution Scenario*
		B **Bentonite swelling**	**Yes**, see discussion of concrete shrinkage/expansion in Section 4.2.4 and 4.4.2 of the System and its Evolution report (Little et al. 2009). *As Normal Evolution Scenario*
		C **Corrosion products**	**Yes**, see discussion of effects of corrosion in the FEPs report (Garisto et al. 2009). *As Normal Evolution Scenario*
	2.1.06.03	**Emplacement room/ tunnel collapse**	**Yes**, consider sequential rockfall affecting the entire repository (see Section 2.3.1.1 of the Normal Evolution Scenario report, Walke et al. 2009b). *As Normal Evolution*

FEP			Included in Conceptual Model for Human Intrusion Scenario
			Scenario
	2.1.06.04	**Container movement**	**Yes**, consider slumping of containers (see Section 2.3.1.2 of the Normal Evolution Scenario report, Walke et al. 2009b). *As Normal Evolution Scenario*
	2.1.06.05	**Fracture formation**	**Yes**, consider through the time-dependent effect on the physical performance of in the concrete bulkhead in the Shallow Bedrock Groundwater Zone and at its interface with the Intermediate Bedrock Groundwater Zone (see Section 2.3.2.1 of the Normal Evolution Scenario report, Walke et al. 2009b). The expected stable geological environment, even under conditions of ice-sheet loading and unloading, is expected to limit the degradation of the lower shaft. *As Normal Evolution Scenario*
	2.1.06.06	Stress-corrosion cracking	**No**, since the various factors (such as oxidants and stress corrosion agents) necessary for crack initiation and propagation are not expected to be operative simultaneously in the repository environment. *As Normal Evolution Scenario*
	2.1.06.07	Gas explosion	**No**, since the rapid use of all oxygen during the first 10 years following closure means that postclosure gas explosions in the repository are highly improbable. *As Normal Evolution Scenario*
	2.1.06.08	**Influence of climate change**	**Yes**, consider mechanical impacts of glacial-interglacial cycling on the upper shaft (see Section 2.3.2.1 of the Normal Evolution Scenario report, Walke et al. 2009b) and rockfall in the repository (see Section 2.3.1 of Normal Evolution Scenario report). *As Normal Evolution Scenario*
2.1.07	Hydraulic/hydrogeological processes and conditions (in wastes, emplacement rooms, tunnels and shafts)		
	2.1.07.01	**Resaturation/desaturation**	**Yes**, consider scenario-specific resaturation profiles based on detailed groundwater modeling (Avis et al. 2009). If it is not already resaturated, the repository becomes resaturated following the intrusion event.
	2.1.07.02	**Water flow**	**Yes**, explicitly consider – see Sections 2.3.1 and 2.3.2 of the Normal Evolution Scenario report, Walke et al. (2009b). *As Normal Evolution Scenario*
	2.1.07.03	**Gas-mediated water flow**	**Yes**, water flow rates (through the borehole) can be driven by repository gas pressurisation (see Section 2.2.2.3).
	2.1.07.04	Failure of drainage system	**No**, no drainage system is operative following closure. *As Normal Evolution Scenario*
	2.1.07.05	Fracturing of repository components due to hydraulic pressure	**No**, pressure gradients not expected to be sufficient to cause such fracturing (see FEPs report, Garisto et al. 2009). *As Normal Evolution Scenario*
	2.1.07.06	Coupled hydraulic processes including temperature, chemical or electrical gradients	**No**, no significant gradients expected to develop (see FEPs report, Garisto et al. 2009). *As Normal Evolution Scenario*

FEP			Included in Conceptual Model for Human Intrusion Scenario
	2.1.07.07	**Influence of climate change**	**Yes**, glacial-interglacial cycling and the hydraulic and hydrogeological impacts of this cycling on the upper shaft are considered to be one of the factors resulting in the degradation of the upper shaft and its properties (see Section2.3.2.1 of the Normal Evolution Scenario, Walke et al. 2009b). *As Normal Evolution Scenario*
2.1.08	Chemical/geochemical processes and conditions (in wastes, emplacement rooms, tunnels and shafts)		
	2.1.08.01	**pH conditions**	**Yes**, it is expected that pH will be mostly in the pH 6 to 8 range, since the concrete used in the DGR is not considered to be present in sufficient amounts to affect the pH beyond the concrete and the adjacent area (see Section (see Section 2.3.1.1 of the Normal Evolution Scenario, Walke et al. 2009b). *As Normal Evolution Scenario*
	2.1.08.02	**Eh conditions**	**Yes**, considered through accounting for effect of aerobic and anaerobic conditions on corrosion, degradation and gas generation rates and associated gas and aqueous release rates (see Section 2.3.1.1 of the Normal Evolution Scenario, Walke et al. 2009b). *As Normal Evolution Scenario*
	2.1.08.03	**Chloride and sulphate conditions**	**Yes**, consider impact on corrosion and microbial degradation rates (see Appendix C and D of Data report, Walke et al. 2009a) and solubility and sorption values (see Appendix B of Data report, Walke et al. 2009a). *As Normal Evolution Scenario*
	2.1.08.04	Corrosion	
		A **General**	**Yes**, consider impact on gas generation rates and failure of packaging (see FEPs report, Garisto et al. 2009). *As Normal Evolution Scenario*
		B Localised	**No**, localised corrosion is expected to occur only during the short (<10 years) aerobic phase (see FEPs report, Garisto et al. 2009). *As Normal Evolution Scenario*
		C **Galvanic**	**Yes**, consider impact on gas generation rates (see FEPs report, Garisto et al. 2009). *As Normal Evolution Scenario*
	2.1.08.05	**Polymer degradation**	**Yes**, consider impact on gas generation rates (see Section 3.2 of T2GGM software document, Suckling et al. 2009). *As Normal Evolution Scenario*
	2.1.08.06	Mineralisation	
		A **Leaching**	**Yes**, consider leaching of concrete in the upper shaft bulkheads (Section 2.3.2.1 of the Normal Evolution Scenario, Walke et al. 2009b). *As Normal Evolution Scenario*
		B **Chloride attack**	**Yes**, consider effect on degradation of concrete (see Section 4.2.3 of the System and its Evolution report, Little et al. 2009). *As Normal Evolution Scenario*
		C **Sulphate attack**	**Yes**, consider effect on degradation of concrete (see Section 4.2.3 of the System and its Evolution report, Little et al. 2009). *As Normal Evolution Scenario*
		D **Carbonation**	**Yes**, in the high pCO_2 groundwaters of the deep and intermediate geosphere, the concrete in the repository and shafts are expected to subject to carbonation (see Section 4.2 of the System and its Evolution report, Little et al. 2009). *As Normal Evolution Scenario*

