OPG's DEEP GEOLOGIC

REPOSITORY

FOR LOW & INTERMEDIATE LEVEL WASTE

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

March 2011

Prepared by: Quintessa Ltd. and SENES Consultants Ltd.

NWMO DGR-TR-2011-27

Quintessa

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Document History

Title:	Postclosure Safety Assessment: Analysis of Human Intrusion and Other Disruptive Scenarios		
Report Number:	NWMO DGR-TR-2011-27		
Revision:	R000	**Date:**	March 2011
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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 nuclear site in the Municipality of Kincardine, Ontario. The Nuclear Waste Management Organization, on behalf of OPG, is preparing the Environmental Impact Statement (EIS) and Preliminary Safety Report (PSR) for the proposed repository.

The postclosure safety assessment evaluates the long-term safety of the proposed facility and provides supporting information for the EIS and PSR.

This report presents an analysis of disruptive events that could potentially affect the DGR and its environment. These are events that are very 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 (the **Human Intrusion Scenario**);
- The unexpected poor performance of the shaft seals (the **Severe Shaft Seal Failure Scenario**);
- Poor sealing of a site investigation/monitoring borehole near the repository (the **Poorly Sealed Borehole Scenario**); and
- A hypothetical transmissive vertical fault in close proximity to the DGR footprint (the **Vertical Fault 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 bounded by the identified scenarios (e.g. earthquakes), 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 of the Disruptive Scenarios considered in this report is very unlikely to occur in any given year. Since these are unlikely or “what if” scenarios, they are assessed using stylized conceptual models, based on simple but conservative assumptions. The consequences are compared with a public dose criterion of 1 mSv/a for disruptive events, as well as a reference health risk value of 10^{-5}/a.

Consistent with the Normal Evolution Scenario, a reference calculation is undertaken for each Disruptive Scenario. To avoid ambiguity with the Normal Evolution Scenario’s Reference Case, the reference calculation for each Disruptive Scenarios is termed the Base Case calculation. In addition to each Base Case calculation, one or more variant calculations have been undertaken for each Disruptive Scenario. The calculated doses to the maximally exposed group for the Disruptive Scenario’s Base Case calculations are summarized in Figure E.1 and discussed below. Calculated doses within the shaded range are negligible and the magnitude of the values within this area is illustrative.

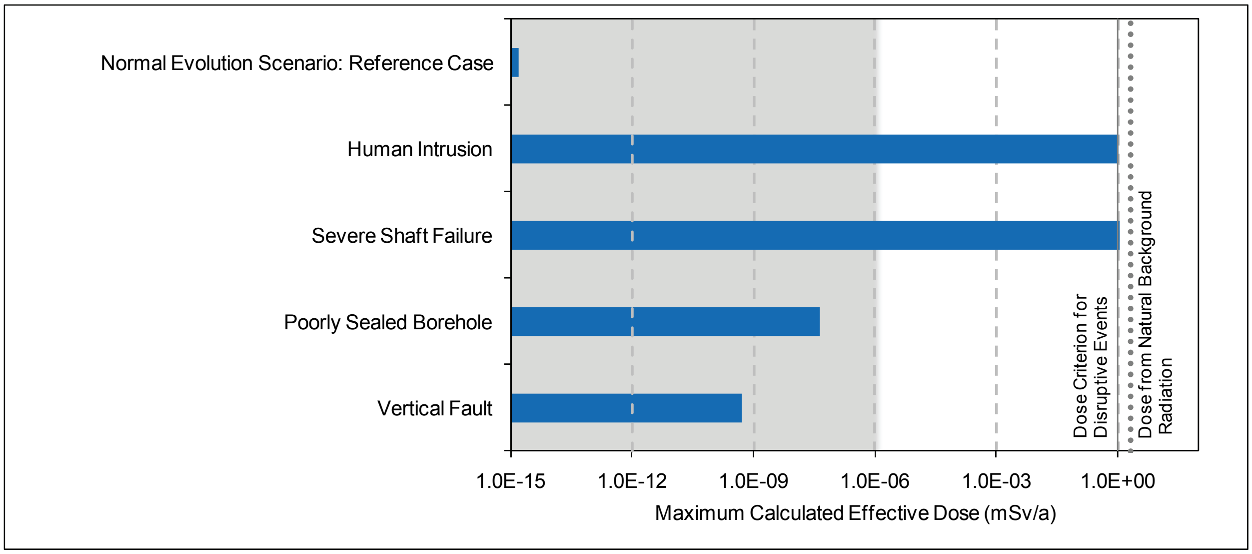

Figure E.1: Disruptive Scenarios: Maximum Calculated Doses for Base Case Calculations

The **Human Intrusion Scenario** could in principle result in contaminated gas and/or drill core containing waste material being released to the surface (there is insufficient saturation in the repository for a water release). Conservative assessment calculations have considered the potential exposure of the drill crew and other people to these materials. The assessment does not take account of good practice and many standard operating procedures that would reduce the likelihood of the scenario and exposure; for example, the drill crew are assumed to leave drill core debris on the site. The calculated peak annual dose of about 1 mSv occurs about 300 a after closure of the DGR and is to a future resident who uses the contaminated drill site for farming after the borehole has been abandoned. The doses to other potential critical groups are below the dose criterion for disruptive events of 1 mSv/a for the base case calculations considering a surface release of contaminants. By around 5 ka, doses for the future site resident is below the dose criterion, and by 70 ka doses for all critical groups are more than an order of magnitude below the criterion.

The **Severe Shaft Seal Failure Scenario** indicates that, assuming significant degradation of the shaft seals and excavation damage zone, the peak calculated dose to a person living directly on the site is about 1 mSv/a after about 23 ka. The calculated doses are dominated by C-14, which reaches the Shallow Bedrock Groundwater Zone in the gas phase with a breakthrough of bulk gas from the DGR at around 20 ka. The C-14 then reaches the biosphere directly in gaseous form, and by dissolving in groundwater and being pumped via a well. The dominant exposure pathways are the inhalation of gas and ingestion of plants that have taken up C-14, each of which contributes about 40% of the calculated peak dose. The calculated dose rapidly falls from the peak at 23 ka, so that by 30 ka it is an order of magnitude below the criterion and by 100 ka it is more than four orders of magnitude below.

The **Poorly Sealed Borehole Scenario** considers a site investigation/monitoring borehole 100 m from the site that is poorly sealed and provides an enhanced permeability pathway up through the geosphere. The calculations show that it has an influence on the performance of the system, compared with the Normal Evolution Scenario. However, the calculated doses are about seven orders of magnitude below the dose criterion (Figure E.1).

There is strong geological, hydrogeological, and geochemical evidence that transmissive vertical faults/fracture zones do not exist within the footprint or vicinity of the DGR. Despite this evidence, the **Vertical Fault Scenario** is a "what if" scenario that investigates the safety implications of a hypothetical transmissive vertical fault, either undetected or representing the displacement of an existing structural discontinuity, which propagates from the Precambrian into the Intermediate Bedrock Groundwater Zone in close proximity to the DGR. The assessment calculations show the calculated doses are many orders of magnitude below the dose criterion.

As all the scenarios represent unusual events, the results can also be expressed as risks (where risk is the product of probability and consequences, using an appropriate factor to convert dose to health risk). Scenarios with dose consequences in the range of 1 mSv would meet the reference health risk value of 10^{-5}/a if the probability of occurrence were less than about 1 per 10 years. Although the probability cannot be reliably estimated for the various Disruptive Scenarios, their probability should be considerably lower than this value.

For example, based on current practice and the size of the repository, the probability of an exploratory borehole inadvertently intercepting the repository can be estimated as around 10^{-5}/a. The Severe Shaft Seal Failure Scenario and Poorly Sealed Borehole Scenario would also require unlikely conditions that result in the very poor performance of the entire shaft and borehole seal materials. In addition, the Vertical Fault Scenario is not consistent with site characterization information. Overall, the probability of the Disruptive Scenarios is low enough that they all fall below the reference health risk value.

Calculations have also been undertaken to assess the impact of radionuclides on non-human biota and the impact of non-radioactive elements and chemical species in the waste on humans and other biota for the Disruptive Scenario base cases. The results indicate that potential impacts are low. All non-radioactive contaminants and most radionuclides are below their screening concentration criteria. There could be some local exceedance of screening criteria for the Human Intrusion Scenario and the Severe Shaft Seal Failure Scenario. In particular, the concentration of C-14 and Nb-94 would locally exceed soil criteria if drilling debris from the repository were to be dumped on the surface at the site in the Human Intrusion Scenario. In addition, C-14 would locally exceed the surface water screening criteria in the Severe Shaft Seal Failure Scenario. Since these higher concentrations are local, the screening criteria are conservative, and the scenarios are very unlikely, the risk to non-human biota from these scenarios is low.

Overall, the isolation afforded by the location and design of the DGR limits the disruptive events potentially able to bypass the natural barriers to a small number of situations with very low probability. Even if these events were to occur, the analysis shows that the contaminants in the waste would continue to be contained effectively by the DGR system such that dose criteria are met in almost all circumstances, even with conservative assessment modelling assumptions. Risk criteria would be met in all cases when account is taken of the probability of occurrence.

The assessment has adopted scientifically informed, physically realistic assumptions for processes and data that are understood and can be justified on the basis of the results of research and/or site investigation. Where there are high levels of uncertainty associated with processes and data, conservative assumptions have been adopted to allow the impacts of uncertainties to be bounded. Thus, the results presented in this report should be seen as being generally conservative and liable to overestimate potential impacts.

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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 nuclear site in the Municipality of Kincardine, Ontario (Figure 1.1). The Nuclear Waste Management Organization, on behalf of OPG, is preparing the Environmental Impact Statement (EIS) and the Preliminary Safety Report (PSR) for the proposed repository.

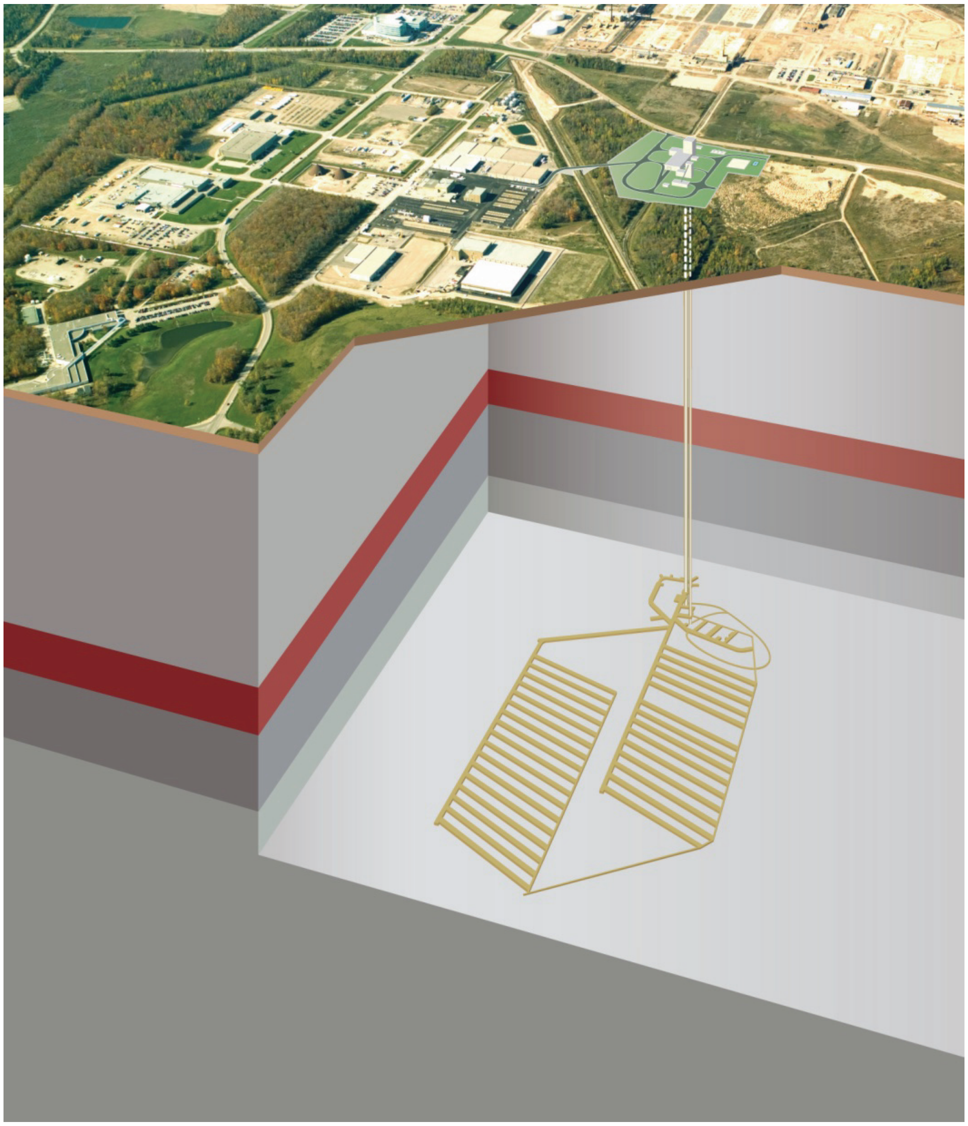

Figure 1.1: The DGR Concept at the Bruce Nuclear Site

The postclosure safety assessment (SA) evaluates the long-term safety of the proposed facility and provides supporting information for the EIS (OPG 2011a) and PSR (OPG 2011b).

This report (Human Intrusion and Other Disruptive Events) is one of a suite of documents that presents the safety assessment (Figure 1.2), which also includes the Postclosure SA main report (QUINTESSA et al. 2011a), the Normal Evolution Scenario Analysis report (QUINTESSA 2011a), the System and Its Evolution report (QUINTESSA 2011b), the Features, Events and Processes (FEPs) report (QUINTESSA et al. 2011b), the Data report (QUINTESSA and GEOFIRMA 2011), the Groundwater Modelling report (GEOFIRMA 2011), and the Gas Modelling report (GEOFIRMA and QUINTESSA 2011).

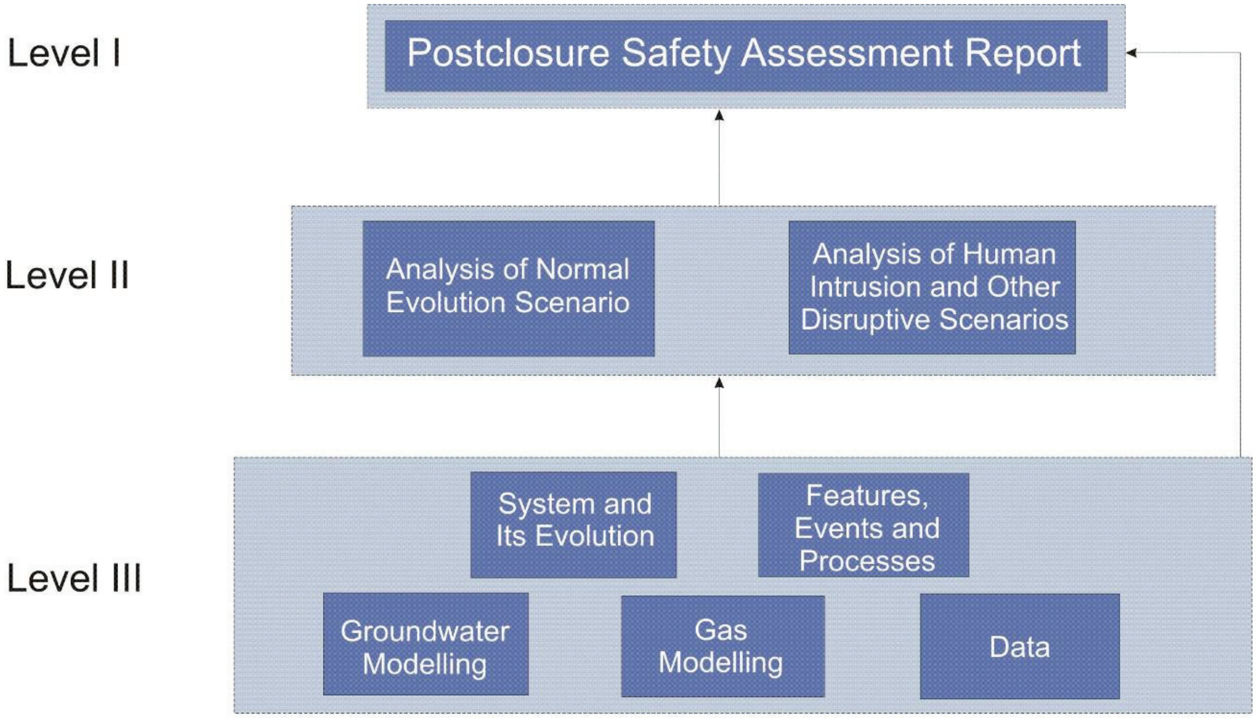

Figure 1.2: Document Structure for the Postclosure Safety Assessment

A high-level description of the DGR system is provided below. More details are provided in the System and Its Evolution report (QUINTESSA 2011b) and the Data report (QUINTESSA and GEOFIRMA 2011).

Waste: The total emplaced volume of low and intermediate level waste (L&ILW) is approximately 200,000 m^3, comprised of low and intermediate level wastes from OPG's owned or operated nuclear reactors. The wastes are emplaced in a range of steel and concrete containers and overpacks. The total activity at closure is about 16,000 TBq. Key radionuclides in terms of total activity include H-3, C-14, Ni-63, Nb-94 and Zr-93 (Table 1.1). The waste generates about 2 kW of decay heat at time of closure.

Repository: The repository is at a depth of about 680 m below ground surface and comprises two shafts, a shaft and services area, access and return ventilation tunnels, and 31 waste emplacement rooms in two panels (Figure 1.1). The repository is not backfilled. At closure, a concrete monolith is emplaced at the base of the shafts and then the shafts are backfilled with a sequence of materials (bentonite/sand, asphalt, concrete and engineered fill).

Geosphere: The DGR is located in competent and low permeability Ordovician argillaceous limestone, with 230 m of Ordovician shales above and 160 m of limestones below. Significant underpressures exist in the Ordovician rocks, whereas overpressures exist in the Cambrian sandstones below the DGR. Above the Ordovician shales, there are 325 m of Silurian shales, dolostones and evaporites. The porewater in the Silurian and Ordovician sediments is highly saline brine (total dissolved solids of 150 to 350 g/L) and reducing, with pH buffered by carbonate minerals. Above the Silurian sediments, there are 105 m of Devonian dolostones, the upper portions of which contain fresh, oxidizing groundwater that discharges to Lake Huron. Site investigations at the Bruce nuclear site have not found commercially viable mineral or hydrocarbon resources.

Biosphere: The present-day topography is relatively flat and includes streams, a wetland, and, at a distance of approximately 1 km, Lake Huron. The annual average temperature is about 8 °C with an average precipitation rate of around 1.1 m/a. The region around the Bruce nuclear site is mainly used for agriculture, recreation and some residential development. Groundwater is used for municipal and domestic water in this region, while the lake provides water for larger communities. The lake is used for recreation and commercial fishing. A significant aboriginal traditional activity in the region is fishing in Lake Huron.

Table 1.1: Amounts of Potentially Important Radionuclides, Elements and Chemical Species in Waste

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

Notes:

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

1.1 Purpose and Scope

The potential future impacts from the repository are evaluated in the postclosure safety assessment by considering a range of possible future evolutions of the DGR system (Chapters 7 and 8 of the System and Its Evolution report, QUINTESSA 2011b).

The **Normal Evolution Scenario** describes the expected evolution of the DGR system and its degradation (gradual loss of barrier function) with time.

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; however, they have an important role in demonstrating the robustness of the DGR's performance in unexpected (or "what if") 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 **Poorly Sealed Borehole Scenario**, which considers the consequences of a site investigation/monitoring borehole in close proximity to the DGR being poorly sealed; and
- The **Vertical Fault Scenario**, which investigates the impact of a hypothetical transmissive vertical fault in close proximity to the DGR.

Other disruptive events have been identified in the assessment of the DGR. However, these are not considered in this report, either because they are addressed in other reports (i.e., ice-sheets in the Normal Evolution Scenario Analysis report, QUINTESSA 2011a), or they are bounded by the identified scenarios (e.g., earthquakes) 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 or low consequence disruptive events are discussed and screened out from further consideration in the Features, Events and Processes report (QUINTESSA et al. 2011b).

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 the Normal Evolution Scenario Analysis report (QUINTESSA 2011a).

The preliminary design for the repository is described in Chapter 6 of the Preliminary Safety Report (OPG 2011b). However, the postclosure safety assessment was initiated based on the original preliminary design, and the design changes were made after the present assessment was largely complete. The key changes were to the ventilation design and the handling of T-H-E packages, and were made for operational safety and reliability reasons. They were not expected to have any significant effect on postclosure safety assessment, as is shown in detailed gas and groundwater modelling for the Normal Evolution Scenario. The detailed gas and groundwater modelling referenced in this report is based on the original preliminary design.

Figure 1.3 shows the locations assumed in the current assessment for the four Disruptive Scenarios. The figure shows that the locations assumed are conservative – for example, the poorly sealed borehole is the closest borehole at repository depth, while two vertical faults are considered – one just outside the well-characterized site area and one within the area. The scenarios are evaluated separately rather than in combination since the individual scenarios have low probability and independent causes, and so their probabilities of occurring together are even lower.

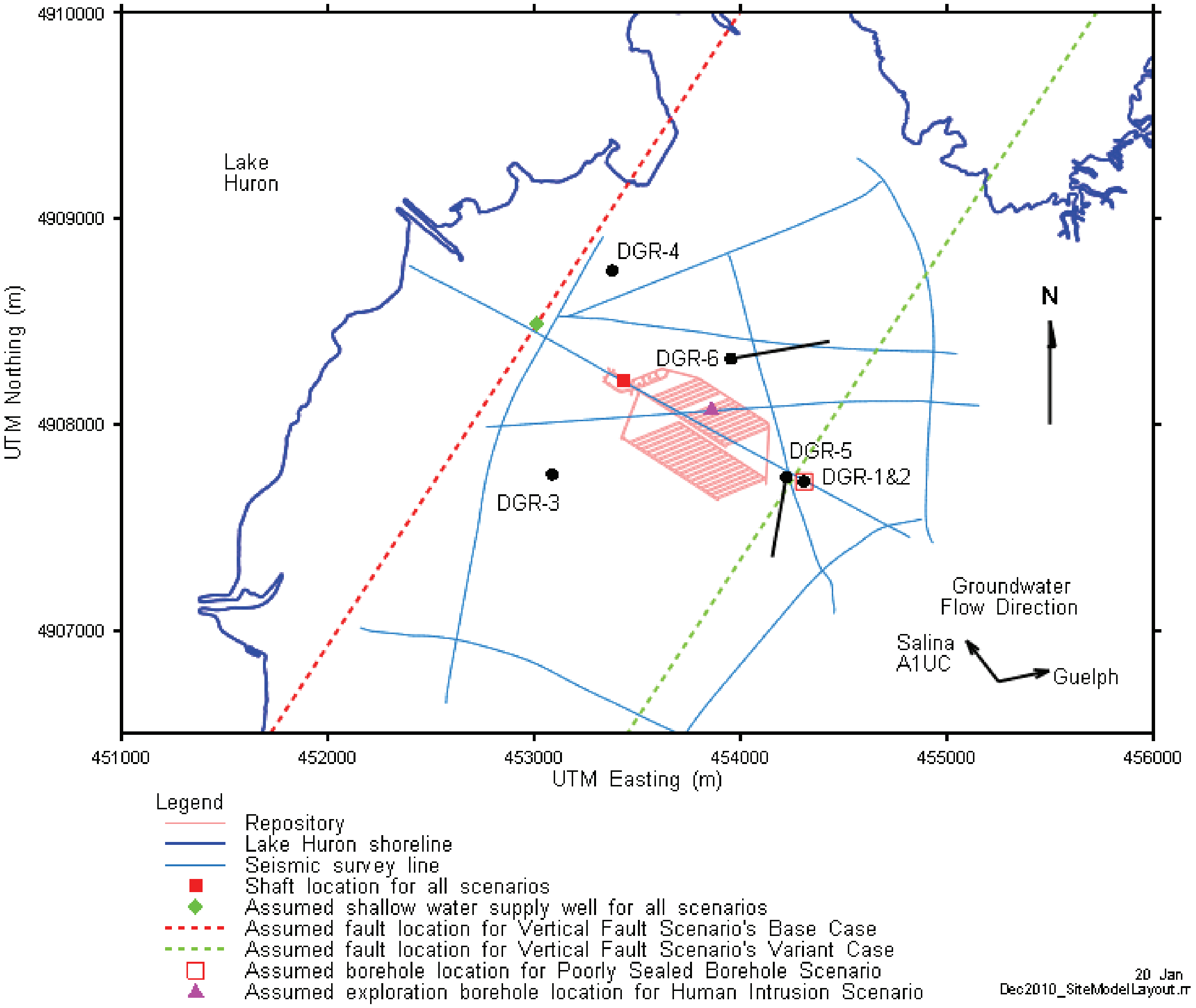

Figure 1.3: Location of Disruptive Scenarios Evaluated in the Safety Assessment Relative to Repository and to Site Characterization Activities

1.2 Report Outline

Each of the four Disruptive Scenarios is considered in turn in Chapters 2 to 5. The following structure, which reflects the approach used to develop the models for assessment (Appendix A), is used in each chapter:

- 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 Chapter 6, and summary and conclusions are provided in Chapter 7.

Due to the good containment provided by the DGR system, some peak impacts may not occur within one million years. Calculated results may, therefore, be presented beyond one million years to show that these impacts are small. Over such long time periods the reliability of quantitative predictions diminishes with increasing timescale due to growing uncertainties. Therefore, graphs showing results beyond 1 million years use a grey background for the period beyond 1 million years to emphasize the illustrative nature of the results over such timescales.

The report has been written for a technical audience that is familiar with the scope of the DGR project, the Bruce nuclear site, and the process of assessing the long-term safety of 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. Intentional intrusion into the repository has not been assessed since it is expected that the intruders would take appropriate precaution.

Given the depth of the DGR, the most likely 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 program (Chapter 8 of the System and Its Evolution report, QUINTESSA 2011b). Such intrusion could only occur after all institutional control of the site was lost, and societal memory or markers had become ineffective. Even in this situation, intrusion is highly unlikely because of the low resource potential of the rocks, the lack of potable groundwaters below about 100 m, the uniform geology across a large area (i.e., nothing unique about the rock at this location), and the small footprint of the DGR[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. 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 drill core. This scenario 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 could 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 drill crew would register a loss of drill fluid to the repository void if the repository pressure is less than the drill fluid pressure, or a sudden release of gas from the repository up the borehole if the repository pressure is greater than the drill fluid pressure. No significant amount of water is expected to be expelled, as the saturation of the repository is projected to be very low (less than 1% for the Normal Evolution Scenario Reference Case, Section 5.1.1.2 of the Gas Modelling report, GEOFIRMA and QUINTESSA 2011). Current technology necessary to drill to 680 m depth would enable the drillers to ascertain the nature of the void that had been encountered, and to limit upflow from the repository ("blowout preventers" are standard practice in sedimentary rocks where one may encounter natural gas). Having noted the presence of the repository, it is very likely that the nature of this anomaly would be checked. Any such checks would be expected to examine the nature of material originating from the repository, and this could result in the identification of significant radioactivity. It is, therefore, very unlikely that drilling would be continued down beyond the repository.

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

If the drilling were to be continued through the repository down into the Cambrian, it would ultimately encounter higher hydraulic heads and sufficient water supply (Sections 2.3.6.2 and 2.3.6.4 of the System and Its Evolution report, QUINTESSA 2011b). If the borehole was poorly sealed (contravening standard practice and drilling regulations), there would then be sufficient pressure for groundwater to flow up from the Cambrian via the borehole into the repository and up to higher formations via the borehole. Groundwater flow modelling (Section 6.2.1 of the Groundwater Modelling report, GEOFIRMA 2011) shows that upwards flows would occur immediately after the intrusion.

In an exploration borehole, 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 high levels of radioactivity (e.g., gamma logging is a standard borehole measurement). Once the investigation was complete, the drillers would close and seal the borehole, and ensure any surface-released materials were appropriately disposed, since this is normal drilling practice. Sealing the borehole would avoid any further release of residual radioactivity direct to the surface. Therefore, under normal drilling, there would be little impact even should inadvertent intrusion occur.

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

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

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

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

Therefore, for this scenario, contaminants could be released and humans and non-human biota exposed via:

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

The scenario is illustrated in Figure 2.1 and Figure 2.2.

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

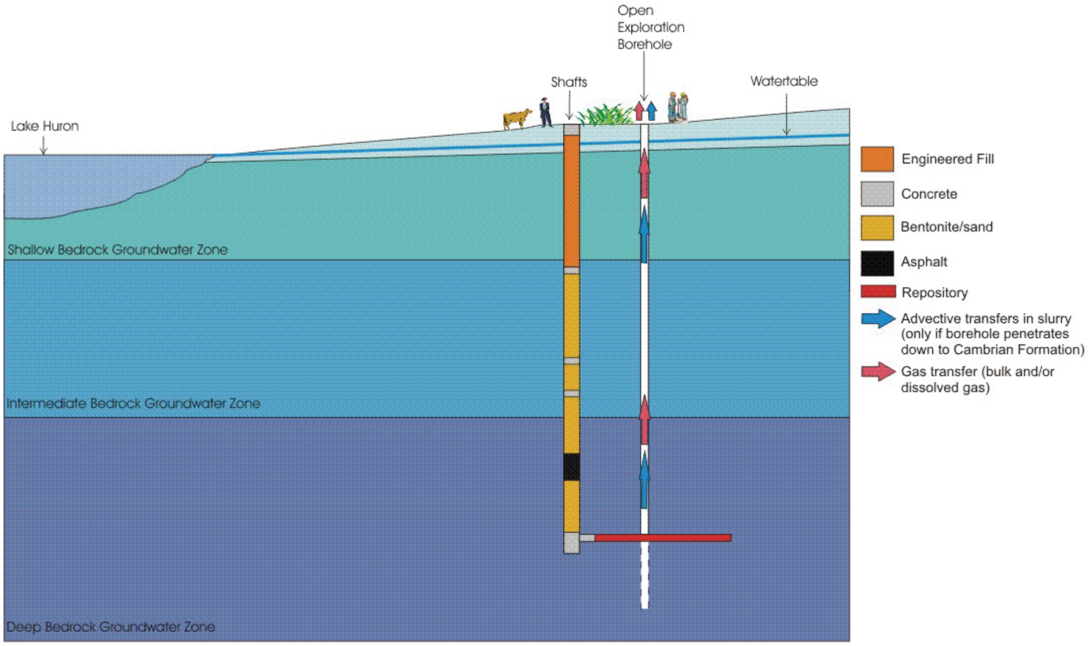

Figure 2.1: Human Intrusion: Schematic Representation of Short-term Gas Release

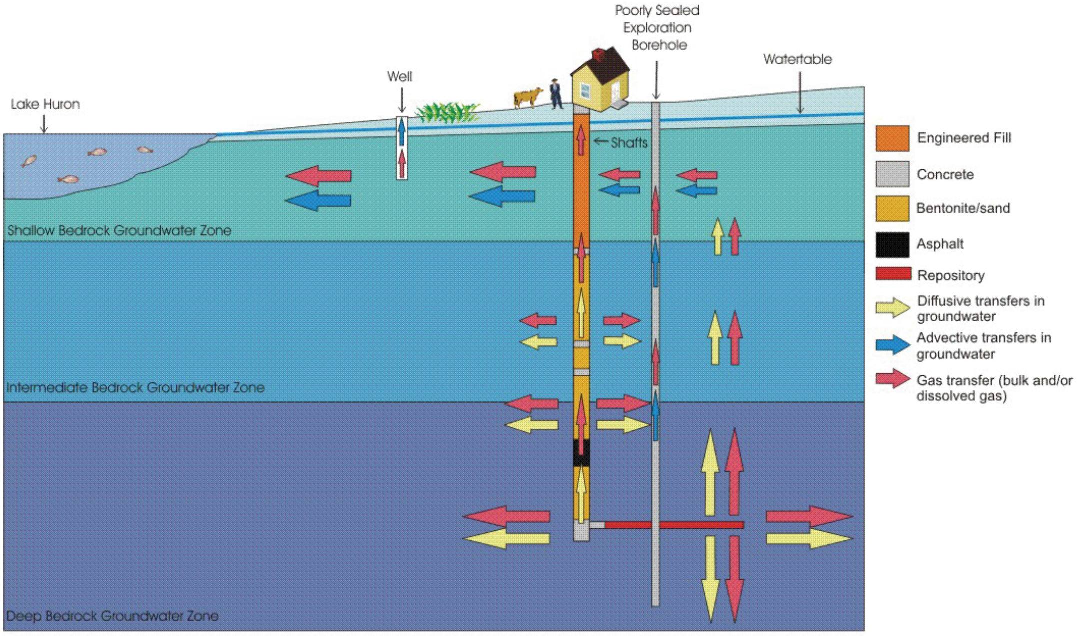

Figure 2.2: Human Intrusion Scenario: Schematic Representation of Long-term Groundwater Release

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, that are relatively homogeneous at any given time (in the context of the overall assessment timescale) and have distinct physical characteristics and associated processes. 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 and those media which significantly impact the migration of contaminants. 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:

- Drill core samples containing solid waste (either in consolidated or unconsolidated form);
- Repository gas containing contaminants (mostly C-14) that have been released through corrosion and degradation of the wastes; and
- Groundwater that has entered the repository and picked up contaminants.

The borehole itself is considered to act as a **pathway** by which contaminated materials from the repository can be transported through the geosphere barriers. A release to the Shallow Bedrock Groundwater Zone could persist for many thousands of years if the borehole was not appropriately sealed after the intrusion, but only in the unlikely event that the borehole had been continued down to the pressurized Cambrian and poorly sealed. If the borehole stops at the repository horizon, then, even over long times, there is a slow downward groundwater flux into the repository and then into the underpressured Ordovician formations (see Section 6.2 of the Groundwater Modelling report, GEOFIRMA 2011).

The **receptors** reside in the biosphere. Because of the inherent uncertainties associated with the Human Intrusion Scenario, it is appropriate to adopt a simple stylized representation[2] of the biosphere. Specifically, a set of basic biosphere features have been identified consistent with describing the media that could contain the highest concentrations of contaminants released via the borehole, and to which people could be exposed.

The key features for the Human Intrusion Scenario are summarized in Table 2.1 and described in greater detail in Appendix B.

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

Table 2.1: Summary of Key Features for the Human Intrusion Scenario

Waste and Repository Features[1]	Geosphere Features[1]	Biosphere Features[1]
- Waste packages - Water[2] (Panels 1 and 2 emplacement rooms, access tunnels, and shaft & service area) - Gas (Panels 1 and 2 emplacement rooms, access tunnels, and shaft & service area) - Engineered Structures (concrete monolith shaft seals and shaft backfill)	- **Borehole** - Shallow Bedrock Groundwater Zone[3]	- Well Water[3] - Surface Water and Sediment (stream and wetland)[3] - Lake Water and Sediment[3] - **Soil** - Biota - **Atmosphere**

Notes

1. Features in **Bold** require specific modelling assumptions for this scenario that differ from the Normal Evolution Scenario.
2. Contaminants in water would only be released in significant volumes if the borehole were continued through the repository and down to the pressurized Cambrian formation.
3. Only considered for long-term groundwater release.

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.

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 these are sedimentary rocks which hold oil and gas in other parts of southern Ontario, whereas there is no mineral exploitation in these rocks at depth in the region (Section 2.3.5 of the System and Its Evolution report, QUINTESSA 2011b). It is also noted that an oil and gas borehole would have a larger diameter than a mineral exploration borehole.

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

Box 1: Key Aspects of the Conceptual Model for the Human Intrusion Scenario[1]

Gas Release:

- Intrusion via exploration borehole directly into an emplacement room in Panel 1 at some time after controls are no longer effective (i.e., after 300 years – Section 3.8 of the Postclosure SA main report, QUINTESSA et al. 2011).
- Resaturation profile prior to borehole intrusion consistent with the Normal Evolution Scenario.
- H-3, C-14, Cl-36, Se-79, I-129 and Rn-222, released via borehole from repository into surface environment as gas due to pressure gradient between repository and surface.
- Gas release via the borehole is limited by blowout preventers, as per normal practice in sedimentary rocks, but depressurization is allowed to occur.
- Atmospheric dispersion of released gas.
- Direct impacts on drill crew and nearby resident (100 m) considered.

