

OPG's DEEP GEOLOGIC

# REPOSITORY

FOR LOW & INTERMEDIATE LEVEL WASTE

## **Postclosure Safety Assessment: Analysis of the Normal Evolution Scenario**

March 2011

Prepared by: Quintessa Ltd.

NWMO DGR-TR-2011-26

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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, based on a range of likely and unlikely future scenarios.

The present report analyzes the likely future evolution of the DGR system (the Normal Evolution Scenario) and its radiological and non-radiological impacts. A comparable analysis of the unlikely or Disruptive Scenarios is provided in a separate report.

Based on the measured characteristics of the site and the host rock, it is expected that the low-permeability host rock will provide long-term isolation and containment of the waste. However, the slow migration of some contaminants from the repository and through the geosphere and shafts may lead to the eventual release of certain contaminants into the biosphere. This report assesses the potential extent and consequences of these releases. In particular, the report describes the Normal Evolution Scenario 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 conceptual model for the DGR system is described, covering the way that the system is expected to evolve together with the processes and events that are expected to result in the transport of contaminants. The conceptual model covers the entire system, including waste packages, releases into the repository, subsequent transport from the repository into the host rock and via the shafts to potential release to the biosphere, along with subsequent impact assessment.

The model is informed by detailed gas and groundwater calculations using FRAC3DVS-OPG and T2GGM that provide information concerning the repository saturation, gas pressures, gas flow rates, and groundwater flow rates. These are described in detail in separate reports. An assessment-level mathematical model has been developed to represent the expected evolution of the entire repository system in order to provide an assessment of the Normal Evolution Scenario and its consequences. This is fully described in the appendices to this report. This model is implemented in the compartment modelling code AMBER. The results of the assessment-level calculations for base and variant cases are presented and analyzed in the present report.

The Reference Case (NE-RC) includes the most details from the site investigations and geosynthesis and is the calculation case which acts as a benchmark against which relevant acceptance criteria can be compared and against which any variant calculation cases can be compared. It considers the measured overpressure in the Cambrian sandstone below the DGR together with measured underpressures and partial gas saturations in the Ordovician formations within which the DGR is located. Contaminants are tracked in the repository and through shafts and/or geosphere into the shallow groundwater system. From there, they may enter the environment through a groundwater well located on the site and used for domestic and agricultural purposes or through discharge into Lake Huron.

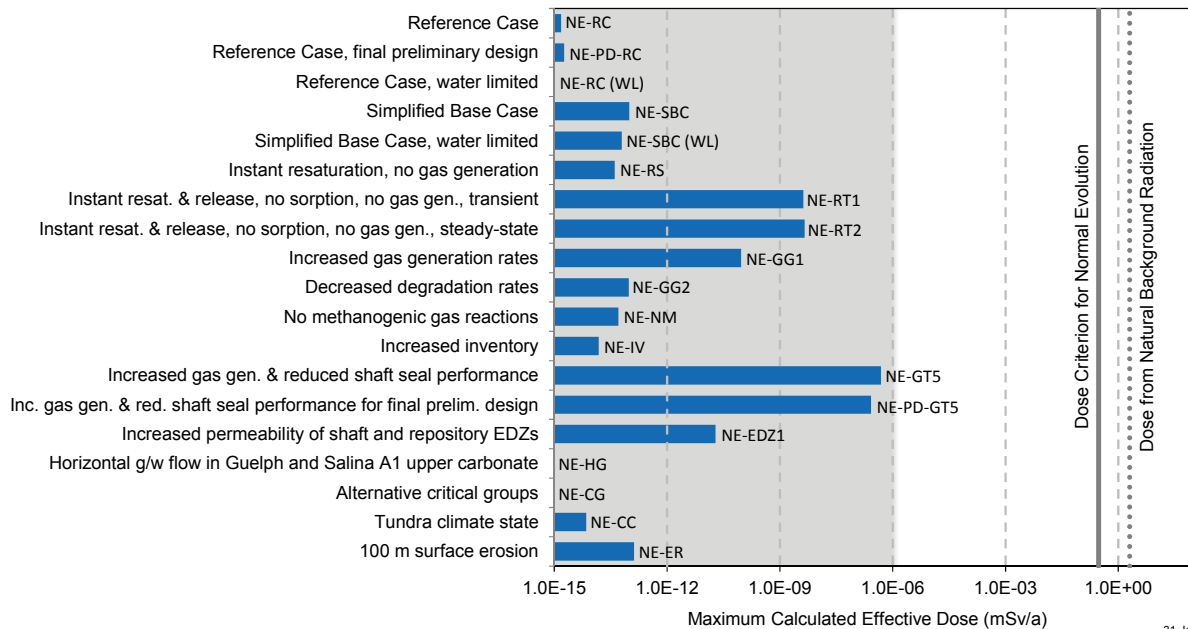
A Simplified Base Case (NE-SBC) includes a steady-state overpressure in the Cambrian sandstone, without the underpressures or partial gas saturations observed in the Ordovician formations. The case conservatively has a steady-state vertical upwards hydraulic gradient from the DGR to the shallow groundwater system, which maximizes the potential for flow up the shafts. Other variant calculation cases evaluate the effect of other model and data uncertainties associated with the Normal Evolution Scenario.

**RESULTS**

The key results from the Reference Case dose calculations are as follows.

- The repository isolates and contains the wastes, and protects groundwater and Lake Huron. Most radionuclides decay within the repository or the deep geosphere.
- The 0.3 mSv/a dose criterion is not exceeded for the Site Resident Group. The calculated maximum effective dose for the Reference Case (NE-RC) is much smaller than the criterion, and does not occur until after one million years.
- C-14, Nb-93m, Nb-94 and Zr-93 represent the greatest releases from the repository; however, the host rock and shaft seals prevent these radionuclides from reaching the surface.
- I-129 and Cl-36 are the main dose contributors due to their mobility and longevity.

The results of the Reference Case and variant cases on maximum calculated adult effective doses are summarized in Figure E.1. Calculated doses within the shaded range are negligible and the magnitude of the values within this area is illustrative.



**Figure E.1: Maximum Calculated Doses to Adults for All Calculation Cases for the Normal Evolution Scenario**



The variant cases investigate model and data uncertainties through the adoption of alternative assumptions to those adopted for the Reference Case. The specific cases were generally selected in the direction of the uncertainty that could increase releases – for example, the effect of uncertainty in waste inventory was explored with an increased inventory case, but not with decreased inventory. The findings are summarized below.