FEP			Included in Conceptual Model for Human Intrusion Scenario
	2.1.08.07	**Precipitation reactions**	**Yes**, consider solubility limitation of releases from waste to groundwater (see Section 2.3.1.1 of Normal Evolution Scenario, Walke et al. 2009b). In addition, C-14 is assumed to be incorporated in the formation of siderite ($FeCO_3$). *As Normal Evolution Scenario*
	2.1.08.08	Chelating agent effects	**No**, only small amounts of complexing agents and assumed that have no significant effects (see FEP report, Garisto et al. 2009). *As Normal Evolution Scenario*
	2.1.08.09	Colloid formation	**No**, not expected to be important because colloids will not tend to form in the highly saline porewater, and will be further transport limited by the low permeabilities. *As Normal Evolution Scenario*
	2.1.08.10	Osmotic effects	**No**, not considered to be a significant process (see FEP report, Garisto et al. 2009). *As Normal Evolution Scenario*
	2.1.08.11	Chemical concentration gradients	**No**, not considered to be a significant process (see FEP report, Garisto et al. 2009). *As Normal Evolution Scenario*
	2.1.08.12	**Influence of climate change**	**Yes**, glacial-interglacial cycling and the chemical/geochemical impacts of this cycling on the upper shaft are considered to be one of the factors resulting in the degradation of the upper shaft and its properties (see Section 2.3.2.1 of the Normal Evolution Scenario, Walke et al. 2009b). *As Normal Evolution Scenario*
2.1.09	Biological/biochemical processes and conditions (in wastes, emplacement rooms, tunnels and shafts)		
	2.1.09.01	**Microbial growth and poisoning**	**Yes**, consider through impact on corrosion, degradation and gas generation rates and associated gas and aqueous release rates (see Section 2.3.1.1 of Normal Evolution Scenario report, Walke et al. 2009b). *As Normal Evolution Scenario*
	2.1.09.02	**Microbially/biologically mediated processes**	**Yes**, consider through impact on corrosion, degradation and gas generation rates and associated gas and aqueous release rates (see Section 2.3.1.1 of Normal Evolution Scenario report, Walke et al. 2009b). *As Normal Evolution Scenario*
	2.1.09.03	**Microbial/biological effects of evolution on redox (Eh) and acidity/alkalinity (pH)**	**Yes**, consider through accounting for effect on Eh evolution of the repository (see Section 2.3.1.1 of the Normal Evolution Scenario, Walke et al. 2009b). Assume that there is no significant microbial/biological effect on repository pH. *As Normal Evolution Scenario*
	2.1.09.04	Influence of climate change	**No**, it is expected that the impact of glacial-interglacial cycling on mechanical (FEP 2.1.06.08), hydraulic/hydrogeological (FEP 2.1.07.07), chemical/geochemical (FEP 2.1.08.12) and thermal (FEP 2.1.10.05) processes and conditions will have a greater impact on the evolution of the upper shaft. *As Normal Evolution Scenario*
2.1.10	Thermal processes and conditions (in wastes, emplacement rooms, tunnels and shafts)		

FEP			Included in Conceptual Model for Human Intrusion Scenario
	2.1.10.01	Radiogenic, chemical and biological heat production from the waste packages	**No**, although a small temperature rise may occur in retube wastes, not considered to cause significant rise in repository temperature due to the large thermal sink provided by the host rock (see FEPs report, Garisto et al. 2009). *As Normal Evolution Scenario*
	2.1.10.02	Heat production from engineered features	**No**, any heat from concrete hydration will have dissipated prior to closure. *As Normal Evolution Scenario*
	2.1.10.03	Temperature evolution	**No**, assume no significant temperature evolution (see FEPs report, Garisto et al. 2009). *As Normal Evolution Scenario*
	2.1.10.04	Temperature dependence of processes	
		A Mechanical	**No**, assume no significant temperature evolution and so no effect on mechanical processes (see FEPs report, Garisto et al. 2009). *As Normal Evolution Scenario*
		B Hydraulic	**No**, assume no significant temperature evolution and so no effect on hydraulic processes (see FEPs report, Garisto et al. 2009). *As Normal Evolution Scenario*
		C Chemical	**No**, assume no significant temperature evolution and so no effect on chemical processes (see FEPs report, Garisto et al. 2009). *As Normal Evolution Scenario*
		D Biological	**No**, assume no significant temperature evolution and so no effect on biological processes (see FEPs report, Garisto et al. 2009). *As Normal Evolution Scenario*
	2.1.10.05	**Influence of climate change**	**Yes**, the shaft in the near-surface environment will be significantly affected by temperature changes with the formation of discontinuous permafrost down to 60 m (see Section 5.1 of System and its Evolution report, Little et al. 2009). The associated freeze-thaw cycling could be one of the factors resulting in the degradation of the upper shaft and its properties considered in the Version 1 SA. *As Normal Evolution Scenario*
2.1.11	**Gas sources (in wastes, emplacement rooms, tunnels and shafts)**		
	2.1.11.01	**Radioactive decay**	**Yes**, consider Rn-222 ingrown from Ra-226 (see Section 2.2.2.2).
	2.1.11.02	**Metal corrosion**	**Yes**, see Section 2.3.1.1 of the Normal Evolution Scenario, Walke et al. 2009b. *As Normal Evolution Scenario*
	2.1.11,03	**Organic waste degradation**	**Yes**, see Section 2.3.1.1 of the Normal Evolution Scenario, Walke et al. 2009b. *As Normal Evolution Scenario*
	2.1.11.04	Cement degradation	**No,** gases formed due to any radiolysis of cement is expected to be small compared with that due formed due to corrosion and microbiological degradation, see FEPs report (Garisto et al. 2009). *As Normal Evolution Scenario*
	2.1.11.05	Asphalt degradation	**No**, the volume of CO_2 and CH_4 produced will be small compared with that produced from the microbiological degradation of the wastes (see FEPs report, Garisto et al.