Drill Core Release:

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

Groundwater Release:

Consistent with the Normal Evolution Scenario. In addition consider:

- Intrusion via exploration borehole into an emplacement room in Panel 1 at some time after controls are no longer effective (i.e., after 300 years).
- Resaturation profile prior to borehole intrusion consistent with the Normal Evolution Scenario.
- The borehole is poorly sealed (seal has the properties of engineered fill) and the casing degrades allowing relatively rapid resaturation of the repository following borehole intrusion.
- If the repository pressurizes (i.e., the borehole penetrates down into the pressurized Cambrian formation), then there will be a gradient causing contaminated groundwater flow from the repository up via the borehole. The rate of release of groundwater into the Shallow Bedrock Groundwater Zone is based on detailed groundwater modelling[2].
- Impacts calculated for site resident group assumed living directly on site and pumping groundwater for domestic use and irrigation.

Notes

1. All other modelling assumptions are as described for the Normal Evolution Scenario (Chapter 2 of QUINTESSA 2011a)
2. See Section 6.2 of the Groundwater Modelling report (GEOFIRMA 2011).

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

2.2.2.2 Sources

The borehole could in principle penetrate any part of the repository with equal likelihood. For this analysis, calculations are made on the basis of the average concentrations of contaminants in gas, water and waste in Panel 1 which has the largest proportion of ILW (8 out of the 12 ILW emplacement rooms; see Table 4.2 of the Data report, QUINTESSA and GEOFIRMA 2011), and consequently a higher radionuclide inventory than Panel 2. The assumption is reasonable for gas and water because the repository is anticipated to be sufficiently permeable that contaminants would have dispersed within panels. It is conservatively assumed that the borehole could extract a specific piece of waste material. Therefore, contaminant concentrations in any extracted core are calculated for the average over the whole panel (as a representative indication of the contents of the panel), and for each waste category.

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

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

- H-3 gas can be liberated from tritiated water in waste and in H2 generated during corrosion reactions;
- C-14 as CH_4 - detailed calculations show that more than 90% of C-14 is present in gas in this form (Figure 5.12 of the Gas Modelling report, GEOFIRMA and QUINTESSA 2011);
- Cl-36, Se-79 and I-129 from methylation and volatilization; and
- Rn-222 ingrown from Ra-226.

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

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

2.2.2.3 Release Pathways

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

Two main points of release are assessed:

- Immediate release at the surface upon intrusion and shortly afterwards; and
- Long-term release to the Shallow Bedrock Groundwater Zone.

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

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

The calculations show that contaminants would be released into the Guelph and the Salina A1 upper carbonate formations, as well as the Shallow Bedrock Groundwater Zone. The assessment adopts conservative assumptions that (a) there is no dilution of contaminated water during its transit up the borehole, and (b) all the contaminated water is released into the Shallow Bedrock Groundwater Zone (closest to the surface). The subsequent transport of contaminants in the Shallow Bedrock Groundwater Zone is by advection and dispersion in the relevant formations. A portion may be intercepted by a well, the remainder ultimately entering Lake Huron. This is referred to as the **Shallow Bedrock Groundwater Zone Release Pathway**. The conceptual model for this element of the transport pathway is consistent with the conceptual model used for the Shallow Bedrock Groundwater Zone for the Normal Evolution Scenario and is described fully in the Normal Evolution Scenario Analysis report (QUINTESSA 2011a).

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 contaminants in gas and drill core.

Gas

The conceptual model for exposure following a gas release is shown in Figure 2.3. Two potential critical groups are assessed:

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

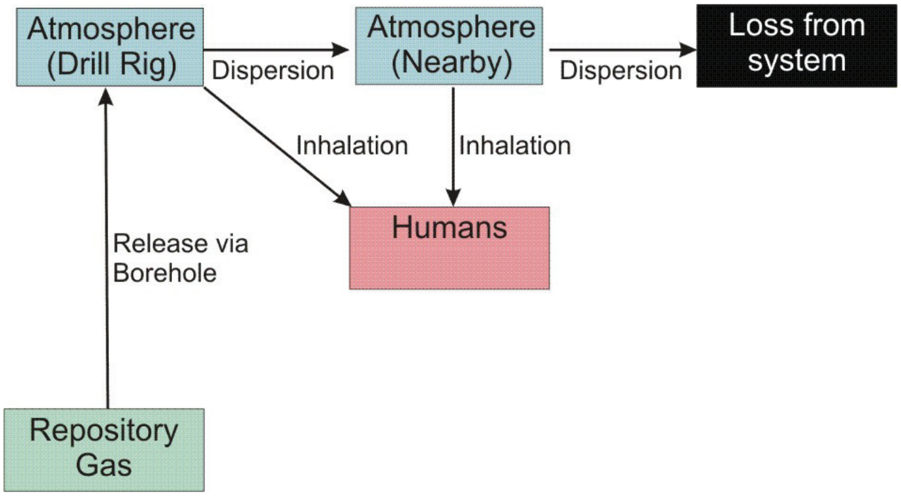

Figure 2.3: Human Intrusion Scenario: Conceptual Model for Gas Release

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

A **nearby resident** could also be exposed, but would live further from the borehole (as the drilling site would not permit dwellings). A close distance of 100 m has been used in the assessment. Potential exposure pathways associated with the uptake of contaminated gas by plants, and inhalation by animals, are expected to be of limited significance compared with the direct exposure of people by gas inhalation, and so are not assessed.

Drill Core Sample

While it is unlikely that an intact sample of waste could be retrieved via a borehole, a solid sample of some quality and integrity might be retrieved. In this context, the most relevant potential receptor is a **laboratory technician** due to the duration and proximity of the exposure resulting from examining a core sample containing waste. Irradiation from a small (several kg) sample of waste could occur when it is analyzed in the laboratory. Inadvertent ingestion (by contamination of the skin during handling) and inhalation (of dust generated when cutting the core into samples) may also expose the technician to the contaminants in the sample. The conceptual model is illustrated in Figure 2.4. Note that exposure via dermal absorption is expected to be minor for relevant radionuclides (only important for tritium, which will have decayed) and so is excluded from the model.

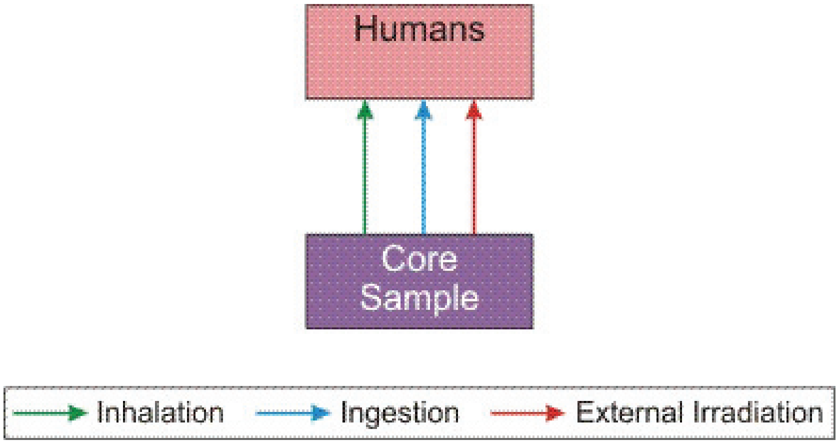

Figure 2.4: Human Intrusion Scenario: Conceptual Model for Exposure of the Laboratory Technician to Contaminated Drill Core Sample

Drill Core Debris Left on Site

Drill core debris extracted from the borehole would be collected and disposed of with other drilling wastes under current requirements. It is conservatively assumed, however, that this waste is left on site where it becomes mixed with soil. This situation has been assessed with the conceptual models shown in Figure 2.5 and Figure 2.6. Consideration of the potential exposure pathways, with allowance for the scenario definition, indicates that two potential critical groups should be assessed:

- Those directly exposed to contaminated drill core at the point of release (i.e., the drill crew) (Figure 2.5); and
- Those exposed for a longer duration to contamination in the soil (e.g., a future resident using the contaminated site for growing food after the completion of drilling) (Figure 2.6).

Exposure to contaminated material disposed of in a controlled manner elsewhere is not evaluated as it would be controlled, and would result in less exposure than considered here for the ‘future resident’ case.

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

A **future resident** could use the contaminated drill site for farming after the borehole has been abandoned. The drill crew are assumed to leave drill core debris on the site, which is contrary to current drilling practice. The characteristics of the future resident are the same as defined for the site resident group in the Normal Evolution Scenario (QUINTESSA 2011a) but, due to the limited volume of extracted wastes and so the limited area of contamination, only the growing of fruit and vegetables on the site is considered. The main exposure routes of relevance are external irradiation from the soil and volatilized gas, inadvertent soil ingestion, consumption of vegetables and fruit, and inhalation of volatilized contaminants and radon.

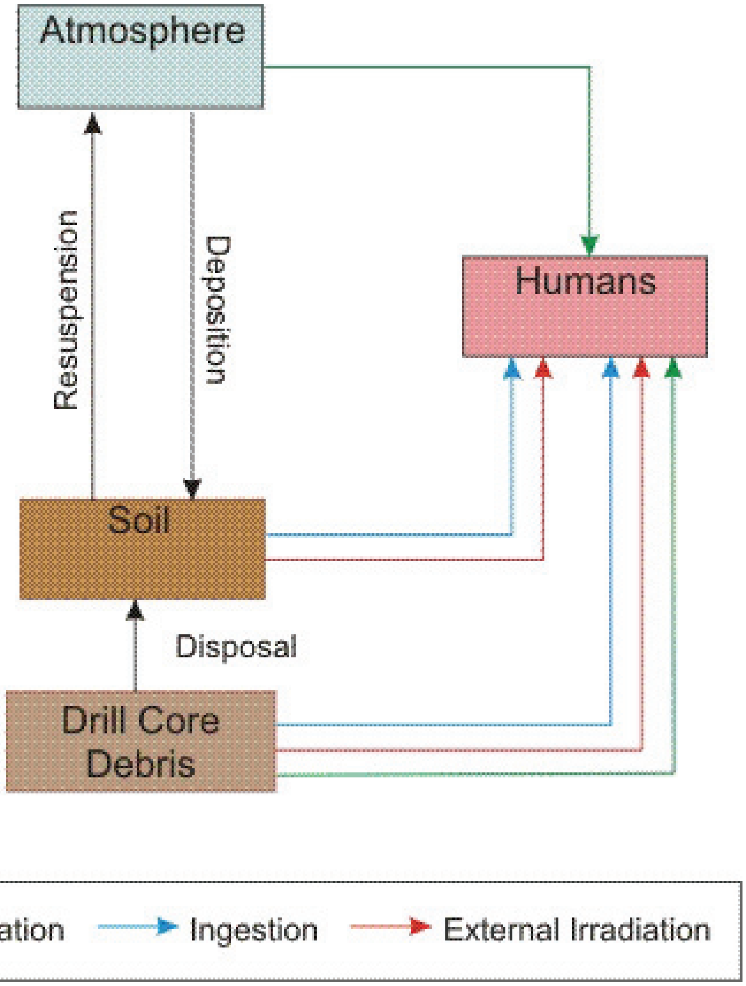

Figure 2.5: Human Intrusion Scenario: Conceptual Model for Exposure of the Drill Crew from Contaminated Drill Core Debris

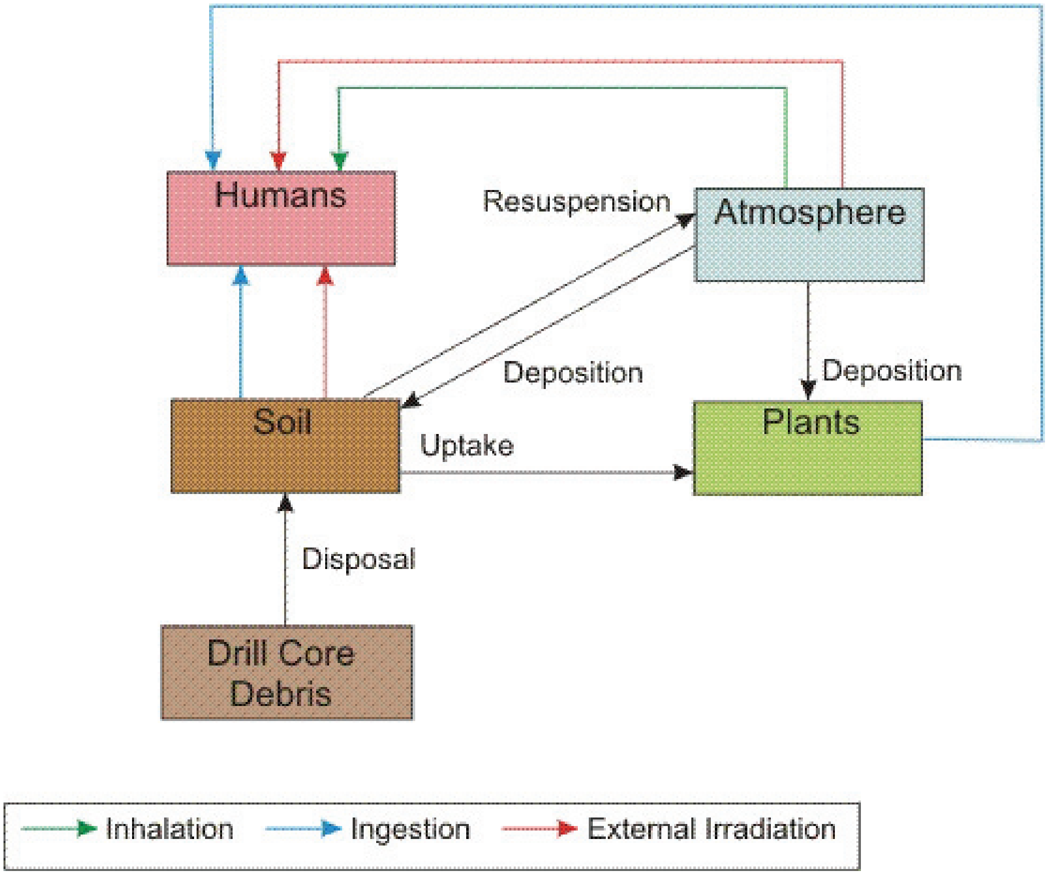

Figure 2.6: Human Intrusion Scenario: Conceptual Model for Exposure of the Future Resident to Soil from Contaminated Drill Core Debris

2.2.2.5 Receptors for the Shallow Bedrock Groundwater Zone Release Pathway

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

The model assesses the effects of release of contaminated groundwater from the borehole into the shallow groundwater system, by considering exposure via a shallow well, and also to Lake Huron. The relevant potential critical group is a **site resident group**. The group lives on a self-sufficient farm and uses 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 group raises livestock, and hunt and fish locally. This is the same potential critical group considered in the Normal Evolution Scenario, and further details of the biosphere conceptual model and critical group characteristics are included in the Normal Evolution Scenario Analysis report (Section 2.3.3 of QUINTESSA 2011a).

2.2.3 FEP Audit

The features, events and processes considered in the conceptual model have been audited against the DGR FEPs list documented in QUINTESSA et al. (2011b). The FEPs 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 uncertain, 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 stylized exposure situations.

The quantity of gas or solid that could be released at a given time is dependent on the repository conditions at that time. The uncertainties in repository conditions are discussed in the Normal Evolution Scenario Analysis report (Section 2.5 of QUINTESSA 2011a). Consistent with detailed modelling results (Chapter 8 of the Gas Modelling report, GEOFIRMA and QUINTESSA 2011), the Human Intrusion Scenario's base case considers a repository that is largely unsaturated, but contains a significant gas pressure and a significant fraction of the C-14 in the gas phase.

2.3 Calculation Cases

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

- A **Base Case** that considers the short-term **surface release** of contaminated gas and drill core for the expected conditions in the DGR, which includes unsaturated conditions extending beyond 1 Ma.
- A “what if” variant case that considers the borehole extending to the Cambrian which is subsequently poorly sealed leading to a long-term **release of contaminated groundwater to the Shallow Bedrock Groundwater Zone**, driven by the hydraulic head in the Cambrian. This situation could also lead to an initial surface release of gas, but the concentrations will be no greater than the surface release case and, therefore, that aspect of the exposure pathway is not assessed.

In addition, a case needs to be considered for the non-radioactive elements and chemical species; this is based on the Base Case, but considers the non-radioactive contaminants that may be present. These calculation cases are summarized 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 Chapter 3 of the Normal Evolution Scenario Analysis report, QUINTESSA 2011a, for more details).

Table 2.2: Calculation Cases for the Human Intrusion Scenario

Case ID^	Brief Description	Associated Detailed Modelling Cases*
HI-BC-A	Normal Evolution Scenario Reference Case (NE-RC-A) but with an exploration borehole drilled from surface down to Panel 1 of the repository at some time after controls are no longer effective (i.e., after 300 years). Borehole terminated at repository depth. As in the Reference Case, it is most likely that the repository is largely unsaturated. The case considers the consequences of surface release of contaminated gas immediately following intrusion. Retrieval of contaminated drill core is also assessed.	-
HI-NR-A	As for HI-BC-A, but assesses the consequences of a release of non-radioactive elements and chemical species.	-
HI-GR2-A	As HI-BC-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 into Panel 1 of the repository and subsequently poorly sealed. The borehole is assumed to penetrate down to the pressurized Cambrian, which provides sufficient head to sustain a flow through the repository and up the borehole for many thousands of years.	HI-GR2-F3

Notes:
^ Case naming conventions are as follows: HI – Human Intrusion Scenario; NE- Normal Evolution Scenario; BC – Base Case; NR – non-radioactive contaminants; GR – groundwater release; RC – Reference Case; A – AMBER model; F3 – FRAC3DVS model.
* Detailed modelling case is described in Section 6.2 of the Groundwater Modelling report (GEOFIRMA 2011).

For the Surface Release Pathway, the impacts of drilling the borehole can be evaluated at a range of different times of intrusion in order to identify the time of peak impacts. For the Shallow Bedrock Groundwater Zone Release Pathway, a fixed time of intrusion must be assessed due to the need to model contaminant migration dynamically in the Shallow Bedrock Groundwater Zone. The time at which controls are assumed to be no longer effective (300 years after DGR closure – see Section 3.8 of the Postclosure SA main report, QUINTESSA et al. 2011a) 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.

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 (QUINTESSA 2011a). These include a full description of:

- The spatial discretization of the repository, geosphere and biosphere: the repository includes distinct components to represent the wastes, which reflect the LLW and ILW waste categories; the geosphere includes distinct components to represent the groundwater zones, each discretized into a series of components that are spatially compatible with the repository design and location, as well as being sufficiently discretized 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, effective diffusivity and saturation) 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 and congruent releases) and the precipitation of C-14 in siderite (a corrosion by-product);
- Diffusion in the geosphere;
- Diffusion, advection and dispersion in the shafts and their associated Excavation Damaged Zones (EDZs);
- 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 gas released into the biosphere,
    - Drill core containing waste,
    - Soil contaminated by waste from drill core,
- To evaluate the impacts of exposure (via ingestion, inhalation, and external irradiation) to contaminated drill core; and
- To determine the amounts of contaminated gas and water that could be released to the surface and Shallow Bedrock Groundwater Zone, respectively.

Mathematical models for calculating exposures are specified in Appendix D, and the calculation of the amounts of gas released from the repository is documented in Appendix E.

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 5.3 (QUINTESSA 2009a, 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, QUINTESSA 2011a). 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 and the released contaminants enter water and gas, which is distinguished between Panel 1 and 2 emplacement rooms and the access tunnels and service area. Precipitation of C-14 in siderite ($FeCO_3$), formed under the geochemical conditions in the emplacement rooms, is also modelled.

The contaminant concentrations used in the Human Intrusion calculations in AMBER for the surface release of contaminated gas and retrieval of drill 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 critical groups are implemented using equations based on those specified in Appendix D.1.2. The amount of gas released is calculated using the approach described in Appendix E.

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_OPG code (see below) between the repository water compartments and the Shallow Bedrock Groundwater Zone compartment overlying the point of intrusion. The water is assumed to originate from the Cambrian and travel through the borehole to the repository, where it mixes with water already in the entire repository (which is assumed to have resaturated), before travelling up the borehole to be released into the Shallow Bedrock Groundwater Zone. This transfer provides a “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 site resident group).

Supporting models have been implemented in the FRAC3DVS_OPG and T2GGM codes to allow the derivation of certain input data for the assessment calculations. The implementation of these models is described in Chapter 4 of the Groundwater Modelling report (GEOFIRMA 2011) (FRAC3DVS_OPG) and Section 4.3 of the Gas Modelling report (GEOFIRMA and QUINTESSA 2011) (T2GGM).

2.4.3 Data

A data report has been developed to support the postclosure safety assessment (QUINTESSA and GEOFIRMA 2011). This comprises reference data that describe the wastes, repository, geosphere and biosphere for the Normal Evolution Scenario’s Reference Case. For context, these data are summarized in Table 2.3.

Where the reference data are available and appropriate 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 (see Appendix F) and other sources of information where possible.

Table 2.3: Key Parameter Values for the Normal Evolution Scenario's Reference Case (Also Used in the Human Intrusion Scenario)

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

PARAMETER	VALUE(S)
EDZ	Inner EDZ, 0.5 x shaft radius thick, K_v x 100 rock, K_h = K_v; porosity 2 x rock mass Outer EDZ, 0.5 x shaft radius thick, K_v x 10 rock, K_h = K_v; porosity = rock mass
Sorption in shaft and EDZ	Certain elements (see Tables 4.25 and 5.13 of the Data report, QUINTESSA and GEOFIRMA 2011)
Geosphere	
Host rock type	Low permeability argillaceous limestone (Cobourg Formation)
Temperature at repository depth	22 °C
Groundwater composition at depth	Na-Ca-Cl dominated brine; TDS: 131-375 g/l; pH: 6.5 to 7.3; Eh: reducing
Hydraulic heads	+165 m at top of the Cambrian sandstone Observed variable head profile with underpressures in the Ordovician (up to -290 m) 0 m at the top of the Lucas formation (top of the Shallow Bedrock Groundwater Zone)
Deep Bedrock Groundwater Zone:	
horizontal hydraulic conductivity	8 x 10^{-15} to 4 x 10^{-12} m/s (1 x 10^{-9} in the Shadow Lake and 3.0 x 10^{-6} in the Cambrian sandstone)
vertical hydraulic conductivity	10% of horizontal hydraulic conductivity for all, but Coboconk and Gull River (0.1%) and Cambrian which is isotropic
transport porosity	0.009 to 0.097
effective diffusion coefficient	2.2 x 10^{-13} to 2.4 x 10^{-11} m^2/s (some anisotropy – Section 5.5.1.4 of the Data report, QUINTESSA and GEOFIRMA 2011a)
horizontal hydraulic gradient	0
Intermediate Bedrock Groundwater Zone:	
horizontal hydraulic conductivity	5 x 10^{-14} to 2 x 10^{-7} m/s
vertical hydraulic conductivity	10% of horizontal hydraulic conductivity for all formations other than Guelph and Salina A1 upper carbonate formations which are isotropic
transport porosity	0.007 to 0.2
effective diffusion coefficient	3 x 10^{-14} to 6.4 x 10^{-11} m^2/s (some anisotropy – Section 5.5.1.4 of the Data report, QUINTESSA and GEOFIRMA 2011a)
horizontal hydraulic gradient	0
Shallow Bedrock Groundwater Zone:	
horizontal hydraulic conductivity	1 x 10^{-7} to 1 x 10^{-4} m/s
vertical hydraulic conductivity	10% of horizontal hydraulic conductivity for all formations
transport porosity	0.057 to 0.077
effective diffusion coefficient	6 x 10^{-12} to 2.6 x 10^{-11} m^2/s
horizontal hydraulic gradient	0.003
Sorption in geosphere	Certain elements (see Table 5.13 of the Data report, QUINTESSA and GEOFIRMA 2011)
Biosphere	
Average annual surface temperature	8.2 ºC
Average total precipitation	1.07 m/a
Ecosystem	Temperate
Geosphere-biosphere interface (for long-term release to Shallow Bedrock Groundwater Zone)	1) 80 m deep well located 500 m down gradient of combined shaft. Well demand of 6388 m^3/a for self-sufficient farm with crop irrigation. 2) near shore lake bed (for discharge from Shallow Bedrock Groundwater Zone)
Sorption in biosphere	For all elements except for B, Li, Tl and W
Land use	Agriculture, recreation, forestry
Critical groups	Drill crew, laboratory technician, and residents (nearby, future and site) – see Sections 2.2.2.4 and 2.2.2.5
Volume of waste retrieved via the drill core	0.1 m^3 (based on drill diameter of 15 cm and 6 m waste stack)
Density of the drill core	1000 kg/m^3
Depth of soil in which drill core is initially mixed	15 cm (used for chronic exposure to drill crew)
Abbreviations in this Table	
LLW: Low Level Waste	TDS: Total Dissolved Solids
ILW: Intermediate Level Waste	L: Length
IX: Ion exchange	W: Width
K_v: vertical hydraulic conductivity	H: Height
K_h: horizontal hydraulic conductivity	HDZ: Highly Damaged Zone
LHHPC: Low Heat High Performance Cement	EDZ: Excavation Damaged Zone

2.4.3.1 Surface Release of Contaminated Gas

The repository gas pressure profile is used to determine the availability of gas for release to the surface via the borehole. Modelling for the Normal Evolution Scenario's Reference Case indicates that gas pressure exceeds atmosphere pressure after several thousand years (Figure 2.7; adapted from Figure 5.27 of the Gas Modelling report, GEOFIRMA and QUINTESSA 2011). In practice, the release of any gas upon intercepting the repository would be inhibited by a blowout preventer, routinely used in deep drilling operations.

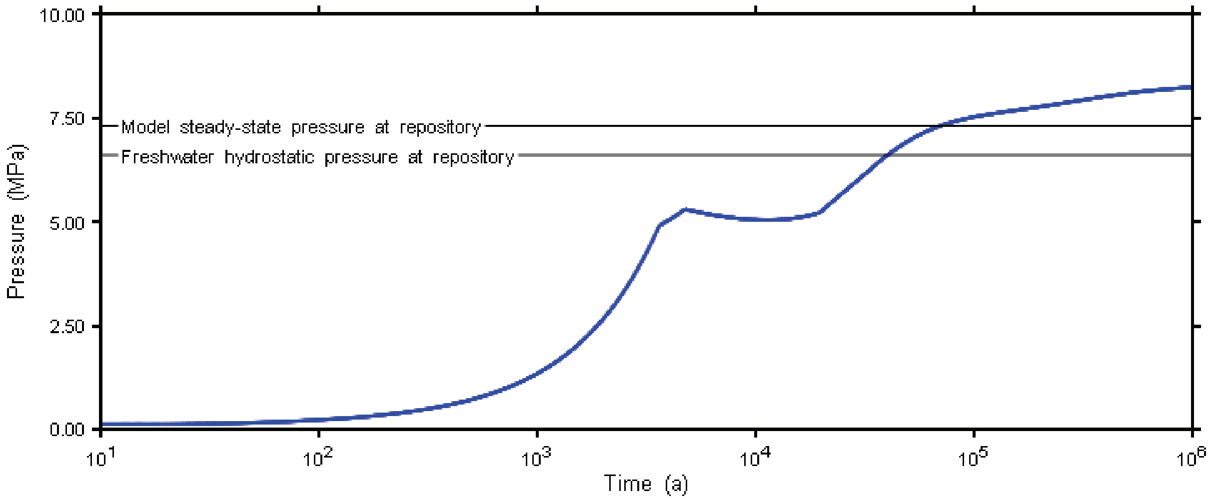

Figure 2.7: Gas Pressure Calculated for the Normal Evolution Scenario Reference Case

The scenario assesses the managed release of the gas by the drillers, using a blowout preventer. A good example of the operation of a blowout preventer is that used during drilling of the DGR investigation boreholes. In these boreholes, any gas release could be vented through a 2-inch diameter pipe, which runs 50 m to a flare pit (stacks are generally required where sour gas is present, but sour gas is not present at the DGR site). The blowout preventers used on the DGR investigation boreholes enable any gas to be bled off at a rate of up to 1 m^3/s at atmospheric pressure. This is similar to typical landfill gas flares, which operate at a gas flux of about 1 m^3/s or less at atmospheric pressure. This value is, therefore, adopted for the assessment. Neglecting change in temperature and taking the volume of gas to equal the repository void and the simulated peak gas pressure, it can be estimated that the gas release would continue for about a year or more if the borehole were not sealed (Appendix E).

The drill crew could inhale released gas while working on the site. Nearby residents could also inadvertently inhale the gas, although there would be greater dilution in the atmosphere. The drill crew is assumed to work in the contaminated area for 12 hours a day over 30 days prior to the sealing of the borehole. For the assessment, a nearby resident is taken to be 100 m from the point of gas release via the borehole. They are assumed to inhale contaminated gas continuously for 30 days (prior to the sealing of the borehole).

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 for the exposure of the drill crew, 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). Using Clarke (1979), a time integrated air dispersion factor of 2.1 x 10^{-4} s/m^3 is used for the longer term exposure of a nearby resident. This value is smaller than the corresponding value for the short-term release, as consideration is given to varying wind direction and atmospheric conditions. Note that if release from the blowout preventer was flared rather than at ground level, the dispersion would be greater than that assumed above.

2.4.3.2 Retrieval of Contaminated Drill Core

The assessment considers a laboratory technician closely examining a sample of core (a mass of 5 kg is adopted, corresponding to a length of about 60 cm) for a duration of 1 hour. The core contains undiluted waste. The concentration of the waste will 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 Panel 1 is used as a reference assumption. A calculation is also made of the consequences of intercepting specific waste categories, to estimate the highest dose that could occur. It is noted that most of the waste is unlikely to be in a form that could be retrieved intact in the drill core.

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 (10 times ambient concentrations given in Table 6.8 of the Data report, QUINTESSA and GEOFIRMA 2011), with inhalation and inadvertent ingestion rates consistent with those considered for the Normal Evolution Scenario (8400 m^3/a and 0.33 g/d, Tables 7.1 and 7.2 of QUINTESSA and GEOFIRMA 2011, respectively). To take account of the limited size of the sample, external irradiation is calculated with the assumption of a point-source geometry and exposure at an average distance, over the one hour period, of 1 m.

2.4.3.3 Contamination of Soil

Material retrieved from the repository may be in an unconsolidated form (drill core and drilling mud), and could become dispersed round the drilling site if poor waste management practices exist. It is assumed that about 0.1 m^3 of waste could be transferred to the surface, and become mixed with soil in this way. This corresponds to the waste in a 6-inch diameter borehole through a waste stack with a nominal height of 5 m.

In calculating contaminant concentrations in the drill core debris, the average activity concentration in waste is assumed. Calculations are also made of the consequences of intercepting specific waste categories to estimate the highest dose that could occur.

Drill Crew

The drill crew is initially exposed to undiluted drill core debris for a period of 4 hours (half a normal shift), and they then continue to work in the contaminated area (taken to be about 1280 m^2 – see next paragraph) 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 x 10^{-7} kg/m^3 (i.e., 10 times the ambient level given in Table 6.8 of the Data report, QUINTESSA and GEOFIRMA 2011), to reflect dusty drilling conditions, with an inhalation rate of 8400 m^3/a (Table 7.1 of QUINTESSA and GEOFIRMA 2011). The inadvertent ingestion rate for the contaminated material is 0.33 g/d (Table 7.2 of QUINTESSA and GEOFIRMA 2011).

Future Resident

For the long-term exposure to drill core debris diluted in soil, the future resident farms the land contaminated with contaminants from the debris. It is conservatively assumed that the contaminants become mixed with soil, but are not leached from it. The habits of the exposed people are the same as adopted for the site resident group assessed in the Normal Evolution Scenario (see QUINTESSA and GEOFIRMA 2011) but, due to the limited volume of the debris, a limited area of contamination is considered. Specifically, an area of about 1280 m^2, sufficient for growing of fruit and vegetables for human consumption, is assumed contaminated by drill core debris.

2.4.3.4 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 (Section 6.2 of the Groundwater Modelling report, GEOFIRMA 2011). The case evaluates the effect of a poorly sealed borehole through the repository extending down to the Cambrian, in which there is a significant overpressure. The flow rate through the borehole is based on the analysis presented in the Groundwater Modelling report that takes account of the Ordovician underpressures (GEOFIRMA 2011). It is assumed that all contaminated repository water is discharged to the Shallow Bedrock Groundwater Zone. The peak flow rate is 15 m^3/a, and the variation with time is illustrated in Figure 2.8 based on output from the HI-GR2-F3 case (Section 6.2.1 of the Groundwater Modelling report, GEOFIRMA 2011). The borehole is assumed to have a hydraulic conductivity of 10^{-4} m/s and porosity of 0.25.

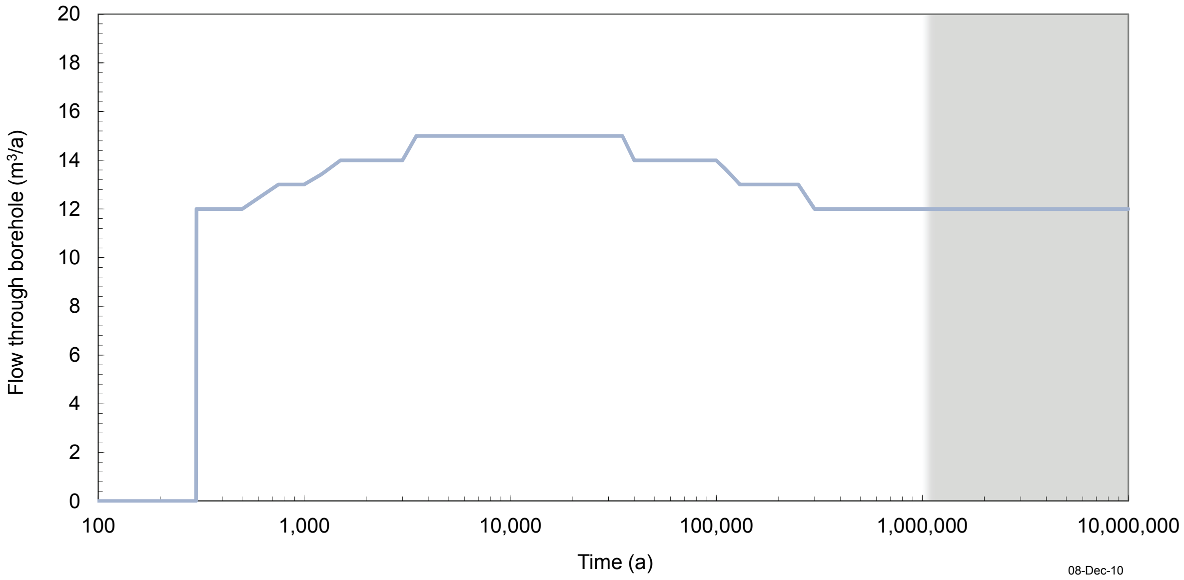

Figure 2.8: Flow through Borehole into Shallow Groundwater in the Human Intrusion Shallow Bedrock Groundwater Zone Pathway

The discharge is conservatively 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 would result in the (relatively) rapid resaturation of the repository, which 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 critical group, are the same as the Reference Case for the Normal Evolution Scenario documented in the Data report (QUINTESSA and GEOFIRMA 2011).

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. 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 – Contaminants in Solid

Under the reference conditions, most of the activity remains in the wastes. The peak saturation of the repository is less than 1%, and under these conditions fluid would not be released from the repository via a borehole. Amounts of radionuclides in the repository decrease over time due to radioactive decay and by migration into the geosphere and shafts. Decay is dominant, and the migration component is very small until very long times because the repository is not expected to resaturate to any significant degree until well after 1 Ma.

Figure 2.9 shows how the average activity concentration in wastes (solids only) changes with time by showing the total volume of waste (solids only) with activity concentration greater than certain levels. This has been calculated with the assessment model, with allowance for the release of contaminants from the wastes by the processes described in Section 2.2.2. In practice the primary mechanism by which contaminant concentrations decrease is radioactive decay. It can be seen that there is an appreciable reduction in the amount of waste with concentrations greater than 100 Bq/g over the first few hundred years (around 75%). By about 100 ka only about 9% of the waste exceeds 10 Bq/g. For comparison, the natural radioactivity of the shale caprock above the repository is around 1 Bq/g.

Average calculated concentrations in the wastes in Panel 1 are given in Figure 2.10, which shows that key contaminants include C-14, Ni-59, Nb-94 and Zr-93/Nb-93m.

For the model that considers the release of drill core debris to the surface, it is assumed that the contaminated material is mixed with soil (Section 2.2.2.3). The ratio of the calculated peak concentrations for radionuclides in the soil to the No Effect Concentrations for soil (listed in Table 7.11 of the Data report, QUINTESSA and GEOFIRMA 2011) is given in Table 2.4. This shows that both C-14 and Nb-94 exceed the screening criterion by about a factor of 20, while all other radionuclides are below the criterion.