- A conservative Simplified Base Case is considered (NE-SBC) in which the measured overpressure in the Cambrian sandstone remains but the measured underpressures in the Ordovician above the DGR are assumed quickly dissipated, resulting in a steady-state vertical upwards hydraulic gradient. The variant case results in an increase in the maximum calculated dose compared to the Reference Case, which remains well below the dose criterion.
- Strictly limiting the gas generation reactions within the DGR based on the amount of water that is available reduces the maximum calculated doses for both the Reference Case (NE-RC-WL) and Simplified Base Case (NE-SBC-WL).
- Instant resaturation of the repository (NE-RS) releases more radionuclides into the groundwater and results in an increase in calculated doses, although they remain much smaller than the dose criterion.
- Conservative variants to the Reference Case (NE-RT1) and Simplified Base Case (NE-RT2) are considered where the DGR is resaturated immediately after closure, and radionuclides are instantly released to groundwater, with zero sorption on engineering or geosphere media. The results are dominated by Zr-93, which increases calculated doses, but they remain well below the dose criterion.
- Increased gas generation rates within the DGR (NE-GG1), in combination with an absence of initial underpressures in Ordovician formations, are sufficient for contaminated gas from the DGR to reach the Intermediate Bedrock Groundwater Zone. Subsequent transport in groundwater via the shafts enables C-14 to reach the Shallow Bedrock Groundwater Zone and then the biosphere, where calculated doses increase, although they remain well below the dose criterion.
- Decreased degradation rates (NE-GG2) decrease calculated doses in comparison to the Simplified Base Case, on which the variant is based, due to a predominantly lower degree of repository saturation (and therefore less contaminant release to groundwater).
- An absence of methanogenic gas reactions (NE-NM) results in higher gas pressures in the repository, lower water levels in the DGR (and therefore lower releases to groundwater) and causes gas to be released from the DGR into the shafts. However, the gas release to the shafts is relatively small and free gas does not reach the shallow system. Consequently calculated doses are slightly lower than those for the Simplified Base Case, on which the variant is based.
- Increasing the radionuclide inventory by a factor of ten (NE-IV) results in an equivalent increase in the calculated dose rate, which remains well below the dose criterion.
- Results for the final preliminary design are very similar to those calculated for the original preliminary design (NE-PD-RC and NE-PD-GT5, compared with NE-RC and NE-GT5).

- Increased gas generation within the DGR, combined with removal of the asphalt shaft seal, reduced performance of the bentonite/sand seal within the shaft and an absence of initial underpressures in some Ordovician formations (NE-GT5), results in a free gas pathway being established to the Intermediate Bedrock Groundwater Zone after 500 years. Subsequent transport in groundwater via the shafts enables C-14 to reach the Shallow Bedrock Groundwater Zone and then the biosphere where calculated doses increase, although, but they remain well below the dose criterion.
- Increased permeability of the shaft and repository Excavation Damaged Zones (EDZs) results in an increase in the calculated doses due to greater groundwater flow via the EDZs (NE-EDZ1), while the results remain well below the dose criterion.
- Horizontal groundwater flow in the Guelph and Salina A1 upper carbonate formations of the Intermediate Bedrock Groundwater Zone (NE-HG) result in much of the contaminant flux via the shafts being diverted into the lake, and significantly reduces calculated doses to a site resident (critical) group.
- If the Guelph and Salina A1 upper carbonate formations include horizontal groundwater flow and are assumed to discharge to the lake close to the site, then the calculated dose to an alternative site shore critical group that drinks water and eats fish from the lake close to the site (NE-CG) is smaller than that for the site resident group evaluated in the Reference Case or Simplified Base Case and well below the dose criterion.
- Release to a potential future tundra biosphere (NE-CC) rather than the reference present-day biosphere results in a small increase in calculated doses, which remain well below the dose criterion.
- Erosion of 100 m of the Surficial and Shallow Bedrock Groundwater Zone (e.g., by glacial erosion) would reduce the depth of the DGR and increase calculated doses (NE-ER). However, the maximum calculated dose remains well below the dose criterion.

In addition to the above specific variant cases, probabilistic calculations (NE-PC) were conducted based on the Reference Case gas generation, groundwater and gas transport rates, but with radionuclide release and transport parameters varying. In the Reference Case, the most important radionuclides were Cs-137 and I-129. In the probabilistic run, calculated well water concentrations for Cs-137 ranged over about six orders of magnitude, while those for I-129 ranged over about two orders of magnitude. The deterministic case concentrations were around the middle of these ranges. The probabilistic doses remained much less than the dose criterion.

The main radionuclides that contribute to calculated effective doses for the Reference Case and Simplified Base Case are Cs-137 (mostly from ILW pressure tubes) and I-129 (mostly from ILW PHT resins), due to their longer half-life and their mobility. While C-14 dominates initial liquid and gaseous releases to the shafts from the repository, the effectiveness of the shaft seals means that it decays (half-life 5700 a) before reaching the surface. Nb-94 and Zr-93 (and its daughter Nb-93m) dominate liquid release to the shafts at later times but are mostly retained within the shafts and so are not significant contributors to the calculated doses.

Calculations have been undertaken to assess the potential impact of radionuclides on non-human biota for the Reference Case. The results indicate that potential impacts of radionuclides on biota are below the relevant criteria. Calculations of the potential impacts of non-radioactive elements and chemical species on human and biota (NE-NR) also are well below the relevant criteria.

The results indicate that the deep limestone and shale host rock, and the shaft seals provide effective barriers to isolate and contain the contaminants in the waste. The low rate of resaturation and the permeable Silurian formations (Guelph and Salina A1 upper carbonate) also contribute.

## KEY UNCERTAINTIES

The long timescales under consideration mean that there are uncertainties about the way in which the system will evolve. The key uncertainties in terms of their importance to potential impacts are as follows.

1. **Gas pressure and repository water saturation** are important in determining the release of radioactivity into repository water, and the potential for C-14 release through gas in the first 60,000 years. The uncertainties in the gas pressure and groundwater saturation modelling are discussed in the detailed Gas and Groundwater Model reports. They were approached in this safety assessment through use of a range of calculation cases to test the importance of uncertainties in the processes that control gas pressure and groundwater saturation.
2. **Shaft seal and EDZ properties** and their evolution with time. Variant calculation cases presented here consider the effects of greater permeability in the shaft seals and repository EDZs, and if the asphalt shaft seal was replaced with bentonite/sand seal, together with reduced performance of the bentonite/sand shaft seal. However, the maximum dose remains many orders of magnitude below the dose criterion.
3. **Glaciation effect.** Although geological evidence at the site indicates that the deep geosphere has not been affected by past glaciation events and that the deep groundwater system has remained stagnant, glaciation is expected to have a major effect on the surface and near-surface environment, and it is not entirely predictable. It should, however, be noted that ice-sheet coverage of the site is likely to occur only after 60,000 to 100,000 years, at which point the primary remaining hazard will be long-lived radionuclides in groundwater rather than gaseous C-14. Calculations have shown that the deep groundwaters are stable and transport is diffusion-dominated, so dissolved radionuclides will be contained in the deep geosphere with large safety margins.
4. **Chemical reactions.** Under the highly saline conditions of the deep geosphere at the DGR site, several aspects of the chemistry are uncertain due to the limited database. In particular, this includes the sorption of contaminants on seal materials and host rocks, as well as mineral precipitation/dissolution reactions. Generally conservative values have been adopted in this assessment.

The Geoscientific Verification Plan outlines plans to initiate tests of important processes and materials in the rock during the repository construction, for example, EDZ measurements. Also, the shaft seal design will not be finalized until the decommissioning application several decades from now, and will take advantage of knowledge gained over the intervening period. While these tests plus further modelling work will improve confidence in these Normal Evolution

Scenario results, the results presented here show that the DGR system safety is robust, i.e., the system will maintain its integrity and reliability under a range of conditions. The uncertainties should be interpreted in the context of the low calculated impacts; for example, calculated doses for all variant cases are more than five orders of magnitude below the dose criterion.