FEP				Included in Conceptual Model for Human Intrusion Scenario
				2009). *As Normal Evolution Scenario*
	2.1.12	Radiation effects (in wastes, emplacement rooms, tunnels and shafts)		**No**, this is not expected to be significant due to the rapid fall in radiation levels after facility closure (see FEPs report, Garisto et al. 2009). *As Normal Evolution Scenario*
	2.1.13	Extraneous materials		**No**, not considered to be a significant process (see FEPs report, Garisto et al. 2009). *As Normal Evolution Scenario*
	2.1.14	Nuclear criticality		**No**, the concentration of fissile material is substantially lower than could result in a criticality (see FEPs report, Garisto et al. 2009). *As Normal Evolution Scenario*
2.2	Geological Environment			
	2.2.01	**Stratigraphy**		**Yes**, consider Deep, Intermediate and Shallow Bedrock Groundwater Zones, although the Shallow Bedrock Groundwater Zone is of most interest since the borehole provides release pathway from the repository directly into this zone – see Section 2.2.2.3.
	2.2.02	**Host lithology**		**Yes**, see Box 1 in Section 2.2.2. *As Normal Evolution Scenario*
	2.2.03	Disturbed zone (host lithology)		
		2.2.03.01	**Emplacement rooms and tunnels**	**Yes**, explicitly consider excavation damaged zone around repository – see Table 2-3 in Section 2.4.3. *As Normal Evolution Scenario*.
		2.2.03.02	**Shafts**	**Yes**, explicitly consider excavation damaged zone around shaft – see Box 1 in Section 2.2.2 and see Table 2-3 in Section 2.4.3. *As Normal Evolution Scenario*.
	2.2.04	Large-scale discontinuities (in geosphere)		
		2.2.04.01	Faults and shear zones	**No**, field evidence suggests that there are no large-scale discontinuities within the site characterisation area (i.e., within 500 m of the DGR) (see Section 5.2.3 of the System and its Evolution report, Little et al. 2009). *As Normal Evolution Scenario*
		2.2.04.02	Fractures and joints	**No**, field evidence suggests that there is no large-scale fracturing or jointing system within the site characterisation area (i.e., within 500 m of the DGR) (see Section 2.3.1 and 5.5 of the System and its Evolution report, Little et al. 2009). *As Normal Evolution Scenario*
		2.2.04.03	Dykes	**No**, no evidence of dykes at the site (see Section 2.3.2 of the System and its Evolution report, Little et al. 2009). *As Normal Evolution Scenario*
	2.2.05	Mechanical processes and conditions (in geosphere)		
		2.2.05.01	**Geomechanical properties**	**Yes**, consider rockfall in emplacement rooms and tunnels (see Section 2.3.1.1 of the System and its Evolution report, Little et al. 2009). *As Normal Evolution Scenario*
		2.2.05.02	**Current stress regime**	**Yes**, see Section 2.3.6 of the System and its Evolution report, Little et al. 2009). *As Normal Evolution Scenario*

FEP			Included in Conceptual Model for Human Intrusion Scenario
	2.2.05.03	**Future stress regime**	**Yes**, consider evolution of stress regime around the repository that causes rockfall (see Section 2.3.1.1 of the System and its Evolution report, Little et al. 2009) and transitory changes in stress due to ice-sheet loading and unloading (see Section 2.3.1.3 of the System and its Evolution report, Little et al. 2009). *As Normal Evolution Scenario*
2.2.06	Hydraulic/hydrogeological processes and conditions (in geosphere)		
	2.2.06.01	**Hydraulic properties**	**Yes**, see Table 2-3 in Section 2.4.3. Note that borehole provides direct release pathway from repository to Shallow Bedrock Groundwater Zone (see Section 2.2.2.3).
	2.2.06.02	**Current hydraulic potentials and gradients**	**Yes**, although simplified case with no representation of Ordovician underpressure assessed (see Table 2-3 in Section 2.4.3).
	2.2.06.03	Future hydraulic potentials and gradients	**No**, no consideration of changes in hydraulic potentials and gradients in geosphere (e.g., due to ice-sheet loading/unloading).
2.2.07	Chemical/geochemical processes and conditions (in geosphere)		
	2.2.07.01	**Mineralogical properties**	**Yes**, properties given in Table 2-8 of the System and its Evolution report (Little et al. 2009). *As Normal Evolution Scenario*
	2.2.07.02	**Geochemical properties**	**Yes**, properties given in Section 2.3.4 of the System and its Evolution report (Little et al. 2009) and used to inform selection of sorption coefficients (Appendix A of the Data report, Walke et al 2009a). *As Normal Evolution Scenario*
	2.2.07.03	Effects of engineered barriers	**No**, expect that any effects will be localised. *As Normal Evolution Scenario*
	2.2.07.04	Effects of climate change	**No**, climate change is expected to alter the geochemical conditions in the Shallow Bedrock Groundwater Zone, for example due to injection of glacial meltwaters (Hobbs et al. 2008), However, for the Version 1 SA, these changes are assumed to have limited effect on the assessment calculations and a stylised approach using constant climate conditions is adopted (see Appendix B.2.3.1 of the Normal Evolution Scenario, Walke et al. 2009b). *As Normal Evolution Scenario*
2.2.08	Biological/biochemical processes and conditions (in geosphere)		**No**, not expected to have significant impact on the migration of contaminants through the geosphere. *As Normal Evolution Scenario*
2.2.09	Thermal processes and conditions (in geosphere)		
	2.2.09.01	Thermal properties	**No**, existing thermal gradient is not considered to have any significant impact on the migration of contaminants through the geosphere. Impact of repository-derived heat on geosphere is assumed to be insignificant. See Garisto et al. (2009). *As Normal Evolution Scenario*

FEP				Included in Conceptual Model for Human Intrusion Scenario
		2.2.09.02	Effects of waste and repository materials	**No**, impact of repository-derived heat on geosphere is assumed to be insignificant due to expected limited temperature increase in repository (see FEP 2.1.10) and the geosphere being a large heat sink. *As Normal Evolution Scenario*
		2.2.09.03	Effects of climate change	**No**, the system at depth is expected to be isolated from the effects of climate change and so the system is assumed to evolve under constant climate conditions. It is recognised that the surface and near-surface environment will be significantly affected and a stylised approach using constant climate conditions is adopted (see Appendix B.2.3.1 of the Normal Evolution Scenario, Walke et al. 2009b). Unlike the Normal Evolution Scenario (which also considers releases to a tundra environment with discontinuous permafrost), only constant temperate conditions are considered.
	2.2.10	Gas processes and effects (in geosphere)		
		2.2.10.01	Gas sources (excluding waste and repository materials)	**No,** it is assumed that there are no significant gas sources in the geosphere. Site characterisation work is currently being undertaken to verify this. *As Normal Evolution Scenario*
		2.2.10.02	**Gas migration**	**Yes**, consider the migration of repository-derived gases through the geosphere as bulk gas (only relevant to the Severe Shaft Seal Failure scenario) and dissolved groundwater (see Section 2.3.2.2 of the Normal Evolution Scenario, Walke et al. 2009b). *As Normal Evolution Scenario*
		2.2.10.03	**Gas dissolution**	**Yes**, dissolution of gases considered (see Section 2.3.2.2 of the Normal Evolution Scenario, Walke et al. 2009b). *As Normal Evolution Scenario*
		2.2.10.04	Gas-induced fractures	**No,** gas pressures are likely to be much less than the lithostatic pressure (see Gas Modelling report, Calder et al. 2009). *As Normal Evolution Scenario*
	2.2.11	**Geological resources (in geosphere)**		**Yes**, although no oil, gas, salt seams or minerals, groundwater aquifer down to around 100 m is used for municipal and domestic water in the region (see Section 2.3 of the System and its Evolution report, Little et al. 2009).The scenario-initiating event for the Human Intrusion Scenario is exploration for ***potential*** resources resulting in an exploratory borehole (Section 2.1).
	2.2.12	**Undetected features (in geosphere)**		**Yes**, the borehole strikes the repository because it is an undetected feature in the geosphere.
2.3	Surface Environment			
	2.3.01	**Topography and morphology**		**Yes**, consider by differentiating terrestrial and lacustrine environments (see Section 2.3.3 of Normal Evolution Scenario report Walke et al. 2009b). *As Normal Evolution Scenario*
	2.3.02	**Biomes**		**Yes**, consider biome consistent with present-day climate and human (see Section 2.3.3.1 of Normal Evolution Scenario report Walke et al. 2009b). *As Normal Evolution Scenario*
	2.3.03	Soil and sediment		
		2.3.03.01	**Surface soils**	**Yes**, receptor of contaminants in groundwater, gas and slurry (Table 2-1 and