For disruptive scenarios, the acceptance in such a situation is to be judged on a case-by-case basis taking into account the likelihood and nature of the exposure, uncertainty in the assessment, and conservatism in the dose criterion (QUINTESSA et al. 2011a). Since this intrusion is an unlikely scenario and the exposure is localized around the drill site, the risk is low. Furthermore, less conservative ecological risk assessment calculations show that the resulting doses to site-specific Valued Ecosystem Components biota are around 3% of relevant dose criterion. Further details of this assessment are presented in Appendix G.

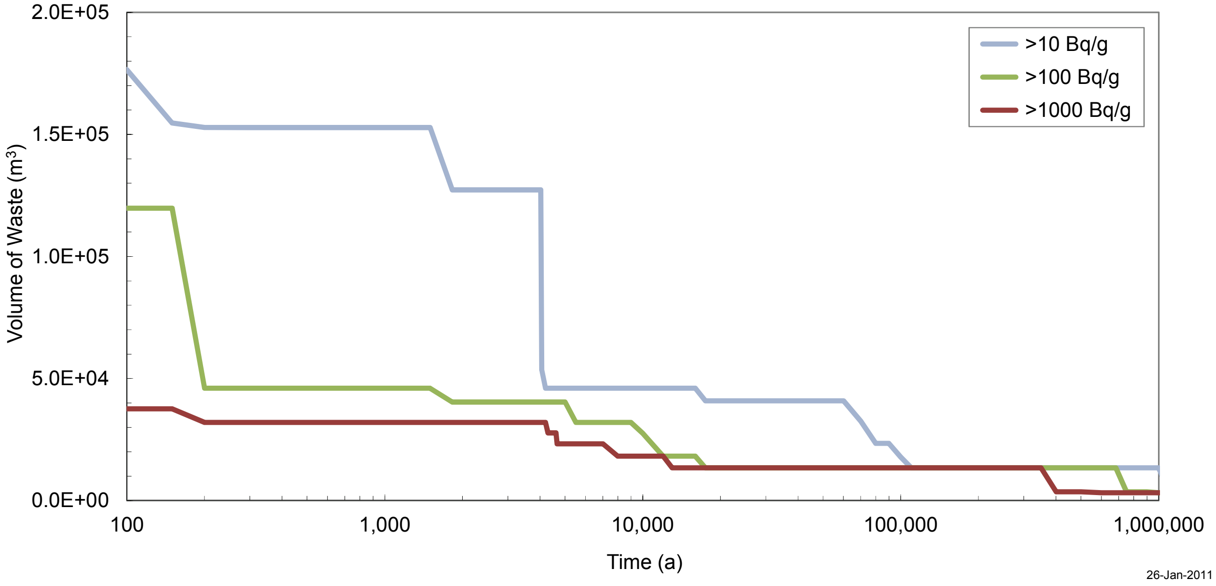

Figure 2.9: Volume of Wastes with Activity Concentration Greater than 10, 100 and 1000 Bq/g, as a Function of Time for the Human Intrusion Base Case (HI-BC)

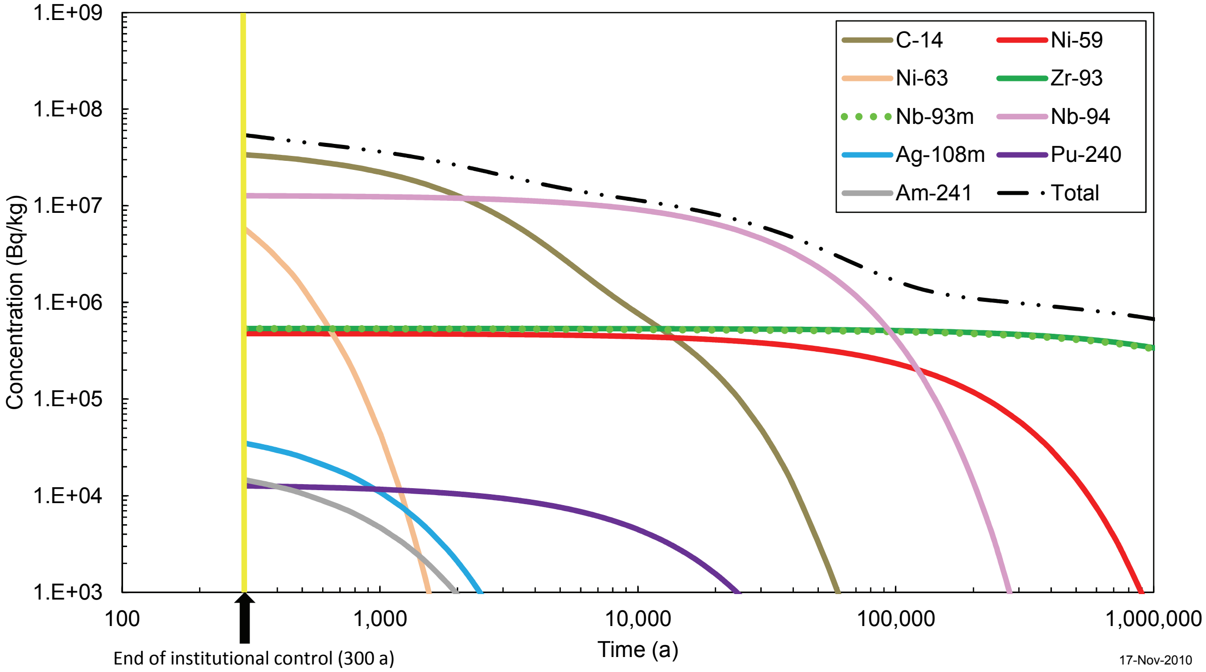

Figure 2.10: Calculated Average Concentrations of Radionuclides in Wastes in Panel 1, as a Function of the Time, for the Human Intrusion Base Case (HI-BC)

Table 2.4: Ratio of Calculated Maximum Concentration of Radionuclides in Soil to No Effect Concentrations for the Human Intrusion Base Case (HI-BC)

Radionuclide	Ratio
C-14	**1.8E+01**
Cl-36	1.5E-01
Zr-93	3.6E-04
Nb-94	**1.9E+01**
Tc-99	1.4E-03
I-129	6.1E-09
Ra-226	1.2E-04
Np-237	2.2E-05
U-238	6.9E-04
Pb-210	8.9E-06
Po-210	1.1E-03

Notes: Exceedances highlighted in **bold**. No Effect Concentrations for non-human biota are given in Table 7.11 of the Data report (QUINTESSA and GEOFIRMA 2011). This case assumes that an intrusion borehole results in drill core debris becoming mixed with soil.

Concentrations of non-radioactive contaminants in soil are also calculated using the same model as for radioactive contaminants. The ratio of the calculated peak concentration of each contaminant in the soil to its Environmental Quality Standard (EQS) for soil (listed in Table 7.12 of the Data report, QUINTESSA and GEOFIRMA 2011) are given in Table 2.5. Even with the conservative assumptions (e.g., drilling debris left on site), the ratio for all contaminants is less than the relevant EQS value.

Table 2.5: Ratio of Calculated Peak Concentration of Non-radioactive Contaminants in Soil to Environmental Quality Standards for the Human Intrusion Base Case (HI-NR)

Contaminant	Ratio
Ag	1.3E-05
As	9.4E-05
B	2.7E-04
Ba	9.0E-05
Be	2.9E-04
Cd	3.3E-02
Co	7.9E-05
Cr	1.1E-01
Cu	2.3E-01
Hg	1.3E-03
Mo	2.7E-01
Ni	1.5E-01
Pb	2.2E-01
Sb	6.0E-03
Se	2.0E-04
Tl	6.1E-07
U	1.1E-03
V	0.0E+00
Zn	1.4E-03
Chlorobenzene/ Chlorophenol	1.6E-04
Dioxins/Furans	8.1E-03
PAH	2.8E-05
PCB	3.2E-07

Notes: Environmental quality standards are given in Table 7.12 of the Data report (QUINTESSA and GEOFIRMA 2011). This case assumes that an intrusion borehole results in drill core debris becoming mixed with soil.

2.5.1.2 Surface Release Pathway – Contaminants in Gas

Gas is present in the repository at significantly greater than atmospheric pressure throughout the assessment timeframe and would be released after the borehole penetrates the repository. Gas is assumed to mix throughout the repository, so the concentrations reflect the overall average. Radionuclides present in repository gas are H-3, C-14, Se-79, I-129 and Rn-222. As shown in Figure 2.11, only C-14 and Rn-222 are present at concentrations above 1 Bq/m^3. C-14, released primarily from ion exchange resins under saturated and unsaturated conditions, is present with the greatest activity. The concentration of C-14 in gas at repository pressure peaks at 3 ka, then decreases due to radioactive decay. The concentration of Rn-222 decreases at first due to the decay of its Ra-226 parent (present as a sealed source in some wastes) at repository pressure but then shows subsequent ingrowth from longer-lived U-238/ U-234[3].

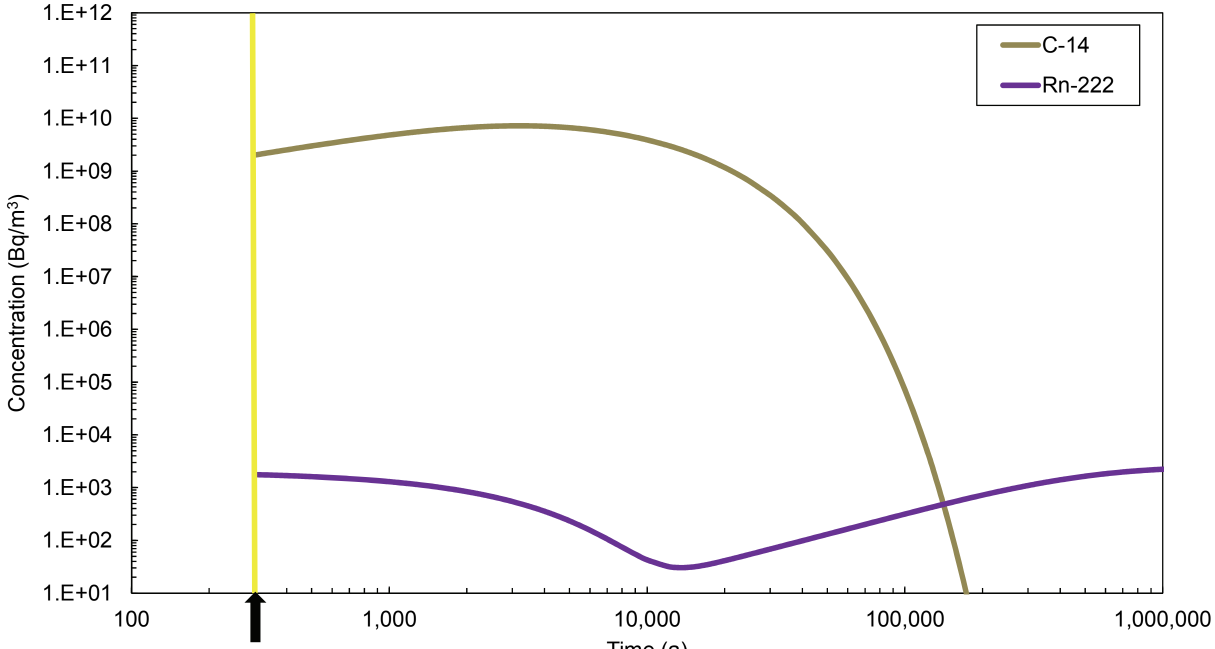

Figure 2.11: Calculated Concentrations of Radionuclides in Repository Gas at Repository Pressure as a Function of Time for the Human Intrusion Base Case (HI-BC)

2.5.1.3 Shallow Bedrock Groundwater Zone Pathway following Intrusion after 300 a

If the borehole were not sealed properly, it could remain as an enhanced permeability pathway over the long-term. Under such circumstances, contaminants could be released from the repository through the borehole, only if the borehole penetrated the repository and continued to the pressurized Cambrian rocks below it. The calculation case conservatively considers this

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

case, with the borehole drilled through the repository 300 a after closure and subsequently only poorly sealed.

The model calculates fluxes of contaminants through the borehole based on the groundwater flow rate provided by the Groundwater Flow model (Figure 2.8; Section 6.2 of the Groundwater Modelling report, GEOFIRMA 2011). The fluxes are presented in Figure 2.12. Contaminants are released to the Shallow Bedrock Groundwater Zone, with peak releases for some contaminants occurring immediately after the intrusion event. For this case, shorter-lived radionuclides such as C-14 and Ni-63 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.

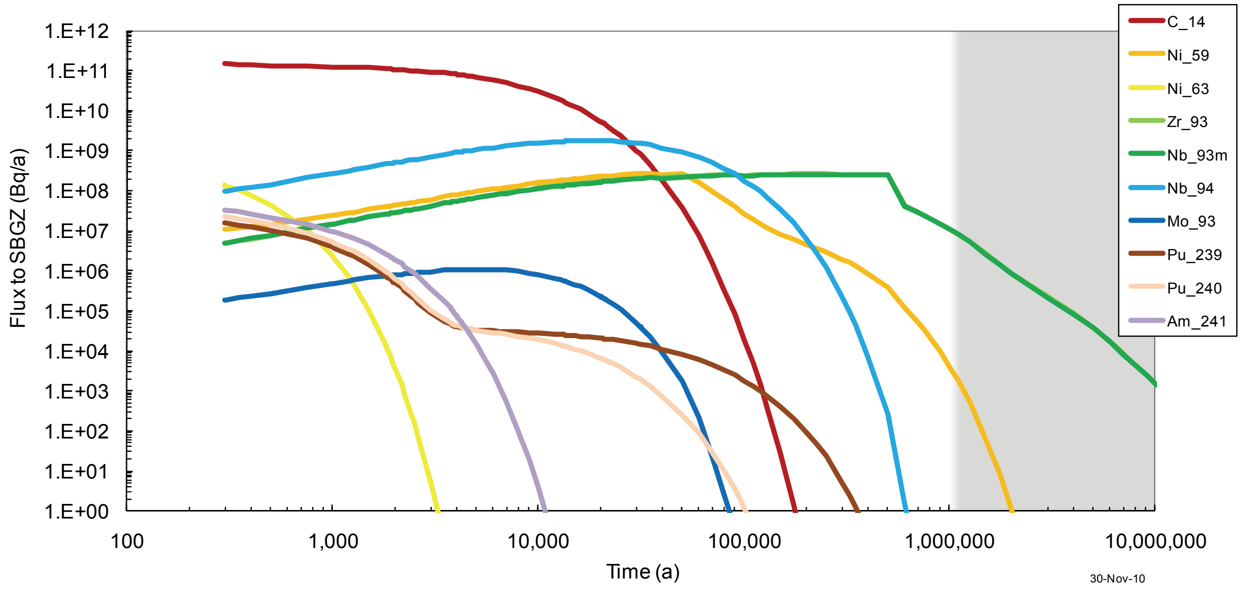

Figure 2.12: Flux of Contaminants Released into the Shallow Bedrock Groundwater Zone via an Intrusion Borehole Drilled into Cambrian Formation 300 years after Repository Closure and Poorly Sealed (HI-GR2)

The result of the borehole pathway is that much 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 engineered shaft seals and the intermediate and deep geological barriers. The dominant calculated doses relate to the release of contaminants in groundwater via a well. Figure 2.13 shows the calculated concentrations of contaminants present in well water. C-14 is dominant up to 25 ka, then Nb-94 to 90 ka, with Nb-93m (ingrown from the Zr-93) dominant thereafter. The ratio of the resulting environmental concentrations to the no effect concentrations (given in Table 7.11 of the Data report, QUINTESSA and GEOFIRMA 2011) are summarized in Table 2.6. It can be seen that there are no exceedances.

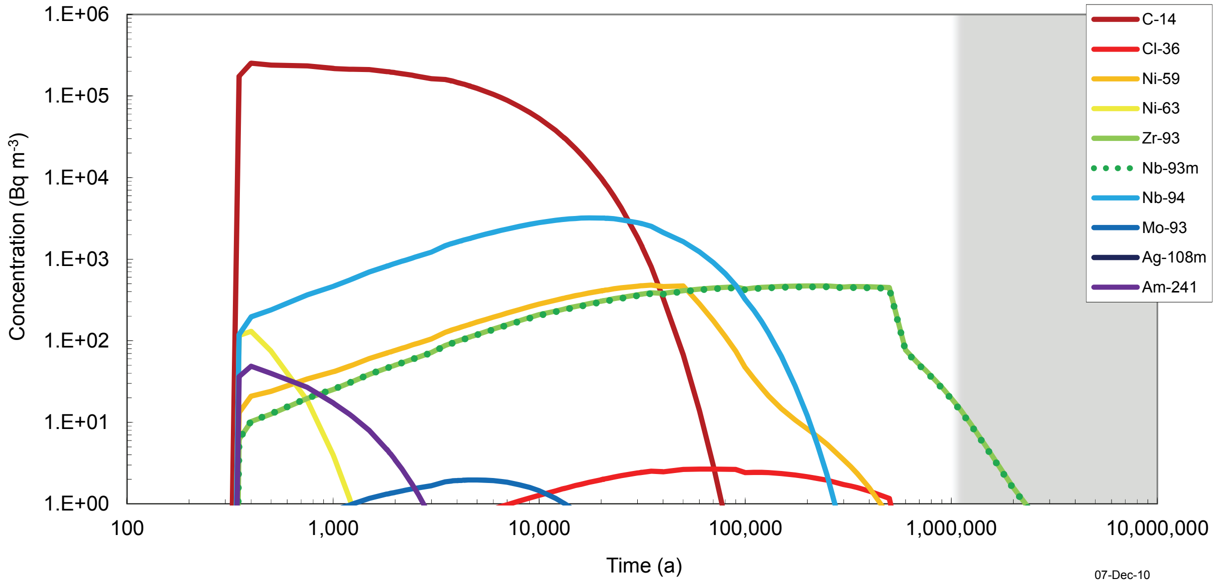

Figure 2.13: Calculated Concentration of Radionuclides in Well Water, Assuming a Poorly Sealed Intrusion Borehole Provides a Pathway from the Cambrian via the Repository to the Shallow Bedrock Groundwater Zone (HI-GR2)

Table 2.6: Ratios of Calculated Peak Concentration of Radionuclides in Surface Media to No Effect Concentrations (HI-GR2)

Radionuclide	Well Water	Irrigated Soil	Sediment	Surface Water
C-14	1.6E-04	3.7E-02	2.7E-05	3.1E-01
Cl-36	9.1E-09	6.6E-04	2.8E-10	1.4E-06
Zr-93	8.0E-08	2.0E-10	1.7E-06	4.4E-04
Nb-94	9.0E-05	1.1E-05	5.7E-04	3.4E-01
Tc-99	6.2E-10	2.3E-06	<1E-10	1.1E-06
I-129	<1E-10	<1E-10	<1E-10	3.4E-09
Ra-226	9.5E-08	1.7E-09	2.4E-08	1.6E-04
Np-237	9.1E-09	1.9E-09	5.6E-10	1.5E-07
U-238	6.0E-08	1.5E-09	9.2E-10	2.4E-06
Pb-210	3.2E-10	<1E-10	1.2E-06	1.9E-08
Po-210	1.1E-07	2.4E-10	1.7E-09	1.3E-05

Notes: No Effect Concentrations for non-human biota are given in Table 7.11 of the Data report (QUINTESSA and GEOFIRMA 2011). This case assumes that a poorly sealed intrusion borehole provides a pathway from the Cambrian via the repository to the Shallow Bedrock Groundwater Zone.

2.5.2 Calculated Radiation Doses

2.5.2.1 Surface Release Pathway – Radionuclides in Solid and Gas

At the time of intrusion, the main release pathway is direct release to surface of gas and contaminated drill core. The peak calculated doses to the various critical groups assessed for the Surface Release Pathway, based on the Base Case, are summarized in Table 2.7. Peak doses for three of the critical groups are below the dose criterion of 1 mSv/a applied to Disruptive Scenarios (see Section 3.4.2 of QUINTESSA et al. 2011a), while the dose for one group (the future resident) is equal to the criterion.

Table 2.7: Summary of Annual Peak Calculated Doses for the Human Intrusion Surface Release Pathway for the Base Case (HI-BC), Showing Time of Peak, Dominant Pathway and Radionuclide, as a Result of Released Gas or Exposure to Contaminated Drill Core

	Critical Group			
	Drill crew	**Laboratory technician**	**Nearby resident**	**Future resident**
Peak dose	7.6E-1 mSv	6.3E-2 mSv	1.0E-1 mSv	1.0E+0 mSv/a
Duration of exposure (h)	360	4	720	8760
Time of peak (a)	300	300	300	300
Dominant pathway	External irradiation	External irradiation	Inhalation (gas)	External irradiation
Dominant radionuclide	Nb-94	Nb-94	C-14	Nb-94

The future resident (i.e., a person subsequently living on the site and using soil contaminated with drill core debris) could receive a peak annual dose of 1.0 mSv, based on the average concentration of radionuclides in Panel 1 wastes, with external irradiation from Nb-94 being the dominant pathway. The drill crew, exposed to contaminated drill core debris receives a dose of 0.76 mSv. A nearby resident assumed to live close to the drilling site and therefore also exposed to the contaminated gas receives a peak dose of 0.1 mSv from the inhalation of C-14. The doses to those involved with inspecting any wastes in retrieved drill core are 0.063 mSv and are dominated by external irradiation by Nb-94.

The Human Intrusion Scenario has a low probability of occurrence of about 10^{-5}/a (see Section 2.5.3). Based on a health risk of 0.057/Sv (ICRP 2007), the associated risk of serious health effects for the future resident is around 6×10^{-10}/a, well below the reference health risk value of 10^{-5}/a given in Section 3.4.2 of QUINTESSA et al. (2011a).

The above doses are calculated using the average concentration of radionuclides in Panel 1. If the wastes with the highest activity concentrations were encountered (retube wastes), the dose to a laboratory technician and future resident could be around an order of magnitude higher. However, the small proportion of the total volume of wastes occupied by such wastes (less than 7%) reduces the probability of such an exposure, resulting in the health risks remaining around 10^{-9}/a.

As 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 2.14, reflect the calculated concentrations presented in Section 2.5.1. The potential dose from human intrusion decreases after about 10 ka due to decay.

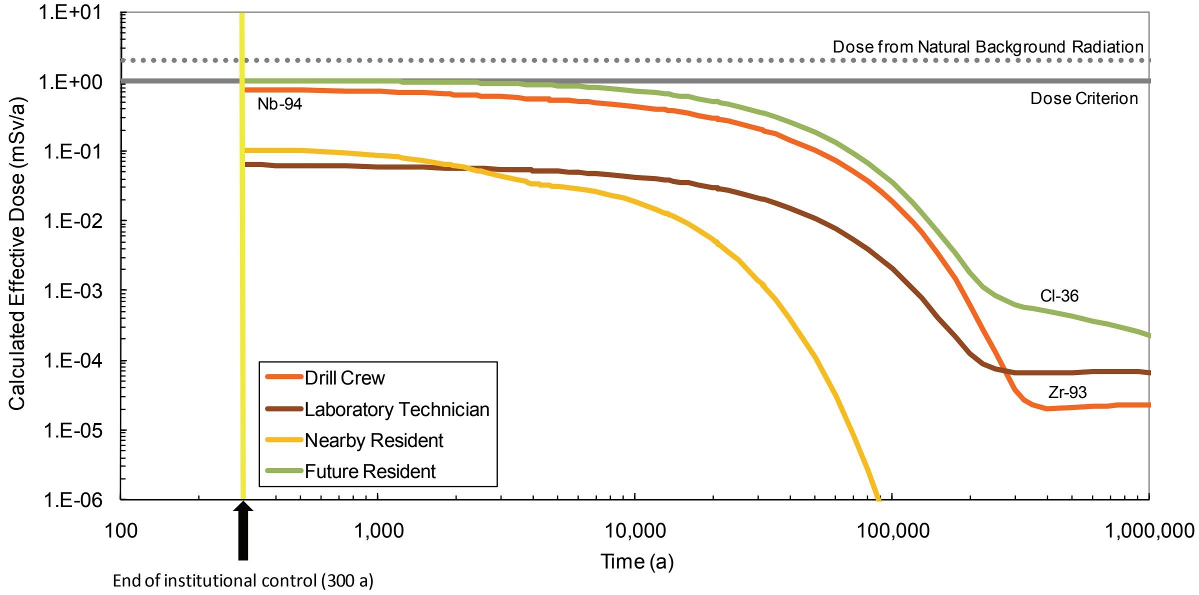

Figure 2.14: Calculated Doses from Human Intrusion Surface Release of Gas and Drill Core, as a Function of the Time of Intrusion, for the Human Intrusion Base Case (HI-BC)

2.5.2.2 Shallow Bedrock Groundwater Zone Release Pathway

The Shallow Bedrock Groundwater Zone Release Pathway evaluates the potential effects of long-term release of contaminated water from the repository through a borehole that has not been properly sealed. This could only occur if the borehole is drilled down to the Cambrian; if it were terminated at the repository there would be no releases as flow would be directed towards the repository since the Ordovician rocks are underpressured (Section 6.1.1 of GEOFIRMA 2011).

The potential exposures arising from the Shallow Bedrock Groundwater Zone Release Pathway are assessed for the same site resident group as in 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 higher than calculated for the Normal Evolution Scenario. The doses peak at approximately 30 mSv/a after 400 a. The dominant contaminant is again C-14, and the dominant pathways are the ingestion of contaminated plants. After 60 ka Nb-94 is the dominant radionuclide, but at this time the calculated annual dose has decreased to 0.003 mSv/a.

Assuming the same probability of occurrence as for intrusion into the repository (thereby conservatively assuming the probability of continuing into the Cambrian and poorly sealing the borehole is unity), the peak dose equates to a risk of serious health effects of around 2 x 10^{-8}/a, more than two orders of magnitude below the reference health risk value of 10^{-5}/a.

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. The likelihood would be very small due to the depth of the DGR (over 680 m), and because the DGR site is located in a regional geology that is relatively uniform and predictable over an extensive area, and does not have any significant resource potential. Although this likelihood cannot be reliably quantified, its general scale can be assessed though the following discussion.

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 range of values from Canadian, Japanese and UK sources suggested deep drilling rates to greater than 500 m as around 0.1-10 x 10^{-10} /(m^2 a) (Section 8.4.2 of Gierszewski et al. 2004).

This estimate is supported by the following conceptual argument. If a geological region of interest is re-surveyed every 100 years, 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 10^{-10} /(m^2 a).

The footprint of the panels is around 0.25 km^2 and about 0.065 km^2 is the actual emplacement room area (Table 4.3 of the Data report, QUINTESSA and GEOFIRMA 2011). This implies a likelihood of intrusion of about 10^{-5}/a. The likelihood of encountering the most radioactive wastes, such as retube wastes, is lower still. For example, retube wastes occupy 7% of the volume of all wastes.

Although there are no specific anti-intrusion aspects of the design, equipment capable of drilling to the depth of the DGR would be sufficiently sophisticated to be able to detect the presence of the DGR, and any retrieved material that was unusual in character would be expected to be carefully investigated. The consequences assessed above are based on assuming that the drilling is handled poorly, that retrieved material is not recognized as radioactive, and that subsequently the site is improperly abandoned.

This estimate of likelihood can be interpreted in two ways as: 1) a measure of the likelihood that an individual is exposed in a given year (see Section 2.5.2.1); 2) a measure of the likelihood that intrusion occurs during the assessment timeframe. Over the 1 Ma timescale under consideration in the assessment, the estimate of likelihood implies a high probability that intrusion will occur at some stage.

However, it is important to recognise that the probability of the consequences occurring is lower than that of intrusion occurring, since the scenario makes a range of additional conservative assumptions, for example:

- **Drill Crew** – the gas is assumed to be released at a relatively high rate, the workers do not recognise and respond to the risk, and there is conservative parameterization of exposure pathways (e.g., inhalation of contaminated gas);
- **Laboratory Technician** – the conservative parameterization of exposure pathways, such as the assumed high dust loading and lack of dust mask;
- **Nearby Resident** – the nearest resident is assumed to be only 100 m from the drill site, and gas is assumed to be released at a relatively high rate; and
- **Future Resident** –drill core debris is assumed to be spread on site contrary to current regulations, the residents start farming on the site immediately after closure of the site, and the parameterization of the critical group is conservative.

Finally, the results show that the peak consequences from Human Intrusion occur within 5 ka. At longer times, especially after 70 ka, although the likelihood of intrusion may increase, the actual consequences become small mostly due to the decay of C-14 and Nb-94.

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 seals fail (Section 8.2.2 of the System and Its Evolution report, QUINTESSA 2011b). This could be because the shaft seal materials are not fabricated or installed appropriately, or the long-term performance of the seal materials is poor due to unexpected physical, chemical and/or biological processes. Either situation could result in an enhanced permeability pathway to the surface environment. The scenario is referred to as the **Severe Shaft Seal Failure Scenario**. Given the quality control measures that will be applied to the DGR shaft seal closure, and the multiple durable material layers in the shaft, 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 rapid and extensive degradation in the shafts seals and the repository/shaft EDZs. The exposure pathways and critical group assessed are the same as those considered in the Normal Evolution Scenario (Section 2.3 of the Normal Evolution Scenario Analysis report, QUINTESSA 2011a). In common with the Normal Evolution Scenario, a house is assumed to be located on the main shaft, and the soil for growing vegetables is above the ventilation shaft.

The scenario is illustrated in Figure 3.1.

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, QUINTESSA 2011a) with the exception that the shaft seals do not function as planned and the repository/shaft EDZs have significantly degraded properties. This could be due to human factors (i.e., the shafts are not sealed to the required specification), or natural factors (i.e., chemical and/or physical conditions in the geosphere cause the seals to degrade more rapidly than anticipated). The key features are summarized in Table 3.1.

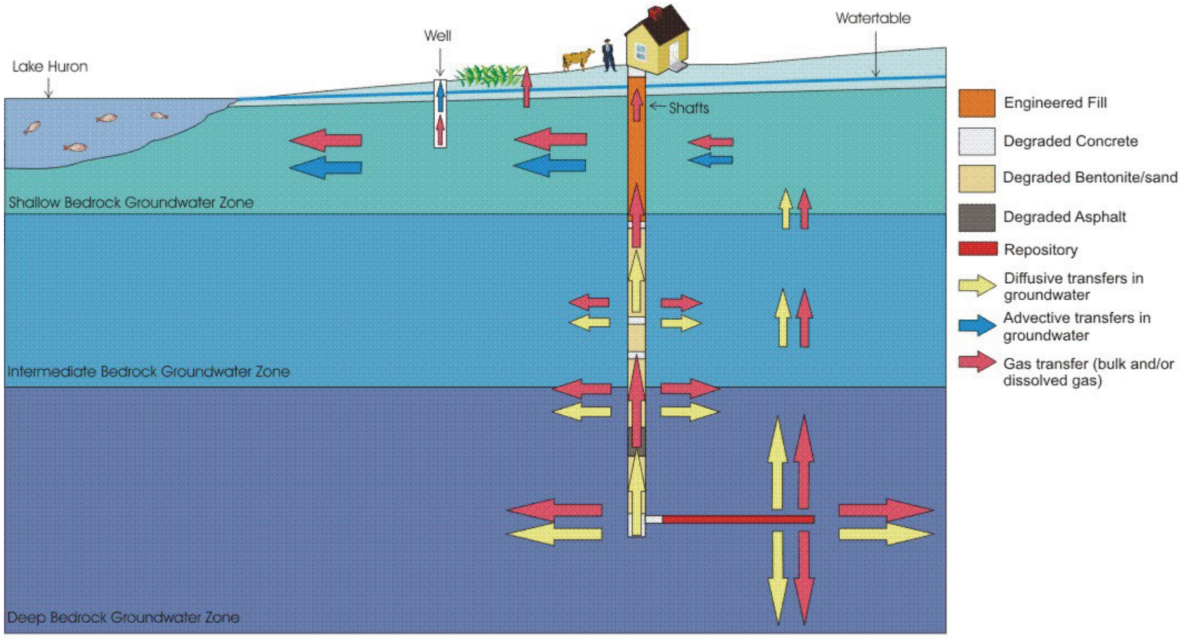

Figure 3.1: Schematic Representation of Severe Shaft Seal Failure Scenario

Table 3.1: Summary of Key Features for the Severe Shaft Seal Failure Scenario

Waste and Repository Features[1]	**Geosphere Features**[1]	**Biosphere Features**[1]
• Waste packages • Water (Panels 1 and 2 emplacement rooms, access tunnels, and shaft & service area) • Gas (Panels 1 and 2 emplacement rooms, access tunnels, and shaft & service area) • **Engineered Structures (concrete monolith, shaft seals** and shaft backfill)	• Deep Bedrock Groundwater Zone • **Repository Highly Damaged Zone** • **Repository and Shaft Excavation Damaged Zones** • Intermediate Bedrock Groundwater Zone • Shallow Bedrock Groundwater Zone	• Well Water • Surface Water and Sediment (stream and wetland) • Lake Water and Sediment • Soil • Biota • Atmosphere

Note:

1. Features in **Bold** require specific modelling assumptions for this scenario that differ from the Normal Evolution Scenario.

3.2.2 Description of the Conceptual Model

The conceptual model is the same as for the Normal Evolution Scenario Reference Case (Section 2.3 of the Normal Evolution Scenario Analysis report, QUINTESSA 2011a), 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 monolith and the shaft seals (from the time of closure); and
- Increased permeability of the repository/shaft EDZs.

Detailed modelling (Sections 6.1 and 6.2 of the Gas Modelling report, GEOFIRMA and QUINTESSA 2011) of the Base Case for the Severe Shaft Seal Failure Scenario shows that these differences initially result in a much increased flow of water via the shafts into the repository. This increases the rate of resaturation of the repository such that it reaches a water saturation of about 68% by about 500 ka. After about 20 ka, the pressure and saturation in the repository is sufficient to create a free gas pathway via the Highly Disturbed Zone above the monolith and up the degraded shafts. A desaturated pathway is established and permits gas transport up the shaft until the water level in the repository rises above the top of the Highly Disturbed Zone at approximately 150 ka. This terminates the high-permeability connection and gas transport up the shaft ceases.

The results of the groundwater modelling (Section 6.3 of GEOFIRMA 2011) indicate that groundwater flows down the shafts towards the DGR in the Ordovician throughout the million year simulations. The gas modelling (Chapter 6 of GEOFIRMA and QUINTESSA 2011) indicates that free gas flow up the shafts is rapid when it occurs and it can reach the Shallow Bedrock Groundwater Zone. The conceptual model for the fate of any free gas reaching the Shallow Bedrock Groundwater Zone is described in Appendix H.

The key aspects of the conceptual model for releases from the repository are summarized in Box 2.

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 Section 2.3 of the Normal Evolution Scenario Analysis report, QUINTESSA 2011a) with only differences relating to parameters describing the performance of the seals and repository/shaft EDZs (Section 3.2.2).

Thus, the only internal FEPs that differ in the Severe Shaft Seal Failure Scenario relate to the seals and EDZs; these are itemized below.

- FEP 2.1.05 (Shaft characteristics) – the shaft seals (including the concrete monolith) 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 may occur 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.

Box 2:
Key Aspects of the Conceptual Model for the Severe Shaft Seal Failure Scenario[1]

Waste and Repository:

- The repository EDZ permeability is increased by an order of magnitude compared with the Normal Evolution Scenario Reference Case.
- Resaturation of the repository is determined by detailed modelling (Chapter 6 of GEOFIRMA and QUINTESSA 2011) which evaluates water inflow/outflow, gas generation, gas inflow/outflow and gas pressure (see Section 3.4.3).
- Contaminants migrate into the host rock and shafts by diffusion and/or advection or by gas permeation (driven by repository gas pressure relative to the porewater pressure) or by gas dissolution into groundwater.

Geosphere and Shafts:

- The entire shaft seals are physically and chemically degraded from the time of closure. This includes increased permeability and zero capillary pressure.
- The shaft EDZs have increased permeability (two orders of magnitude for inner EDZ and one order of magnitude for outer EDZ) compared with the Normal Evolution Scenario Reference Case.
- Reduced sorption of Zr, Nb, Pb, U, Np and Pu by an order of magnitude on bentonite/sand compared with the Normal Evolution Scenario Reference Case.
- Groundwater flows towards the DGR via the shafts throughout the modelled period (Sections 6.3 and 6.4 of GEOFIRMA 2011).
- Flow of free-phase gas via the shafts/EDZs (Chapter 6 of GEOFIRMA and QUINTESSA 2011) to the Shallow Bedrock Groundwater Zone.