## **CONCLUSIONS**

The assessment calculations for the Normal Evolution Scenario indicate that the DGR system provides effective containment of the emplaced contaminants. Most radionuclides decay within the repository or the deep geosphere. The release of contaminants from the waste packages is limited by the slow rate of repository resaturation (due to the low permeability of geosphere and shafts, and eventually the repository gas pressure), and the slow corrosion rate of the higher activity metallic wastes. The low permeability of geosphere and the shaft seals further limit the migration of contaminants in water or as free gas. The amount of contaminants reaching the surface is extremely small, such that the calculated maximum impacts for the Reference Case are far below the relevant criteria for humans and biota, including people who may live on the site in the far future.

## TABLE OF CONTENTS

	<u>Page</u>
<b>EXECUTIVE SUMMARY .....</b>	<b>v</b>
<b>1. INTRODUCTION.....</b>	<b>1</b>
<b>1.1 PURPOSE AND SCOPE.....</b>	<b>5</b>
<b>1.2 REPORT OUTLINE.....</b>	<b>5</b>
<b>2. CONCEPTUAL MODEL .....</b>	<b>6</b>
<b>2.1 SCENARIO OVERVIEW .....</b>	<b>6</b>
<b>2.2 KEY FEATURES, EVENTS AND PROCESSES .....</b>	<b>8</b>
<b>2.3 DESCRIPTION OF THE CONCEPTUAL MODEL .....</b>	<b>9</b>
2.3.1 Waste and Repository.....	15
2.3.1.1 Evolution of Repository Conditions.....	15
2.3.1.2 Release of Contaminants.....	20
2.3.1.3 Migration of Contaminants.....	23
2.3.2 Geosphere and Shafts.....	24
2.3.2.1 Evolution of Geosphere and Shaft Conditions.....	24
2.3.2.2 Migration of Contaminants.....	29
2.3.3 Biosphere.....	32
2.3.3.1 Evolution of Biosphere Conditions.....	32
2.3.3.2 Migration of Contaminants.....	32
<b>2.4 FEP AUDIT.....</b>	<b>37</b>
<b>2.5 KEY CONCEPTUAL MODEL UNCERTAINTIES .....</b>	<b>37</b>
2.5.1 Repository Design.....	38
2.5.2 Waste and Repository Evolution.....	38
2.5.2.1 Waste Package Degradation and Contaminant Release.....	38
2.5.2.2 Availability of Water and Resaturation.....	38
2.5.2.3 Repository Chemistry.....	39
2.5.2.4 Rockfall.....	39

2.5.3	Geosphere .....	39
2.5.3.1	Over- and Underpressures .....	39
2.5.3.2	Intermediate Bedrock Permeable Zones .....	40
2.5.4	Biosphere .....	40
2.5.4.1	Biosphere Evolution .....	40
2.5.4.2	Geosphere-Biosphere Interface.....	41
2.5.4.3	Critical Groups .....	41
<b>3.</b>	<b>CALCULATION CASES .....</b>	<b>42</b>
<b>4.</b>	<b>MATHEMATICAL MODELS, SOFTWARE IMPLEMENTATION AND DATA .....</b>	<b>50</b>
<b>4.1</b>	<b>MATHEMATICAL MODELS .....</b>	<b>50</b>
<b>4.2</b>	<b>SOFTWARE IMPLEMENTATION .....</b>	<b>50</b>
<b>4.3</b>	<b>DATA.....</b>	<b>53</b>
<b>4.4</b>	<b>VARIANT CALCULATION CASES.....</b>	<b>58</b>
4.4.1	Calculation Case NE-PD-RC-A (Reference Case, Final Preliminary Design). 58	
4.4.2	Calculation Case NE-CG-A (Alternative Critical Groups).....	58
4.4.3	Calculation Case NE-CC-A (Tundra Climate State).....	59
4.4.3.1	Surface Water, Atmosphere, Soil and Sediment .....	60
4.4.3.2	Plants and Animals .....	60
4.4.3.3	Human Lifestyle Data.....	60
4.4.4	Calculation Case NE-ER-A (Surface Erosion) .....	62
4.4.5	Calculation Case NE-NR-A (Non-radioactive Contaminants) .....	63
4.4.6	Calculation Case NE-PC-A (Probabilistic Case) .....	64
<b>5.</b>	<b>REFERENCE CASE RESULTS .....</b>	<b>65</b>
<b>5.1</b>	<b>RELEASE FROM THE WASTES AND REPOSITORY ROOMS AND TUNNELS.....</b>	<b>65</b>
5.1.1	Releases from the Wastes .....	65
5.1.2	Releases from the DGR to the Shafts and Geosphere .....	69
<b>5.2</b>	<b>MIGRATION VIA THE SHAFTS AND GEOSPHERE .....</b>	<b>71</b>
5.2.1	Groundwater Transport via the Host Rock.....	71

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5.2.2	Groundwater Transport via the Shafts and their Associated EDZs.....	72
5.3	<b>BIOSPHERE CONCENTRATIONS AND DOSES .....</b>	<b>73</b>
5.4	<b>RESULTS FOR THE FINAL PRELIMINARY DESIGN (NE-PD-RC-A) .....</b>	<b>74</b>
6.	<b>VARIANT CASES .....</b>	<b>76</b>
6.1	<b>NE-SBC-A: SIMPLIFIED BASE CASE (NO ORDOVICIAN UNDERPRESSURE AND PARTIAL GAS SATURATION) .....</b>	<b>76</b>
6.2	<b>NE-RC-WL-A AND NE-SBC-WL-A: WATER-LIMITED REACTIONS.....</b>	<b>78</b>
6.3	<b>NE-RS-A: RESATURATED REPOSITORY .....</b>	<b>79</b>
6.4	<b>NE-RT1-A: REFERENCE CASE WITH CONSERVATIVE RADIONUCLIDE RELEASE AND TRANSPORT.....</b>	<b>82</b>
6.5	<b>NE-RT2-A: SIMPLIFIED BASE CASE WITH CONSERVATIVE RADIONUCLIDE RELEASE AND TRANSPORT .....</b>	<b>84</b>
6.6	<b>GAS GENERATION VARIANTS.....</b>	<b>85</b>
6.7	<b>NE-IV-A: INCREASED RADIONUCLIDE INVENTORY.....</b>	<b>89</b>
6.8	<b>NE-BF-A: BACKFILLED REPOSITORY .....</b>	<b>89</b>
6.9	<b>NE-GT5-A: INCREASED GAS GENERATION AND REDUCED SHAFT SEAL PERFORMANCE .....</b>	<b>92</b>
6.10	<b>NE-PD-GT5-A: INCREASED GAS GENERATION AND MODIFIED SHAFT SEAL PROPERTIES FOR FINAL PRELIMINARY DESIGN .....</b>	<b>94</b>
6.11	<b>NE-EDZ1-A: ENHANCED EDZ PERMEABILITY .....</b>	<b>95</b>
6.12	<b>NE-HG-A: HORIZONTAL GRADIENTS IN GUELPH AND SALINA A1 UPPER CARBONATE FORMATIONS .....</b>	<b>96</b>
6.13	<b>NE-CG-A: ALTERNATIVE CRITICAL GROUPS.....</b>	<b>97</b>
6.14	<b>NE-CC-A: CLIMATE CHANGE – TUNDRA BIOSPHERE.....</b>	<b>97</b>
6.15	<b>NE-ER-A: SURFACE EROSION.....</b>	<b>98</b>
6.16	<b>NE-NR-A: NON-RADIOACTIVE CONTAMINANTS .....</b>	<b>98</b>
6.17	<b>NE-PC-A: PROBABILISTIC CASE.....</b>	<b>101</b>
7.	<b>SUMMARY AND CONCLUSIONS .....</b>	<b>104</b>
7.1	<b>SUMMARY RESULTS .....</b>	<b>104</b>
7.2	<b>CONCLUSIONS .....</b>	<b>110</b>
8.	<b>REFERENCES.....</b>	<b>111</b>