FEP			Included in Conceptual Model for Human Intrusion Scenario
			Sections 2.2.2.4 and 2.2.2.5).
	2.3.03.02	**Overburden**	**Yes**, included for the Shallow Bedrock Groundwater Zone (see Appendix B.1.2 of Normal Evolution Scenario report Walke et al. 2009b) but not relevant for the Surface Release Pathway.
	2.3.03.03	**Aquatic sediments**	**Yes,** included for the Shallow Bedrock Groundwater Zone Release Pathway (see Section 2.2.2.5) but not relevant for the Surface Release Pathway.
2.3.04	**Near-surface aquifers and water-bearing features**		**Yes**, included for the Shallow Bedrock Groundwater Zone Release Pathway as a potential primary receptor for releases from the repository via the borehole (see Section 2.2.2.3) but not relevant for the Surface Release Pathway.
2.3.05	Terrestrial surface-water bodies		
	2.3.05.01	**Wetlands**	**Yes,** consider wetlands for the Shallow Bedrock Groundwater Zone Release Pathway (see Table 2-1 and Section 2.2.2.5) but not relevant for the Surface Release Pathway.
	2.3.05.02	**Lakes and rivers**	**Yes,** consider lake and stream for the Shallow Bedrock Groundwater Zone Release Pathway (see Table 2-1 and Section 2.2.2.5) but not relevant for the Surface Release Pathway.
	2.3.05.03	**Springs and discharge zones**	**Yes,** consider groundwater discharge to lake for the Shallow Bedrock Groundwater Zone Release Pathway (see Section 2.2.2.5) but not relevant for the Surface Release Pathway.
2.3.06	Coastal features		**No**, not considered due to site's inland location. *As Normal Evolution Scenario*
2.3.07	Marine features		**No**, not considered due to site's inland location. *As Normal Evolution Scenario*
2.3.08	**Atmosphere**		**Yes**, consider for all releases (see Table 2-1, Figure 2-3, and Figure 2-5).
2.3.09	**Vegetation**		**Yes**, consider for slurry and groundwater releases (see Sections 2.2.2.4 and 2.2.2.5).
2.3.10	**Animal populations**		**Yes**, consider for slurry and groundwater releases (see Sections 2.2.2.4 and 2.2.2.5).
2.3.11	**Climate and weather**		**Yes**, consider in atmospheric dispersion calculations for gas release via borehole (Section 2.2.2.4) and water balance calculations for the Shallow Bedrock Groundwater Zone Release Pathway (Section 2.2.2.5).
2.3.12	**Hydrological regime and water balance (near-surface)**		**Yes**, consider for the Shallow Bedrock Groundwater Zone Release Pathway (see Figure 2.16 of Normal Evolution Scenario report, Walke et al.) and for the site resident for the slurry release (see Figure 2-4).
2.3.13	**Erosion and deposition**		**Yes**, consider for the Shallow Bedrock Groundwater Zone Release Pathway (see Figure 2.16 of Normal Evolution Scenario report, Walke et al. 2009b) and for the site resident for the slurry release (see Figure 2-4).
2.3.14	**Ecological/biological/microbial systems**		**Yes**, consider for the Shallow Bedrock Groundwater Zone Release Pathway (see Figure 2.16 of Normal Evolution Scenario report, Walke et al. 2009b) and for the site resident for the slurry release (see Figure 2-4).

FEP	Included in Conceptual Model for Human Intrusion Scenario
2.3.15 Biotic intrusion	**No**, not relevant for deep repository (see FEPs report, Garisto et al. 2009). *As Normal Evolution Scenario*
2.4 Human Behaviour	
2.4.01 **Human characteristics (physiology, metabolism)**	**Yes**, consider ICRP Reference Man (see FEPs report, Garisto et al. 2009). *As Normal Evolution Scenario*
2.4.02 **Age, gender and ethnicity**	**Yes**, consider infants, children and adults but no distinction of genders or ethnicity (see FEPs report, Garisto et al. 2009). *As Normal Evolution Scenario*.
2.4.03 Diet and fluid intake	
2.4.03.01 **Farming diet**	**Yes**, the Site Resident and Local Exposure Groups are exposed via a wide range of pathways associated with the use of the land including farming (see Sections 2.2.2.4 and 2.2.2.5).
2.4.03.02 Hunter/gatherer diet	**No**, not directly. However, since the Site Resident and Local Exposure Groups diets are varied (including consumption of some wild food such as deer, rabbit, fish, berries, mushrooms and honey) (see Section 7.1 of the Data report, Walke et al. 2009a), potential impacts for groups that might maximise specific pathways (e.g., consumption of large amounts of deer by hunters or large amounts of fish by a fishing group) can be assessed by scaling the results for the resident group associated with those particular pathways.
2.4.03.03 Other diets	**No**, since self-sufficient farming diet usually gives a reasonable or conservative estimate of dose, it is not considered necessary to include any other diets. *As Normal Evolution Scenario*.
2.4.04 **Habits (non-diet-related behaviour)**	**Yes**, consider habits resulting in inadvertent ingestion, inhalation and external irradiation/dermal exposure (see Sections 2.2.2.4 and 2.2.2.5).
2.4.05 Community characteristics	
2.4.05.01 **Community type**	**Yes**, consider range of exposure groups (nearby resident, site resident, drill crew, laboratory technician and local exposure group) (see Sections 2.2.2.4 and 2.2.2.5).
2.4.05.02 **Community location**	**Yes**, assume exposure groups are exposed to contaminated media in the vicinity of the site (see Sections 2.2.2.4 and 2.2.2.5).
2.4.05.03 **Water source**	**Yes**, consider local exposure group takes water from well pumping from Shallow Bedrock Groundwater Zone for the Shallow Bedrock Groundwater Zone Release Pathway (see Section 2.2.2.5). Water assumed to come from uncontaminated source for Surface Release Pathway.
2.4.06 Food preparation and water processing	**No**, conservatively ignored, consistent with CSA (2008) (see FEPs report, Garisto et al. 2009). *As Normal Evolution Scenario*
2.4.07 **Dwellings**	**Yes**, consider house dwelling for local exposure group (see Section 2.2.2.5) for the Shallow Bedrock Groundwater Zone Release Pathway and the site resident for the Surface Release Pathway (Section 2.2.2.4).