Biosphere:

- Model is the same as the Normal Evolution Scenario.

Note:
1. All other modelling assumptions are as described for the Normal Evolution Scenario Reference Case (Section 2.3 of QUINTESSA 2011a)

- Degradation of the shaft materials from time of closure.
- FEP 2.1.09 (Biological/biochemical processes and conditions in shafts) – enhanced degradation of the shaft materials from time of closure.
- FEP 2.2.03 (Disturbed Zone (in geosphere)) – enhanced permeability in repository and shaft EDZs.

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 largely the same. These are discussed in Section 2.5 of the Normal Evolution Scenario Analysis report (QUINTESSA 2011a) and so are not repeated 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 repository/shaft EDZs (a key conceptual model uncertainty for the Normal Evolution Scenario). The Severe Shaft Seal Failure Scenario investigates these uncertainties by considering “what if” treatment of the performance of the shaft seals and the repository/shaft EDZs.

3.3 Calculation Cases

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

Table 3.2: Calculation Cases for the Severe Shaft Seal Failure Scenario

Case ID	Brief Description	Associated Detailed Modelling Cases*
SF-BC-A	As for the Normal Evolution Scenario Reference Case (NE-RC-A) but properties of shaft seals and repository/shaft EDZs set to significantly degraded values from closure (e.g., hydraulic conductivity of 10^{-9} m/s for the seals), zero capillary pressure for shaft sealing materials, and reduced sorption on bentonite/sand. Groundwater flow from the DGR via the shafts based on detailed gas and groundwater modelling. Free gas flows via the shafts based on detailed gas modelling case.	SF-BC-F3 and SF-BC-T2
SF-ED-A	As SF-BC-A, but increased bentonite/sand, asphalt and concrete hydraulic conductivity (10^{-7} m/s) in order to understand the sensitivity of system performance to shaft seal properties. This is in the range of a fine sand/silt material, about 4-5 orders of magnitude more permeable than the design-basis bentonite/sand and asphalt seals.	SF-ED-F3 and SF-ED-T2
SF-NR-A	As SF-BC-A, but assesses consequences of non-radioactive elements and chemical species.	SF-BC-F3 and SF-BC-T2

Notes:
SF – Severe Shaft Seal Failure Scenario; BC – Base Case; ED – Extra Degradation; NR – non-radioactive contaminants; RC – Reference Case; A – AMBER; F3 – FRAC3DVS; T2 – T2GGM
* Detailed modelling cases are described in Sections 6.3 and 6.4 of the Groundwater Modelling report (GEOFIRMA 2011) and Chapter 6 of the Gas Modelling report (GEOFIRMA and QUINTESSA 2011).

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 Reference Case for the Normal Evolution Scenario (see Chapter 3 of the Normal Evolution Scenario Analysis report, QUINTESSA 2011a, for more details). The only modifications for SF-BC-A, SF-ED-A and SF-NR-A cases are:

- Both cases adopt the initial vertical head gradient from the Reference Case of the Normal Evolution Scenario, which includes the underpressures observed in Ordovician formations;
- The properties of shaft seals and repository/shaft EDZ are set to significantly degraded values from closure, with zero capillary pressure for all shaft seal materials;
- More rapid transfers of groundwater through the shafts are specified (based on detailed groundwater modelling of the scenario, Sections 6.3 and 6.4 of GEOFIRMA 2011);

- Periodic free gas flow occurs via the shafts (based on detailed gas modelling of the scenario, Chapter 6 of GEOFIRMA and QUINTESSA 2011); and
- A resaturation profile based on detailed gas modelling of the scenario (Sections 6.1.2.2 and 6.2.2.2 of GEOFIRMA and QUINTESSA 2011). Figure 3.2 compares the depth of water in the repository for the SF-BC and SF-ED cases with that calculated for the Reference Case of the Normal Evolution Scenario (NE-RC).

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

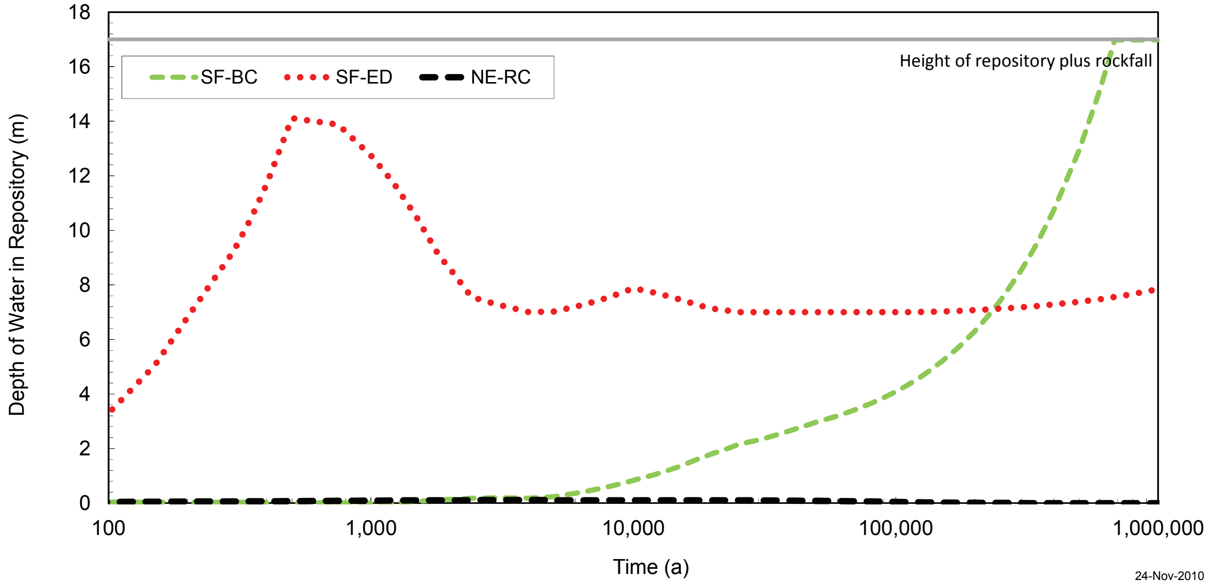

Figure 3.2: Repository Resaturation Profiles Assessed for the Severe Shaft Seal Failure Scenario

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 repository/shaft EDZs and simulating the associated flow rates of groundwater and gas. The mathematical models used are described in detail in Section 4.1 of the Normal Evolution Scenario Analysis report (QUINTESSA 2011a).

3.4.2 Software Implementation

The scenario is implemented in AMBER Version 5.3 (QUINTESSA 2009a, 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.

In addition, models have been implemented in the FRAC3DVS and T2GGM codes to allow the derivation of certain input data for the assessment calculations (see Appendix F). The implementation of these models is described in Chapter 4 of the Groundwater Modelling report (GEOFIRMA 2011) (FRAC3DVS) and Chapter 4 of the Gas Modelling report (GEOFIRMA and QUINTESSA 2011) (T2GGM).

3.4.3 Data

The Severe Shaft Seal Failure Scenario adopts the same parameter values as for the Normal Evolution Scenario Reference Case (summarized in Table 2.3) with the exception that pessimistic values are adopted for the engineered materials in the shaft and the repository and shaft EDZs. These are conservatively assigned to the model from closure onwards. The hydraulic conductivities, porosities, densities and diffusion coefficients are summarized in Table 3.3. The sorption values are presented in Table 3.4 and are an order of magnitude lower than the reference values given in the Data report (QUINTESSA and GEOFIRMA 2011). The Data report only presents values for bentonite/sand; no sorption is assumed for other materials.

It is assumed that the hydraulic conductivity of the inner and outer shaft EDZs are four and two orders of magnitude greater than the rock mass, respectively (rather than the two and one orders of magnitude assumed for the Normal Evolution Scenario Reference Case). The hydraulic conductivity of the repository EDZ is four orders of magnitude greater than the rock mass (rather than the three orders of magnitude assumed for the Normal Evolution Scenario Reference Case). The advective velocities that are used in the AMBER model are taken directly from the results of groundwater modelling (Sections 6.3 and 6.4 of GEOFIRMA 2011). The models include the underpressures observed in the Ordovician formations above the DGR. The detailed modelling indicates that groundwater flow via the shafts, within the Deep Bedrock Groundwater Zone, remains downwards throughout the million year simulations for both severe shaft seal failure cases.

The detailed gas modelling indicates the potential for free gas to travel up the shafts. Some of this gas will dissolve in the Shallow Bedrock Groundwater Zone (Sections 6.1 and 6.2 of GEOFIRMA and QUINTESSA 2011), and some may reach the surface as free gas. The gas reaching the surface via the ventilation shaft is directed to the soil, whereas that reaching the surface via the main shaft is directed into a house. The area of soil that may receive gas from the ventilation shaft is taken to be ten times the area of the shaft itself, to reflect the potential dispersion of the gas through the relatively high permeability Shallow Bedrock Groundwater Zone.

The resaturation profile used is based on detailed model results (Section 6.1.2.2 and 6.2.2.2 of GEOFIRMA and QUINTESSA 2011) (see Figure 3.2).

Table 3.3: Properties of Shaft Sealing Materials for the Severe Shaft Seal Failure Scenario

Parameter	Shaft Sealing Material	SF-BC and SF-NR	SF-ED	NE-RC (9)
Vertical and Horizontal Hydraulic Conductivity (m/s) (1)	Concrete (3)	1E-09 (4)	1E-07 (4)	1E-10 (10)
	Bentonite/sand			1E-11 (10)
	Asphalt			1E-12 (10)
	Engineered Fill	1E-04 (5)	1E-04 (5)	1E-04 (10)
Diffusion and Transport Porosities (-) (2)	Concrete (3)	0.3 (4)	0.3 (4)	0.1 (10)
	Bentonite/sand			0.29 (10)
	Asphalt			0.02 (10)
	Engineered Fill	0.25 (5)	0.25 (5)	0.25 (10)
Dry Bulk Density (kg/m^3)	Concrete (3)	1860 (6)	1860 (6)	2390 (11)
	Bentonite/Sand			1600 (11)
	Asphalt			1960 (11)
	Engineered Fill			1990 (11)
Horizontal and Vertical Effective Diffusion Coefficient (m^2/s)	Concrete (3)	3.0E-10 (7)	3.0E-10 (7)	1.25E-10 (8)
	Bentonite/Sand			3.0E-10 (8)
	Asphalt			1.0E-13 (8)
	Engineered Fill	2.5E-10 (8)	2.5E-10 (8)	2.5E-10 (8)

Notes:

1. 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 (QUINTESSA and GEOFIRMA 2011) adopts freshwater hydraulic conductivity values irrespective of salinity 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 LHHPC concrete.
4. For the SF-BC-A and SF-NR-A cases the value corresponds to a two orders of magnitude increase in the bentonite/sand value compared to the NE-RC case. Value for SF-ED-A case corresponds to a value for compacted sand fill.
5. Reference value for engineered fill in Table 4.22 of the Data report (QUINTESSA and GEOFIRMA 2011).
6. Consistent with porosity of 0.3 and nominal grain density of 2650 kg/m^3.
7. Consistent with porosity of 0.3 and free water diffusion coefficient of 1 x 10^{-9} m^2/s.
8. Table 4.27of the Data report (QUINTESSA and GEOFIRMA 2011).
9. Normal Evolution Scenario Reference Case.
10. Table 4.22 of the Data report (QUINTESSA and GEOFIRMA 2011).
11. Table 4.26 of the Data report (QUINTESSA and GEOFIRMA 2011).

Table 3.4: Sorption Coefficients for Bentonite/Sand for the Severe Shaft Seal Failure Scenario

Element	Sorption Coefficient (m^3/kg)
Zr	0.005
Nb	0.01
Pb	0.0001
U	0.001
Np	0.0004
Pu	0.05
All other elements and organic contaminants	0

3.5 Results

3.5.1 Release of Contaminants via the Shaft

3.5.1.1 Base Case

The FRAC3DVS modelling indicates that there is no advective groundwater flow away from the DGR via the shafts (Section 6.3.1 of GEOFIRMA 2011). T2GGM indicates that gas pressures in the DGR for the Base Case (SF-BC) are sufficient to force a free gas pathway after about 20 ka (Section 6.1.1 of GEOFIRMA and QUINTESSA 2011). Figure 3.3 shows the calculated flux of radionuclides to the Shallow Bedrock Groundwater Zone. The flux to the shallow system is dominated by C-14 in gaseous form. Because the only release is of gas, there is essentially no transfer of radionuclides in groundwater to the shallow system.

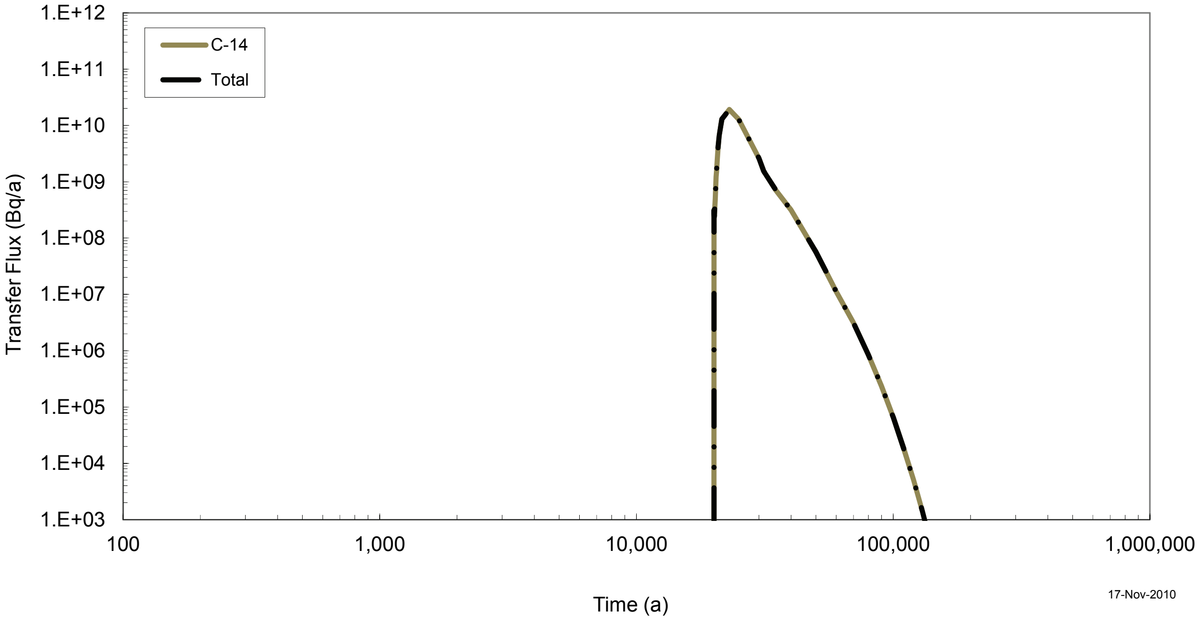

Figure 3.3: Calculated Radionuclide Transfer Flux to the Shallow Bedrock Groundwater Zone from the Shaft for the Severe Shaft Seal Failure Scenario, Base Case (SF-BC)

T2GGM indicates that free gas breaks through via the shaft after about 22 ka at a rate of about 840 kg/a (Table 8.2 of GEOFIRMA and QUINTESSA 2011). Insight calculations (see Appendix H), that are used to parameterise the AMBER model, indicate that about 5% of the gas flux reaching the Shallow Bedrock Groundwater Zone would dissolve in the flowing groundwater. The free gas carries C-14 labelled gases from the DGR, which can similarly dissolve in groundwater in the shallow system. AMBER modelling results shown in Figure 3.4 indicate that the calculated concentrations in well water peak at about 3000 Bq/m^3 after about 23 ka and are directly related to the release of C-14 in gas to the Shallow Bedrock Groundwater Zone.

About 95% of the gas flux to the Shallow Bedrock Groundwater Zone does not dissolve in the groundwater and reaches the biosphere as free gas. Some of this gas enters a house that is conservatively taken to be positioned directly above the main shaft. The calculated radionuclide concentrations in the air inside the house peak at about 16,000 Bq/m^3 after about 23 ka.

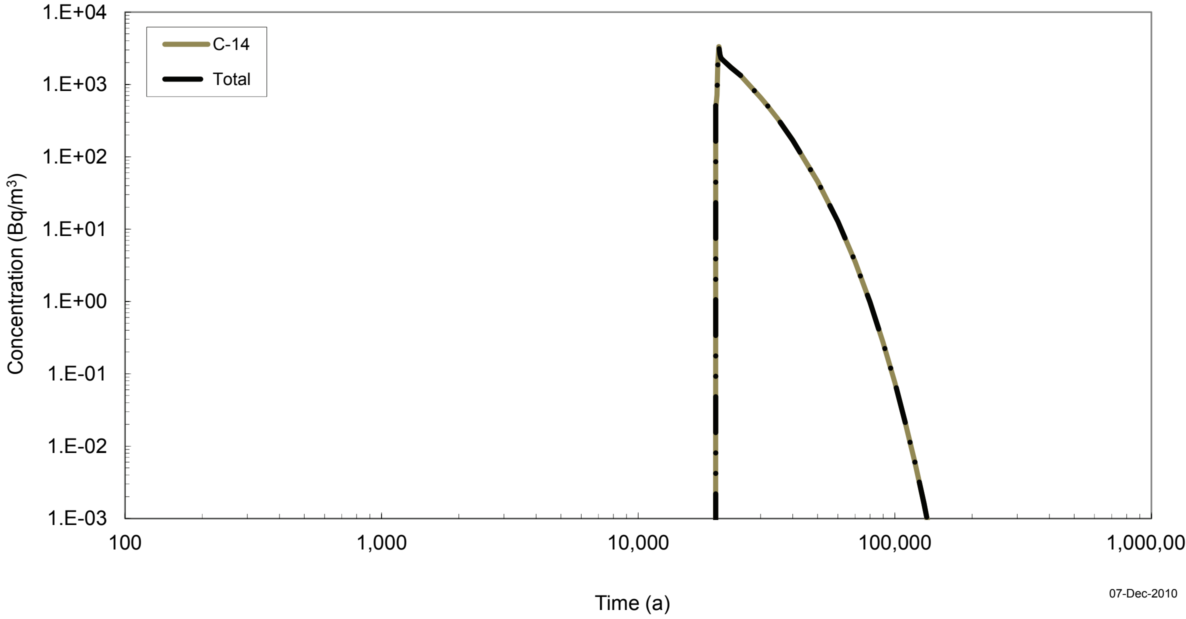

Figure 3.4: Calculated Radionuclide Concentrations in Well Water for the Severe Shaft Seal Failure Scenario, Base Case (SF-BC)

Calculated concentrations of radionuclides in biosphere media (soils, surface water and sediment) are well below the reference no effect concentrations for protection of non-human biota (Table 3.5). The only exception is the peak calculated concentration of C-14 in surface water around the site (i.e., the highest concentrations are in Stream C), which is a factor of 1.4 above the associated no effect concentration.

For disruptive scenarios, the acceptance in such a situation is to be judged on a case-by-case basis taking into account the likelihood and nature of the exposure, uncertainty in the assessment, and conservatism in the dose criterion (QUINTESSA et al. 2011a). In this case, the shaft seal failure is an unlikely scenario and these consequences would only apply if the failure is within about 50 ka (due to C-14 decay). Also, the high concentration is in the local stream not the larger downstream area, and is slightly above the screening no effect concentration criterion. Based on these points, and the conservatisms in the screening criterion (see Appendix G), the actual risk to non-human biota is expected to be low.

There is a negligible release of non-radioactive contaminants via the groundwater pathway, and all calculated values lie many orders of magnitude below the relevant EQS values (Table 3.6).

Table 3.5: Ratio of Calculated Peak Concentrations of Radionuclides in Biosphere Media to No Effect Concentrations for the Severe Shaft Seal Failure Scenario Base Case (SF-BC)

Radionuclide	Well Water	Irrigated Soil	Sediment	Surface Water
C-14	2.1E-06	1.8E-01	1.2E-04	**1.4E+00**
Cl-36	<1E-10	4.8E-08	<1E-10	1.0E-10
Zr-93	<1E-10	<1E-10	<1E-10	<1E-10
Nb-94	<1E-10	<1E-10	<1E-10	<1E-10
Tc-99	<1E-10	<1E-10	<1E-10	<1E-10
I-129	<1E-10	<1E-10	<1E-10	<1E-10
Ra-226	<1E-10	<1E-10	<1E-10	<1E-10
Np-237	<1E-10	<1E-10	<1E-10	<1E-10
U-238	<1E-10	<1E-10	<1E-10	<1E-10
Pb-210	<1E-10	<1E-10	<1E-10	<1E-10
Po-210	<1E-10	<1E-10	<1E-10	<1E-10

Notes: Exceedance highlighted in **bold**. No effect concentrations for non-human biota are given in Table 7.11 of the Data report (QUINTESSA and GEOFIRMA 2011).

Table 3.6: Ratio of Calculated Peak Concentration of Non-radioactive Contaminants in Biosphere Media to Environmental Quality Standards for the Severe Shaft Seal Failure Scenario Base Case (SF-NR)

Contaminant	Well Water	Irrigated Soil	Sediment	Surface Water
Ag	3.2E-09	<1E-10	<1E-10	<1E-10
As	4.4E-09	<1E-10	<1E-10	<1E-10
B	<1E-10	<1E-10	-	<1E-10
Ba	2.1E-09	<1E-10	-	-
Be	3.5E-08	<1E-10	-	<1E-10
Br	-	-	-	<1E-10
Cd	3.0E-06	<1E-10	8.3E-10	1.5E-07
Co	2.3E-08	<1E-10	<1E-10	<1E-10
Cr	3.8E-05	<1E-10	4.1E-09	6.9E-07
Cu	9.4E-05	<1E-10	1.3E-07	7.8E-07
Gd	-	-	-	1.7E-10
Hf	-	-	-	<1E-10
Hg	9.1E-08	<1E-10	<1E-10	3.8E-09
I	-	-	-	<1E-10
Li	-	-	-	<1E-10
Mn	-	-	-	2.0E-09
Mo	1.9E-06	<1E-10	-	1.8E-09
Nb	-	-	-	<1E-10
Ni	3.1E-05	<1E-10	6.7E-08	2.8E-08
Pb	<1E-10	<1E-10	<1E-10	<1E-10
Sb	2.8E-07	<1E-10	-	<1E-10
Sc	-	-	-	<1E-10
Se	<1E-10	<1E-10	-	<1E-10
Sn	-	-	-	<1E-10
Sr	-	-	-	<1E-10
Te	-	-	-	<1E-10
Tl	1.5E-10	<1E-10	-	<1E-10
U	<1E-10	<1E-10	-	<1E-10
V	<1E-10	<1E-10	-	<1E-10
W	-	-	-	<1E-10
Zn	1.2E-07	<1E-10	1.8E-09	1.6E-09
Zr	-	-	-	<1E-10
Chlorobenzene/ Chlorophenol	3.6E-08	<1E-10	1.5E-10	<1E-10
Dioxins/Furans	8.2E-07	<1E-10	-	<1E-10
PAH	4.5E-09	<1E-10	<1E-10	9.3E-10
PCB	<1E-10	<1E-10	<1E-10	<1E-10

Note: Environmental quality standards are given in Table 7.12 of the Data report (QUINTESSA and GEOFIRMA 2011). ‘-‘ indicates no environmental quality standard identified.

3.5.1.2 Extra Degradation Case

The SF-ED calculation case assumes that there is additional degradation of the bentonite/sand shaft seals so that it essentially becomes a fine sand and silt material.

The primary effect of the assumption of greater degradation of the shaft seal materials is to permit greater flows of water and gas through the shafts. The consequence is a more rapid ingress of groundwater to the repository, increased saturation and greater generation of gas. As can be seen from Figure 3.2, the repository saturation is very much higher than for the Normal Evolution Scenario's Reference Case and, up to about 220 ka, higher than that for SF-BC. Results from detailed gas modelling (Section 6.2 of GEOFIRMA and QUINTESSA 2011) indicate that the increased gas pressure results in a series of degassing events in which there are a significant gas release via the shaft. These occur because overpressure in the repository builds up until a free gas breakthrough can occur. The pressure is then dissipated as gas escapes, with gas flow rates reducing significantly from the peak. Pressures then increase until another free gas release can occur. These events occur at about 2 ka, 4 ka and 13 ka as a result of the repository gas pressure exceeding a critical value that permits a release of free gas.

Calculated fluxes of contaminants are illustrated in Figure 3.5 for the case in which the whole shaft seal system is severely degraded (SF-ED). Results from the Normal Evolution Scenario are not included for comparison because the peak flux is extremely small, only 4 x 10^{-6} Bq/a.

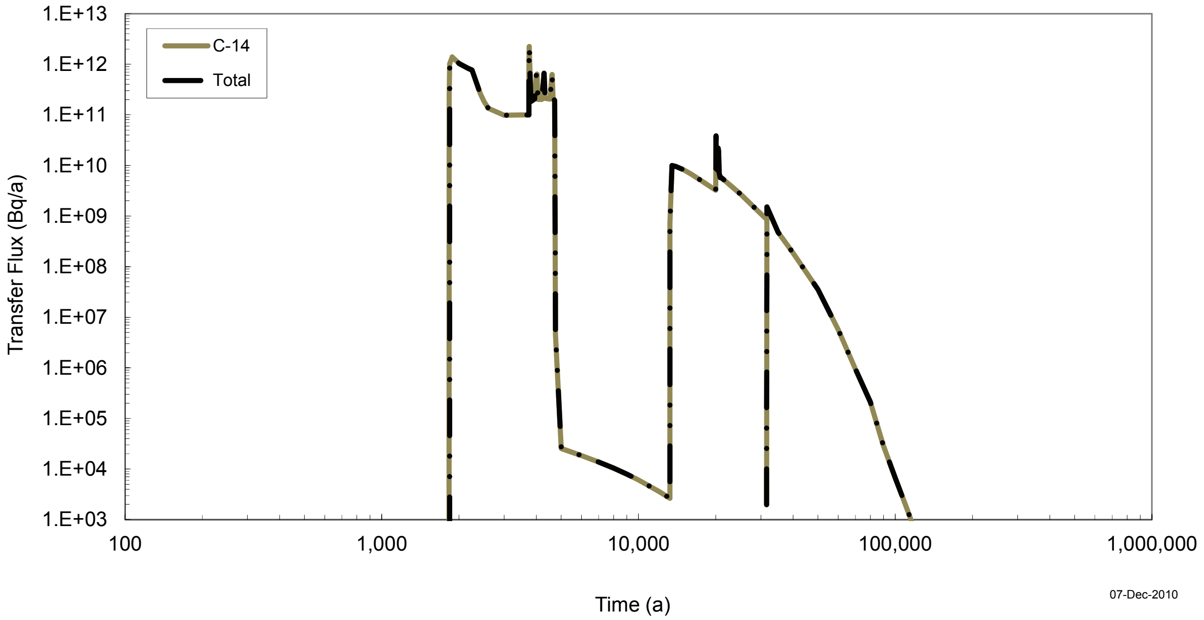

Figure 3.5: Calculated Fluxes of Contaminants through the Shaft to the Shallow Bedrock Groundwater Zone for the Severe Shaft Seal Failure Scenario, Extra Degradation Case (SF-ED)

For this case, the degassing events result in substantial fluxes of free gas containing C-14 into the Shallow Bedrock Groundwater Zone as shown in Figure 3.5. The peak flux occurs at 3.8 ka. After 20 ka there is a gradual decrease and radioactive decay of C-14 becomes significant.

T2GGM indicates that free gas breaks through via the shaft after about 1.9 ka, at a rate of about 3500 kg/a, although the peak flow of about 9300 kg/a occurs at 3.8ka[4]. Simple calculations (see Appendix H) indicate that only 0.6% of this gas flux would dissolve in the flowing groundwater in the Shallow Bedrock Groundwater Zone. The majority of the gas is, therefore, released directly to the biosphere, which results in peak calculated concentration in indoor air of 1.6 x 10^6 Bq/m^3 in a house positioned directly above the main shaft after 3.8 ka.

Calculated concentrations in well water peak at about 3 x 10^4 Bq/m^3 after 1.9 ka.

3.5.2 Calculated Radiation Doses

3.5.2.1 Base Case

The base case assumptions for the shaft seal failure result in doses, to persons living directly over the repository, that reach a maximum of 1.1 mSv/a after about 23 ka (see Figure 3.6). This coincides with the release of C-14 labelled gases to groundwater in the Shallow Bedrock Groundwater Zone and directly to the biosphere. The dominant exposure pathways are the inhalation of gas and ingestion of plants that have taken up C-14, each of which contributes about 40% of the calculated peak dose. It is noted that a scenario likelihood of around 10^{-1} or less would result in the risk of serious health effects being less than the reference health risk value of 10^{-5}/a. The probability of instant severe shaft seal degradation combined with a house positioned directly above one of the shafts can reasonably be considered to be significantly lower than this.

3.5.2.2 Extra Degradation Case

The assumptions for the extra degradation of the shaft seals results in calculated doses to the site resident group that reach about 80 mSv/a after 3.8 ka. The dominant radionuclide is C-14 and the dominant pathway is the inhalation of the gas under the very conservative assumption of a house located on the point of release of C-14 gas. Other exposure pathways such as the ingestion of animal products and crops give rise to peak doses of around 10 mSv/a. It is emphasized that this calculation case is a highly conservative case and was undertaken with the purpose of investigating the sensitivity of dose impacts to shaft seal properties.

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[4] T2GGM results (that do not include the Ordovician underpressures) suggest that dissolved gases will also reach the Shallow Bedrock Groundwater Zone, but at a rate more than two orders of magnitude less than the free gas (Table 8.2 of the Gas Modelling report, GEOFIRMA and QUINTESSA 2011).

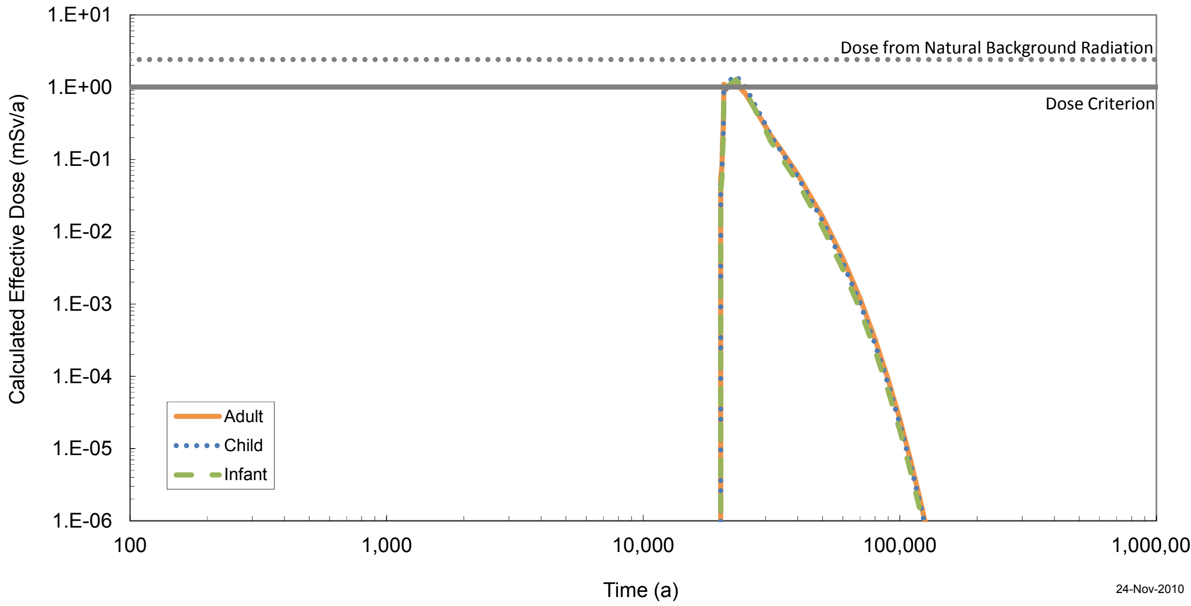

Figure 3.6: Calculated Effective Doses to the Site Resident Group for the Severe Shaft Seal Failure Scenario, Base Case (SF-BC)

3.5.3 Likelihood

The Severe Shaft Seal Failure Scenario makes a range of additional conservative assumptions, such as the instant (rather than gradual) degradation of the shaft seals and the existence of a house directly on a shaft It illustrates the consequences of poor performance of the shaft seals, for example as a result of unexpected physical, chemical and/or biological processes that cause much more extensive degradation of materials than are anticipated in the Normal Evolution Scenario. This could include, for example, a profound change in geochemical conditions. However, such processes are very unlikely due to the stability of the deep geosphere at the DGR site as demonstrated by site characterization evidence (Section 2.3 of the System and Its Evolution report, QUINTESSA 2011b). Also, geomechanical modelling of the shaft indicates that seismic shaking due to large earthquakes with 10^{-5}/a and 10^{-6}/a probabilities had little effect (Section 6.4.3 of NWMO 2011).

4. POORLY SEALED 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 close proximity to the repository not being properly sealed (Section 8.2.3 of the System and Its Evolution report, QUINTESSA 2011b).

The DGR site will have several deep boreholes around the repository. Six have been drilled for site investigation and monitoring purposes. These boreholes respect the requirement that the separation distance between any part of the repository and deep boreholes is at least 100 m (NWMO 2010) and are licensed through the Ontario Ministry of Natural Resources. Furthermore, they will be appropriately sealed on completion of site investigation/monitoring activities and consequently they will have no effect on the repository performance.

However, if a deep borehole were not properly sealed or were to extensively degrade, then it could provide a small but relatively permeable pathway for the migration of contaminants from the repository horizon. Like the Severe Shaft Seal Failure Scenario, such a situation would be prevented by normal quality control. 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 **Poorly Sealed Borehole Scenario**.

The evolution of the system considered for the Poorly Sealed Borehole Scenario is similar to the Normal Evolution Scenario with the key difference being that the poorly 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 critical group assessed are the same as those considered in the Normal Evolution Scenario (Section 2.3 of the Normal Evolution Scenario Analysis report, QUINTESSA 2011a).

The scenario is illustrated in Figure 4.1.

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 Section 2.2 of the Normal Evolution Scenario Analysis report, QUINTESSA 2011a) with the exception that the DGR-2 site investigation borehole is taken to be poorly sealed. The borehole provides an enhanced permeability connection between the geosphere in close proximity to the repository, the overlying groundwater zones and the biosphere. DGR-2 has been selected as it is the closest of the existing boreholes to the repository footprint. It extends from the surface to the Precambrian and is located 100 m to the south east of Panel 2 (Figure 1.3).

The key features are summarized in Table 4.1.

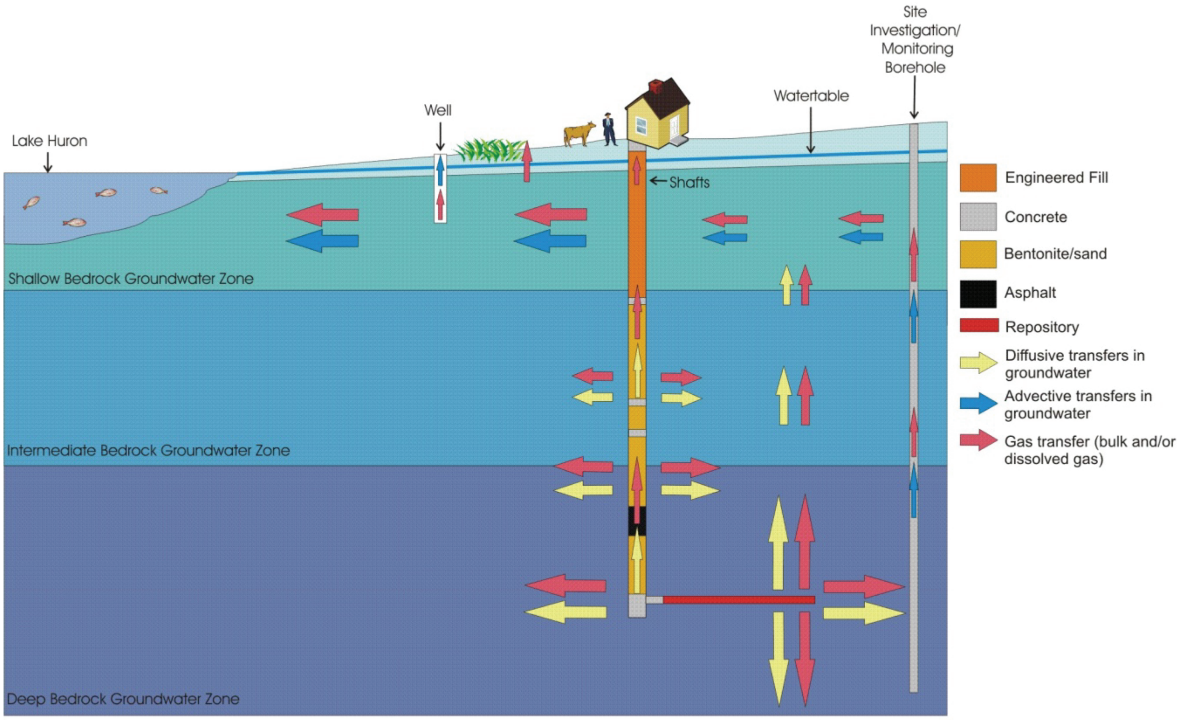

Figure 4.1: Schematic Representation of Poorly Sealed Borehole Scenario

Table 4.1: Summary of Key Features for the Poorly Sealed Borehole Scenario

Waste and Repository Features [1]	**Geosphere Features** [1]	**Biosphere Features** [1]
• Waste packages • Water (Panels 1 and 2 emplacement rooms, access tunnels, and shaft & service area) • Gas (Panels 1 and 2 emplacement rooms, access tunnels, and shaft & service areas) • Engineered Structures (concrete monolith, shaft seals and shaft backfill)	• **Poorly sealed borehole** • Deep Bedrock Groundwater Zone • Repository Highly Damaged Zone • Repository and Shaft Excavation Damaged Zones • Intermediate Bedrock Groundwater Zone • Shallow Bedrock Groundwater Zone	• Well Water • Surface Water and Sediment (stream and wetland) • Lake Water and Sediment • Soil • Biota • Atmosphere

Note:
1. Features in **Bold** require specific modelling assumptions for this scenario that differ from the Normal Evolution Scenario.