**9. ABBREVIATIONS AND ACRONYMS..... 114****APPENDIX A: MODEL DEVELOPMENT APPROACH****APPENDIX B: KEY FEATURES, EVENTS AND PROCESSES****APPENDIX C: FEP AUDIT OF CONCEPTUAL MODEL****APPENDIX D: MATHEMATICAL MODEL****APPENDIX E: MATHEMATICAL MODEL FOR C-14 IN THE REPOSITORY****APPENDIX F: MODELLING ADVECTION, DISPERSION AND DIFFUSION IN  
COMPARTMENT MODELS****APPENDIX G: AMBER CODE****APPENDIX H: MODEL IMPLEMENTATION****APPENDIX I: DGR AMBER MODELS****APPENDIX J: AMBER DATA**



**LIST OF TABLES**

	<b><u>Page</u></b>
Table 1.1: Total Amounts of Potentially Important Radionuclides, Elements and Chemical Species in Waste .....	4
Table 2.1: Summary of Key Features for the Normal Evolution Scenario.....	8
Table 2.2: Summary of Key Events and Processes for the Normal Evolution Scenario .....	9
Table 2.3: Contaminant Release Models from Waste to Repository Water.....	21
Table 3.1: Assessment Modelling Calculation Cases .....	44
Table 4.1: Key Parameter Values for the Normal Evolution Scenario Reference Case .....	54
Table 4.2: Repository and Geosphere Sorption Coefficients (m <sup>3</sup> /kg).....	56
Table 4.3: Summary of Changes from the Original to the Final Preliminary Design for the DGR .....	56
Table 4.4: Caribou Characteristics.....	60
Table 4.5: Occupancies for Tundra Resident Group.....	61
Table 4.6: Ingestion Rates for Tundra Resident Group .....	62
Table 4.7: Inventory of Metallic Elements in Sources Other than Waste in the DGR for the Non-radioactive Assessment (NE-NR-A).....	63
Table 4.8: Distributions for Effective Diffusion Coefficients (m <sup>2</sup> /s) for Shaft Materials for Use in Probabilistic Calculations (NE-PC-A).....	64
Table 6.1: Ratio of Calculated Maximum Concentration of Non-radioactive Contaminants in Biosphere Media to Environmental Quality Standards for the Normal Evolution Scenario (NE-NR) .....	100
Table 6.2: Maximum Calculated Well Water Concentrations from Probabilistic Sensitivity Calculations (NE-PC) Based on the Reference Case.....	101
Table 6.3: Rank Correlation Coefficients for Varied Parameters against the Maximum Flux to the Shaft and the Maximum Concentration in Well Water.....	102
Table 7.1: Summary of Maximum Calculated Doses to Adults for All Calculation Cases for the Normal Evolution Scenario .....	105

**LIST OF FIGURES**

	<b><u>Page</u></b>
Figure 1.1: The DGR Concept at the Bruce Nuclear Site.....	1
Figure 1.2: Document Structure for the Postclosure Safety Assessment .....	2
Figure 2.1: Schematic Representation of Potential Transport Pathways for the Normal Evolution Scenario .....	10
Figure 2.2: Timeframes for Key Processes Considered in the Normal Evolution Scenario .....	12
Figure 2.3: Interaction Matrix Representation of the Conceptual Model for the Normal Evolution Scenario .....	13
Figure 2.4: Detailed Representation of Potential Transport Pathways in the Repository and Geosphere for the Normal Evolution Scenario.....	14
Figure 2.5: Gas Amounts in the DGR for the Normal Evolution Scenario's Reference Case ..	16
Figure 2.6: Repository Gas Pressures for the Normal Evolution Scenario's Reference Case.	17
Figure 2.7: Saturation, Flows and Pressures around the Repository for the Normal Evolution Reference Case after about 100,000 Years.....	18
Figure 2.8: Rockfall within and around the Emplacement Rooms after Four Glacial Cycles ...	19
Figure 2.9: General Illustration of Repository Conceptual Model before and after Rockfall.....	20