FEP			Included in Conceptual Model for Human Intrusion Scenario
	2.4.08	**Natural/semi-natural land and water use**	**Yes**, local exposure group uses natural/semi-natural land and water (e.g., for fishing and recreation) for the Shallow Bedrock Groundwater Zone Release Pathway (see Section 2.2.2.5). Not considered for the Surface Release Pathway.
	2.4.09	**Rural and agricultural land and water use**	**Yes**, local exposure group uses rural and agricultural land and water for the Shallow Bedrock Groundwater Zone Release Pathway (see Section 2.2.2.5). Site resident uses land for farming for the Surface Release Pathway (Section 2.2.2.4).
	2.4.10	Urban and industrial land and water use	**No**, due to absence of significant urban and industrial land in immediate vicinity of site (see System and its Evolution report, Little et al. 2009) and the expected lower impacts than for farming and fishing exposure groups (see FEPs report, Garisto et al. 2009). *As Normal Evolution Scenario*
	2.4.11	**Leisure and other uses of environment**	**Yes,** local exposure group uses land for recreation (see Section 2.2.2.5) for the Shallow Bedrock Groundwater Zone Release Pathway. Not considered for the Surface Release Pathway.
3. CONTAMINANT FACTORS			
3.1	Contaminant Characteristics		
	3.1.01	**Radioactive decay and in-growth**	**Yes**, explicitly consider progeny with half live of great than 25 days. Those with half lives less than or equal to 25 days are assumed to be in secular equilibrium with the parent (see Section 3.5.1 of the Data report, Walke et al. 2009a). *As Normal Evolution Scenario*
	3.1.02	**Organics and potential for organic forms**	**Yes**, consider organic contaminants (Cl-Benzenes & Cl-Phenols, Dioxins & Furans, PAHs and PCBs) (see Section 3.6.1 of the Data report, Walke et al. 2009a). *As Normal Evolution Scenario*
	3.1.03	**Chemical/organic toxin stability**	**Yes**, conservatively assume that, for the purpose of health and environmental impact calculations, organic contaminants do not degrade (see Normal Evolution Scenario report, Walke et al. 2009b), although their degradation is considered for the purpose of gas generation rates. *As Normal Evolution Scenario*
	3.1.04	**Inorganic solids/solutes**	**Yes**, consider inorganic contaminants (see Section 3.5.1 and 3.6.1 of the Data report, Walke et al. 2009a). *As Normal Evolution Scenario*
	3.1.05	**Volatiles and potential for volatility**	**Yes**, consider generation of gases in the repository (Section 2.2.2.2) and volatilisation in the biosphere (see Sections 2.2.2.4 and 2.2.2.5).
	3.1.06	**Noble gases**	**Yes**, consider radon (Section 2.2.2.2).
3.2	Contaminant Release and Migration Factors		
	3.2.01	**Contaminant release pathways**	**Yes**, consider two release pathways (surface and groundwater) (see Section 2.2.2.3).
	3.2.02	Water-mediated migration of contaminants	

FEP		Included in Conceptual Model for Human Intrusion Scenario
3.2.02.01	Water-mediated effects (repository)	
	A **Advection**	**Yes**, water release from the repository via borehole (see Sections 2.2.2.2 and 2.2.2.3).
	B **Molecular diffusion**	**Yes**, consider in the repository (see Section 2.3.1.3 of Normal Evolution Scenario report, Walke et al. 2009b). *As Normal Evolution Scenario*
	C **Dispersion**	**Yes,** dispersive transport is considered since advection is considered (see FEP 3.2.02.01.A). *As Normal Evolution Scenario*
3.2.02.02	Water-mediated effects (geosphere)	
	A **Advection**	**Yes**, for Shallow Bedrock Groundwater Zone release (see Section 2.2.2.3). For surface release, advection is via borehole to the surface (see Section 2.2.2.3).
	B **Molecular diffusion**	**Yes**, consider for Shallow Bedrock Groundwater Zone release (see Section 2.3.2.2 of Normal Evolution Scenario report, Walke et al. 2009b).
	C **Dispersion**	**Yes**, dispersive transport is considered since advection is considered (see FEP 3.2.02.02.A). *As Normal Evolution Scenario*
	D Matrix diffusion	**No**, assume no dual porosity systems (see FEPs report, Garisto et al. 2009). *As Normal Evolution Scenario*
3.2.02.03	Water-mediated effects (biosphere)	
	A **Groundwater discharge to biosphere**	**Yes**, for the Shallow Bedrock Groundwater Zone Release Pathway (see Section 2.2.2.5) but not relevant for the Surface Release Pathway.
	B **Infiltration**	**Yes**, consider for the Shallow Bedrock Groundwater Zone Release Pathway (seeFigure 2-16 of the Normal Evolution Scenario report, Walke et al. 2009b) and for the site resident for the slurry release (see Figure 2-4).
	C Capillary rise	**No**, not considered to be a significant process for transfer of contaminants (see FEPs report, Garisto et al. 2009). *As Normal Evolution Scenario*
	D **Transport by surface run-off**	**Yes**, consider as part of erosion process for the Shallow Bedrock Groundwater Zone Release Pathway (see Figure 2-16 of the Normal Evolution Scenario report, Walke et al. 2009b) and for the site resident for the slurry release (see Figure 2-4).
	E **Transport by interflow**	**Yes**, consider for the Shallow Bedrock Groundwater Zone Release Pathway (see Section 2.2.2.5) and for the site resident for the slurry release (see Figure 2-4).
	F **Transport in surface-water bodies**	**Yes**, consider for the Shallow Bedrock Groundwater Zone Release Pathway (see Figure 2-16 of the Normal Evolution Scenario report, Walke et al. 2009b). Not considered for the Surface Release Pathway.
3.2.02.04	**Multiphase transport processes**	**Yes**, consider movement in gas and water phases (see Section 2.2.2). *As Normal Evolution Scenario*