4.2.2 Description of the Conceptual Model

The conceptual model is largely the same as for the Normal Evolution Scenario (as described in Section 2.3 of the Normal Evolution Scenario Analysis report, QUINTESSA 2011a) 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 following release into the Shallow Bedrock Groundwater Zone.

Groundwater flow modelling (Section 6.5.2 of GEOFIRMA 2011) shows that the presence of the borehole does not perturb the transport of contaminants in the vicinity of the repository to any notable degree due to the very low permeability host rock around the DGR. Flow rates from the repository horizontally towards the borehole are comparable to diffusion rates, and contaminants transported by the borehole have diffused through the rock prior to intercepting the conductive pathway. The conceptual model for contaminant transport, therefore, only considers a diffusive flux of contaminants from repository to the borehole.

The key aspects of the conceptual model for releases from the repository are summarized in Box 3.

Box 3:
Key Aspects of the Conceptual Model for the Poorly Sealed Borehole Scenario [1]

Waste and Repository:
- Instantaneous resaturation of the repository, which maximises the release of contaminants into groundwater that may subsequently migrate via the borehole.

Geosphere and Shafts:
- Poorly sealed site investigation/monitoring borehole located 100 m from south east edge of Panel 2. Borehole extends from surface down to Precambrian.
- Contaminants may migrate along the poorly sealed borehole by advection, and no sorption is assumed to occur.

Biosphere:
- Model is the same as the Normal Evolution Scenario.

Note:
1. All other modelling assumptions are as described for the Normal Evolution Scenario (QUINTESSA 2011a)

4.2.3 FEP Audit

As noted in Section 4.2.2, the conceptual model for the Poorly Sealed Borehole Scenario is broadly the same as the Normal Evolution Scenario (as described in the Normal Evolution Scenario Analysis report, QUINTESSA 2011a) with only differences relating to presence of the poorly sealed site investigation/monitoring borehole. For the purposes of the FEP assessment, the borehole can be treated as 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 sealed 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 Poorly Sealed Borehole Scenario and the Normal Evolution Scenario have essentially the same conceptual models, the main conceptual model uncertainties are also the same. These are discussed in Section 2.5 of the Normal Evolution Scenario Analysis report

(QUINTESSA 2011a) and so are not replicated here. One of the motivations behind considering the Poorly Sealed 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 the conceptual model developed in Section 4.2 that consider the release of radioactive and non-radioactive contaminants (Table 4.2).

Table 4.2: Calculation Cases for the Poorly Sealed Borehole Scenario

Case ID	Brief Description	Associated Detailed Modelling Cases*
BH-BC-A	As for the Normal Evolution Scenario with immediate resaturation after closure (NE-RS-A), but assuming the presence of a poorly sealed site investigation/monitoring borehole from surface down to Precambrian located 100 m from the southeast edge of Panel 2 (i.e., DGR-2). Borehole flow conditions are based on the detailed groundwater case (BH-BC-F3) (see Section 4.4.3) assuming a hydraulic conductivity of the borehole of 10^{-4} m/s and porosity of 0.25, equivalent to graded sand fill. No sorption on borehole seal.	BH-BC-F3
BH-NR-A	As for BH-BC-A, but with the inventory of non-radioactive elements and chemical species emplaced in the repository.	BH-BC-F3

Notes:
BH – Poorly Sealed Borehole Scenario; NE- Normal Evolution Scenario; RS – instant repository resaturation; NR – non-radioactive contaminants; BC - Base Case; A – AMBER; F3 – FRAC3DVS
* Detailed modelling cases are described in Section 6.5 of the Groundwater Modelling report (GEOFIRMA 2011).

The instantaneous resaturation of the repository (see Chapter 3 of the Normal Evolution Scenario Analysis report, QUINTESSA 2011a, for more details) is chosen conservatively to maximise the release of contaminants into groundwater that may subsequently migrate via the borehole. The only modification for the BH-BC-A and BH-NR-A cases is the introduction of the poorly sealed borehole that provides an enhanced permeability connection between the level of the repository and the overlying Shallow Bedrock Groundwater Zone.

4.4 Mathematical Models, Software Implementation and Data

4.4.1 Mathematical Models

The Poorly Sealed 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 (QUINTESSA 2011a). 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 5.3 (QUINTESSA 2009a, 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 site resident group).

A T2GGM model has not been developed for the Poorly Sealed Borehole Scenario. This is because the scenario is primarily concerned with the transport of contaminants in groundwater. The Severe Shaft Failure Scenario presented in Chapter 3 provides an indication of the significance of gas transport through a permeable shaft pathway to the Shallow Bedrock Groundwater Zone. The Poorly Sealed Borehole case will have much lower impacts because there is no permeable connection between the repository gas and the borehole. Any gas would be required to migrate through the low-permeability formations by diffusion before intercepting the borehole.

4.4.3 Data

The borehole is located 100 m from the south eastern edge of Panel 2 (i.e., consistent with the location of DGR-2 since it is the closest of the existing boreholes to the repository footprint). 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 analysis. The approach has been to use the calculated volumetric flow rate through the borehole to the Salina F formation. The FRAC3DVS results indicate a flow rate from the repository horizon via the borehole that varies with time, between 11 and 15 m^3/a (see Figure 4.2 and discussion in Section 6.5 of the Groundwater Modelling report, GEOFIRMA 2011). The detailed modelling shows that the flow rate is reduced above the relatively conductive Guelph Formation, where horizontal flow may occur; however, for the purposes of the assessment modelling, it is conservatively taken to be maintained up to and enter the Shallow Bedrock Groundwater Zone.

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 and a porosity of 0.25, i.e., graded sand engineered fill).

All other data considered for the calculations, including the description of potential critical group, are the same as the Reference Case for the Normal Evolution Scenario documented in the Data report (QUINTESSA and GEOFIRMA 2011).

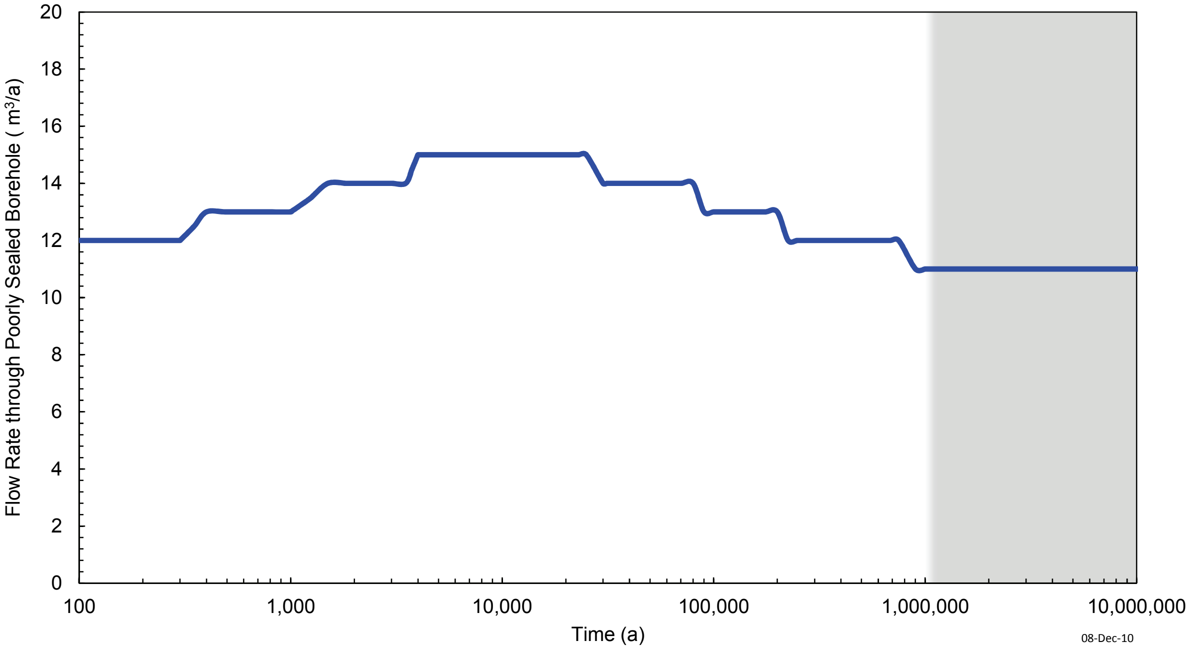

Figure 4.2: Calculated Flow Rate through the Poorly Sealed Borehole, Assuming the Repository is Resaturated at Closure

4.5 Results

4.5.1 Release of Contaminants via the Poorly Sealed 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 (11 to 15 m^3/a, via the borehole), they are not insignificant in the context of the transport of contaminants through the DGR geosphere. Indeed, the calculated fluxes via the borehole (shown in Figure 4.3) are substantially higher than the fluxes that occur via the shaft and geosphere for the Normal Evolution Scenario's Reference Case (which peak at 3 x 10^{-6} Bq/a, Section 5.2.2 of QUINTESSA 2011a). The dominant radionuclides are Ni-59 and Zr-93 (and Nb-93m).

The results illustrate that the enhanced permeability pathway could increase the release of contaminants to the Shallow Bedrock Groundwater Zone. Although there is insufficient permeability in the rocks to sustain advective flow between the DGR and the borehole, the borehole, nevertheless, captures contaminants diffusing from the repository and provides a short-cut to the overlying groundwater system.

While the calculated concentrations in biosphere media are increased by the presence of the poorly sealed borehole, they remain extremely small, with concentrations in the well water for the self-sufficient farmer living on the site peaking at 0.05 Bq/m^3 after 0.9 Ma. Calculated concentrations in irrigated soil peak at a similar time (1 Ma) but are much lower. The calculated concentrations are far below the relevant no effect concentrations for non-human biota by more than six orders of magnitude (Table 4.3).

The calculated concentrations of non-radioactive contaminants in well water, soil and sediment are also very low. The highest concentration in well water (Cu) is less than a thousandth of a µg/L. Consequently the calculated values are far below the EQS for all non-radioactive contaminants. The closest value is for Pb in well water, which is about one five thousandth of the EQS value (Table 4.4).

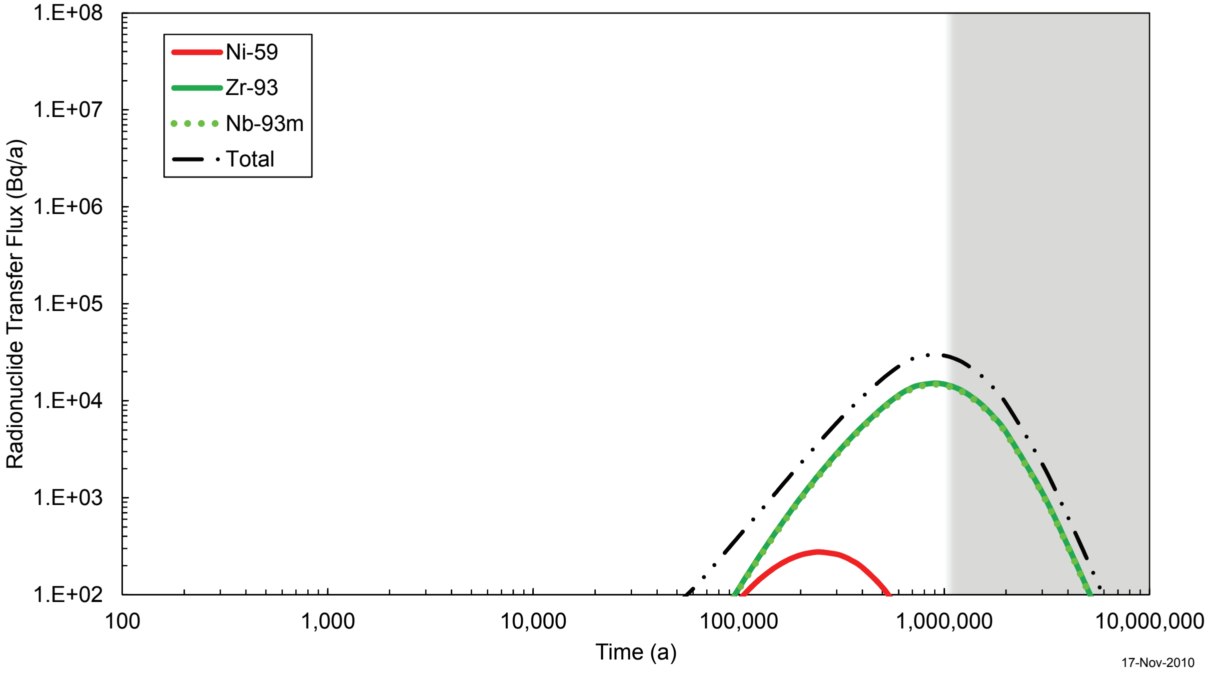

Figure 4.3: Calculated Radionuclide Transfer Flux to the Shallow Bedrock Groundwater Zone via the Poorly Sealed Borehole

Table 4.3: Ratio of Calculated Peak Concentrations of Radionuclides in Biosphere Media to No Effect Concentrations for the Poorly Sealed Borehole Scenario (BH-BC)

Radionuclide	Well Water	Irrigated Soil	Sediment	Surface Water
C-14	<1E-10	<1E-10	<1E-10	<1E-10
Cl-36	<1E-10	2.8E-09	<1E-10	<1E-10
Zr-93	<1E-10	<1E-10	<1E-10	2.6E-08
Nb-94	<1E-10	<1E-10	<1E-10	1.6E-08
Tc-99	<1E-10	<1E-10	<1E-10	<1E-10
I-129	<1E-10	<1E-10	<1E-10	<1E-10
Ra-226	<1E-10	<1E-10	<1E-10	3.2E-09
Np-237	<1E-10	<1E-10	<1E-10	<1E-10
U-238	<1E-10	<1E-10	<1E-10	<1E-10
Pb-210	<1E-10	<1E-10	<1E-10	<1E-10
Po-210	<1E-10	<1E-10	<1E-10	2.7E-10

Notes: No effect concentrations for non-human biota are given in Table 7.11 of the Data report (QUINTESSA and GEOFIRMA 2011).

Table 4.4: Ratio of Calculated Peak Concentration of Non-radioactive Contaminants in Biosphere Media to Environmental Quality Standards for the Poorly Sealed Borehole Scenario (BH-BC)

Contaminant	Well Water	Irrigated Soil	Sediment	Surface Water
Ag	6.8E-09	<1E-10	<1E-10	<1E-10
As	9.4E-09	<1E-10	<1E-10	<1E-10
B	5.1E-10	<1E-10	-	<1E-10
Ba	4.8E-09	<1E-10	-	-
Be	7.9E-08	<1E-10	-	<1E-10
Br	-	-	-	<1E-10
Cd	6.9E-06	<1E-10	1.9E-09	3.3E-07
Co	4.7E-08	<1E-10	<1E-10	3.3E-10
Cr	7.8E-05	<1E-10	8.3E-09	1.4E-06
Cu	1.9E-04	<1E-10	2.6E-07	1.6E-06
Gd	-	-	-	3.2E-10
Hf	-	-	-	<1E-10
Hg	2.1E-07	<1E-10	<1E-10	8.7E-09
I	-	-	-	<1E-10
Li	-	-	-	<1E-10
Mn	-	-	-	3.7E-09
Mo	3.7E-06	1.8E-10	-	3.5E-09
Nb	-	-	-	<1E-10
Ni	6.2E-05	<1E-10	1.3E-07	5.7E-08
Pb	2.3E-04	<1E-10	1.8E-06	7.2E-07
Sb	6.5E-07	<1E-10	-	<1E-10
Sc	-	-	-	<1E-10
Se	2.6E-09	<1E-10	-	<1E-10
Sn	-	-	-	<1E-10
Sr	-	-	-	<1E-10
Te	-	-	-	<1E-10
Tl	3.0E-10	<1E-10	-	<1E-10
U	<1E-10	<1E-10	-	<1E-10
V	<1E-10	<1E-10	-	<1E-10
W	-	-	-	<1E-10
Zn	2.7E-07	<1E-10	3.9E-09	3.6E-09
Zr	-	-	-	4.9E-08
Chlorobenzene/ Chlorophenol	8.4E-08	<1E-10	3.5E-10	2.1E-10
Dioxins/Furans	1.9E-06	<1E-10	-	<1E-10
PAH	1.0E-08	<1E-10	<1E-10	2.2E-09
PCB	2.1E-10	<1E-10	<1E-10	<1E-10

Note: Environmental quality standards are given in Table 7.12 of the Data report (QUINTESSA and GEOFIRMA 2011). ‘-‘ indicates no environmental quality standard identified.

4.5.2 Calculated Radiation Doses

The calculated radiation doses for the Poorly Sealed Borehole scenario are greater than those calculated for the equivalent Normal Evolution Scenario case, as the radionuclide flux through the borehole is greater than the transport through the geosphere and shaft in the Normal Evolution Scenario Reference Case. However, the calculated doses are still extremely small, and are well below the 1 mSv/a dose criterion. Figure 4.4 shows that the calculated peak dose is 4 x 10^{-8} mSv/a at 0.9 Ma.[5] The dominant radionuclide is Zr-93 and the dominant pathway is ingestion of well water.

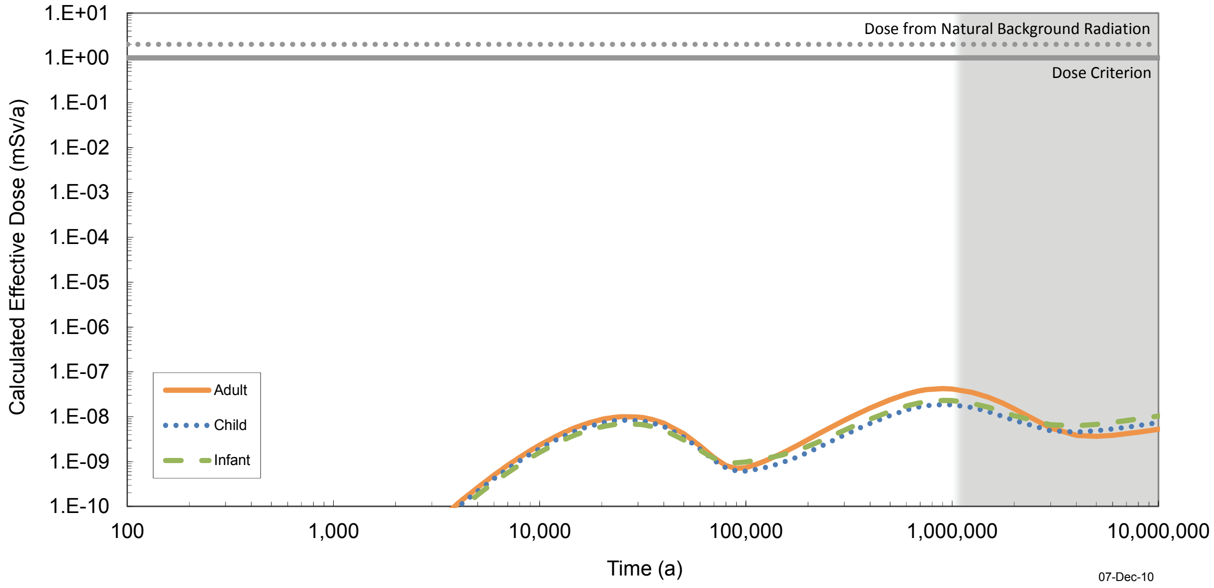

Figure 4.4: Calculated Effective Doses to the Site Resident Group for the Poorly Sealed Borehole Scenario

4.5.3 Likelihood

The Poorly Sealed Borehole scenario is deliberately speculative. It assumes the failure of future society to properly seal a borehole close to the DGR, which would be very unlikely. The scenario also illustrates the consequences of very poor performance of the borehole seals as a result of unexpected physical, chemical and/or biological processes. These could include, for example, a change in geochemical conditions. Such processes are unlikely due to the stability of the deep geosphere at the DGR site (Section 2.3 of the System and Its Evolution report, QUINTESSA 2011b). However, due to the relatively small size of the boreholes, some

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

degradation of these seals is plausible and, therefore, a high permeability value similar to graded sand fill has been considered as a conservative limit for this scenario.

The results show that the presence of a poorly sealed borehole does not affect the overall safety performance of the system. This is because the very low permeability of the host rocks limits the influence of the borehole. Specifically, in order to reach the borehole, contaminants must diffuse 100 m through rock. The impact of the borehole is further limited by its small diameter.

5. VERTICAL FAULT SCENARIO

5.1 Scenario Overview

There is strong geological, hydrogeological, and geochemical evidence that transmissive vertical faults/fracture zones do not exist within the footprint or vicinity of the DGR (Section 2.3 of the System and Its Evolution report, QUINTESSA 2011b). This evidence has been gathered through a deep drilling/coring program, a 2-D seismic reflection survey, petrophysics, in-situ borehole testing and micro-seismic monitoring.

Despite this evidence, a “what if” scenario is considered to investigate the safety implications of a hypothetical transmissive vertical fault, either undetected or representing the displacement of an existing structural discontinuity. Regionally, any such discontinuities are often associated with hydrothermal dolomitized carbonate and are found to originate in the Precambrian or Cambrian and extend up to the Ordovician shales where they terminate (Armstrong and Carter 2010). The hypothetical fault is assumed to be in close proximity to the DGR and is assume to extend beyond the Ordovician shales and into the permeable Guelph Formation. The scenario is termed the **Vertical Fault Scenario**.

The evolution of the system is the same as the Normal Evolution Scenario, except that a hypothetical transmissive vertical fault connects the Precambrian into the Guelph Formation in the Intermediate Bedrock Groundwater Zone. Such a fault could provide an enhanced permeability pathway that bypasses the Deep Bedrock Groundwater Zone, one of the natural barriers to contaminant migration from the DGR. Groundwater flow in the Guelph is assumed to be horizontal and to discharge to the lake. Consideration is given to exposure of a critical group that obtains its water and fish from the lake near shore (the site shore group), as well as the site resident group which has the same characteristics as those considered in the Normal Evolution Scenario.

The scenario is illustrated in Figure 5.1.

5.2 Conceptual Model

5.2.1 Key Features, Processes and Events

The internal features, processes and events considered for the Vertical Fault Scenario are the same as for the Normal Evolution Scenario (as described in Section 2.2 of the Normal Evolution Scenario Analysis report, QUINTESSA 2011a) with the exception that a hypothetical transmissive fault connects the Precambrian to the permeable Guelph Formation in close proximity to the DGR. The key features are summarized in Table 5.1.

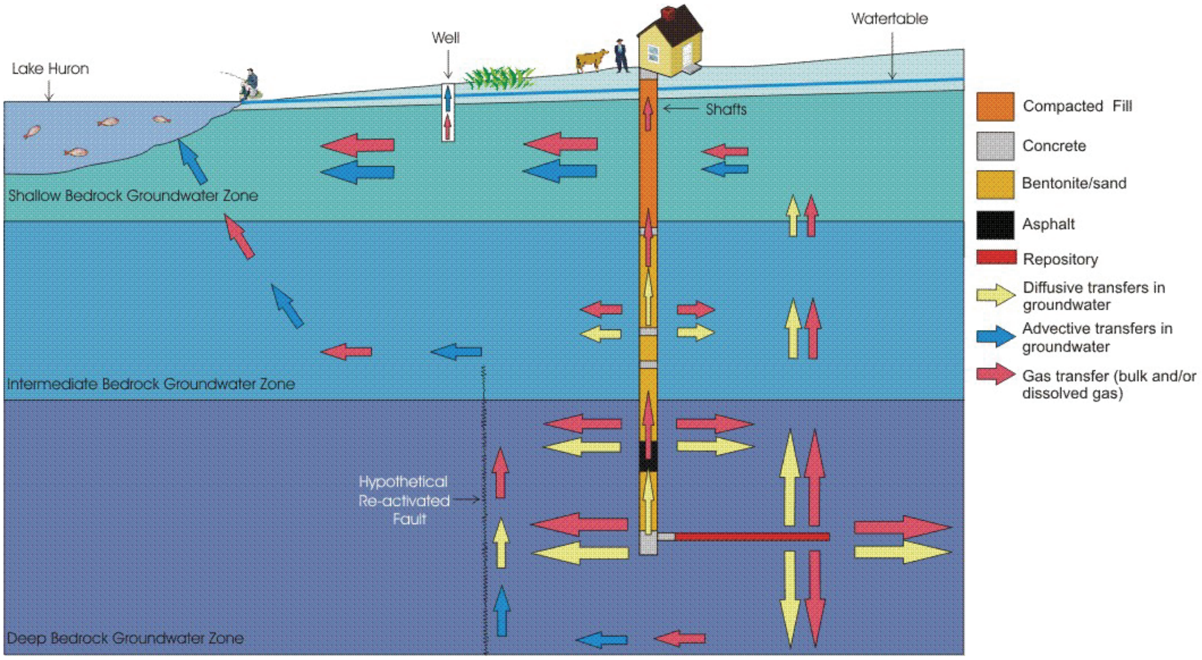

Figure 5.1: Schematic Representation of Vertical Fault Scenario

Table 5.1: Summary of Key Features for the Vertical Fault Scenario

Waste and Repository Features[1]	Geosphere Features[1]	Biosphere Features[1]
• Waste packages • Water (Panels 1 and 2 emplacement rooms, access tunnels, and shaft & service area) • Gas (Panels 1 and 2 emplacement rooms, access tunnels, and shaft & service areas) • Engineered Structures (concrete monolith, shaft seals and shaft backfill)	• Deep Bedrock Groundwater Zone • Repository Highly Damaged Zone • Repository and Shaft Excavation Damaged Zones • Intermediate Bedrock Groundwater Zone • Shallow Bedrock Groundwater Zone • **Vertical Fault**	• Well Water • Surface Water and Sediment (stream and wetland) • Lake Water and Sediment • Soil • Biota • Atmosphere

Note:

1. Features in **Bold** require specific modelling assumptions for this scenario that differ from the Normal Evolution Scenario.

5.2.2 Description of the Conceptual Model

The conceptual model is largely the same as for the Normal Evolution Scenario (as described in Section 2.3 of the Normal Evolution Scenario Analysis report, QUINTESSA 2011a). The only difference is that it is conservatively assumed that there is a transmissive vertical fault connecting the Precambrian and Guelph Formation and there is horizontal groundwater flow in the Cambrian, the Guelph and Salina A1 upper carbonate formations. The fault provides an additional pathway for contaminants to migrate vertically from the repository horizon into the overlying Guelph Formation. In this case, since losses to the Guelph Formation may be important, the formation is conservatively assumed to connect to the near-shore lake bottom.

The fault is taken to be 500 m to the northwest of the repository - i.e., beyond the area considered in the site investigation program (Figure 1.3). A vertical fault is also considered at 100 m southeast from the repository, i.e., within the site investigation program footprint (Figure 1.3). This is a variant case.

The key aspects of the conceptual model for releases from the repository are summarized in Box 4. In the conceptual model, the overpressurized Cambrian is assumed to be unaffected, despite being connected by a permeable path to the lower head and permeable Guelph Formation.

5.2.3 FEP Audit

The conceptual model for the Vertical Fault Scenario is broadly the same as the Normal Evolution Scenario (Section 2.3 of the Normal Evolution Scenario Analysis report, QUINTESSA 2011a) with only the difference relating to the presence of a hypothetical transmissive fault. Thus, only two internal FEPs differ, both of which relate to the hypothetical fault:

- FEP 2.2.04.01 (Large-scale discontinuities (in geosphere): faults and shear zones) – a transmissive vertical fault is present in close proximity to the DGR; and
- FEP 2.2.12 (Undetected features in geosphere) – a transmissive vertical fault is present in close proximity to the DGR that is not detected during site characterization.

5.2.4 Key Conceptual Model Uncertainties

There are various uncertainties associated with the Vertical Fault Scenario, additional to those associated with the Normal Evolution Scenario (discussed in Section 2.5 of the Normal Evolution Scenario Analysis report, QUINTESSA 2011a). These relate to the position of the hypothetical fault with respect to the DGR footprint. To evaluate the robustness of the DGR, a transmissive vertical fault was considered at different distances (100 m and 500 m) from the repository (Figure 1.3). A currently undetected fault that intercepts the repository location would, in fact, be detected during excavation of the repository. Formation of new fractures through the repository is not plausible – fault movement is much more likely to occur along existing faults, and geomechanical modelling of the repository under seismic and glacial loading did not identify any such fracturing (Section 6.4.4 of NWMO 2011).

Box 4:
Key Aspects of the Conceptual Model for the Vertical Fault Scenario[1]

Waste and Repository:

- Repository is assumed to be completely saturated from closure onwards. This is chosen conservatively to maximise the release of contaminants into groundwater that may subsequently migrate via the fault.

Geosphere and Shafts:

- Hypothetical vertical fault connects the Precambrian to Guelph Formation.
- The overpressure in the Cambrian sandstone drives groundwater flow through the transmissive fault vertically upwards.
- No sorption of contaminants in the fault.
- Horizontal flow in Guelph leading into lake near shore.

Biosphere:

- Model is the same as the Normal Evolution Scenario but, as well as considering a self-sufficient family farm located on the repository site and using groundwater from a well, also considers a group located in the shore region that receives the contaminated groundwater from the Guelph Formation and Shallow Bedrock Groundwater Zone.

Note:

1. All other modelling assumptions are as described for the Normal Evolution Scenario (QUINTESSA 2011a).

5.3 Calculation Cases

Three 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 5.2).

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 instant resaturation case for the Normal Evolution Scenario (see Chapter 3 of the Normal Evolution Scenario Analysis report, QUINTESSA 2011a, for more details). The only modifications are the presence of a hypothetical transmissive fault connecting the Precambrian to the Guelph (thereby providing an enhanced permeability connection between the level of the repository and the overlying Intermediate Bedrock Groundwater Zone), the horizontal groundwater flow in the Cambrian, Guelph and Salina A1 upper carbonate formations, and the discharge of the Guelph and Salina A1 upper carbonate formations to the near-shore lake bottom. Two locations for the hypothetical fault are considered (500 m to the northwest of the DGR and 100 m to the southeast of the DGR) to investigate the sensitivity of results to the location of the fault (Figure 1.3). The former is orientated such that it preferentially captures contaminants from Panel 1 (in which more radioactivity is present) whereas the latter is closer to the repository, but oriented towards Panel 2.

Table 5.2: Calculation Cases for the Vertical Fault Scenario

Case ID	Brief Description	Associated Detailed Modelling Cases*
VF-BC-A	As for the Normal Evolution Scenario case with instant resaturation (NE-RS-A) but with a hypothetical transmissive fault 500 m northwest of the repository from the Precambrian to the Guelph Formation. Characteristics of fault and associated flow conditions to be the same as used for detailed groundwater case VF-BC-F3, notably a hydraulic conductivity of 10^{-8} m/s with horizontal groundwater flow in the Cambrian, the Guelph and Salina A1 upper carbonate formations. Flow in Guelph and Salina A1 upper carbonate formations to the near-shore lake bottom.	VF-BC-F3
VF-NR-A	As for VF-BC-A, but with the inventory of non-radioactive elements and chemical species emplaced in the repository.	VF-BC-F3
VF-AL-A	As for the VF-BC-A case but with hypothetical transmissive fault 100 m southeast of the repository.	VF-AL-F3

Notes:
VF – Vertical Fault Scenario; NE- Normal Evolution Scenario; RS – instant repository resaturation variant; NR – non-radioactive contaminants; BC - Base Case; AL – alternative location; A – AMBER model; F3 – FRAC3DVS model.
* Detailed modelling cases are described in Sections 6.6 and 6.7 of the Groundwater Modelling report (GEOFIRMA 2011).

5.4 Mathematical Models, Software Implementation and Data

5.4.1 Mathematical Models

The Vertical Fault 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 (QUINTESSA 2011a). The exception is the incorporation of a specific pathway to represent the more rapid transport of contaminants in the fault zone formations to the near-shore lake bottom.

Detailed groundwater flow modelling shows that the fault only has an influence on contaminant transport below the Formation. The flows calculated by detailed groundwater modelling (see Sections 6.6 and 6.7 of GEOFIRMA 2011) have been used directly in the AMBER model to determine contaminant transport through the fault.

5.4.2 Software Implementation

The scenario is implemented in AMBER Version 5.3 (QUINTESSA 2009a, b). The modified Normal Evolution Scenario model requires the fault zone to be explicitly represented with model compartments. The compartments are discretized in the vertical direction in the same manner as the other geosphere units; however, each represents a sub-vertical planar feature, within the width of the fault zone, with enhanced permeability. Advective and diffusive transfers are then assigned to represent the near-vertical transport along the fault, with the rate being determined using the groundwater flows calculated by detailed groundwater modelling.

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. A similar approach is used to distinguish between the reference and alternative location of the fault (calculation cases VF-BC-A and VF-AL-A). The detailed modelling is described in Chapter 4 of the Groundwater Modelling report (GEOFIRMA 2011).

A T2GGM model has not been developed for the Vertical Fault Scenario, because the distance of the fault from the repository is such that gas will not migrate in any significant quantities to its zone of influence. It is expected that the impacts would be much less than those associated with the Severe Shaft Failure Scenario presented in Chapter 3 due to the additional lateral travel distance and the small fault width.

5.4.3 Data

The Vertical Fault Scenario adopts the same parameter values as for the Normal Evolution Scenario (summarized in Table 2.3) with the exception that a hypothetical vertical fault is considered. The fault is taken to be either 500 m to the northwest of the repository (i.e., beyond the area considered in the site investigation program) or 100 m southeast of the repository (a case to investigate the sensitivity of results to the location of the fault). Consistent with the detailed groundwater modelling (which does not represent the Precambrian), the fault is taken to extend from the Shadow Lake to the Goat Island Formations, thereby connecting the Cambrian and Guelph Formation. The fault zone is 1 m wide, with a hydraulic conductivity of 1×10^{-8} m/s and porosity of 0.1 (Section 4.4.3 of the Groundwater Modelling report, GEOFIRMA 2011).

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 (Sections 6.6 and 6.7 of GEOFIRMA 2011). For both fault locations, the calculated groundwater flow in the fault is approximately 20 m^3/a for a 500 m lateral section of fault (Sections 6.6.1 and 6.7.1 of GEOFIRMA 2011). The flow path in the Guelph from the fault to the discharge point in the lake is taken to be about 1 km.

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 repository horizon and the more permeable formations in the Intermediate Bedrock Groundwater Zone such as the Guelph. This pathway is more permeable than the surrounding geosphere, enabling contaminants to migrate via it. A measure of the comparative significance of this pathway is given in Figure 5.2. This shows that if the fault is located closer to the DGR (VF-AL assesses a vault located 100 m from the repository), the flux is increased at times less than 100 ka, by about an order of magnitude compared with a fault at 500 m distance. This is due to geometrical factors, as a fault located closer to the DGR will intercept diffusing contaminants earlier and at higher concentrations than one further away. Beyond 100 ka, however, the difference in flux decreases with the result that the peak flux of 3×10^6 Bq/a is the same for both cases and occurs at about 1.8 Ma.