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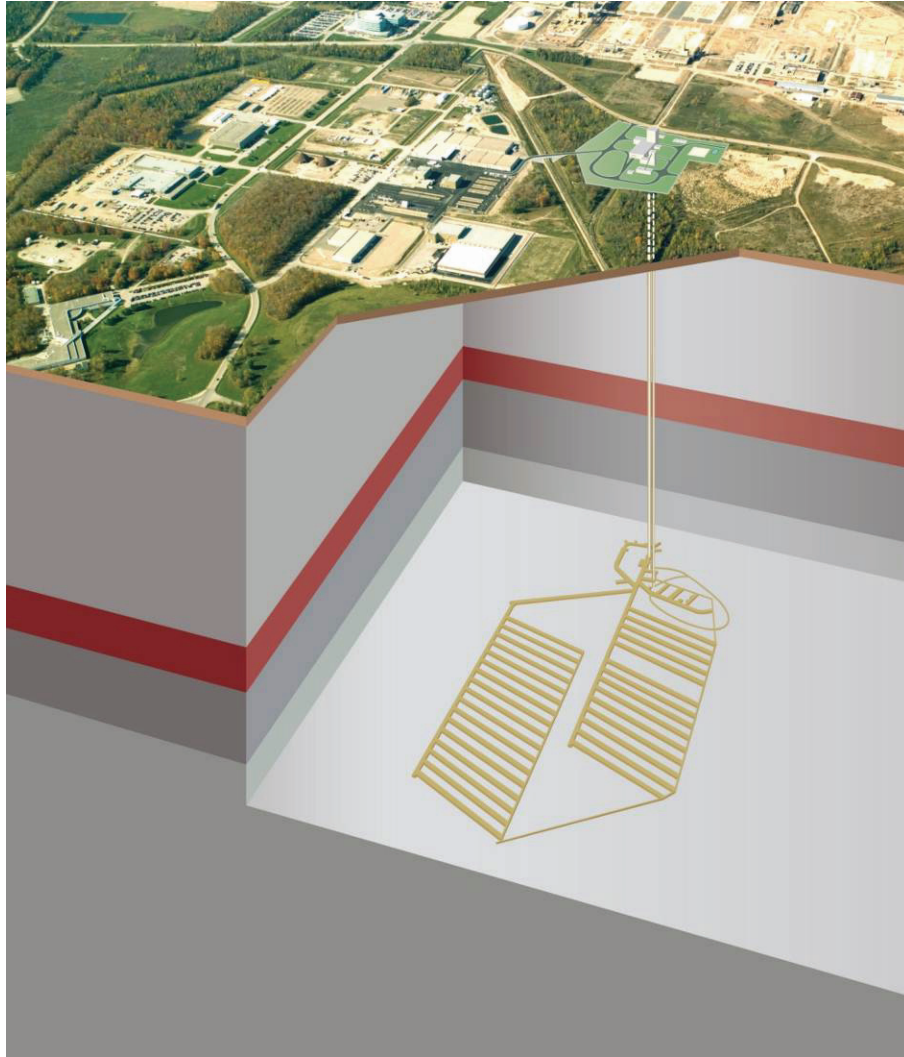
Figure 2.10: Conceptual Model for the Repository - Contaminant Release and Migration Processes .....	24
Figure 2.11: Geological Stratigraphy, Hydrogeological Zones, Shaft Seals and Shaft EDZ .....	26
Figure 2.12: Effect of One Glacial Cycle on Hydraulic Heads and Salinity Profile .....	27
Figure 2.13: Hydraulic Heads and Pressure Profiles for the Reference Case (NE-RC-F3) and Simplified Base Case (NE-SBC-F3) from Detailed Groundwater Modelling .....	28
Figure 2.14: Advective Velocities in the Lower Shaft for the Reference Case (NE-RC-F3) at 1,000,000 Years from the Detailed Groundwater Modelling .....	29
Figure 2.15: Mass Transport Results for Cl-36 for the Reference Case Plus Instant Resaturation and Release (NE-RC-F3) from the Detailed Groundwater Modelling.....	30
Figure 2.16: Conceptual Model for the Biosphere – Contaminant Migration Processes.....	34
Figure 2.17: Conceptual Model for the Biosphere – Transfers to Plants, Animals, Fish and Honey.....	34
Figure 2.18: Conceptual Model for the Biosphere – Human Exposure Pathways .....	35
Figure 2.19: Conceptual Layout of the Biosphere System.....	36
Figure 2.20: Calculated Cl-36 Concentration in the Shallow Bedrock Groundwater Zone Resulting from a Constant Source at the Shaft Location from the Detailed Groundwater Modelling .....	37
Figure 3.1: Assessment Modelling Cases for the Normal Evolution Scenario .....	49
Figure 4.1: Information Flow between the Detailed Groundwater (FRAC3DVS-OPG) and Gas (T2GGM) Codes and the Assessment Model (AMBER) .....	52
Figure 4.2: General Layout of the Original Preliminary Repository Design.....	57
Figure 4.3: General Layout of the Final Preliminary Repository Design .....	57
Figure 4.4: Illustration of the Tundra Biosphere State.....	59
Figure 5.1: Depth of Water in the Repository and Resaturation Rate for the Reference Case (NE-RC-A) .....	66
Figure 5.2: Total Radionuclide Releases from Example Waste-Streams to Repository Water for the Reference Case .....	67
Figure 5.3: C-14 Releases to Gas and Groundwater for the Reference Case (NE-RC-A) .....	67
Figure 5.4: Total Radionuclide Inventory for the Reference Case (NE-RC-A).....	68
Figure 5.5: Total Radionuclide Concentrations in Gas and Groundwater within the DGR for the Reference Case (NE-RC-A).....	69
Figure 5.6: Total Aqueous Radionuclide Fluxes from Repository to the Shafts and Geosphere for the Reference Case (NE-RC-A).....	70
Figure 5.7: Radionuclide Fluxes in Groundwater to the Geosphere for the Reference Case (NE-RC-A).....	71
Figure 5.8: Volumetric Concentrations in Host Rock Compartments above the DGR (Bq per m <sup>3</sup> of Rock) for the Reference Case (NE-RC-A) .....	72
Figure 5.9: Volumetric Concentration in Successive Shaft Compartments (Bq per m <sup>3</sup> of Shaft Seal Material) for the Reference Case (NE-RC-A).....	73
Figure 5.10: Total Radionuclide Releases from the Disposed Waste for the Final Preliminary Design Case (NE-PD-RC-A).....	74
Figure 5.11: Volumetric Concentration in Successive Shaft Compartments (Bq per m <sup>3</sup> of Shaft Seal Material) for the Reference Case (NE-RC-A) and Final Preliminary Design Case (NE-PD-RC-A).....	75
Figure 6.1: Depth of Water in the Repository for the Simplified Base Case (NE-SBC-A), in Comparison to the Reference Case (NE-RC-A) .....	76
Figure 6.2: Radionuclide Flux to the Base of the Shafts for the Simplified Base Case (NE-SBC-A).....	77

Figure 6.3:	Total Volumetric Concentration in Successive Shaft Compartments for the Simplified Base Case (NE-SBC-A) .....	78
Figure 6.4:	Height of Water in the DGR for the Reference Case (NE-RC) and Simplified Base Case (NE-SBC) with and without Water-Limited Corrosion/Degradation Reactions .....	79
Figure 6.5:	Total Radioactivity in Waste and Released for the NE-RS-A Case .....	80
Figure 6.6:	Radionuclide Flux to the Base of the Shafts for the NE-RS-A Case .....	81
Figure 6.7:	Radionuclide Concentration in Successive Shaft Compartments (Bq per m <sup>3</sup> of Shaft Seal Material) for the NE-RS-A Case .....	81
Figure 6.8:	Radionuclide Flux to the Base of the Shafts for the NE-RT1-A Case .....	83
Figure 6.9:	Radionuclide Flux into the Shallow Bedrock Groundwater Zone for the NE-RT1-A Case .....	83
Figure 6.10:	Radionuclide Flux to the Base of the Shafts for the NE-RT2-A Case .....	84
Figure 6.11:	Radionuclide Flux into the Shallow Bedrock Groundwater Zone for the NE-RT2-A Case .....	85
Figure 6.12:	Depth of Water in the Repository for the NE-GG1-A, NE-GG2-A and NE-NM-A Cases, in Comparison to the Simplified Base Case (NE-SBC-A).....	86
Figure 6.13:	C-14 Gas Flux to the Shafts and to Groundwater within the Shafts at the Level of the Guelph Formation for the NE-GG1-A and NE-NM-A Cases .....	88
Figure 6.14:	Radionuclide Flux in Groundwater to the Base of the Shafts for the NE-GG1-A, NE-GG2-A and NE-NM-A Cases .....	88
Figure 6.15:	Depth of Water in the Repository for the NE-BF-A Case, in Comparison to the Simplified Base Case (NE-SBC-A) .....	89
Figure 6.16:	C-14 Gas Flux to the Shafts and to Groundwater within the Shafts at the Level of the Guelph Formation for the NE-BF-A Case .....	91
Figure 6.17:	Radionuclide Flux in Groundwater to the Base of the Shafts for the NE-BF-A Case .....	91
Figure 6.18:	Depth of Water in the Repository for the NE-GT5-A Case, in Comparison to the Simplified Base Case (NE-SBC-A) and NE-GG1-A .....	92
Figure 6.19:	C-14 Gas Flux to the Shafts and to Groundwater within the Shafts at the Level of the Guelph Formation for the NE-BF-A Case .....	93
Figure 6.20:	Water Level in the Repository for the Case with Increased Gas Generation and Reduced Seal Performance with the Final Preliminary Design (NE-PD-GT5-A) ...	94
Figure 6.21:	Radionuclide Flux to the Base of the Shafts for the NE-EDZ1-A Case.....	96
Figure 6.22:	Contaminant Transfer Flux from the Monolith to the Shafts for the Non-radioactive Case (NE-NR-A) .....	99
Figure 6.23:	Concentration of Ni in Repository Water and in Shaft Seals (g per m <sup>3</sup> of Repository Water or per m <sup>3</sup> of Sealing Material) for the Non-radioactive Case (NE-NR-A).....	99
Figure 6.24:	Calculated Well Water Concentrations for Cl-36 and I-129 from Probabilistic Sensitivity Calculations (NE-PC) Based on the Reference Case.....	102
Figure 6.25:	Sensitivity of the Maximum Calculated Well Water Concentrations for Cl-36 to the Effective Diffusion Coefficient for Cl-36 in Bentonite-Sand (NE-PC) .....	103
Figure 6.26:	Sensitivity of the Maximum Calculated Well Water Concentrations for I-129 to the I-129 Inventory (NE-PC).....	103
Figure 7.1:	Distribution of Activity in System at Different Times for the Normal Evolution Scenario Reference Case .....	106
Figure 7.2:	Maximum Calculated Doses to Adults for All Calculation Cases for the Normal Evolution Scenario .....	106