FEP				Included in Conceptual Model for Human Intrusion Scenario
3.2.03	**Solid-mediated migration of contaminants**			**Yes**, consider removal of contaminated core from repository (see Section 2.2.2). Also consider in erosion and deposition in biosphere for the Shallow Bedrock Groundwater Zone Release Pathway (see Figure 2-16 of the Normal Evolution Scenario report, Walke et al. 2009b) and for the site resident for the slurry release (see Figure 2-3).
3.2.04	**Gas-mediated migration of contaminants**			**Yes**, consider gas migration from repository to biosphere via borehole (Section 2.2.2.3), atmospheric dispersion of gas released from the borehole (Section 2.2.2.3), and volatilisation in the biosphere (see Sections 2.2.2.4 and 2.2.2.5). For Shallow Bedrock Groundwater Zone Release Pathway consider degassing from groundwater (see Figure 2-21 of the Normal Evolution Scenario report, Walke et al. 2009b).
3.2.05	**Atmospheric migration of contaminants**			**Yes**, consider for all releases (see Table 2-1, Figure 2-3, and Figure 2-5).
3.2.06	**Microbial/biological-mediated processes, effects on contaminant release and migration**			**Yes**, consider through impact on corrosion, degradation and gas generation rates and associated gas and aqueous release rates (see Section 2.3.1.1 of Normal Evolution Scenario report, Walke et al. 2009b). *As Normal Evolution Scenario*
3.2.07	**Animal, plant and microbe mediated migration of contaminants**			**Yes**, consider animal and plant uptake for the site resident for the slurry release (Section 2.2.2.4) and for the Shallow Bedrock Groundwater Zone Release Pathway (Section 2.2.2.5).
3.2.08	**Human-action-mediated migration of contaminants**			**Yes**, consider release of contaminated materials via a borehole penetrating the repository and pumping of contaminated water from Shallow Bedrock Groundwater Zone and establishment of agricultural system (Section 2.2.2.3).
3.2.09	Colloid-mediated migration of contaminant			**No**, not expected to be important because colloids will not tend to form in the highly saline porewater, and will be further transport limited by the low permeabilities. *As Normal Evolution Scenario*
3.2.10	Dissolution, precipitation and mineralisation			
		3.2.10.01	**Dissolution and Precipitation (repository)**	**Yes**, consider aqueous release from wasteform and solubility limitation (see Section 2.3.1.1 of Normal Evolution Scenario, Walke et al. 2009b). Also consider leaching, chloride & sulphate attack and carbonation of concrete (see FEP 2.1.08.06). C-14 can be precipitated as siderite under repository conditions. *As Normal Evolution Scenario*
		3.2.10.02	Dissolution and Precipitation (geosphere)	**No**, assume no dissolution/precipitation in geosphere (see FEPs report, Garisto et al. 2009). *As Normal Evolution Scenario*
		3.2.10.03	Dissolution and Precipitation (biosphere)	**No**, assume no dissolution/precipitation in biosphere (see FEPs report, Garisto et al. 2009). *As Normal Evolution Scenario*
		3.2.10.04	**Change in mineralisation**	**Yes**, consider mineralisation of concrete (see System and its Evolution report, Little et al. 2009).

FEP			Included in Conceptual Model for Human Intrusion Scenario
3.2.11	Speciation and solubility (contaminant)		
	3.2.11.01	**Speciation and solubility (solubility limitation, repository)**	**Yes**, consider dissolution of solids and solubility (see Section 2.3.1.1 of Normal Evolution Scenario, Walke et al. 2009b). Speciation considered through choice of solubility limits (see Data report, Walke et al. 2009a). *As Normal Evolution Scenario*
	3.2.11.02	Speciation and solubility (solubility limitation, geosphere)	**No**, concentrations assumed to be too low for solubility limitation to occur. *As Normal Evolution Scenario*
	3.2.11.03	Speciation and solubility (solubility limitation, biosphere)	**No**, concentrations assumed to be too low for solubility limitation to occur. *As Normal Evolution Scenario*
	3.2.11.04	**Solubility changes caused by chemical interaction between waste and pore water**	**Yes**, consider through choice of solubility limits (see Appendix A of Data report, Walke et al. 2009a). *As Normal Evolution Scenario*
	3.2.11.05	Solubility changes caused by change in temperature	**No**, no significant temperature change expected (see FEP 2.1.10). *As Normal Evolution Scenario*
	3.2.11.06	Species equilibrium change caused by change in temperature	**No**, no significant temperature change expected (see FEP 2.1.10). *As Normal Evolution Scenario*
3.2.12	Sorption and desorption (contaminant)		
	3.2.12.01	**Sorption and desorption (repository)**	**Yes**, consider sorption for certain elements (see Section 3.6.4 of the Data report, Walke et al 2009a). *As Normal Evolution Scenario*
	3.2.12.02	**Sorption and desorption (geosphere)**	**Yes**, consider sorption for certain elements (see Section 5.5.1.2 of the Data report, Walke et al 2009a). *As Normal Evolution Scenario*
	3.2.12.03	**Sorption and desorption (biosphere)**	**Yes**, see Section 6.2 of the Data report (Walke et al 2009a). *As Normal Evolution Scenario*
	3.2.12.04	Chemical reactions caused by adsorption or desorption	**No**, no need to identify this issue as a separate FEP (see FEPs report, Garisto et al. 2009). *As Normal Evolution Scenario*
	3.2.12.05	**Anion exclusion effects**	**Yes**, Diffusion experiments have shown that ion exclusion effects occur (see discussion in Walke et al. 2009a). *As Normal Evolution Scenario*
	3.2.12.06	Sorption change caused by change in temperature	**No**, no significant temperature change expected (see FEP 2.1.10 and FEP 2.2.09). *As Normal Evolution Scenario*
3.2.13	Complexing agent effects (contaminant)		
	3.2.13.01	Organics	**No,** screened out by use of conservative parameters (see FEPs report, Garisto et al. 2009).
	3.2.13.02	Chelating agents	**No**, not considered to be a significant process (see FEPs report, Garisto et al. 2009). *As Normal Evolution Scenario*