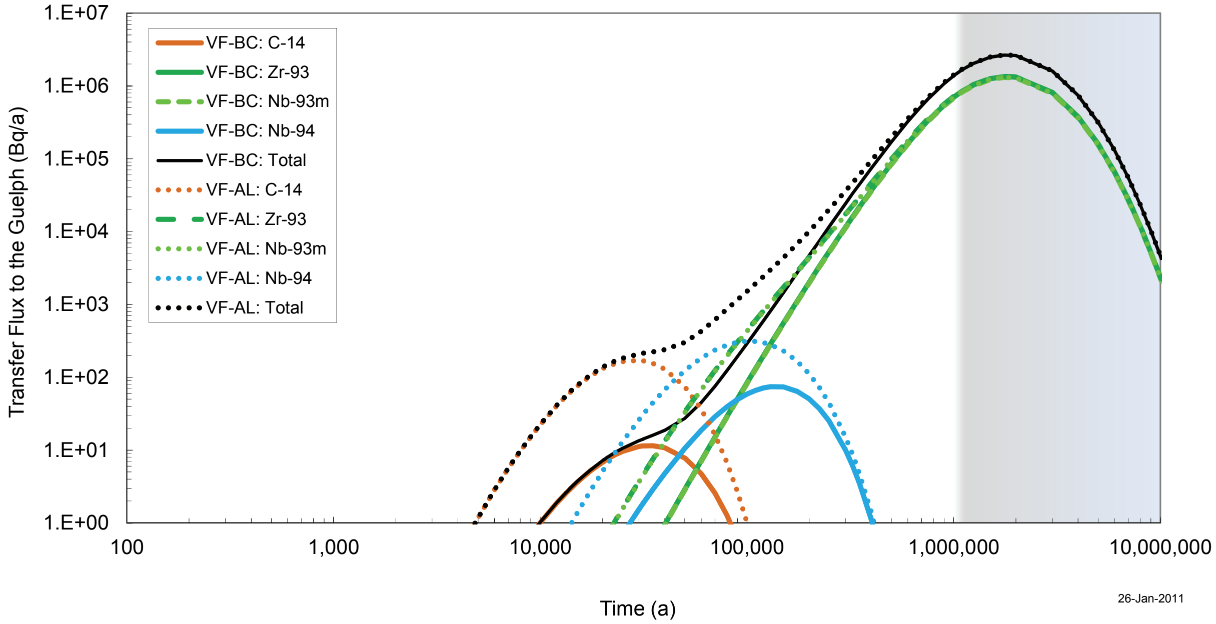

Figure 5.2: Calculated Fluxes of Contaminants in Groundwater from the Fault to the Guelph for a Vertical Fault Located 500 m (VF-BC) and 100 m (VF-AL) from the DGR

These contaminants are present with the highest concentrations in the shore region of the lake close to the site, which receives contaminated groundwater from the Guelph Formation. The peak calculated concentrations in the both cases are very small, at 3 x 10^{-4} Bq/m^3 after 1 Ma (dominated by Zr-93 and its daughter Nb-93m).

The relatively low contaminant fluxes to the Guelph, together with dispersion within the lake mean that calculated concentrations are much smaller than the no effect concentrations for non-human biota (Table 5.3). The concentrations of non-radioactive contaminants in well water, surface water, soil and sediment are all far below the EQS values for the VF-NR case. The nearest to a limit is Cu, which remains almost five orders of magnitude below the EQS value for surface water (Table 5.4).

Table 5.3: Ratio of Calculated Peak Concentrations of Radionuclides in Biosphere Media to No Effect Concentrations for the Vertical Fault Scenario Base Case (VF-BC)

Radionuclide	Well Water	Irrigated Soil	Sediment	Surface Water
C-14	<1E-10	<1E-10	<1E-10	<1E-10
Cl-36	<1E-10	<1E-10	<1E-10	<1E-10
Zr-93	<1E-10	<1E-10	2.1E-10	1.0E-07
Nb-94	<1E-10	<1E-10	<1E-10	3.0E-10
Tc-99	<1E-10	<1E-10	<1E-10	<1E-10
I-129	<1E-10	<1E-10	<1E-10	<1E-10
Ra-226	<1E-10	<1E-10	<1E-10	5.7E-10
Np-237	<1E-10	<1E-10	<1E-10	<1E-10
U-238	<1E-10	<1E-10	<1E-10	<1E-10
Pb-210	<1E-10	<1E-10	<1E-10	<1E-10
Po-210	<1E-10	<1E-10	<1E-10	<1E-10

Notes: No effect concentrations for non-human biota are given in Table 7.11 of the Data report (QUINTESSA and GEOFIRMA 2011).

Table 5.4: Ratio of Calculated Peak Concentration of Non-radioactive Contaminants in Biosphere Media to Environmental Quality Standards for the Vertical Fault Scenario Base Case (VF-NR)

Contaminant	Well Water	Irrigated Soil	Sediment	Surface Water
Ag	<1E-10	<1E-10	<1E-10	2.6E-10
As	<1E-10	<1E-10	<1E-10	3.1E-10
B	<1E-10	<1E-10	-	<1E-10
Ba	<1E-10	<1E-10	-	-
Be	<1E-10	<1E-10	-	<1E-10
Br	-	-	-	<1E-10
Cd	4.8E-09	<1E-10	5.1E-08	2.4E-06
Co	<1E-10	<1E-10	<1E-10	2.6E-09
Cr	6.1E-08	<1E-10	2.9E-07	1.1E-05
Cu	1.5E-07	<1E-10	4.3E-06	1.3E-05
Gd	-	-	-	2.8E-09
Hf	-	-	-	2.3E-10
Hg	1.5E-10	<1E-10	2.0E-10	6.3E-08
I	-	-	-	<1E-10
Li	-	-	-	<1E-10
Mn	-	-	-	3.2E-08
Mo	3.0E-09	<1E-10	-	2.9E-08
Nb	-	-	-	<1E-10
Ni	4.9E-08	<1E-10	2.9E-06	4.6E-07
Pb	<1E-10	<1E-10	3.0E-07	3.4E-06
Sb	4.6E-10	<1E-10	-	5.9E-10
Sc	-	-	-	<1E-10
Se	<1E-10	<1E-10	-	1.6E-10
Sn	-	-	-	1.2E-10
Sr	-	-	-	<1E-10
Te	-	-	-	<1E-10
Tl	<1E-10	<1E-10	-	<1E-10
U	<1E-10	<1E-10	-	<1E-10
V	<1E-10	<1E-10	-	<1E-10
W	-	-	-	<1E-10
Zn	2.0E-10	<1E-10	9.0E-09	2.7E-08
Zr	-	-	-	3.0E-07
Chlorobenzene/ Chlorophenol	<1E-10	<1E-10	5.0E-09	1.5E-09
Dioxins/Furans	1.3E-09	<1E-10	-	<1E-10
PAH	<1E-10	<1E-10	5.7E-10	1.6E-08
PCB	<1E-10	<1E-10	<1E-10	5.0E-10

Note: Environmental quality standards are given in Table 7.12 of the Data report (QUINTESSA and GEOFIRMA 2011). ‘-‘ indicates no environmental quality standard identified.

5.5.2 Calculated Radiation Doses

The calculated radiation doses for the Vertical Fault Scenario Base Case are very small. The peak calculated dose to the maximally exposed group (the site shore group) is 5 x 10^{-10} mSv/a (an order of magnitude higher than the dose to the site resident group). This value is very far below the relevant dose criterion of 1 mSv/a. The dominant pathway is ingestion of water, and the key radionuclides are Zr-93 (via the ingestion of water) and its daughter Nb-93m (via the ingestion of fish).[6]

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

5.5.3 Likelihood

There is strong geological, hydrogeological, and geochemical evidence indicating that there is no transmissive fault within the footprint or in close proximity to the DGR that could provide an enhanced permeability pathway from the repository horizon to an overlying aquifer (Section 2.3 of the System and Its Evolution report, QUINTESSA 2011b) (Sections 2.3.9 and 7.2 of NWMO 2011). Geomechanical modelling has also not indicated any tendency to formation of such fractures, under likely gas pressure, seismic, or glacial loading (Section 6.4 of NWMO 2011).

The results demonstrate that even if such a situation were to occur, the consequence would be very low. The consequences are limited by the slow diffusion of contaminants downward to the Cambrian, or horizontally from the repository to the fault.

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

6. UNCERTAINTIES

All Disruptive Scenarios are influenced by uncertainties in the undisturbed performance of the system, described in Chapter 6 of the Normal Evolution Scenario Analysis report (QUINTESSA 2011a).

An additional significant source of uncertainty is the probability that the Disruptive Scenarios occur. Disruptive Scenarios related to human actions, such as Human Intrusion Scenario, are distinct because their probability of occurrence and nature cannot be reliably determined since this is intrinsically linked to the character of human society and technology. It is possible to make estimates based on current behaviour and technology, and these are used to identify illustrative scenarios to test the robustness of the DGR concept.

The likelihood of inadvertent intrusion is expected to increase with time, in part due to the assumed eventual loss of institutional control or society memory about the site. However, the consequences of intrusion also decrease with time.

Unlike human events, the probability of occurrence, and nature of, natural disruptive events themselves can, to some degree, be gauged by careful examination of site and historical evidence. For example, the DGR is located at the edge of the Stable Cratonic Core Region of Canada, the most stable part of the continent. The region's seismic stability is generally manifested by a lack of detectable structural features and low seismicity. This is supported by historic monitoring of seismicity through the national network and the recent micro-seismicity monitoring array installed in 2007 (Sections 2.2.6.5 and 6.2.2.1 of NWMO 2011). Furthermore, modelling study investigations of the impact of earthquakes and ice-sheets loading and unloading (e.g., Section 6.4 of NWMO 2011) indicate that the integrity and barrier capacity of the host rock remains intact and that long-term safety is not compromised. This evidence has been used to inform the assessment. Uncertainties in the nature and consequences of large earthquakes have been approached by (1) assuming there is rockfall within the repository to a stable equilibrium point; and (2) by bounding the consequences through the Severe Shaft Seal Failure and Vertical Fault Scenarios.

Finally, in all the scenarios, the uncertainties associated with the potential exposure of humans are managed through the adoption of conservative assumptions. In particular, they are located at the most sensitive location (e.g., on land above the repository), and follow lifestyles that maximise their exposure to any contaminant releases.

7. SUMMARY AND CONCLUSIONS

The Normal Evolution Scenario analysis considers the likely evolution of the repository and site over a 1 million year time frame, with illustrative calculations beyond this to 10 million years (QUINTESSA 2011a). The present report considers Disruptive Scenarios – in particular, events or processes that would potentially bypass the significant geological and engineered barriers that provide long-term isolation and containment of the wastes.

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 (the **Human Intrusion Scenario**);
- the unexpected poor performance of the shaft seals (the **Severe Shaft Seal Failure Scenario**);
- poor sealing of a site investigation/monitoring borehole near the repository (the **Poorly Sealed Borehole Scenario**); and
- a hypothetical transmissive vertical fault in close proximity to the DGR footprint (the **Vertical Fault Scenario**).

Any one of the events that could initiate these scenarios is very unlikely to occur in any given year. The likelihood of the modelled conditions occurring is even lower as the scenarios make additional conservative assumptions, for example, relating to assumed material properties, human practices and exposure mechanisms.

The calculated doses to the maximally exposed group for the Disruptive Scenario's Base Case calculations are summarized in Figure 7.1 and discussed below.

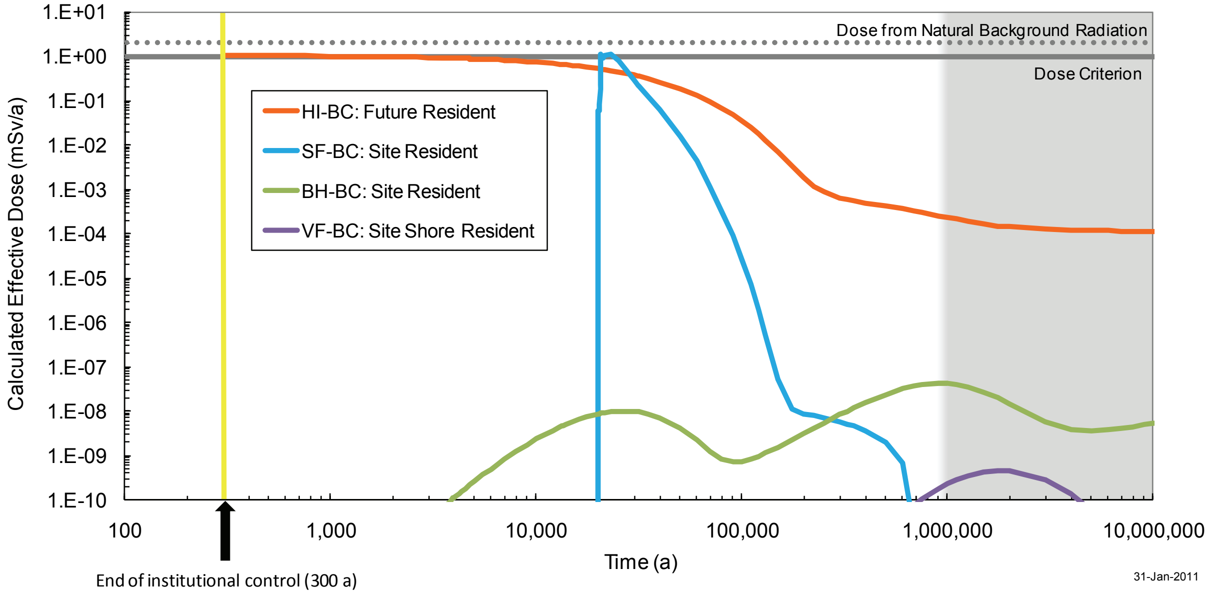

Figure 7.1: Calculated Doses to the Maximally Exposed Groups for the Disruptive Scenario Base Case Calculations

The Human Intrusion Scenario could in principle result in contaminated gas and/or waste (in drill core) being released to the surface. There is insufficient saturation in the repository for a water release at time of intrusion. Assessment calculations have considered the potential exposure of the drill crew and other critical groups to these materials. The assessment does not take account of good practice and many standard operating procedures that would reduce the likelihood of consequences; for example, the drill crew are assumed to leave drill core debris on the site. The calculated peak dose of about 1 mSv occurs about 300 a after closure of the DGR and is to a future resident who uses the contaminated drill site for farming after the borehole has been abandoned. The doses to other potential critical groups are below the dose criterion for disruptive events of 1 mSv/a for the base case calculations considering a surface release of contaminants. By around 5 ka, the dose to the future site resident is below the dose criterion, and by 70 ka the doses for all critical groups are more than an order of magnitude below the criterion.

The Severe Shaft Seal Failure Scenario indicates that significant degradation of the shaft seals and EDZ causes the peak calculated dose to a site resident group (living over the repository) to reach about 1 mSv/a after about 23 ka. The calculated doses are dominated by C-14, which reaches the Shallow Bedrock Groundwater Zone in the gas phase with a breakthrough of bulk gas from the DGR at around 20 ka. The C-14 then reaches the biosphere directly in gaseous form, and by dissolving in groundwater and being abstracted via a well. The dominant exposure pathways are inhalation of gas and ingestion of plants that have taken up C-14, each of which contributes about 40% of the calculated peak dose. The calculated dose rapidly falls from the peak at 23 ka, so that by 30 ka, it is an order of magnitude below the criterion and by 100 ka it is more than four orders of magnitude below (Figure 7.1).

The Poorly Sealed Borehole Scenario considers a site investigation/monitoring borehole 100 m from the site that is poorly sealed and provides an enhanced permeability pathway up through the geosphere. The calculations show that it has some influence on the performance of the system, compared with the Normal Evolution Scenario's Reference Case. However, the calculated doses are less than 10^{-7} mSv/a, many orders of magnitude below the criterion (Figure 7.1).

There is strong geological, hydrogeological, and geochemical evidence that transmissive vertical faults/fracture zones, which could provide an enhanced permeability pathway from the repository horizon to an overlying aquifer, do not exist within the footprint or vicinity of the DGR. Nevertheless, a "what if" scenario has been considered to investigate the safety implications of a hypothetical transmissive vertical fault, either undetected or representing the displacement of an existing structural discontinuity that propagates from the Precambrian into the Intermediate Bedrock Groundwater Zone in close proximity to the DGR. The assessment calculations show the calculated doses to the most exposed group are less than 10^{-9} mSv/a, far below the dose criterion (Figure 7.1).

Taken as a whole, the assessment of disruptive events has shown that, even with conservatively defined critical groups, the impacts of the unlikely events that have been assessed would not exceed the dose criterion for disruptive events of 1 mSv/a. It is only if extreme assumptions are taken that calculated doses could exceed about 10 mSv/a. For example, if the human intrusion borehole is continued to the Cambrian and then poorly sealed, or if the entire shaft seals degrading to a graded fine sand/silt type of fill and people were living on top of the shafts. Even in these cases, these peak doses are to people living directly on the site - consequences to those living off the site would be much smaller, and consequences decrease significantly after about 30 ka due to C-14 decay.

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

As all the scenarios represent unusual events, the results can also be expressed as risks (where risk is the product of probability and consequences, using an appropriate factor to convert dose to health risk). Scenarios with dose consequences in the range of 1 mSv would meet the reference health risk value of 10^{-5}/a if the probability of occurrence were less than about 1 per 10 years. Although the likelihood cannot be reliably estimated for the various Disruptive Scenarios, their probability should be considerably lower than this value. For example, based on current practice and the size of the repository, the likelihood of an exploratory borehole inadvertently intercepting the repository can be estimated as around 10^{-5}/a. Overall, the likelihood of the Disruptive Scenarios is low enough that they all fall below the reference health risk value.

Calculations have also been undertaken to assess the impact of radionuclides on non-human biota and the impact of non-radioactive elements and chemical species in the waste on humans and other biota for the Disruptive Scenario base cases. The results indicate that potential impacts are low. All non-radioactive contaminants and most radionuclides are below their screening concentration criteria. There could be some local exceedance of screening criteria for the Human Intrusion Scenario and the Severe Shaft Seal Failure Scenario. In particular, the concentration of C-14 and Nb-94 would locally exceed soil criteria by a factor of 20 if drilling debris from the repository were to be dumped on the surface at the site in the Human Intrusion Scenario. In addition, C-14 would locally exceed the surface water screening criteria by a factor of 1.4 in the Severe Shaft Seal Failure Scenario. Since these higher concentrations are local, the screening criteria are conservative, and the scenarios are very unlikely, the risk to non-human biota from these scenarios is low.

In summary, the isolation afforded by the location and design of the DGR limits the likelihood of disruptive events potentially able to bypass the natural barriers to a small number of situations with very low probability. Even if these events were to occur, the analysis shows that the contaminants in the waste would continue to be contained effectively by the DGR such that dose criteria are met in almost all circumstances, even with conservative assessment modelling assumptions. Risk criteria would be met in all cases when account is taken of the probability of occurrence.

The assessment has adopted scientifically informed, physically realistic assumptions for processes and data that are understood and can be justified on the basis of the results of research and/or site investigation. Where there are high levels of uncertainty associated with processes and data, conservative assumptions have been adopted to allow the impacts of uncertainties to be bounded, consistent with the recommendations of G-320 (CNSC 2006). Thus, the results presented in this report should be seen as being generally conservative and liable to overestimate potential impacts.

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9. ABBREVIATIONS AND ACRONYMS

A	AMBER model
BH	Poorly Sealed Borehole Disruptive Scenario
BH-BC	Poorly Sealed Borehole Base Case
BH-NR	Poorly Sealed Borehole Non-Radioactive Contaminants Case
CNSC	Canadian Nuclear Safety Commission
CSA	Canadian Standards Association
DBGZ	Deep Bedrock Groundwater Zone
DGR	Deep Geologic Repository
EDZ	Excavation Damaged Zone
EIS	Environmental Impact Statement
ENEV	Estimated No Effect Values
EQS	Environmental Quality Standards
ERA	Ecological Risk Assessment
F3	FRAC3DVS model
FEP	Features, Events and Processes
HDZ	Highly Damaged Zone
HI	Human Intrusion Disruptive Scenario
HI-BC	Human Intrusion Scenario Base Case
HI-GR2	Exploration Borehole Intersecting the Repository and the Cambrian Case
HI-NR	Human Intrusion Scenario Non-Radioactive Contaminants Case
IAEA	International Atomic Energy Agency
IBGZ	Intermediate Bedrock Groundwater Zone
ICRP	International Commission on Radiological Protection
ILW	Intermediate Level Waste
L&ILW	Low and Intermediate Level Waste
LHHPC	Low-Heat, High-Performance Cement
LLW	Low Level Waste
NECs	No Effect Concentrations
NE-RC	Normal Evolution Scenario Reference Case
OPG	Ontario Power Generation
PSR	Preliminary Safety Report
SA	Safety Assessment
SBGZ	Shallow Bedrock Groundwater Zone
SF	Shaft Failure Disruptive Scenario
SF-BC	Shaft Failure Scenario Base Case
SF-ED	Severe Shaft Seal Failure – Extra Degradation Case

SF-NR	Shaft Failure Scenario Non-Radioactive Contaminants Case
T	T2GGM model
VEC	Valued Ecosystem Components
VF	Vertical Fault Disruptive Scenario
VF-AL	Vertical Fault Alternative Location Case
VF-BC	Vertical Fault Base Case
VF-NR	Vertical Fault Non-Radioactive Contaminants Case
WWMF	Western Waste Management Facility

APPENDICES

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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. It is consistent with model formulation and implementation processes described in International Atomic Energy Agency (IAEA) (2004).

First, the conceptual models are developed for each scenario using input from the assessment context (documented in Chapter 3 of the Postclosure SA main report, QUINTESSA et al. 2011a), the system description (documented in Chapter 2 of the System and Its Evolution report, QUINTESSA 2011), the DGR FEPs list (documented in QUINTESSA et al. 2011b), and the scenarios for assessment (documented in Chapters 7 and 8 of the System and Its Evolution report, QUINTESSA 2011). The aim is to provide, for each scenario considered, a description of the release, migration and fate of contaminants from the repository through the identification of key features, events and processes. The conceptual model provides the set of qualitative and quantitative assumptions used to describe the DGR system for the purposes of the postclosure SA. These assumptions concern the geometry and dimensionality of the system, its temporal and spatial boundary conditions, and the nature of the relevant physical and chemical processes. The associated features, events and processes are audited against the DGR FEPs list to ensure that important issues have not been neglected in the conceptual models (for example the audited FEPs list for the Human Intrusion Scenario is provided in Appendix C).

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

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

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

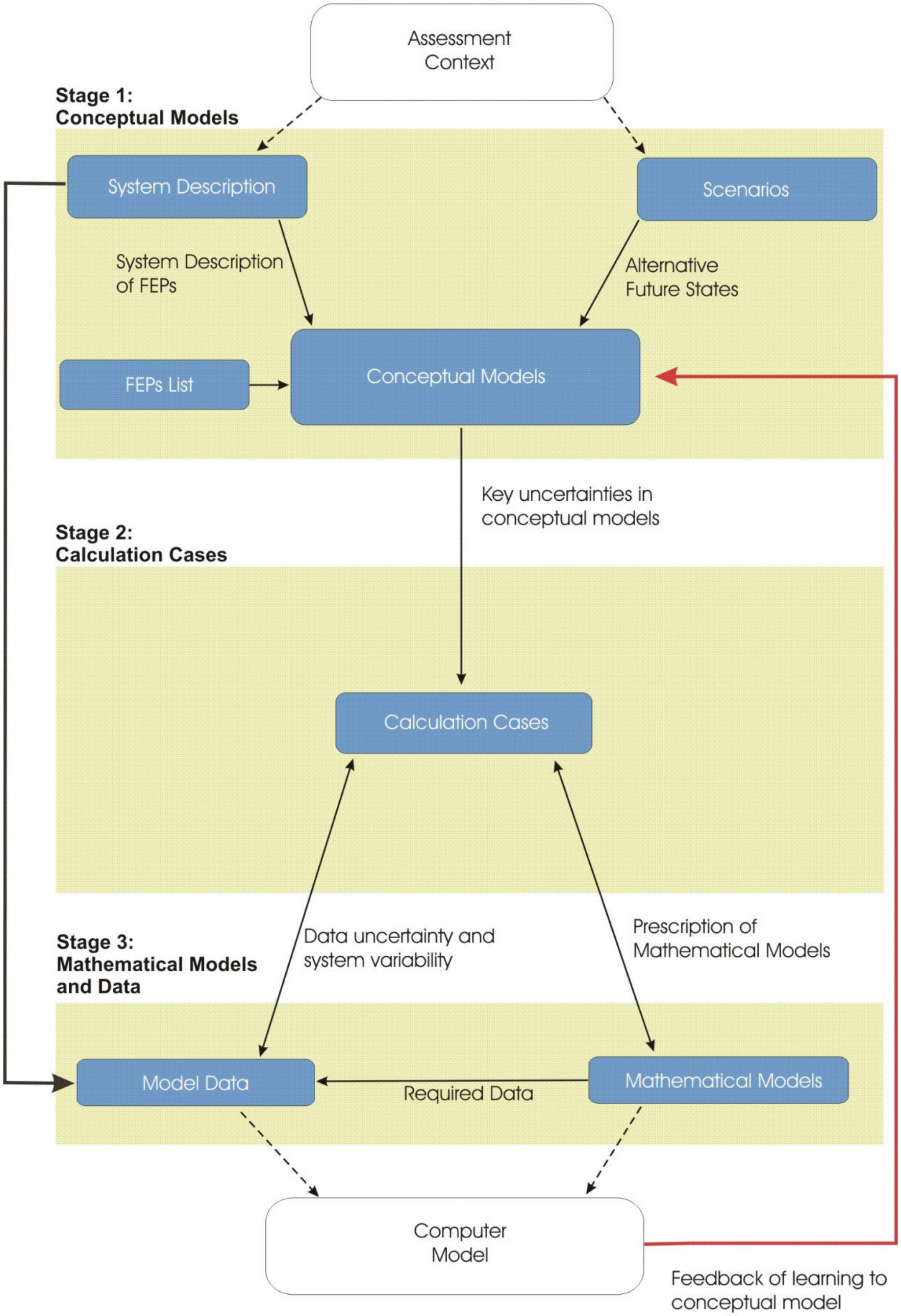

Figure A.1: Model Development Approach

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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 (QUINTESSA 2011).

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

- The wasteforms (corresponding to OPG waste categories);
- Water flowing through the repository (in the case of an exploration borehole penetrating down to the Cambrian);
- The engineered features (e.g., the shaft seals determine, in part, the rate of release of the contaminants from the repository and are, therefore, relevant); and
- The repository gas (distinguishing between Panel 1 and Panel 2 emplacement rooms and the associated access tunnels and service area).

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: water from the Cambrian flowing through the repository (only in the case of the exploration borehole penetrating down to the Cambrian), gas, and solid waste. The highest concentrations occur in Panel 1; 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 any groundwater from the Cambrian flowing through the repository that are released, therefore, relate to those calculated for Panel 1. Repository gas, however, will mix throughout the repository as the top of the walls sealing the emplacement rooms will allow gas migration. 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 geological barriers to contaminant migration. Detailed groundwater modelling presented in Section 6.2 of the Groundwater Modelling report (GEOFIRMA 2011) indicates advective flow could occur in the more permeable Guelph and Salina A1 Upper Carbonate formations, which could therefore be receptors for releases of water from the repository via a borehole. However, it is conservative to assume that releases are to the formations closest to the surface; therefore, the only geological features represented 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. The key media that receive contaminant releases are:

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

The temperate biosphere is taken as the reference state for the Human Intrusion Scenario. It is comparable to current conditions, and allows the impacts to be calculated for receptors such as farmers.

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 categorized 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 enter the geosphere (the Shallow Bedrock Groundwater Zone has been conservatively assumed, 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 (QUINTESSA 2011).

The following processes are relevant to the conceptual model of the **repository** component of the DGR system for the Human Intrusion Scenario, and should 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 and congruent release);
- Gas release from saturated and unsaturated wasteforms;
- Aqueous mixing in the repository;
- Gas transport;
- Gas dissolution in water;
- Elemental solubility; and

- 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 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** should be assessed for 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 to the surface are more limited, consistent with the more limited range of exposure pathways relevant to the critical groups assessed, 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. For release to the Shallow Bedrock Groundwater Zone, the borehole is assumed to be drilled immediately after the cessation of post-closure controls for the DGR (assumed to be after 300 a). For other pathways, doses can be calculated as a function of the time at which the intrusion occurs.

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.

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 equalized or the borehole is sealed. The well would be expected to be fitted with blowout 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 (GEOFIRMA and QUINTESSA 2011).

Groundwater Release via Borehole: Contaminated groundwater may be released, but only if it is assumed that the borehole is continued through the repository to the Cambrian and is poorly sealed. The possibility is examined in detailed groundwater modelling (Section 6.2 of GEOFIRMA 2011). The volume discharged via the borehole would be driven by the head in the Cambrian and hydraulic conductivity of the borehole seal. Released water may re-enter the geosphere along the path of the borehole; however, it is assumed that the primary release is to the Shallow Bedrock Groundwater Zone.

Solid Release via Borehole: Solid waste could be retrieved during coring activity if the drilling is designed to extract drill cores intercepts waste. The contaminated drill core is taken for examination in a laboratory. Potential exposures to waste have also been assessed assuming that an amount of material is extracted from the repository as drill (core) debris and subsequently discarded and dispersed in surface soil, where it has the potential to both expose drill workers, and also subsequent users of the site.

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

The features, events and processes considered in the conceptual model for the Human Intrusion and Scenario have been audited against the DGR FEPs list documented in QUINTESSA et al. (2011a).

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 **bold** 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 Components	
2.1.01 Waste inventory	
2.1.01.01 **Radionuclide content**	**Yes**, consider - see Table 2.6 of the System and Its Evolution report (QUINTESSA 2011a). *As Normal Evolution Scenario*
2.1.01.02 **Chemical content**	**Yes**, explicitly consider - see Table 2.6 of the System and Its Evolution report (QUINTESSA 2011a). *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 2.7 of the System and Its Evolution report (QUINTESSA 2011a). *As Normal Evolution Scenario*
2.1.02.02 **Organic wastes**	**Yes**, consider - see Tables 2.1, 2.2 and 2.7 of the System and Its Evolution report (QUINTESSA 2011a). *As Normal Evolution Scenario*
2.1.02.03 **Non-metallic, inorganic wastes**	**Yes**, consider - see Tables 2.1, 2.2 and 2.7 of the System and Its Evolution report (QUINTESSA 2011a). *As Normal Evolution Scenario*
2.1.03 Waste-packaging characteristics	
2.1.03.01 **Containers**	**Yes**, consider - see Tables 2.3 and 2.7 of the System and Its Evolution report (QUINTESSA 2011a) and Tables 3.3 and 3.4 of the Data report (QUINTESSA and GEOFIRMA 2011a). *As Normal Evolution Scenario*
2.1.03.02 **Overpacks**	**Yes**, consider - see Tables 2.3 and 2.7 of the System and Its Evolution report (QUINTESSA 2011a) and Tables 3.3 and 3.4 of the Data report (QUINTESSA and GEOFIRMA 2011a). *As Normal Evolution Scenario*
2.1.04 Emplacement room, access tunnel and shaft & services area characteristics	

FEP		Included in Conceptual Model for Human Intrusion Scenario
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 the Data report, QUINTESSA and GEOFIRMA 2011a). *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 the Data report, QUINTESSA and GEOFIRMA 2011a). *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 the Data report, QUINTESSA and GEOFIRMA 2011a). *As Normal Evolution Scenario*
2.1.04.04	**Room and closure walls**	**Yes**, but conservatively assume they have no impact on migration of contaminants - see Section 2.3.1.3 of the Normal Evolution Scenario Analysis report (QUINTESSA 2011b). However, included in calculation of mass of concrete and steel in the repository (see Tables 4.8 and 4.9 of the Data report, QUINTESSA and GEOFIRMA 2011a). *As Normal Evolution Scenario*
2.1.04.05	Backfill	**No**, no backfill considered in the reference repository design - see Section 2.2.3.1 of the System and Its Evolution report (QUINTESSA 2011a).
2.1.05	**Shaft characteristics**	
2.1.05.01	**Lining**	**Yes**, consider but only for shafts in Shallow Bedrock Groundwater Zone and below repository level 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, QUINTESSA 2011a). *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, QUINTESSA 2011a). *As Normal Evolution Scenario*
2.1.05.03	**Plugs**	**Yes**, consider basal monolith, three concrete bulkheads and a surface cap – see Section 2.2.3.4 of the System and Its Evolution report, QUINTESSA 2011a). *As Normal Evolution Scenario*
2.1.05.04	Rock bolts	**No**, the only rock bolts would be in the Shallow Bedrock Groundwater Zone and below repository level since liner removed from repository level up to the start of this

FEP			Included in Conceptual Model for Human Intrusion Scenario
			zone at closure (see Section 2.2.3.4 of the System and Its Evolution report, QUINTESSA 2011a). *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 Analysis report (QUINTESSA 2011b). *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 Analysis report (QUINTESSA 2011b). *As Normal Evolution Scenario*
	2.1.06.02	Material volume changes	
		A **Concrete shrinkage/ expansion**	**Yes**, see discussion of concrete shrinkage/expansion in Section 4.5.3 of the System and Its Evolution report (QUINTESSA 2011a). *As Normal Evolution Scenario*
		B **Bentonite swelling**	**Yes**, see discussion of bentonite expansion in Section 4.5.4 of the System and Its Evolution report (QUINTESSA 2011a). *As Normal Evolution Scenario*
		C **Corrosion products**	**Yes**, see discussion of effects of corrosion in Section 4.5.1 of the System and Its Evolution report (QUINTESSA 2011a). *As Normal Evolution Scenario*
	2.1.06.03	**Emplacement room/ tunnel collapse**	**Yes**, consider sequential rockfall affecting the entire repository (see Section 4.4.1 of the System and Its Evolution report, QUINTESSA 2011a). *As Normal Evolution Scenario*
	2.1.06.04	**Container movement**	**Yes**, consider collapse of containers (see Section 2.3.1.2 of the Normal Evolution Scenario Analysis report, QUINTESSA 2011b). *As Normal Evolution Scenario*

FEP			Included in Conceptual Model for Human Intrusion Scenario
	2.1.06.05	**Fracture formation**	**Yes**, consider through effect on the physical degradation of concrete bulkheads and monolith (see Section 2.3.2.1 of the Normal Evolution Scenario Analysis report, QUINTESSA 2011b). *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 concrete bulkheads and monolith (see Section 2.3.2.1 of the Normal Evolution Scenario Analysis report, QUINTESSA 2011b) and rockfall in the repository (see Section 2.3.1.1 of the Normal Evolution Scenario Analysis report, QUINTESSA 2011b). *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 modelling (GEOFIRMA and QUINTESSA 2011). 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 Analysis report, QUINTESSA (2011b). *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 pressurization (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*

FEP			Included in Conceptual Model for Human Intrusion 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 the FEPs report, QUINTESSA et al. 2011a). *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 the FEPs report, QUINTESSA et al. 2011a). *As Normal Evolution Scenario*
	2.1.07.07	**Influence of climate change**	**Yes**, glacial-interglacial cycling and the hydraulic and hydrogeological impacts of this cycling are considered to be one of the factors resulting in the degradation of the concrete bulkheads and monolith (see Section 2.3.2.1 of the Normal Evolution Scenario Analysis report, QUINTESSA 2011b). *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 2.3.1.1 of the Normal Evolution Scenario Analysis report, QUINTESSA 2011b). *As Normal Evolution Scenario*
	2.1.08.02	**Redox 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 Analysis report, QUINTESSA 2011b). *As Normal Evolution Scenario*
	2.1.08.03	**Chloride and sulphate conditions**	**Yes**, consider impact on corrosion and microbial degradation rates (see Appendices E and F of the Data report, QUINTESSA and GEOFIRMA 2011a) and solubility and sorption values (see Appendices C and D of the Data report, QUINTESSA and GEOFIRMA 2011a). *As Normal Evolution Scenario*
	2.1.08.04	Corrosion	
		A **General**	**Yes**, consider impact on gas generation rates and failure of packaging (see the