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## 1. INTRODUCTION

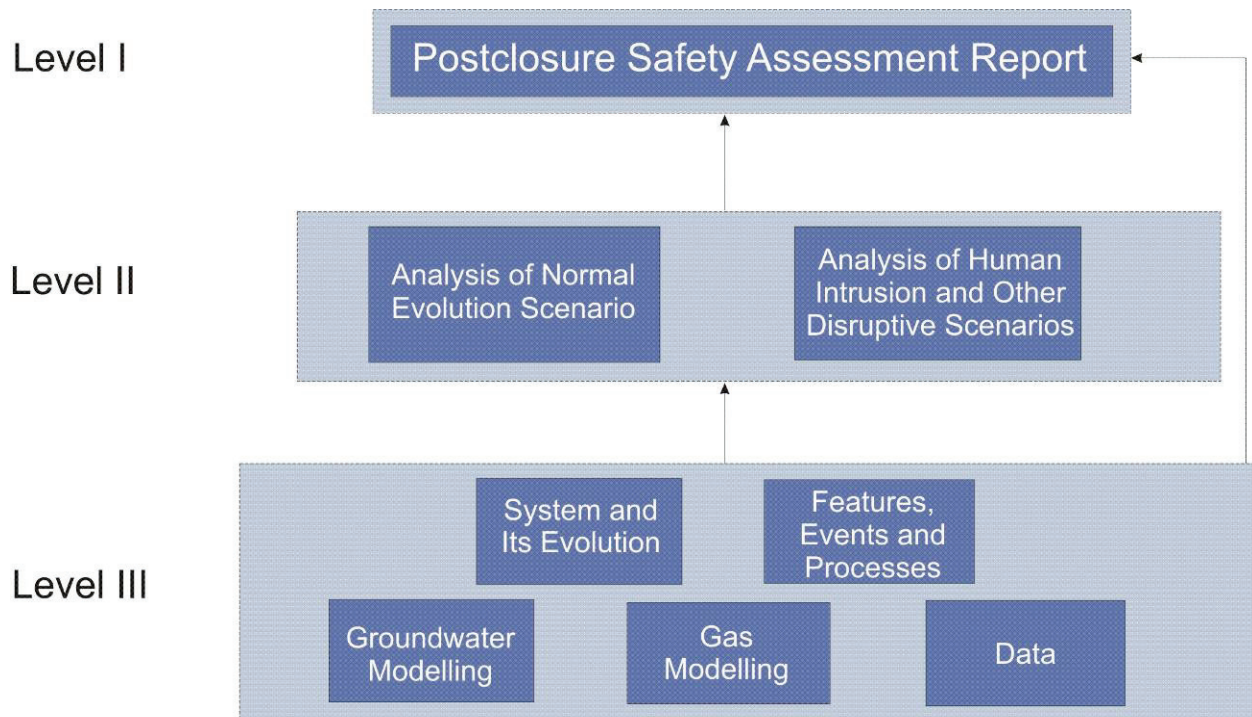
Ontario Power Generation (OPG) is proposing to build a Deep Geologic Repository (DGR) for Low and Intermediate Level Waste (L&ILW) near the existing Western Waste Management Facility (WWMF) at the Bruce nuclear site in the Municipality of Kincardine, Ontario (Figure 1.1). The Nuclear Waste Management Organization, on behalf of OPG, is preparing the Environmental Impact Statement (EIS) and 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 (Analysis of the Normal Evolution Scenario) 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 Analysis of Human Intrusion and Other Disruptive Scenarios report (QUINTESSA and SENES 2011), the System and Its Evolution report (QUINTESSA 2011), the Features, Events and Processes (FEPs) report (QUINTESSA et al. 2011b), the Data report (QUINTESSA and GEOFIRMA 2011a), 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 2011) and the Data report (QUINTESSA and GEOFIRMA 2011a).

**Waste:** The total emplaced volume of low and intermediate level waste is approximately 200,000 m<sup>3</sup>, comprised of operational and refurbishment wastes from OPG owned or operated nuclear reactors. The wastes are emplaced in a range of steel and concrete waste containers and overpacks. The total activity at closure is about 16,000 TBq. Key radionuclides in terms of total activity include H-3, C-14, Ni-63, Nb-94 and Zr-93 (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, which are then 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 Ordovician limestones below. Significant underpressures exist in the Ordovician rocks above the DGR, whereas the Cambrian sandstones beneath are overpressured. 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 (with 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. Land uses on the Bruce nuclear site are presently restricted to those associated with the nuclear operations and support activities. The region around the site is mainly used for agriculture (arable and livestock), recreation and some residential development. Groundwater is used for municipal and domestic water in this region, 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: Total Amounts of Potentially Important Radionuclides, Elements and Chemical Species in Waste**

Radio-nuclide <sup>(1)</sup>	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 <sup>(2)</sup>	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 <sup>(2)</sup>	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 <sup>(3)</sup>	4.96E+11 <sup>(3)</sup>	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 <sup>(3)</sup>	1.76E+12	1.83E+12 <sup>(3)</sup>	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 <sup>(3)</sup>	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 the 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 (Chapter 7 and 8 of the System and Its Evolution report, QUINTESSA 2011). 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 are:

- 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.

The purpose of the current report is to provide an analysis of the Normal Evolution Scenario. Based on the measured characteristics of the site and the host rock, it is expected that the low permeability host rock will provide long-term isolation and containment of the waste and its contaminants within and near the repository. However, the migration of some small fraction from the repository and through the geosphere and shafts may lead to the eventual release of some contaminants into the biosphere. The extent and consequences of these releases under the Normal Evolution Scenario is assessed in this report. In particular, the report describes the scenario 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 for the four Disruptive Scenarios is provided in the Human Intrusion and Other Disruptive Scenarios report (QUINTESSA and SENES 2011).

## 1.2 Report Outline

The following structure, which reflects the approach used to develop the models for assessment (see Appendix A), is used for the report:

- Overview of the scenario and development of the conceptual model (Chapter 2);
- Identification of the calculation cases (Chapter 3);
- Overview of the mathematical models, software implementation and data (Chapter 4);
- Results for the Reference Case calculations (Chapter 5);
- Identification of uncertainties and issues (Chapter 6); and
- Summary and conclusions (Chapter 7).

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 geological repository for radioactive waste.