FEP			Included in Conceptual Model for Human Intrusion Scenario
	3.2.13.03	Microbes	**No**, not considered to be a significant process (see FEPs report, Garisto et al. 2009). *As Normal Evolution Scenario*
3.2.14	**Food chains and uptake of contaminants**		**Yes**, consider uptake by biota for the slurry release (Section 2.2.2.4) and for the Shallow Bedrock Groundwater Zone Release Pathway (Section 2.2.2.5).
3.3	Exposure Factors		
3.3.01	**Contaminant concentrations in drinking water, foodstuffs and drugs**		**Yes**, consider for the site resident group for the slurry release (see Figure 2-4). Also considered for the local exposure group for groundwater release (see Section 2.2.2.5).
3.3.02	Contaminant concentrations in non-food products		**No**, shown not to be significant in previous assessments (see FEPs report, Garisto et al. 2009). *As Normal Evolution Scenario*
3.3.03	**Contaminant concentrations in other environmental media**		**Yes**, consider for slurry, gas and groundwater releases (see Figure 2-4, Figure 2-5 and Section 2.2.2.5).
3.3.04	Exposure modes		
	3.3.04.01	**Exposure of humans**	**Yes**, consider exposure of nearby resident, site resident, drill crew, laboratory technician and local exposure group (see Figure 2-3, Figure 2-4, Figure 2-5, Figure 2-6 and Section 2.2.2.5).
	3.3.04.02	**Exposure of biota other than humans**	**Yes**, consider for the slurry, gas and groundwater releases (see Figure 2-4 and Section 2.2.2.5).
3.3.05	Dosimetry and biokinetics		
	3.3.05.01	**Dosimetry and biokinetics for humans**	**Yes,** see Section 7.2 of Data report, Walke et al. (2009a). *As Normal Evolution Scenario*
	3.3.05.02	**Dosimetry and biokinetics for biota other than humans**	**Yes**, see Section 7.3.1 of Data report, Walke et al. (2009a). *As Normal Evolution Scenario*
3.3.06	Radiological toxicity/effects		
	3.3.06.01	**Radiological toxicity/effects for humans**	**Yes,** annual individual effective dose is calculated for adults, children and infants (see Section 3.4 of Postclosure Safety Assessment report, Quintessa et al. 2009). *As Normal Evolution Scenario*
	3.3.06.02	**Radiological toxicity/effects for biota other than humans**	**Yes**, considered using no-effect concentrations and if necessary, radiation doses (see Section 3.4 of Postclosure Safety Assessment report, Quintessa et al. 2009). *As Normal Evolution Scenario*
3.3.07	Chemical toxicity/effects		
	3.3.07.01	**Chemical toxicity/effects for humans**	**Yes,** considered using enviromental quality standards and if necessary, toxicity calculations (see Section 3.4 of Postclosure Safety Assessment report, Quintessa et al. 2009). *As Normal Evolution Scenario*

FEP			Included in Conceptual Model for Human Intrusion Scenario
	3.3.07.02	**Chemical toxicity/effects for biota other than humans**	**Yes**, considered using enviromental quality standards and if necessary, toxicity calculations (see Section 3.4 of Postclosure Safety Assessment report, Quintessa et al. 2009). *As Normal Evolution Scenario*
3.3.08	**Radon and radon daughter exposure**		**Yes**, see Section 2.2.2.2. *As Normal Evolution Scenario*.

REFERENCES FOR APPENDIX C

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APPENDIX D: MATHEMATICAL MODEL FOR THE HUMAN INTRUSION SCENARIO

D.1 SURFACE RELEASE PATHWAY

D.1.1 CONTAMINANT CONCENTRATIONS

D.1.1.1 Concentration in Slurry

Human Intrusion calculations involve exposure to materials ejected from the repository (specifically the East Panel), therefore it is necessary to calculate concentrations to which humans may be exposed based on the amounts and concentrations in the repository. Conservatively, for the surface release pathway no account is taken of radioactive decay and leaching of contaminants from soil once the contaminants have been released from the repository.

A characteristic volume of water and particulate is ejected from the borehole, related to the pressure differential between the repository and surface. The volume ejected, V_{BHWat} (m^3) is calculated based on the pressurization of the repository that has been assessed in detailed groundwater modelling.

The concentration in the ejected water (C_{Water}, Bq m^{-3}) at a given time is given by:

$$C_{Water} = \frac{A_{Water}}{V_{Water}} \tag{D.1}$$

where:

A_{Water} is the total amount of contaminants dissolved the water (Bq) in the East Panel at a given time; and

V_{Water} is the total volume of water in the East Panel at a given time.

The concentration of the ejected particulate in water ($C_{SuspSed}$, Bq m^{-3}) at a given time is given by:

$$C_{SuspSed} = C_{Waste}\ \rho_{SuspSed} \tag{D.2}$$

where:

C_{Waste} is the average concentration by mass of contaminants in wastes in the East Panel (Bq kg^{-1}); and

$\rho_{SuspSed}$ is the suspended particulate concentration, in kg m^{-3}.

Siderite ($FeCO_3$) can be formed in the repository, containing C-14. This is cautiously assessed as being available for release via the human intrusion borehole. The concentration of C-14 in suspended siderite released via the borehole is therefore

$$C_{Siderite} = \frac{A_{Siderite}}{V_{Water}} f_{SuspSid} \tag{D.3}$$

where:

C_{Waste} is the total amount of C-14 in siderite in the East Panel (Bq); and

$f_{SuspSid}$ is the proportion of all siderite that is suspended in water in the repository.

It is expected that the concentration of particulate in the water will be sufficiently low that the total concentration of radionuclides (in particulate and dissolved form) is given by:

$$C_{BH} = C_{Water} + C_{SuspSed} + C_{Siderite} \tag{D.4}$$

It is also necessary to determine the concentration of contaminants should they become dispersed in soil. The total amount of activity in the slurry is dispersed into an area of soil to a characteristic depth. The effective concentration in soil (C_{Soil}, Bq m^{-3}) is therefore calculated as follows:

$$C_{Soil} = (C_{Water} + C_{SuspSed} + C_{Siderite}) \frac{V_{BHWat}}{A_{Contam}\ D_{Contam}} \tag{D.5}$$

where:

A_{Contam} is the area of soil contaminated with the water and particulate that is ejected (m^2); and

D_{Contam} is the depth of soil into which it is mixed (m).

D.1.1.2 Concentration in Gas

The concentration of contaminated gas released from the repository (C_{Gas}, Bq m^{-3}) is dependent upon the point of exposure. The concentration in undispersed gas at atmospheric pressure is taken to be the total activity in gas in the East Panel (at a given time) divided by the total void space in the East Panel at closure.

$$C_{Gas} = \frac{A_{Gas}}{V_{Gas}} Q_{Gas}\ \chi_{Gas} \tag{D.6}$$

where:

A_{Gas} is the total activity of a radionuclide present in gas in the East Panel at a given time (Bq);

V_{Gas} is the total space accessible to gas in the East Panel, at closure (m^3);

Q_{Gas} is the gas flux at a given time after release at standard temperature and pressure (m^3 s^{-1}); and

χ_{Gas} is the time integrated air dispersion factor for a ground level discharge, at a given distance from the point of release (calculated on the basis of a Gaussian plume model), in s m^{-3}.