FEP		Included in Conceptual Model for Human Intrusion Scenario
		FEPs report, QUINTESSA et al. 2011a). *As Normal Evolution Scenario*
	B Localized	**No**, localized corrosion is expected to occur only during the short (<10 years) aerobic phase (see the FEPs report, QUINTESSA et al. 2011a). *As Normal Evolution Scenario*
	C Galvanic	**No** consider impact on gas generation rates will be small (see the FEPs report, QUINTESSA et al. 2011a). *As Normal Evolution Scenario*
2.1.08.05	**Polymer degradation**	**Yes**, consider impact on gas generation rates (see Section 4.2 of the T2GGM software document, QUINTESSA and GEOFIRMA 2011b). *As Normal Evolution Scenario*
2.1.08.06	Mineralization	
	A **Leaching**	**Yes**, consider leaching of concrete in the shaft bulkheads and monolith (see Section 4.5.3 of the System and Its Evolution report, QUINTESSA 2011a). *As Normal Evolution Scenario*
	B **Chloride attack**	**Yes**, consider effect on degradation of concrete (see Section 4.5.3 of the System and Its Evolution report, QUINTESSA 2011a). *As Normal Evolution Scenario*
	C **Sulphate attack**	**Yes**, consider effect on degradation of concrete (see Section 4.5.3 of the System and Its Evolution report, QUINTESSA 2011a). *As Normal Evolution Scenario*
	D Carbonation	**No**, not represented explicitly since calculations indicate that it will be slow and of limited spatial extent (see the FEPs report, QUINTESSA et al. 2011a). *As Normal Evolution Scenario*
	E Illitization	**No**, calculations indicate that it will be negligible (see Appendix E.3 of the System and Its Evolution report, QUINTESSA 2011a). *As Normal Evolution Scenario*
2.1.08.07	**Precipitation reactions**	**Yes**, consider solubility limitation of releases from waste to groundwater but only for C (see Section 2.3.1.1 of Normal Evolution Scenario Analysis report, QUINTESSA 2011b). *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 the FEPs report, QUINTESSA et al. 2011a). *As Normal Evolution*

FEP			Included in Conceptual Model for Human Intrusion Scenario
			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 (see the FEPs report, QUINTESSA et al. 2011a). *As Normal Evolution Scenario*
	2.1.08.10	Osmotic effects	**No**, not considered to be a significant process (see the FEPs report, QUINTESSA et al. 2011a). *As Normal Evolution Scenario*
	2.1.08.11	Chemical concentration gradients	**No**, not considered to be a significant process (see the FEPs report, QUINTESSA et al. 2011a). *As Normal Evolution Scenario*
	2.1.08.12	Influence of climate change	**No**, no significant effects expected (see the FEPs report, QUINTESSA et al. 2011a). *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 the Normal Evolution Scenario Analysis report, QUINTESSA 2011b). *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 the Normal Evolution Scenario Analysis report, QUINTESSA 2011b). *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 Analysis report, QUINTESSA 2011b). 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**, no significant effects expected (see the FEPs report, QUINTESSA et al. 2011a). *As Normal Evolution Scenario*

FEP		Included in Conceptual Model for Human Intrusion Scenario
2.1.10	Thermal processes and conditions (in wastes, emplacement rooms, tunnels and shafts)	
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 the FEPs report, QUINTESSA et al. 2011a). *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 the FEPs report, QUINTESSA et al. 2011a). *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 the FEPs report, QUINTESSA et al. 2011a). *As Normal Evolution Scenario*
	B Hydraulic	**No**, assume no significant temperature evolution and so no effect on hydraulic processes (see the FEPs report, QUINTESSA et al. 2011a). *As Normal Evolution Scenario*
	C Chemical	**No**, assume no significant temperature evolution and so no effect on chemical processes (see the FEPs report, QUINTESSA et al. 2011a). *As Normal Evolution Scenario*
	D Biological	**No**, assume no significant temperature evolution and so no effect on biological processes (see the FEPs report, QUINTESSA et al. 2011a). *As Normal Evolution Scenario*
2.1.10.05	Influence of climate change	**No**, the relatively small change in temperature at repository and deep shaft locations, and the absence of continuous permafrost at the site, indicate that temperature variations changes due to climate change are not a significant factor in

FEP	Included in Conceptual Model for Human Intrusion Scenario
	the evolution of the repository (see the FEPs report, QUINTESSA et al. 2011a). *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 Analysis report, QUINTESSA 2011b. *As Normal Evolution Scenario*
2.1.11.03 **Organic waste degradation**	**Yes**, see Section 2.3.1.1 of the Normal Evolution Scenario Analysis report, QUINTESSA 2011b. *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 the FEPs report (QUINTESSA et al. 2011a). *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 the FEPs report, QUINTESSA et al. 2011a). *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 the FEPs report, QUINTESSA et al. 2011a). *As Normal Evolution Scenario*
2.1.13 Effects of extraneous materials	**No**, not considered to be a significant process (see the FEPs report, QUINTESSA et al. 2011a). *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 the FEPs report, QUINTESSA et al. 2011a). *As Normal Evolution Scenario*
2.2 Geological Environment	

FEP			Included in Conceptual Model for Human Intrusion Scenario
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 rock lithology**		**Yes**, see Box 1 in Section 2.2.2. *As Normal Evolution Scenario*
2.2.03	Disturbed zone (in geosphere)		
	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 characterization area (i.e., within 500 m of the DGR) (see Section 2.3.3 of the System and Its Evolution report, QUINTESSA 2011a). *As Normal Evolution Scenario*
	2.2.04.02	**Fractures and joints**	**Yes**, field evidence shows that there are localized fracture zones and paleokarst horizons. However, there are no continuous discrete fracture networks, and so the presence of fractures is subsumed within the measured formation hydraulic conductivities (see the FEPs report, QUINTESSA et al. 2011a). *As Normal Evolution Scenario*
	2.2.04.03	Dykes	**No**, no evidence of dykes at the site (see Section 2.3 of the System and Its Evolution report, QUINTESSA 2011a). *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 5.3.1 of the System and Its Evolution report, QUINTESSA 2011a). *As Normal Evolution Scenario*

FEP			Included in Conceptual Model for Human Intrusion Scenario
	2.2.05.02	**Current stress regime**	**Yes**, see Section 2.3.9 of the System and Its Evolution report, QUINTESSA 2011a). *As Normal Evolution Scenario*
	2.2.05.03	**Future stress regime**	**Yes**, consider evolution of stress regime around the repository that causes rockfall (see Section 5.3.1 of the System and Its Evolution report, QUINTESSA 2011a) and transitory changes in stress due to ice-sheet loading and unloading (see Section 5.3.3 of the System and Its Evolution report, QUINTESSA 2011a). *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**, see Table 2.3 in Section 2.4.3.
	2.2.06.03	**Future hydraulic potentials and gradients**	**Yes**, long-term release of contaminated water to Shallow Bedrock Groundwater Zone is represented using the groundwater model with transient conditions (Section 2.4.3.4).
2.2.07	Chemical/geochemical processes and conditions (in geosphere)		
	2.2.07.01	**Mineralogical properties**	**Yes**, properties discussed in Section 2.3.7.2 of the System and Its Evolution report (QUINTESSA 2011a). *As Normal Evolution Scenario*
	2.2.07.02	**Geochemical properties**	**Yes**, properties given in Section 2.3.7 of the System and Its Evolution report (QUINTESSA 2011a) and used to inform selection of sorption coefficients (Appendix D of the Data report, QUINTESSA and GEOFIRMA 2011a). *As Normal Evolution Scenario*
	2.2.07.03	Effects of engineered barriers	**No**, expect that any effects will be localized. *As Normal Evolution Scenario*

FEP			Included in Conceptual Model for Human Intrusion 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 (Section 4.5.2 of NWMO 2011). However, for the current assessment, these changes are assumed to have limited effect on the assessment calculations and a stylized approach using constant climate conditions is adopted (see Appendix B.2.3.1 of the Normal Evolution Scenario Analysis report, QUINTESSA 2011b). Furthermore, geochemical evidence indicates that the waters below the Shallow Bedrock Groundwater Zone are ancient and will not be perturbed by climate change (Chapter 4 of NWMO 2011). *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 QUINTESSA et al. (2011a). *As Normal Evolution 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 recognized that the surface and near-surface environment will be significantly affected and a stylized approach using constant climate conditions is adopted (see Appendix B.2.3.1 of the Normal Evolution Scenario Analysis report, QUINTESSA 2011b). 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)		

FEP	Included in Conceptual Model for Human Intrusion Scenario
2.2.10.01 Gas sources (excluding waste and repository materials)	**No,** although trace amounts of gas have been found throughout the Intermediate and Deep Bedrock Groundwater zones, there is no significant generation of gas in the deep geosphere in the area of the DGR (see the FEPs report, QUINTESSA et al. 2011a).
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 Analysis report, QUINTESSA 2011b). *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 Analysis report, QUINTESSA 2011b). *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 Figure 8.1 of the Gas Modelling report, GEOFIRMA and QUINTESSA 2011). *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 2.3.5 of the System and Its Evolution report, QUINTESSA 2011a). 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 exploration borehole that penetrates the repository might be drilled because the repository 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 Analysis report, QUINTESSA 2011b). *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 Analysis report, QUINTESSA 2011b). *As Normal Evolution Scenario*
2.3.03 Soil and sediment	

FEP			Included in Conceptual Model for Human Intrusion Scenario
	2.3.03.01	**Surface soils**	**Yes**, receptor of contaminants in groundwater, gas and dispersed drill core debris (Table 2.1 and 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 Analysis report, QUINTESSA 2011b) 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 and Figure 2.3).
2.3.09	**Vegetation**		**Yes**, consider for drill core debris dispersed in soils and groundwater releases (see Sections 2.2.2.4 and 2.2.2.5).

FEP	Included in Conceptual Model for Human Intrusion Scenario
2.3.10 **Animal populations**	**Yes**, consider for drill core debris dispersed in soils (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 the Normal Evolution Scenario Analysis report, QUINTESSA 2011b).
2.3.13 **Erosion and deposition**	**Yes**, consider for the Shallow Bedrock Groundwater Zone Release Pathway (see Figure 2.16 of the Normal Evolution Scenario Analysis report, QUINTESSA 2011b).
2.3.14 **Ecological/biological/microbial systems**	**Yes**, consider for the Shallow Bedrock Groundwater Zone Release Pathway (see Figure 2.16 of the Normal Evolution Scenario Analysis report, QUINTESSA 2011b) and for the future resident for the drill core debris dispersed in soils (see Figure 2.6.
2.3.15 Biotic intrusion	**No**, not relevant for deep repository (see the FEPs report, QUINTESSA et al. 2011a). *As Normal Evolution Scenario*
2.4 Human Behaviour	
2.4.01 **Human characteristics (physiology, metabolism)**	**Yes**, consider International Commission on Radiological Protection (ICRP) Reference Man (see the FEPs report, QUINTESSA et al. 2011a). *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 the FEPs report, QUINTESSA et al. 2011a). *As Normal Evolution Scenario.*
2.4.03 Diet and liquid intake	
2.4.03.01 **Farming diet**	**Yes**, the future and site resident 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 future and site resident 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, QUINTESSA and

FEP			Included in Conceptual Model for Human Intrusion Scenario
			GEOFIRMA 2011a), 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 critical groups (nearby resident, future resident, drill crew, laboratory technician and site resident) (see Sections 2.2.2.4 and 2.2.2.5).
	2.4.05.02	**Community location**	**Yes**, assume critical 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 site resident 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 Canadian Standards Association (CSA) (2008) (see the FEPs report, QUINTESSA et al. 2011a). *As Normal Evolution Scenario*
2.4.07	**Dwellings**		**Yes**, consider house dwelling for site resident 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).
2.4.08	**Natural/semi-natural land and water use**		**Yes**, site resident 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.

FEP	Included in Conceptual Model for Human Intrusion Scenario
2.4.09 **Rural and agricultural land and water use**	**Yes**, site resident 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 Section 2.4.7 of the System and Its Evolution report, QUINTESSA 2011a) and the expected lower impacts than for farming and fishing critical groups (see the FEPs report, QUINTESSA et al. 2011a). *As Normal Evolution Scenario*
2.4.11 **Leisure and other uses of environment**	**Yes,** site resident 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, QUINTESSA and GEOFIRMA 2011a). *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, QUINTESSA and GEOFIRMA 2011a). *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 Analysis report, QUINTESSA 2011b), 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 Sections 3.5.1 and 3.6.1 of the Data report, QUINTESSA and GEOFIRMA 2011a). *As Normal Evolution Scenario*

FEP	Included in Conceptual Model for Human Intrusion Scenario
3.1.05 **Volatiles and potential for volatility**	**Yes**, consider generation of gases in the repository (Section 2.2.2.2) and volatilization 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	
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 the Normal Evolution Scenario Analysis report, QUINTESSA 2011b). *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 the Normal Evolution Scenario Analysis report, QUINTESSA 2011b).
C **Dispersion**	**Yes**, dispersive transport is considered since advection is considered (see FEP 3.2.02.02.A). *As Normal Evolution Scenario*

FEP			Included in Conceptual Model for Human Intrusion Scenario
		D Matrix diffusion	**No**, assume no dual porosity systems (see the FEPs report, QUINTESSA et al. 2011a). *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 (see Figure 2.16 of the Normal Evolution Scenario Analysis report, QUINTESSA 2011b). For the drill core debris dispersed in soils, leaching is conservatively not modelled (see Figure 2.6).
		C Capillary rise	**No**, not considered to be a significant process for transfer of contaminants (see the FEPs report, QUINTESSA et al. 2011a). *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 Analysis report, QUINTESSA 2011b). For the drill core debris dispersed in soils, leaching is conservatively not modeled (see Figure 2.6).
		E **Transport by interflow**	**Yes**, consider for the Shallow Bedrock Groundwater Zone Release Pathway (see Section 2.2.2.5). For the drill core debris dispersed in soils, leaching is conservatively not modeled (see Figure 2.6).
		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 Analysis report, QUINTESSA 2011b). 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*
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 Analysis report, QUINTESSA 2011b).

FEP		Included in Conceptual Model for Human Intrusion Scenario
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 volatilization 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 2.16 of the Normal Evolution Scenario Analysis report, QUINTESSA 2011b).
3.2.05	**Atmospheric migration of contaminants**	**Yes**, consider for all releases (see Table 2.1 and Figure 2.3).
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 the Normal Evolution Scenario Analysis report, QUINTESSA 2011b). *As Normal Evolution Scenario*
3.2.07	**Animal, plant and microbe mediated migration of contaminants**	**Yes**, consider animal and plant uptake for the future resident for the drill core debris dispersed in soils (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 colloid transport will be limited by the low permeabilities (see the FEPs report, QUINTESSA et al. 2011a). *As Normal Evolution Scenario*
3.2.10	Dissolution, precipitation and mineralization	
	3.2.10.01 **Dissolution and Precipitation (repository)**	**Yes**, consider aqueous release from wasteform and solubility limitation (see Section 2.3.1.1 of the Normal Evolution Scenario Analysis report, QUINTESSA 2011b). 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*

FEP			Included in Conceptual Model for Human Intrusion Scenario
	3.2.10.02	Dissolution and Precipitation (geosphere)	**No**, assume no dissolution/precipitation in geosphere (see the FEPs report, QUINTESSA et al. 2011a). *As Normal Evolution Scenario*
	3.2.10.03	Dissolution and Precipitation (biosphere)	**No**, assume no dissolution/precipitation in biosphere (see the FEPs report, QUINTESSA et al. 2011a). *As Normal Evolution Scenario*
	3.2.10.04	**Change in mineralization**	**Yes**, consider mineralization of concrete (see Appendix E.5 of the System and Its Evolution report, QUINTESSA 2011a). *As Normal Evolution 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 the Normal Evolution Scenario Analysis report, QUINTESSA 2011b). Speciation considered through solubility limitation but only for C (see FEPs report, QUINTESSA et al. 2011a). *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**, but only for C (see the FEPs report, QUINTESSA et al. 2011a). *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)		

FEP			Included in Conceptual Model for Human Intrusion Scenario
	3.2.12.01	**Sorption and desorption (repository)**	**Yes**, consider sorption for certain elements in bentonite/sand (see Section 4.6.3 of the Data report, QUINTESSA and GEOFIRMA 2011a). *As Normal Evolution Scenario*
	3.2.12.02	**Sorption and desorption (geosphere)**	**Yes**, consider sorption for certain elements (see Section 5.5.1.3 of the Data report, QUINTESSA and GEOFIRMA 2011a). *As Normal Evolution Scenario*
	3.2.12.03	**Sorption and desorption (biosphere)**	**Yes**, see Section 6.2.1 of the Data report (QUINTESSA and GEOFIRMA 2011a). *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 the FEPs report, QUINTESSA et al. 2011a). *As Normal Evolution Scenario*
	3.2.12.05	**Anion exclusion effects**	**Yes**, Diffusion experiments have shown that ion exclusion effects occur (see discussion in Section 5.5.1.4 of the Data report, QUINTESSA and GEOFIRMA 2011a). *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 the FEPs report, QUINTESSA et al. 2011a).
	3.2.13.02	Inorganic ligands	**No**, not considered to be a significant process (see the FEPs report, QUINTESSA et al. 2011a). *As Normal Evolution Scenario*
	3.2.13.03	Microbes	**No**, not considered to be a significant process (see the FEPs report, QUINTESSA et al. 2011a). *As Normal Evolution Scenario*
3.2.14	**Food chains and uptake of contaminants**		**Yes**, consider uptake by biota for the drill core debris dispersed in soils (Section 2.2.2.4) and for the Shallow Bedrock Groundwater Zone Release Pathway (Section 2.2.2.5).

FEP	Included in Conceptual Model for Human Intrusion Scenario
3.3 Exposure Factors	
3.3.01 **Contaminant concentrations in drinking water, foodstuffs and drugs**	**Yes**, consider for the future resident group for the drill core debris dispersed in soils (see Figure 2.6). Also considered for the site resident 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 the FEPs report, QUINTESSA et al. 2011a). *As Normal Evolution Scenario*
3.3.03 **Contaminant concentrations in other environmental media**	**Yes**, consider for drill core debris containing waste, gas and groundwater releases (see Figure 2.3 and Section 2.2.2.5).
3.3.04 Exposure modes	
3.3.04.01 **Exposure of humans**	**Yes**, consider exposure of nearby resident, future resident, drill crew, laboratory technician and site resident 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 drill core debris and groundwater releases (see Figure 2.6 and Section 2.2.2.5).
3.3.05 Dosimetry and biokinetics	
3.3.05.01 **Dosimetry and biokinetics for humans**	**Yes,** see Section 7.2.1 of the Data report, QUINTESSA and GEOFIRMA (2011a). *As Normal Evolution Scenario*
3.3.05.02 **Dosimetry and biokinetics for biota other than humans**	**Yes**, see Section 7.2.2 of the Data report, QUINTESSA and GEOFIRMA (2011a). *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 the Postclosure SA main report, QUINTESSA et al. 2011b). *As Normal Evolution Scenario*
3.3.06.02 **Radiological toxicity/effects for biota**	**Yes**, considered using no effect concentrations and if necessary, radiation doses (see Section 3.4 of the Postclosure SA main report, QUINTESSA et al. 2011b). *As*

FEP	Included in Conceptual Model for Human Intrusion Scenario
other than humans	*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 the Postclosure SA main report, QUINTESSA et al. 2011b). *As Normal Evolution 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 the Postclosure SA main report, QUINTESSA et al. 2011b). *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

CSA. 2008. Guidelines for Calculating Derived Release Limits for Radioactive Material in Airborne and Liquid Effluents for Normal Operations of Nuclear Facilities. Canadian Standards Association Standard N288.1-08. Toronto, Canada.

GEOFIRMA and QUINTESSA. 2011. Postclosure Safety Assessment: Gas Modelling. Geofirma Engineering Ltd. and Quintessa Ltd. report for the Nuclear Waste Management Organization, NWMO DGR-TR-2011-31. Toronto, Canada.

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QUINTESSA. 2011b. Postclosure Safety Assessment: Analysis of the Normal Evolution Scenario. Quintessa Ltd. report for the Nuclear Waste Management Organization Report, NWMO DGR-TR-2011-26. Toronto, Canada.

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QUINTESSA and GEOFIRMA. 2011b. T2GGM Version 2: Gas Generation and Transport Code. Quintessa Ltd. and Geofirma Engineering Ltd. report for the Nuclear Waste Management Organization, NWMO DGR-TR-2011-33. Toronto, Canada.

QUINTESSA, SENES and GEOFIRMA. 2011a. Postclosure Safety Assessment: Features, Events and Processes. Quintessa Ltd., SENES Consultants Ltd. and Geofirma Engineering Ltd. report for the Nuclear Waste Management Organization, NWMO DGR-TR-2011-29. Toronto, Canada.

QUINTESSA, GEOFIRMA and SENES. 2011b. Postclosure Safety Assessment. Quintessa Ltd., Geofirma Engineering Ltd. and SENES Consultants Ltd. report for the Nuclear Waste Management Organization, NWMO DGR-TR-2011-25. Toronto, Canada.

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 Gas

The concentration of contaminated gas in the repository ($C_{Gas,rep}$, Bq/m^3) is estimated as the total activity in gas in the Panel (at a given time) divided by the total void space in the Panel at closure (i.e., assuming low resaturation):

$$C_{Gas,rep} = \frac{I_{Gas,rep}}{V_{Gas,rep}} \tag{D.1}$$

where:

$I_{Gas,rep}$ is the total activity of a radionuclide present in gas in the Panel at a given time (Bq);

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

Uncontrolled gas release is assumed to be prevented by the use of a drilling rig blowout preventer. The blowout preventer releases gas at a controlled rate at atmospheric pressure (assumed to be 1 m^3/s at atmospheric pressure). As the gas pressure decreases from the pressure in the DGR to atmospheric pressure the gas expands. Expansion of the gas causes a reduction in the gas concentration. The concentration in the gas released at the surface from the blowout preventer ($C_{Gas,surface}$, Bq/m^3) is:

$$C_{Gas,surface} = C_{Gas,rep} \frac{P_{atmos}}{P_{Gas,rep}} \tag{D.2}$$

where:

P_{atmos} is atmospheric pressure (Pa); and

$P_{Gas,rep}$ is the gas pressure in the DGR (Pa). This is calculated by the T2GGM model, and the time series T2GGM results are imported into the AMBER model (see Appendix F.5).

The concentration of gas in air (C_{Gas}, Bq/m^3) at a point away from the borehole, where a person can inhale it, can then be calculated as follows.

$$C_{Gas} = C_{Gas,surface}\ Q_{Gas}\ \chi_{Gas} \tag{D.3}$$

where:

Q_{Gas} is the rate of release of gas (m^3/s) from the blowout preventer at atmospheric pressure; and

χ_{Gas} is the time integrated air dispersion factor for a ground level discharge, at a given distance from the point of release (s/m^3).

D.1.1.2 Concentration in Drill Core Sample

The contaminant concentrations in the retrieved sample are taken to be the average of the waste concentrations in the Panel for the reference calculation case of the Normal Evolution Scenario. The concentration in the waste (C_{BH} Bq/m^3) is calculated by:

$$C_{BH} = \frac{\sum_{Wastes} I_{Waste}}{\sum_{Wastes} V_{Waste}} \qquad (D.4)$$

where:

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

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

In addition, a concentration calculation is undertaken for each waste category.

D.1.1.3 Concentration in Drill Core Debris

Human intrusion calculations for drill core debris assume that materials brought from the repository to surface become dispersed at the drill site and are mixed into an area of soil. The concentration (C_{Soil}, Bq/m^3) is then given by:

$$C_{Soil} = \frac{C_{BH}\, V_{BH}}{A_{Soil}\, D_{Contam}} \qquad (D.5)$$

where:

V_{BH} is the volume of waste retrieved via the borehole (m^3);

A_{Soil} is the area over which the material is distributed (m^2); and

D_{Contam} is the depth to which the material is mixed (m).

D.1.2 Human Exposures

D.1.2.1 Drill Crew

Both an instantaneous and "chronic" (one month) exposure of the drill crew to drill core debris and gas is assessed.

The ***instantaneous exposure*** includes:

- External irradiation by drill core debris;
- Inadvertent ingestion of drill core debris;
- Inhalation of dust from the drill core debris; and

- Inhalation of discharged repository gas at the well head immediately adjacent to the release.

The effective dose resulting from external irradiation, $E_{ExtSoilSed}$ (Sv/a), is calculated using:

$$E_{ExtSoilSed} = C_{BH} \; V_{BH} \; DCF_{ePt} \; t_{ExpHI} \tag{D.6}$$

where:

t_{ExpHI} is the exposure duration as a fraction of a year (a); and

DCF_{ePt} is the dose coefficient for external irradiation by a point source (Sv/a/Bq).

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

$$E_{IngSoilSed} = \frac{C_{BH}}{\rho_S} \; I_S \; DCF_f \; t_{ExpHI} \tag{D.7}$$

where:

ρ_S is the bulk density of the drill core debris containing waste (kg/m^3);

DCF_f is dose coefficient for intake by ingestion (Sv/Bq); and

I_s is the incidental intake of drill core debris containing waste (kg dry weight/a).

The effective dose from the inhalation of particulate is calculated with:

$$E_{Inh} = \frac{C_{BH}}{\rho_S} \; c_{Dust} \; I_h \; DCF_{iPart} \; t_{ExpHI} \tag{D.8}$$

where:

c_{Dust} is the concentration of contaminated aerosol, which can conservatively be assumed to be the average dust concentration in air, i.e., assuming all dust is contaminated (kg/m^3);

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

I_h is the inhalation rate (m^3/a).

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

$$E_{InhG} = C_{Gas} \; I_h \; DCF_i \; t_{ExpHI} \tag{D.9}$$

where:

DCF_i is the dose coefficient for inhalation (Sv/Bq).

The ***chronic exposure*** situation for the drill crew includes:

- External irradiation by drill core debris diluted in soil;
- Inadvertent ingestion of drill core debris diluted in soil;

- Inhalation of drill core debris diluted in soil and resuspended in air at a characteristic dust-loading; and
- Inhalation of dispersed gas (at 50 m from the well head).

For chronic exposure, the effective dose resulting from external irradiation by drill core debris dispersed in soil, $E_{ExtSoilSed}$ (Sv/a), is calculated using:

$$E_{ExtSoilSed} = C_{Soil}\ f_r\ DCF_g\ t_{ExpHI} \tag{D.10}$$

where:

f_r is the dose reduction factor to account for non-uniformity of the ground surface (unitless) (see Clause 6.14.1 of CSA 2008); and

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

The equations used to calculate the chronic exposures due to ingestion and inhalation 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 bulk density of soil (ρ_B kg/m^3) are used in place of C_{BH} and ρ_S, and other exposure parameter values are specific to chronic exposure.

D.1.2.2 Residents

Both instantaneous and chronic exposures are assessed to residents living in the vicinity of the borehole.

The instantaneous exposure to the **nearby resident** group 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 for the drill crew, above, but with alternative parameter values.

The chronic exposure of a **future resident** group involves the assessment of exposures to contaminated soil. A person lives upon land contaminated by the drill core debris from the borehole. Conservatively, no account is taken of leaching of contaminants from the soil or radioactive decay prior to exposure. The total activity in waste in the drill core debris is mixed into the soil used for growing of fruit and vegetables. The exposure pathways and individual doses are calculated using the same models described in Appendix D of the Normal Evolution Scenario Analysis report (QUINTESSA 2011), and the same habits as the site resident group defined for that scenario, but, due to the limited volume of extracted core and so the limited area of contamination, only the growing of fruit and vegetables is considered.

D.1.2.3 Laboratory Technician

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

- External irradiation by the sample (taken to be a point source at a time-averaged distance over the exposure duration of 1 m from the worker);
- Inadvertent ingestion of undiluted waste (as a result of handling the sample); and

- Inhalation of undiluted waste in dust form (e.g., when a consolidated sample is cut or an unconsolidated sample handled).

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

$$E_{ExtPt} = \frac{C_{BH}}{\rho_S} m_{Core} \, DCF_{ePt} \, t_{ExpHI} \tag{D.11}$$

where:

m_{Core} is the mass of the sample being inspected (kg).

Other doses are calculated using the same mathematical models described for the drill crew (Appendix D.1.2.1). However, 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 Panel 1 of the repository to the overlying Shallow Bedrock Groundwater Zone. The value of the transfer rate ($\lambda_{Borehole}$, /a) is given by:

$$\lambda_{Borehole} = \frac{Q_{Borehole}}{V_{Water[Panel 1]}} \tag{D.12}$$

where:

$Q_{Borehole}$ is the flow rate of water via the intruding borehole (m^3/a); and

$V_{Water[Panel\ 1]}$ is the volume of water in Panel 1 (m^3).

The flow rate via the borehole ($Q_{Borehole}$) has been determined on the basis of groundwater modelling, described in the groundwater modelling report (Section 6.2 of GEOFIRMA 2011). It is only applied once the intrusion has occurred (i.e., after controls are no longer effective), but is taken to continue indefinitely; see Section 2.4.3.4.

The exposure pathways and individual doses are calculated using the same models described for the Normal Evolution Scenario Analysis report (QUINTESSA 2011), and the same habits as the site resident group defined for that scenario.

REFERENCES FOR APPENDIX D

CSA. 2008. Guidelines for Calculating Derived Release Limits for Radioactive Material in Airborne and Liquid Effluents for Normal Operations of Nuclear Facilities. Canadian Standards Association Standard N288.1-08. Toronto, Canada.

GEOFIRMA. 2011. Postclosure Safety Assessment: Groundwater Modelling. Geofirma Engineering Ltd. report for the Nuclear Waste Management Organization, NWMO DGR-TR-2011-30. Toronto, Canada.

QUINTESSA. 2011. Postclosure Safety Assessment: Analysis of the Normal Evolution Scenario. Quintessa Ltd. report for the Nuclear Waste Management Organization, NWMO DGR-TR-2011-26. Toronto, Canada.

APPENDIX E: CALCULATED RELEASES OF GAS FROM THE REPOSITORY VIA A BOREHOLE

It is standard practice for blowout preventers to be used when undertaking the type of drilling that could reach the repository horizon. These limit the release of gas, water or oil from the borehole if it encounters a high-pressure formation.

If a borehole were to intercept the repository, the most likely situation is that the repository would be largely unsaturated but contain pressurized gas. In this case, the blowout preventers would be activated and set to stop or manage the rate of release of gas. In the Human Intrusion Scenario, it is assumed that the gas is allowed to bleed off at a rate of 1 m^3/s (atmospheric pressure), consistent with the deep borehole blowout preventer system used during DGR site characterization exploration drilling. The potential duration of the release is dependent on the pressurization of the repository. Assuming a peak pressure of 8.2 MPa (Table 8.1 of the Gas Modelling report, GEOFIRMA and QUINTESSA 2011), the number of moles of gas in the repository can be calculated using the ideal gas law. The repository void volume is 4.2×10^5 m^3 and the repository is at a temperature of about 22 ^{o}C (Table 4.5 and Section 5.1 of QUINTESSA and GEOFIRMA 2011). The number of moles of gas in the repository is:

$$n = \frac{PV}{RT} = \frac{8.2x10^6(Pa) \times 4.2x10^5(m^3)}{8.314(J / (K \text{ mol})) \times 295.14K} = 1.40x10^9 \text{ moles}$$

After depressurization the repository will be at atmospheric pressure of 101 kPa, and would contain the following number of moles of gas,

$$n = \frac{PV}{RT} = \frac{101325(Pa) \times 4.2x10^5(m^3)}{8.314(J / (K \text{ mol})) \times 295.14K} = 1.73x10^7 \text{ moles}$$

The difference is the number of moles of gas released, i.e.,1.39×10^9 moles.

The number of moles of gas in 1 m^3 at STP is given by,

$$n = \frac{PV}{RT} = \frac{101325(Pa) \times 1.0(m^3)}{8.314(J / (K \text{ mol})) \times 273.15K} = 45 \text{ moles}$$

Thus, if the repository gas pressure is discharged through the blowout preventer at a constant rate of 1 m^3/s (STP), the repository will take ($1.39\ 10^9 / 45$) seconds, or approximately 350 days, to depressurise.

REFERENCES FOR APPENDIX E

GEOFIRMA and QUINTESSA. 2011. Postclosure Safety Assessment: Gas Modelling. Geofirma Engineering Ltd. and Quintessa Ltd. report for the Nuclear Waste Management Organization, NWMO DGR-TR-2011-31. Toronto, Canada.

QUINTESSA and GEOFIRMA. 2011. Postclosure Safety Assessment: Data. Quintessa Ltd. and Geofirma Engineering Ltd. report for the Nuclear Waste Management Organization, NWMO DGR-TR-2011-32. Toronto, Canada.

APPENDIX F: AMBER DATA

F.1 INTRODUCTION

The AMBER models for the Human Intrusion and other Disruptive Scenarios are based on those used for analysis of the Normal Evolution Scenario. The underlying models and data are, therefore, described in Analysis of the Normal Evolution Scenario report (QUINTESSA 2011). This appendix presents additional data that are needed to represent the Disruptive Scenarios, where that data is not included in the model descriptions given in the main body of this report. The additional data covers the importing of information from FRAC3DVS_OPG and T2GGM.

F.2 GROUNDWATER FLOW RATES

Appendix J to the Normal Evolution Scenario report (QUINTESSA 2011) describes how groundwater flow rates are imported into the AMBER model from FRAC3DVS_OPG. The FRAC3DVS_OPG calculation cases for the Disruptive Scenarios and the associated AMBER cases are given in Table F.1.

Table F.1: FRAC3DVS_OPG Calculation Cases (3DS) for which Volumetric Groundwater Flows are Used in the AMBER Models

FRAC3DVS_OPG Calculation Case	AMBER Cases that use the Associated Groundwater Flows
HI-GR2 (Transient)	HI-GR2-A
SF-BC (Transient)	SF-BC-A
SF-ED (Transient)	SF-ED-A
BH-BC (Transient)	BH-BC-A
VF-BC (Transient)	VF-BC-A
VF-AL (Transient)	VF-AL-A

The volumetric groundwater flows are stored in the FRAC_26Oct10.aaf import file. A copy of this file needs to be located in the same directory as the associated AMBER file when calculations are undertaken.

F.3 INITIATION OF GROUNDWATER FLOWS

The times of initial groundwater flow away from the DGR, based on the T2GGM results, are shown in Table F.2, together with the AMBER cases for which the times are used. Note that for instant resaturation cases (HI-GR2, BH-BC, VF-BC and VF-AL) the time of initial groundwater flow away from the DGR is set to zero.

Table F.2: Time of Initial Groundwater Flows

T2GGM Case	Time of Initial Groundwater Flow away from the DGR (a)	Associated AMBER Cases
SF-BC (WL)	60,000	SF-BC-A
SF-ED (WL)	600	SF-ED-A

Note: WL indicates water-limited case.

F.4 GAS MASSES AND GAS FLOW RATES

The gas masses and gas flow rates used for the SF-BC-A and SF-ED-A cases are imported from the T2GGM calculations, as described in Appendix J.4.3 of the Normal Evolution Scenario Analysis report (QUINTESSA 2011).

F.5 SATURATIONS, PARTIAL AND TOTAL PRESSURES, GAS FRACTIONS, AND SIDERITE FRACTIONS

For the disruptive event cases that involve a potential gas pathway (SF-BC-A and SF-ED-A), the AMBER model draws the repository saturation, partial pressures and gas compositions from the associated T2GGM calculation. For the human intrusion case (HI-BC-A), the total gas pressure in the repository is required and is taken from the T2GGM calculation for the NE-RC(NWL) case. The information is stored in GGM output files.

The GGM output includes several thousand output times for each case. A reduced set of times is used in importing the saturation fractions, and partial and total pressures; the data is presented in Tables F.3 and F.4.

The saturations, partial and total pressures, and gas fractions are stored in the GGM_20Jan11.aaf import file. A copy of this file needs to be located in the same directory as the associated AMBER file when calculations are undertaken.

For cases that are taken to be fully resaturated at closure (i.e., HI-GR2, BH-BC, VF-BC and VF-AL), the saturation is taken to occur over the first 1 year of the calculation and gas releases/partitioning are not modelled.

In addition to the fractional repository saturation, the AMBER model requires the resaturation rate. This is calculated in the spreadsheet and used to generate time-dependent lookup functions that are used in REP_ResatFrac parameter.

Gas fractions are only needed for cases that may include a free gas pathway via the shafts (i.e., the SF_BC and SF_ED cases).