## **2. CONCEPTUAL MODEL**

### **2.1 Scenario Overview**

The scenario identification process described in the System and Its Evolution report (QUINTESSA 2011) has identified the following Normal Evolution Scenario.

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

During the years following closure, there is corrosion of the carbon steel containers and degradation of organic materials in the wastes. The atmosphere in the repository become anaerobic as oxygen is consumed by corrosion. Subsequent slow anaerobic degradation of the wastes and packaging materials (i.e., containers and overpacks) in the DGR generate various decomposition products, in particular gases (predominantly CO<sub>2</sub> and CH<sub>4</sub> from the microbial decomposition of organics, and H<sub>2</sub> from the corrosion of metals).

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

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

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

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

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

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

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

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

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

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

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

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

**2.2 Key Features, Events and Processes**

The conceptual model for the Normal Evolution Scenario has been developed by identifying the key FEPs associated with the scenario.

In the context of the safety assessment, “features” are distinct physical elements of the repository system, the waste, engineering structures, 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. The description of the system and its evolution presented in QUINTESSA (2011) is the starting point for the identification of features for consideration. The key features are summarized in Table 2.1; details are provided in Appendix B and the FEPs report (QUINTESSA et al. 2011b). These include features that are currently present at the site and those that might develop during the site’s future evolution.

Processes and events that require consideration are those that result in the release and subsequent migration of contaminants from the repository into and around the surface environment. These can be grouped together as: processes internal to features; processes resulting in transfer of contaminants between features; and events and processes changing features with time. The description of the processes and events given in the System and Its Evolution report (QUINTESSA 2011) is the starting point for the identification of processes and events for consideration. The key processes and events are summarized in Table 2.2; details are provided in Appendix B and the FEPs report (QUINTESSA et al. 2011b).

**Table 2.1: Summary of Key Features for the Normal Evolution Scenario**

<b>Waste And Repository Features</b>	<b>Geosphere Features</b>	<b>Biosphere Features</b>
<ul style="list-style-type: none"> <li>• Waste packages</li> <li>• Water (Panel 1 and 2 emplacement rooms, access tunnels, and shaft &amp; service area)</li> <li>• Gas (Panel 1 and 2 emplacement rooms, access tunnels, and shaft &amp; service area)</li> <li>• Engineered Structures (concrete monolith, shaft seals and shaft backfill)</li> </ul>	<ul style="list-style-type: none"> <li>• Deep Bedrock Groundwater Zone</li> <li>• Repository Highly Damaged Zone</li> <li>• Repository and Shaft Excavation Damaged Zones</li> <li>• Intermediate Bedrock Groundwater Zone</li> <li>• Shallow Bedrock Groundwater Zone</li> </ul>	<ul style="list-style-type: none"> <li>• Well Water</li> <li>• Surface Water and Sediment (stream and wetland)</li> <li>• Lake Water and Sediment</li> <li>• Soil</li> <li>• Biota</li> <li>• Houses and Buildings</li> <li>• Atmosphere</li> <li>• Permafrost</li> <li>• Ice-sheet</li> </ul>

**Table 2.2: Summary of Key Events and Processes for the Normal Evolution Scenario**

Processes Internal to Features	Processes Resulting in Transport of Contaminants Between Features	Events and Processes Changing Features with Time
<ul style="list-style-type: none"> <li>• Radioactive decay</li> <li>• Gas generation</li> <li>• Sorption</li> <li>• Solubility</li> <li>• Chemical effects and reactions</li> <li>• Radiation dosimetry</li> </ul>	<ul style="list-style-type: none"> <li>• Gas release from saturated and unsaturated waste packages</li> <li>• Gas transport in the repository, geosphere and biosphere</li> <li>• Gas dissolution in water</li> <li>• Gas volatilization from water</li> <li>• Resaturation of the repository</li> <li>• Aqueous release from saturated waste packages (instant release and congruent release)</li> <li>• Groundwater transport (advection, dispersion and diffusion)</li> <li>• Surface water transport</li> <li>• Infiltration and interflow</li> <li>• Resuspension and sedimentation</li> <li>• Erosion and deposition</li> <li>• Water well pumping</li> <li>• Uptake by biota</li> <li>• Human ingestion, inhalation, and external irradiation</li> </ul>	<ul style="list-style-type: none"> <li>• Climate change due to glacial/interglacial cycling</li> <li>• Physical and chemical degradation of waste packages</li> <li>• Rockfall in repository tunnels and emplacement rooms</li> <li>• Degradation of engineered structures</li> <li>• Biosphere change</li> </ul>

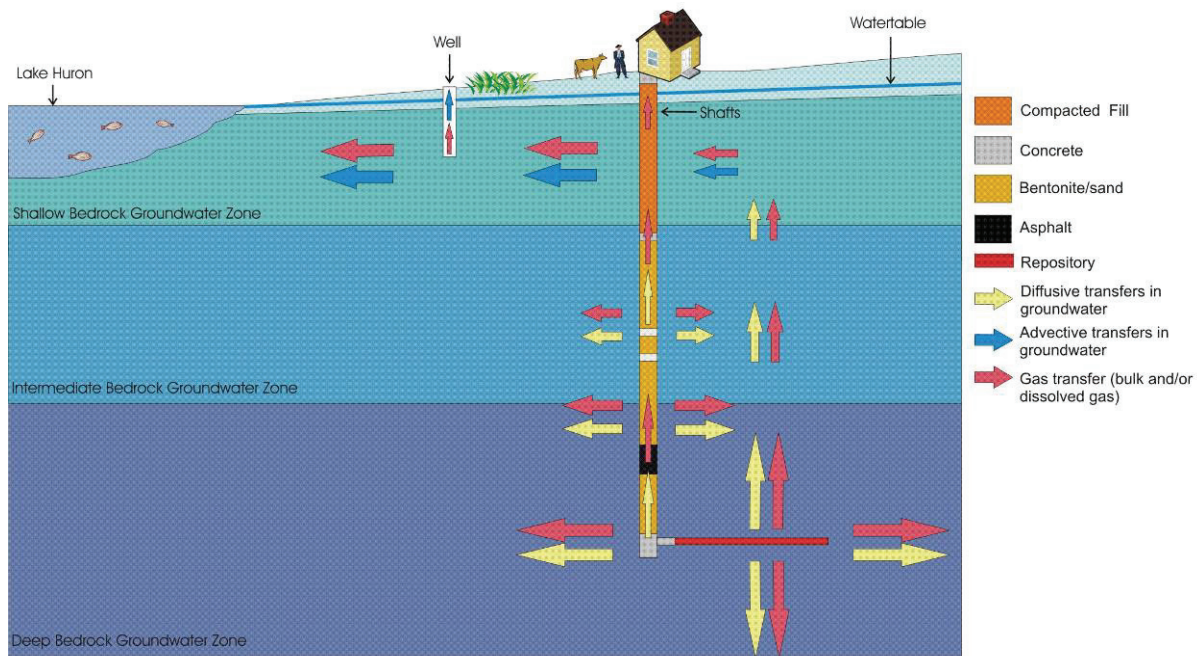
**2.3 Description of the Conceptual Model**

Box 1 and Figure 2.1 summarize the main assumptions or aspects of the Reference Case’s conceptual model for the Normal Evolution Scenario, and Figure 2.2 illustrates the key timescales. A detailed description of the conceptual model is given in the following subsections based on the identification of key features, processes and events associated with the scenario (Section 2.2 and Appendix B), and the results of the detailed groundwater modelling (GEOFIRMA 2011) and gas modelling (GEOFIRMA and QUINTESSA 2011).