D.1.1.3 Concentration in Core

The contaminant concentrations in the retrieved sample are taken to be the average of the individual waste stream concentrations in the East Panel for the reference calculation case of the Normal Evolution Scenario. The concentration C_{Waste} is calculated by:

$$C_{Waste} = \frac{\sum\limits_{Wastes} A_{Waste}}{\sum\limits_{Wastes} V_{Waste}} \quad \text{(D.7)}$$

where:

A_{Waste} is the total activity of a radionuclide present in a given wasteform in the East Panel at a given time (Bq); and

V_{Waste} is the total volume of a given wasteform in the East Panel (m^3).

D.1.2 HUMAN EXPOSURES

D.1.2.1 Drill Crew

Both an instantaneous and chronic exposure of the drill crew to ejected material is assessed. The instantaneous exposure includes:

- external irradiation by undiluted slurry;
- inadvertent ingestion of undiluted slurry;
- inhalation of undiluted slurry in aerosol form; and
- inhalation of discharged repository gas at the well head immediately adjacent to the release.

The effective dose resulting from external irradiation, $E_{ExpSoilSed}$, is calculated using:

$$E_{ExtSoilSed} = C_{BH} \ f_r \ DCF_g \ t_{ExpHI} \quad \text{(D.8)}$$

where:

t_{ExpHI} is the exposure duration (h);

f_r is the dose reduction factor to account for non-uniformity of the ground surface (unitless); and

DCF_g is the effective dose coefficient for ground contamination to an infinite depth (Sv a^{-1} per Bq^{-1} m^{-3}).

The effective dose from inadvertent ingestion, $E_{IngSoilSed}$ is calculated using:

$$E_{IngSoilSed} = \frac{C_{BH}}{\rho_S} \ I_S \ DCF_f \ t_{ExpHI} \quad \text{(D.9)}$$

where:

DCF_f is dose coefficient for intake by ingestion (Sv Bq^{-1});

I_s is the incidental intake of slurry (kg dw d^{-1}); and

ρ_S is the bulk density of slurry, kg m^{-3}.

The exposure calculations do not consider inhalation of particulate by the local exposure group, as it is noted that the conditions of exposure mean that airborne concentrations of particulate are very low. However, in the environment encountered by the drill crew, significant concentrations of aerosol are anticipated. The effective dose from the inhalation of particulate is calculated with:

$$E_{Inh} = \frac{C_{BH}}{\rho_S} c_{Dust} \ I_h \ DCF_{iPart} \ t_{ExpHI} \tag{D.10}$$

where:

c_{Dust} is the concentration of contaminated aerosol (kg m^{-3});

DCF_{iPart} is the dose coefficient for inhalation of contaminants in particulate form (Sv Bq^{-1}); and

I_h is the inhalation rate (m^3 a^{-1}).

The drill crew can also be exposed by the inhalation of gas from the borehole. The effective dose is calculated with:

$$E_{InhG} = C_{Gas} \ I_h \ DCF_i \ t_{ExpHI} \tag{D.11}$$

where:

DCF_i is the dose coefficient for inhalation (Sv Bq^{-1}).

The chronic exposure situation includes:

- external irradiation by slurry diluted in soil;
- inadvertent ingestion of slurry diluted in soil;
- inhalation of slurry diluted in soil and resuspended in air at a characteristic dust-loading; and
- inhalation of dispersed gas (at 5 m from the well head).

The equations used to calculate the chronic exposures are the same as applied to calculate the dose associated with the instantaneous exposure, with the exception that the contaminants are diluted in soil, therefore C_{Soil} and ρ_B are used in place of C_{BH} and ρ_S, and other exposure parameter values differ.

D.1.2.2 Nearby Residents

Nearby residents are also exposed. Again, both instantaneous and chronic exposures are assessed.

The instantaneous exposure only involves the assessment of the inhalation of discharged repository gas (C_{Gas}) at a nominal distance from the well head (100 m). The effective dose is calculated using the same expression as the drill crew, above, but with alternative parameter values.

The chronic exposure situation involves the assessment of exposures to contaminated soil. A person lives upon land contaminated by the slurry ejected from the borehole. No account is taken of leaching of contaminants from the soil or radioactive decay prior to exposure. The total activity in water and particulate that is released from the borehole is mixed into the soil used for grazing and crops (50% in each soil type). The exposure pathways and individual doses are calculated using the same models described in the Normal Evolution Scenario Analysis report (Walke et al. 2009), and the same habits as the local exposure group defined for that scenario.

D.1.2.3 Laboratory Technician

The calculation considers a laboratory technician who is examining a piece of retrieved core. The technician is exposed by:

- external irradiation by the sample (taken to be a point source at 1 m from the worker);
- inadvertent ingestion of undiluted waste (as a result of handling the sample); and
- inhalation of undiluted waste in aerosol form (when the sample is cut).

The exposure by external irradiation, E_{ExtPt} is calculated by:

$$E_{ExtPt} = C_{Waste}\ m_{Core}\ DCF_{ePt}\ t_{ExpHI} \tag{D.12}$$

where:

m_{Core} is the mass of the sample being inspected (kg); and
DCF_{ePt} is the dose coefficient for external irradiation by a point source (Sv h^{-1} Bq^{-1}).

Other doses are calculated using the same mathematical models described for the drill crew (Appendix D.1.3.1). However, the contaminant concentrations relate to undiluted waste (C_{Waste}), and other data are specific to the inspection of contaminated core.

D.2 SHALLOW BEDROCK GROUNDWATER ZONE PATHWAY

The Shallow Bedrock Groundwater Zone Release Pathway adopts mathematical models that are identical to those considered in the Normal Evolution Scenario with a single exception – the modelling of the release of contaminants from the repository to the Shallow Bedrock Groundwater Zone via the borehole.

This is represented with a direct transfer of water in the East Panel of the repository to the overlying Shallow Bedrock Groundwater Zone. The value of the transfer rate (in a^{-1}) has been determined on the basis of groundwater modelling, described in the groundwater modelling report (Walsh et al. 2009). It is only applied once the intrusion has occurred (once controls are no longer effective), but is taken to continue indefinitely.

The exposure pathways and individual doses are calculated using the same models described for the Normal Evolution Scenario Analysis report (Walke et al. 2009), and the same habits as the local exposure group defined for that scenario.

REFERENCES FOR APPENDIX D

Avis, J., N. Calder and R. Walsh. 2009. Postclosure Safety Assessment (V1): Groundwater Modelling. Nuclear Waste Management Organization (NWMO) Report DGR-TR-2009-06. Toronto, Canada.

Walke, R. L. Limer, R. Little, J. Penfold and G. Towler. 2009. Postclosure Safety Assessment (V1): Analysis of the Normal Evolution Scenario. Nuclear Waste Management Organization (NWMO) Report DGR-TR-2009-02. Toronto, Canada.