Table F.3: Fractional Repository Saturation and Partial Pressure based on T2GGM

Time (a)	Saturation (-)		Partial Pressure (Pa)	
	SF-BC	SF-ED	SF-BC	SF-ED
0.1	1.77E-03	1.78E-03	3.16E+01	3.16E+01
0.5	1.76E-03	1.78E-03	2.09E+02	2.09E+02
10	1.94E-03	2.31E-03	9.19E+02	9.17E+02
50	2.10E-03	8.62E-02	1.42E+04	1.51E+04
100	2.15E-03	1.94E-01	3.77E+04	4.14E+04
200	2.05E-03	4.01E-01	7.37E+04	9.16E+04
500	1.10E-03	8.30E-01	1.44E+05	2.40E+05
750	1.26E-04	8.16E-01	3.48E+05	1.94E+06
1000	1.26E-04	7.49E-01	4.96E+05	2.58E+06
1019	1.26E-04	7.44E-01	5.75E+05	2.49E+06
1400	2.77E-03	6.41E-01	5.81E+05	2.49E+06
1800	6.68E-03	5.36E-01	7.95E+05	2.38E+06
2400	1.04E-02	4.44E-01	1.02E+06	2.30E+06
3070	1.18E-02	4.27E-01	1.32E+06	2.17E+06
4000	1.07E-02	4.12E-01	1.62E+06	2.53E+06
5000	1.42E-02	4.13E-01	1.99E+06	2.89E+06
10000	4.90E-02	4.63E-01	2.34E+06	3.18E+06
18700	1.02E-01	4.22E-01	3.68E+06	5.64E+06
25000	1.26E-01	4.12E-01	5.28E+06	6.68E+06
46800	1.71E-01	4.12E-01	4.78E+06	6.63E+06
50000	1.75E-01	4.12E-01	3.92E+06	6.70E+06
75000	2.08E-01	4.12E-01	3.91E+06	6.70E+06
100000	2.40E-01	4.12E-01	3.90E+06	6.70E+06
150000	3.06E-01	4.13E-01	3.90E+06	6.71E+06
225000	4.03E-01	4.18E-01	3.90E+06	6.71E+06
325000	5.34E-01	4.24E-01	3.90E+06	6.71E+06
400000	6.31E-01	4.28E-01	3.90E+06	6.71E+06
500000	7.62E-01	4.34E-01	3.90E+06	6.71E+06
683000	9.99E-01	4.44E-01	3.90E+06	6.71E+06
1000000	9.99E-01	4.61E-01	3.90E+06	6.71E+06
1500000	9.99E-01	4.88E-01	3.90E+06	6.71E+06
2000000	9.99E-01	5.15E-01	3.90E+06	6.71E+06
3000000	9.99E-01	5.68E-01	3.90E+06	6.71E+06
5000000	9.99E-01	6.74E-01	3.90E+06	6.71E+06
10000000	9.99E-01	9.40E-01	3.90E+06	6.71E+06

Table F.4: Total Pressure based on T2GGM

Time (a)	Total Pressure (Pa) for HI-BC-A
0.0	9.9037E+04
0.5	9.6450E+04
10	1.2126E+05
50	1.6026E+05
100	2.2581E+05
200	3.5211E+05
500	7.2100E+05
750	1.0319E+06
1000	1.3464E+06
1019	1.3701E+06
1400	1.8592E+06
1800	2.3869E+06
2400	3.2010E+06
3070	4.1266E+06
4000	5.0366E+06
5000	5.2689E+06
10000	5.0461E+06
18700	5.1813E+06
25000	5.6866E+06
46800	6.8445E+06
50000	6.9384E+06
75000	7.3523E+06
100000	7.5139E+06
150000	7.6636E+06
225000	7.8000E+06
325000	7.9328E+06
400000	8.0064E+06
500000	8.0794E+06
683000	8.1608E+06
1000000	8.2234E+06
1500000	8.2592E+06
2000000	8.3005E+06
3000000	8.4442E+06
5000000	8.7172E+06
10000000	8.8389E+06

F.6 SIDERITE FRACTIONS

The final fraction of carbon that is incorporated into siderite within the repository is also used in the AMBER model and is based on the GGM output. The siderite fractions used are given in Table F.5.

Table F.5: Final Fraction of Carbon in Siderite, based on T2GGM

T2GGM Case	Siderite Fraction	Associated AMBER Cases
NE-RC (NWL)	0.0138	HI-BC-A, HI-GR2-A, BH-BC-A, VF-BC-A, VF-AL-A
SF-BC (WL	0.0180	SF-BC-A
SF-ED (WL)	0.0394	SF-ED-A

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APPENDIX G: ECOLOGICAL RISK ASSESSMENT

G.1 INTRODUCTION

Screening No Effect Concentrations (NECs) have been specifically developed for 11 representative radionuclides (SENES 2008) and have been accepted by the Canadian Nuclear Safety Commission (CNSC) for application to the DGR Project (CNSC 2009). The NECs are derived from Estimated No Effect Values (ENEVs) for numerous indicator species relevant to environmental conditions at the DGR location. NECs are limiting radionuclide concentrations that will not result in undue risk to the identified biota.

According to the assessment criteria (QUINTESSA et al 2011, CNSC 2009), if the NECs are exceeded for Normal Evolution Scenario calculation cases, an Ecological Risk Assessment (ERA) is carried out for those specific radionuclides with concentrations estimated to exceed the NECs. If concentrations exceed these NECs under Disruptive Scenarios, then the acceptability is judged on a case-by-case basis taking into account the likelihood and nature of the exposure, uncertainty in the assessment, and conservatism in the dose criterion.

Calculations presented separately in the Normal Evolution Scenario did not indicate any exceedances of the NECs. Calculations presented in Section 2.5.1.1 of this main report, show that the NECs for C-14 and Nb-94 in soil are exceeded for the release of drill core debris to soil in the Human Intrusion Scenario. This scenario is unlikely, and assumes among other points that the contaminated drill core is dispersed on site rather than properly disposed. These soil concentrations are also localized around the site. Nonetheless, this appendix undertakes ERA calculations of dose to non-human biota for these C-14 and Nb-94 concentrations in soil.

G.2 APPROACH

G.2.1 Receptor Characterization

The selection of biota takes into consideration the Valued Ecosystem Components identified in the DGR Environmental Assessment, and in particular those biota that are likely to be directly affected by the soil contamination (e.g., terrestrial vegetation, invertebrates, mammals and birds). Table G.1 below provides a brief comparison of the biota selected for ERA calculations and those identified as VECs in the associated DGR Environmental Assessment (GOLDER 2011).

Based on the environmental pathways and modes of exposure known for each receptor group, ecological profiles have been developed. These profiles specify parameters such as food intake rate, time in area, diet composition, etc. Ecological profiles are provided in Tables G.2 to G.6 for biota that are added in this ERA, i.e., those that were not already profiled in SENES (2008).

Table G.1: Comparison of Biota Chosen for the ERA with Relevant VECs Identified in the DGR Environmental Assessment

Identified EA VECs	Indicator Species	Biota Chosen for ERA
Benthic Invertebrates	Burrowing Crayfish	These are not terrestrial biota. Only terrestrial biota have been considered for study in this ERA. However, many of these biota were included within the development of the NECs (SENES 2008).
Aquatic Vegetation	Sago Pondweed	
Benthic Fish	Deepwater Sculpin	
	Lake Whitefish	
	Bluntnose Minnow	
	Redbelly Dace	
	Creek Chub	
Pelagic Fish	Spotted Shiner	
	Smallmouth Bass	
	Brook Trout	
Aquatic Birds	Double-Crested Cormorant	
	Mallard	
Aquatic Mammals	Muskrat	
Terrestrial Vegetation	Eastern White Cedar	Eastern White Cedar
	Common Cattail	Assessed in NEC study (SENES 2008)
	Heal-All	Heal-All
Terrestrial Mammals	-	White Tailed Deer
	-	Meadow Vole
Terrestrial Invertebrates	-	Earthworms
Terrestrial Birds	Bald Eagle	Bald Eagle
	Yellow Warbler	Yellow Warbler
	Wild Turkey	Wild Turkey
	Red-Eyed Vireo	Red-Eyed Vireo
	Great Horned Owl	Great Horned Owl

Table G.2: Ecological Profile for the Bald Eagle

Exposure Characteristics		
Body Weight (kg)	3.75	U.S. EPA 1993, Harris 2002, CORNELL 2003
Food Intake Rate (g (ww)/d)	450	U.S. EPA 1993
Soil Ingestion Rate: (g(dw)/d)	4.5	
Fraction of ww diet:	0.01	Beyer *et al.* 1994
Water Intake Rate (L/d)	0.14	U.S. EPA 1993 (allometric scaling)
Inhalation Rate (m^3/d)	1.13	U.S. EPA 1993 (allometric scaling)
Fraction of Time in Area	0.5	Assumed - migratory
Fractional Composition of Diet		
Fish	1.0	Based on information from Canadian Wildlife Service (CWS) 1992, NatureServe 2008, CORNELL 2003

Note: dw – Dry weight, ww – Wet weight.

Table G.3: Ecological Profile for the Great Horned Owl

Exposure Characteristics		
Body Weight (kg)	1.5	CWS 1986, CORNELL 2009
Food Intake Rate (g (ww)/d)	379	U.S. EPA 1993 (allometric scaling)
Soil Ingestion Rate: (g(dw)/d)	3.79	
Fraction of ww diet:	0.01	Beyer *et al.* 1994
Water Intake Rate (L/d)	0.08	U.S. EPA 1993 (allometric scaling)
Inhalation Rate (m^3/d)	0.56	U.S. EPA 1993 (allometric scaling)
Fraction of Time in Area	1	Assumed – non-migratory
Fractional Composition of Diet		
Small mammals	0.8	Based on information from CWS 1986 and NatureServe 2009
Ducks	0.2	Assumed - balance

Table G.4: Ecological Profile for the Meadow Vole

Exposure Characteristics		
Body Weight (kg)	0.04	NatureServe 2007, U.S. EPA 1993, Neuburger 1999
Food Intake Rate (g (ww)/d)	13	U.S. EPA 1993
Soil Ingestion Rate: (g(dw)/d)	0.09	
Fraction of ww diet:	0.007	Beyer *et al.* 1994
Water Intake Rate (L/d)	0.007	U.S. EPA 1993
Inhalation Rate (m^3/d)	0.048	U.S. EPA 1993
Fraction of Time in Area	1	Assumed
Fractional Composition of Diet		
Terrestrial plants-grass	1	U.S. EPA 1993, assumed

Table G.5: Ecological Profile for the Red-Eyed Vireo

Exposure Characteristics		
Body Weight (kg)	17	NatureServe 2007
Food Intake Rate (g (ww)/d)	14	U.S. EPA 1993
Soil Ingestion Rate: (g(dw)/d) Fraction of ww diet:	0.2 0.02	Beyer et al. 1994
Water Intake Rate (L/d)	0.004	U.S. EPA 1993 (allometric scaling)
Inhalation Rate (m^3/d)	0.02	U.S. EPA 1993 (allometric scaling)
Fraction of Time in Area	1	Assumed
Fractional Composition of Diet		
Insects	1	NatureServe 2007

Table G.6: Ecological Profile for the Yellow Warbler

Exposure Characteristics		
Body Weight (kg)	0.013	Bachynski and Kadlec. 2003, NatureServe 2008
Food Intake Rate (g (ww)/d)	11	U.S. EPA 1993 (allometric scaling)
Soil Ingestion Rate: (g(dw)/d) Fraction of ww diet:	0.2 0.015	Beyer et al. 1994
Water Intake Rate (L/d)	0.003	U.S. EPA 1993 (allometric scaling)
Inhalation Rate (m^3/d)	0. 014	U.S. EPA 1993 (allometric scaling)
Fraction of Time in Area	1	Assumed (migratory)
Fractional Composition of Diet		
Insects	0.9	Bachynski and Kadlec., 2003, assumed
Berries	0.1	Bachynski and Kadlec., 2003, assumed

Table G.7 outlines the conceptual model considered for the ERA, designed to encompass a wide range of ecological receptors and modes of exposure. The modelled ecological receptor locations are shown in Figure G.1.

Table G.7: ERA Exposure Pathways

Receptor	Environmental Pathways	Modes of Exposure	Exposure Model
Terrestrial Invertebrates	soil	- uptake from soil - immersion in soil	Internal and external dose from soil
Terrestrial Mammals and Birds	soil	- ingestion (terrestrial vegetation, soil) - exposure to soil	Internal dose from ingestion and external dose from soil.
Terrestrial Plants	soil	- uptake from soil - exposure to soil	Internal and external dose from soil.

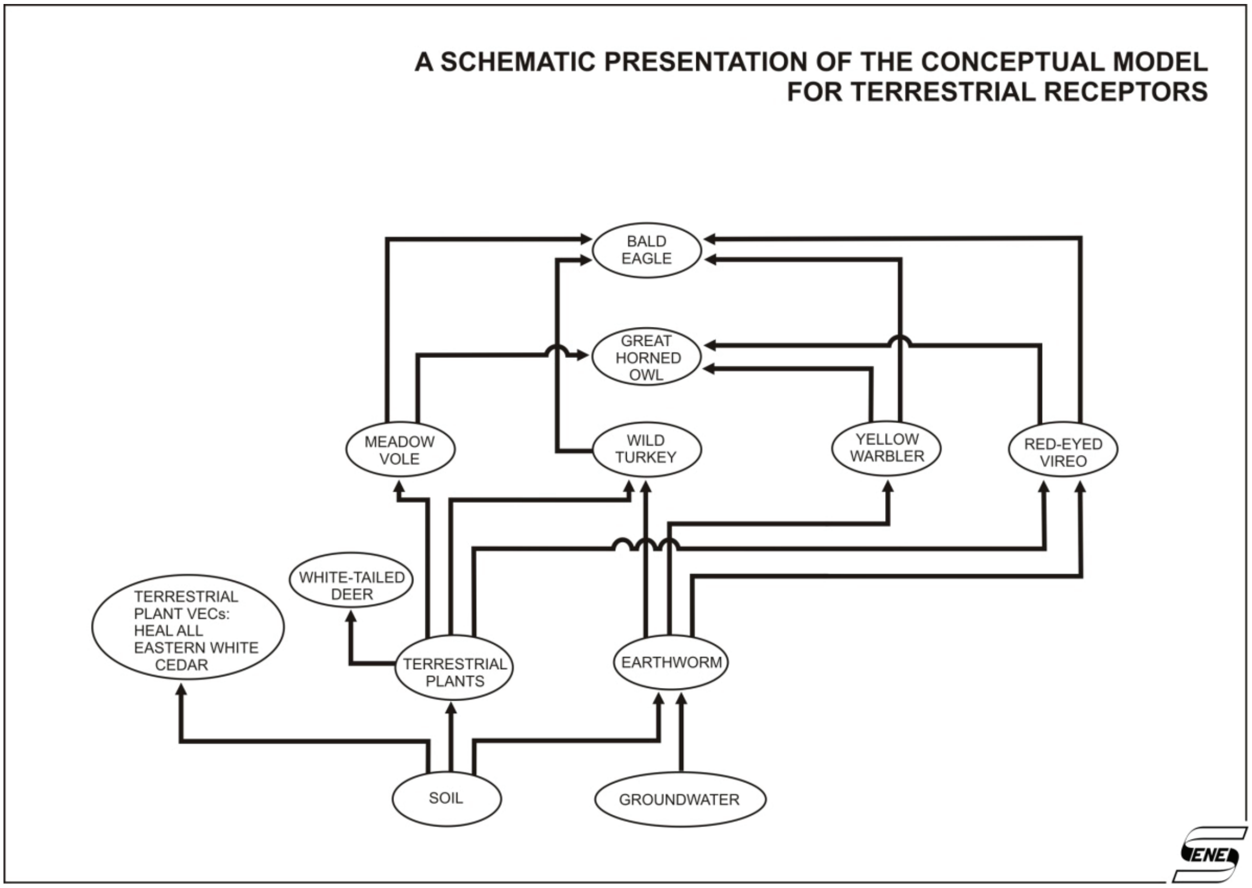

Figure G.1: ERA Exposure Pathways

Note: The figure shows only contaminated food sources for each biota. For example, the bald eagle's diet is primarily fish; however, since fish are not considered as part of this assessment, they are not included on the diagram.

G.2.2 Dose Criteria

The toxicity assessment for terrestrial wildlife determines the concentrations or levels of the individual radioactive constituents that can cause harm in ecological species (i.e., VECs). The radiological benchmarks used in the ERA are ENEVs based on literature compilations. ENEVs are used for *population-level* impacts on non-human biota.

The selected ENEV values for terrestrial biota, and terrestrial plants and earthworms are shown in Tables G.8 and G.9, respectively. These values are higher by a factor of up to five than those used in the development of the NECs (SENES 2008), in which the most conservative of various literature sources was used. For example, SENES (2008) used an ENEV of 1 mGy/d for mammals, whereas the reference Environment Canada and Health Canada (2003) value is 3 mGy/d.

Table G.8: Radiological ENEVs Selected for Terrestrial Biota (mGy/d)

Species	Value	Reference
Great Horned Owl	5	*1*
Yellow Warbler	5	*1*
Meadow vole	3	*2*
Wild Turkey	5	*1*
Bald Eagle	5	*1*
Red-Eyed Vireo	5	*1*
White-tailed Deer	3	*2*

References:
[1] Garisto (2005)
[2] Environment Canada and Health Canada (2003)

Table G.9: Radiological ENEVs Selected for Terrestrial Plants and Earthworms (mGy/d)

Species	Value	Reference
Soil invertebrates	5.5	*1*
Terrestrial plants	2.4	*1*

References:
[1] Environment Canada and Health Canada (2003)

G.2.3 Exposure Assessment

G.2.3.1 Transfer Factors

Transfer factors are used to estimate the transfer of contaminants through the food chain from contaminated surface media. The transfer factors used are given in Tables G.10 to G.12.

Table G.10: Transfer Factors – To Vegetation from Soil (g/g(dw))

Radionuclide	Transfer Factor	Reference
C	1	Sheppard (1995)
Nb	0.00551	CSA (2008)

Table G.11: Transfer Factors – To Mammal from Feed (d/kg(ww))

Radionuclide	Transfer Factor	Reference
C	0.088	CSA (2008)
Nb	0.0002	CSA (2008)

Table G.12: Transfer Factors – To Birds from Feed (d/kg(ww))

Radionuclide	Transfer Factor	Reference
C	8.5	CSA (2008)
Nb	0.0014	CSA (2008)

G.2.3.2 Dose Coefficients

The biota dose coefficients used in the ERA calculations are taken from Amiro (1997) and are presented in Table G.13.

Table G.13: Dose Coefficients for ERA Calculations

Radionuclide	Selected Weighted Internal Dose Coefficient	Selected External-soil Dose Coefficient
	(Gy/a per Bq/kg)	(Gy/a per Bq/kg)
C-14	2.5E-07	9.8E-09
Nb-94	8.8E-06	9.8E-06

G.2.3.3 Mathematical Model

Peak C-14 and Nb-94 concentrations in the soil calculated by the AMBER model for the Human Intrusion Scenario's Base Case (i.e., 6.3 x 10^3 and 2.4 x 10^3 Bq/kg, respectively) are transferred to the VECs through food and incidental soil consumption and external exposure to soil based on the biota profiles (given in Tables G.2 to G.6). Transfer from soil to food and food to animals or birds is estimated using the transfer factors given in Tables G.10 to G.12. The intake is then converted to a dose using dose coefficients given in Table G.13. The resulting doses are compared in Table G.14 with appropriate benchmarks (derived from Tables G.8 and G.9).

G.3 RESULTS

The results of the ERA are presented in Table G.14. The ratio of the calculated doses to the benchmarks are all less than unity indicating that adverse ecological effects are not expected for any of the biota evaluated.

Table G.14: Doses to Biota for the Human Intrusion Base Case

Radionuclides	Bald Eagle	Earthworm	Great Horned Owl	Meadow Vole	Red-Eyed Vireo	Vegetation	White-Tailed Deer	Wild Turkey	Yellow Warbler
Dose for C-14 (mGy/d)	2.67E-03	8.16E-04	9.66E-03	2.02E-03	4.27E-03	1.46E-03	4.24E-03	3.99E-03	3.61E-03
Dose for Nb-94 (mGy/d)	6.34E-02	7.21E-02	6.34E-02	6.34E-02	6.36E-02	6.36E-02	6.36E-02	6.34E-02	6.36E-02
Benchmark Dose (mGy/d)	5	5.5	5	3	5	2.4	3	5	5
Dose to Benchmark Ratio for C-14 (-)	5.33E-04	1.48E-04	1.93E-03	6.74E-04	8.55E-04	6.07E-04	1.41E-03	7.97E-04	7.22E-04
Dose to Benchmark Ratio for Nb-94 (-)	1.27E-02	1.31E-02	1.27E-02	2.11E-02	1.27E-02	2.65E-02	2.12E-02	1.27E-02	1.27E-02

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APPENDIX H: DISSOLUTION OF GAS IN THE SHALLOW BEDROCK GROUNDWATER ZONE

H.1 INTRODUCTION

Gas can either be present in the gas phase, termed free gas, or dissolved in water. The majority of gas present in the DGR is not radioactive. This is termed bulk gas. Small quantities of radioactive gases are also present in the DGR. These are termed trace gases. They include gases labelled with C-14, in particular methane and carbon dioxide.

T2GGM model results (GEOFIRMA and QUINTESSA 2011) indicate that free gas formed by reactions within the repository could migrate from the repository to the Shallow Bedrock Groundwater Zone (SBGZ) via the shaft for the Severe Shaft Seal Failure Scenario (SF-BC and SF-ED cases). Gas fluxes up the shaft have been calculated for these two cases as far as the Guelph Formation, within the Intermediate Bedrock Groundwater Zone (IBGZ), which is the top of the T2GGM model used.

It is anticipated that gas reaching the Guelph Formation will migrate quickly to the Shallow Bedrock Groundwater Zone. Some of the gas will dissolve in water in the shallow groundwater and some will discharge at the ground surface. The amount of dissolution may be significant because the rock formations in the shallow groundwater zone are relatively permeable and porous, and there is significant horizontal groundwater flow through the shaft location.

Doses from C-14 labelled trace gases that have been transported to the shallow groundwater zone can occur via two potential exposure pathways:

- C-14 labelled gases dissolved in the shallow groundwater and pumped via a well; and
- Uptake of C-14 by plants from gas released to surface soils.

The dose per unit contaminant flux is different for these two potential exposure pathways. This appendix presents scoping calculations used to estimate the amount of free gas that dissolves in the shallow groundwater. The potential for dissolution of gases in water in the deeper parts of the Shallow Bedrock Groundwater Zone and subsequent exsolution from water in the shallower parts of the zone, and the potential for exsolution from well water, are considered.

H.2 CONCEPTUAL MODEL

T2GGM results for the SF-BC and SF-ED cases show that gases are transported within the failed shaft seals. Figure H.1 shows the upper shaft seal arrangement, plus key parameters for the seals and rock formations (QUINTESSA and GEOFIRMA 2011). It is assumed that gas transported up the shaft within the Intermediate Bedrock Groundwater Zone enters the engineered fill in the SBGZ. The engineered fill has a permeability of 1E-11 m^2 (QUINTESSA and GEOFIRMA 2011). This is significantly higher than the assumed permeability of the failed seals (1E-16 m^2 for the SF-BC case and 1E-14 m^2 for the SF-ED case), and higher than the permeability of most of the formations in the SBGZ. Therefore, it is expected that gas will dominantly rise vertically within the engineered fill. The upper shaft EDZ is neglected, because the shaft itself has a high permeability relative to the rock.

The shafts within the SBGZ have a concrete liner that will not be removed when the DGR is sealed and closed. If this liner remains intact, its' low permeability will significantly limit the volume of groundwater that the gas can interact with and the majority of gas will be released to the ground surface. However, if all the shaft seals in the Intermediate and Deep Bedrock Groundwater Zones have failed, it is reasonable to assume that this liner has fully degraded too.

Groundwater flow in the SBGZ is sub-horizontal and, therefore, perpendicular to the vertical shaft. The relative velocities of sub-horizontal groundwater flow through the shaft, and the vertical gas flow through the shaft will determine the volume of groundwater that the gas interacts with, and hence the amount of gas that can potentially dissolve.

Groundwater in the SBGZ already contains some dissolved gas, i.e., dissolved air from when the water fell as rain and infiltrated the ground. The amount of dissolved air is in equilibrium with atmospheric pressure. However, the gas flux up the shaft is dominantly methane (see below), and the atmosphere contains very little methane. Therefore, the groundwater is assumed to be completely gas unsaturated with respect to methane.

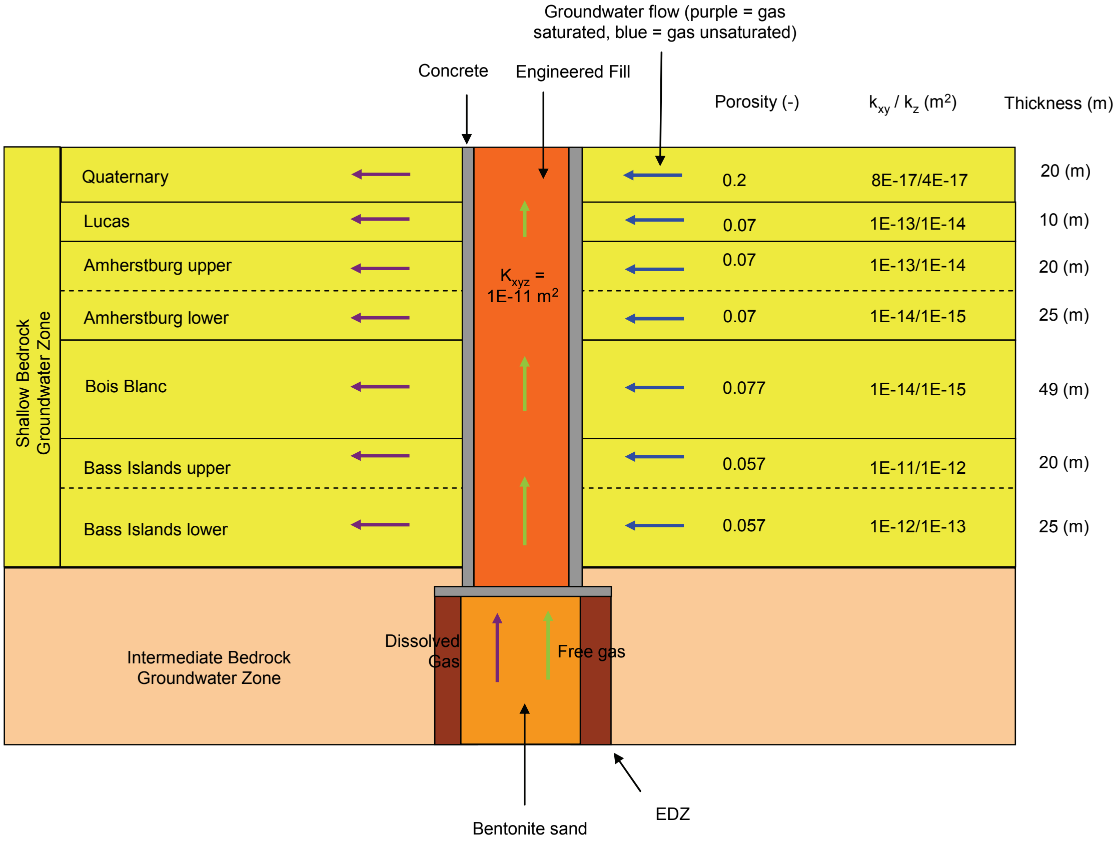

Figure H.1: Conceptual Model and Key Data

H.2.1 TRANSPORT OF GAS THROUGH THE SHAFT IN THE SBGZ

The engineered fill is much more permeable than the (failed) underlying shaft seals. This suggests that gas entering the engineered fill will rapidly flow to the ground surface. However, the permeability of the engineered fill also varies with saturation. The mass of gas leaving the engineered fill (either as free gas or dissolved gas) should balance with the mass of gas entering the engineered fill, accounting for any change in the mass of gas ‘stored’ in the pore space within the engineered fill. Because the gas flux into the fill changes relatively slowly compared with the travel time through the fill, it is expected that the engineered fill will attain an equilibrium state where the flux out is equal to the flux in, and there is no significant change in storage with time. The saturation and hence permeability of the engineered fill will be consistent with these equilibrium conditions.

H.3 WHAT PROPORTION OF THE FREE GAS FLUX WILL DISSOLVE IN THE SBGZ?

The peak gas fluxes into the engineered fill calculated using the T2GGM models (Table 8.2 of GEOFIRMA and QUINTESSA 2011) are:

- 840 kg/a at 23 ka for the SF-BC case, comprising 97% CH_4, 0.1% CO_2, and 3% N_2; and
- 9300 kg/a at 3.8 ka for the SF-ED case, comprising 79% CH_4, 0.0003% CO_2, 7% N_2 and 14% H_2.

The contribution from CO_2 is negligible and can be ignored. The peak fluxes of methane are, therefore, 815 kg/a for the SF-BC case and 7347 kg/a for the SF-ED case respectively.

Under equilibrium conditions, the flux into the engineered fill per year is equal to the flux out per year. Therefore, the time taken for the above fluxes to flow through the engineered fill is one year in both cases. However, note that the gas saturation and hence permeability (i.e., intrinsic permeability times relative permeability) of the engineered fill will be different for the two cases.

It is assumed that there is no lateral migration of free gas from the engineered fill into the SBGZ, due to the buoyancy of the gas, and because the horizontal permeability of the SBGZ is lower than the vertical permeability of the engineered fill for all formations except the Bass Islands upper. There may be a small amount of lateral dispersion into the Bass Islands upper, but this will be a secondary effect.

H.3.1 VOLUME OF GROUNDWATER WITH WHICH THE GAS INTERACTS

Groundwater is considered to flow sub-horizontally through the engineered fill, orthogonal to the shaft. The volume of groundwater with which the gas interacts can be calculated using a simple Darcy flow calculation.

$$Q = KiA \qquad \text{(H.1)}$$

Where,

Q is the groundwater flow rate (m^3/a).

i is the hydraulic gradient (-).

K is the hydraulic conductivity (m/a) (~10^7 times the intrinsic permeability for water).

A is the cross-sectional area of the flow path (m^2).

There are two other factors that need to be considered. First, where the permeability of the engineered fill is higher than that of the geosphere, there will be focussing of groundwater flow from the geosphere into the shaft. Second, as the gas saturation in the engineered fill increases, the relative permeability of the engineered fill for water decreases, thereby decreasing the amount of water the gas can interact with. If the relative permeability for water of the partially saturated engineered fill falls below the permeability of the geosphere, there may be flow divergence in the geosphere away from the shaft.

The gas saturations in the shaft engineered fill are calculated below for the SF-BC and SF-ED cases, conservatively neglecting any dissolution. The maximum gas saturation is shown to be low for both cases.

In both cases the relative permeability for water is reduced a little due to the presence of the gas. This will tend to reduce the volume of water the gas interacts with. For these simple calculations it is assumed that the coupled effects of flow focussing and the reduction in the permeability for water approximately cancel each other.

The gas Darcy velocity, u (m/a), can simply be calculated from:

$$u = F/\rho A \tag{H.2}$$

Where,

F is the flux of gas up the shaft (mol/a)

ρ is the density of gas (mol/m^3)

A is the area of the shaft (m^2)

Note that as the gas migrates up the shaft, the pressure will decrease, the gas will expand, its density will decrease, the gas saturation will increase, the relative permeability for gas will increase and the gas velocity will increase. However, the gas mass flux will be constant with depth. The gas saturation will be a maximum at the top of the shaft.

The gas Darcy velocity depends on the relative permeability for gas according to (Bond et al. 2009):

$$u = \frac{k.k_{rg}}{\mu}\left(\frac{\Delta P}{\Delta z} + \rho g\right) \tag{H.3}$$

Where,

k is the intrinsic permeability of the medium (m^2).

k_{rg} is the relative permeability for gas, which is a function of the saturation (-).

μ is the viscosity of the gas (Pa s)

ΔP is the change in pressure (Pa)

Δz is the change in elevation (m)

ρ is the density of gas (kg/m^3)

g is acceleration due to gravity (m/s^2)

The relative permeability varies with saturation according to the van Genuchten-Mualem-Luckner relationship (GEOFIRMA and QUINTESSA 2011):

$$k_{rl} = S_{ek}^{1/2}\left[1-(1-S_{ek}^{1/m})^m\right]^2 \tag{H.4}$$

$$k_{rg} = (1-S_{ek})^{1/3}\left[1-S_{ek}^{1/m}\right]^{2m} \tag{H.5}$$

$$S_{ek} = \frac{S_l - S_{lr}}{1-S_{lr}-S_{gr}} \tag{H.6}$$

Where,

k_{rl} is the liquid phase relative permeability (ratio);

k_{rg} is the gas phase relative permeability (ratio);

S_{ek} is the effective saturation for the relative permeability relationship (volume ratio);

S_l is the liquid saturation (volume ratio);

S_{lr} is the residual liquid saturation (volume ratio);

S_{gr} is the residual gas saturation (volume ratio);

m is a van Genuchten fitting parameter (unitless);

n is a van Genuchten fitting parameter (unitless); and

α is a van Genuchten fitting parameter, /Pa.

Using equations H.4 to H.6, the density and viscosity data given in Table H.1, the two-phase flow parameters given in Section 4.6 of the data report (QUINTESSA and GEOFIRMA 2011), and a combined shaft area of 84.85 m^2 (QUINTESSA and GEOFIRMA 2011), the water saturation, k_{rg} and k_{rl} were calculated at the top of the shaft for the SF-BC and SF-ED cases. The results are given in Table H.2. They show that k_{rl} will be close to unity throughout the engineered fill. Note that the results give the maximum gas saturation, and hence minimum k_{rl} conservatively ignoring dissolution. Therefore, in all subsequent calculations, k_{rl} is assumed to be unity.

Table H.1: Density and Viscosity of Methane (Lide et al. 2006)

Pressure	Density 275K	Viscosity 275K	Density 300K	Viscosity 300K
MPa	mol/L	µPa s	mol/L	µPa s
0.1 MPa	0.044	10.4	0.040	11.2

Table H.2: Saturation and Relative Permeabilities at the Top of the Shaft

Case	Saturation (Water)	k_{rg}	k_{rl}
SF-BC	0.997	1.18E-3	0.83
SF-ED	0.985	1.07E-2	0.64

The volume of groundwater the gas can interact with (calculated using equation H.1) is shown in Table H.3. The horizontal hydraulic gradient in the SBGZ was taken to be 0.003 (QUINTESSA and GEOFIRMA 2011). Flow in the Quaternary is small and has been neglected.

Table H.3: Calculation of the Volume of Groundwater for Gas Interaction

	Bass Islands Lower	Bass Islands Upper	Bois Blanc	Amherstburg Lower	Amherstburg Upper	Lucas
K_{xy} (m/s)	1E-5	1E-4	1E-7	1E-7	1E-6	1E-6
i (-)	0.003	0.003	0.003	0.003	0.003	0.003
b (unit thickness, m)	25	20	49	25	20	10
w (flow path width, m)[1]	10.4	10.4	10.4	10.4	10.4	10.4
Volume of Water (m^3/a)	2.46E2	1.97E3	4.82E0	2.46E0	1.97E1	9.84E0

Note: [1] Derived from the vertical cross-section area of the combined main and vent shafts.

H.3.2 AMOUNT OF GAS THAT CAN DISSOLVE IN THE GROUNDWATER WITH WHICH THE GAS INTERACTS

The amount of gas that can dissolve in the groundwater with which the gas interacts is calculated using a Henry's Law coefficient of 8.49E-4 mol/L/MPa derived from Table B.1 of QUINTESSA and GEOFIRMA (2011) for methane in freshwater at 10 °C. The results are shown in Table H.4. The total amount of methane gas that can dissolve in the SBGZ is 2.58E3 mol/a.

Table H.4: Amount of Gas that can Dissolve

	Bass Islands Lower	Bass Islands Upper	Bois Blanc	Amherstburg Lower	Amherstburg Upper	Lucas
Volume of Water (m^3/a)	2.46E2	1.97E3	4.82E0	2.46E0	1.97E1	9.84E0
Hydrostatic Pressure (MPa)	1.57	1.34	1.00	0.63	0.40	0.25
Amount CH_4 in solution (mol/a)	3.3E2	2.2E3	4.1E0	1.3E0	6.68E0	2.1E0

H.3.3 FRACTION OF GAS THAT DISSOLVES FOR THE SEVERE SHAFT SEAL FAILURE CASES

The peak methane gas fluxes for the SF-BC and SF-ED cases are 5.09E4 mol/a, and 4.59E5 mol/a respectively (GEOFIRMA and QUINTESSA 2011). The fraction of the gas that dissolves in groundwater for the SF-BC and SF-ED cases are 5.1% and 0.56% respectively (i.e., a maximum amount that can dissolve of 2.58E3 mol/a compared with the peak gas flow). The maximum amount that can dissolve (2.58E3 mol/a) is specified in the AMBER model, and used to calculate the fraction of the gas flux that dissolves in the Shallow Bedrock Groundwater Zone with time.

REFERENCES FOR APPENDIX H

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