Figure 2.3 summarizes the conceptual model for contaminant transport using an interaction matrix approach. The leading diagonal elements are the key physical components of the

system (consistent with those identified in Table 2.1) through which contaminants can migrate. Repository (brown), geosphere (blue) and biosphere (green) related components are differentiated through colour coding. The interaction matrix shows the migration of contaminants from the waste packages (top left of the matrix) through the disposal system resulting in the eventual uptake by humans (bottom right of the matrix). Key processes (consistent with those identified in Table 2.1) that influence the system and/or result in the migration of contaminants between the system’s physical components appear in the matrix’s off-diagonal elements. The figure is a high-level summary figure and so, out of necessity, simplifies the system’s components and processes.

Further details of the potential transport pathways in the repository and geosphere are summarized in Figure 2.4.



**Figure 2.1: Schematic Representation of Potential Transport Pathways for the Normal Evolution Scenario**

**Box 1: Key Aspects of the Conceptual Model for the Normal Evolution Scenario****Waste and Repository:**

- Reference waste inventory of about 200,000 m<sup>3</sup> (emplaced volume) and 16,000 TBq.
- Reference repository design with no backfill, except for the concrete monolith at shaft base.
- Rockfall occurs from closure, reaching a stable equilibrium.
- Metals degrade anaerobically to release H<sub>2</sub>; organics degrade microbially to release CH<sub>4</sub> and CO<sub>2</sub>.
- Resaturation of repository is determined by water inflow/outflow, gas generation, gas inflow/outflow and gas pressure.
- Contaminants released into water via instantaneous and congruent release processes; no credit given to waste packaging as a chemical or physical barrier.
- H-3 and C-14 are also released as gas as a result of waste degradation.
- Once released from waste, H-3, C-14, Cl-36, Se-79, and I-129 partition between water and gas in the repository.
- No sorption of contaminants, and solubility limitation only considered for stable carbon.
- Contaminants may migrate into the host rock and shafts by diffusion and/or advection<sup>1</sup>.

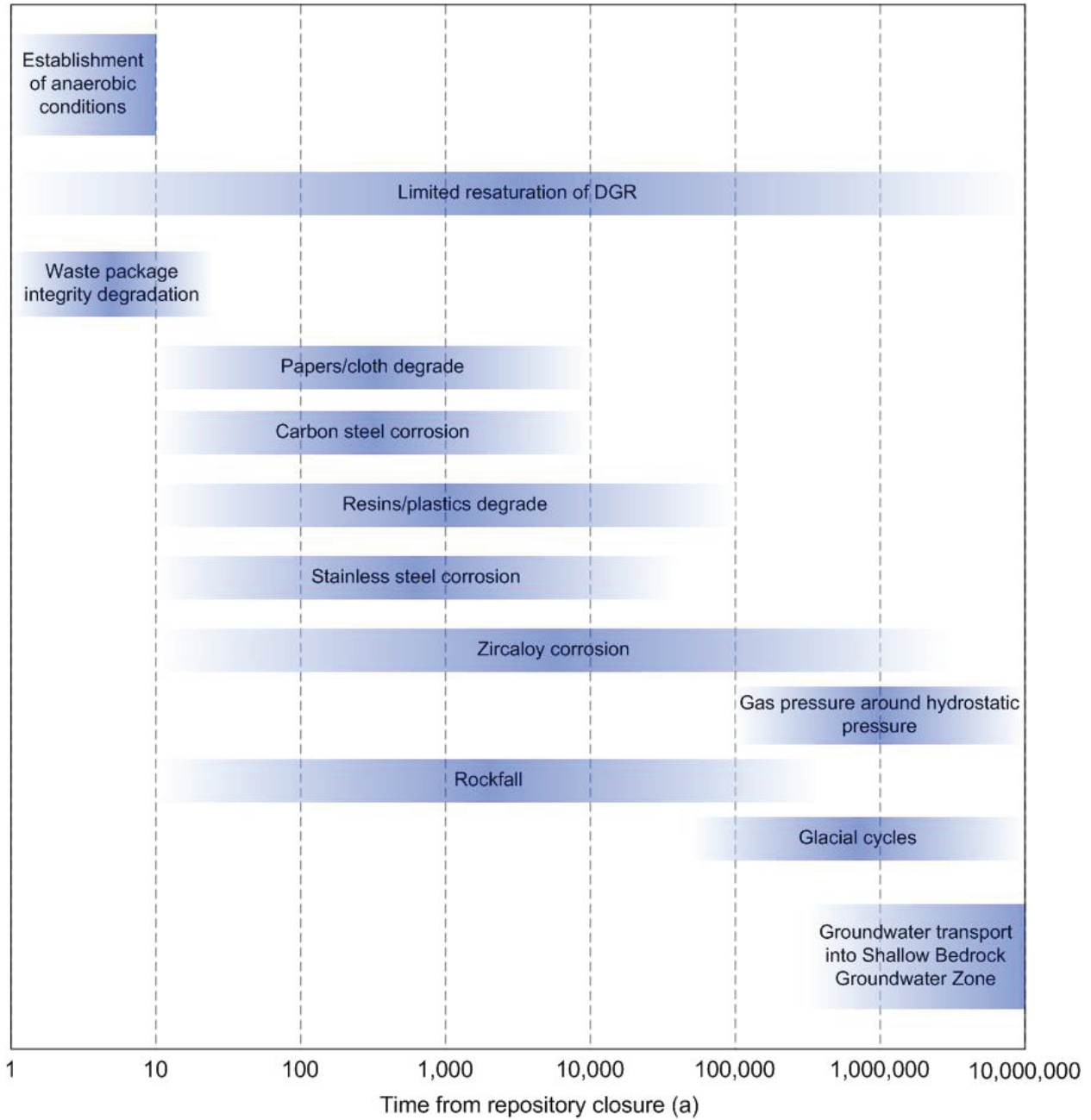
**Geosphere and Shafts:**

- Very low permeability host rock with no significant fracturing or joints, some anisotropy in diffusion and permeability along versus across bedding planes.
- Underpressures in the Ordovician sediments above the DGR are present initially but may equilibrate over time.
- Overpressure in the Cambrian sandstone remains constant over assessment timeframe.
- Ordovician rocks are partially unsaturated, with some methane gas.
- No significant groundwater flow in permeable Guelph or Salina A1 upper carbonate formations.
- Excavation damaged zones exist around all excavations, including the shafts; no self-sealing due to creep or precipitation processes.
- Some degradation of concrete structures, but no further significant change in bulk properties of shaft seal materials or damage zones occurs over assessment timescale.
- Relative permeability of gas phase is described by van Genuchten models for capillary pressure.
- Contaminants may migrate through the intact host rock by diffusion.
- Contaminants may migrate up the shafts by diffusion and/or advection in groundwater and in gas through the shaft seals and/or excavation damaged zones (EDZs)<sup>1</sup>.
- Zr, Nb, Cd, Pb, U, Np and Pu may sorb in the shafts and geosphere.

**Biosphere:**

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

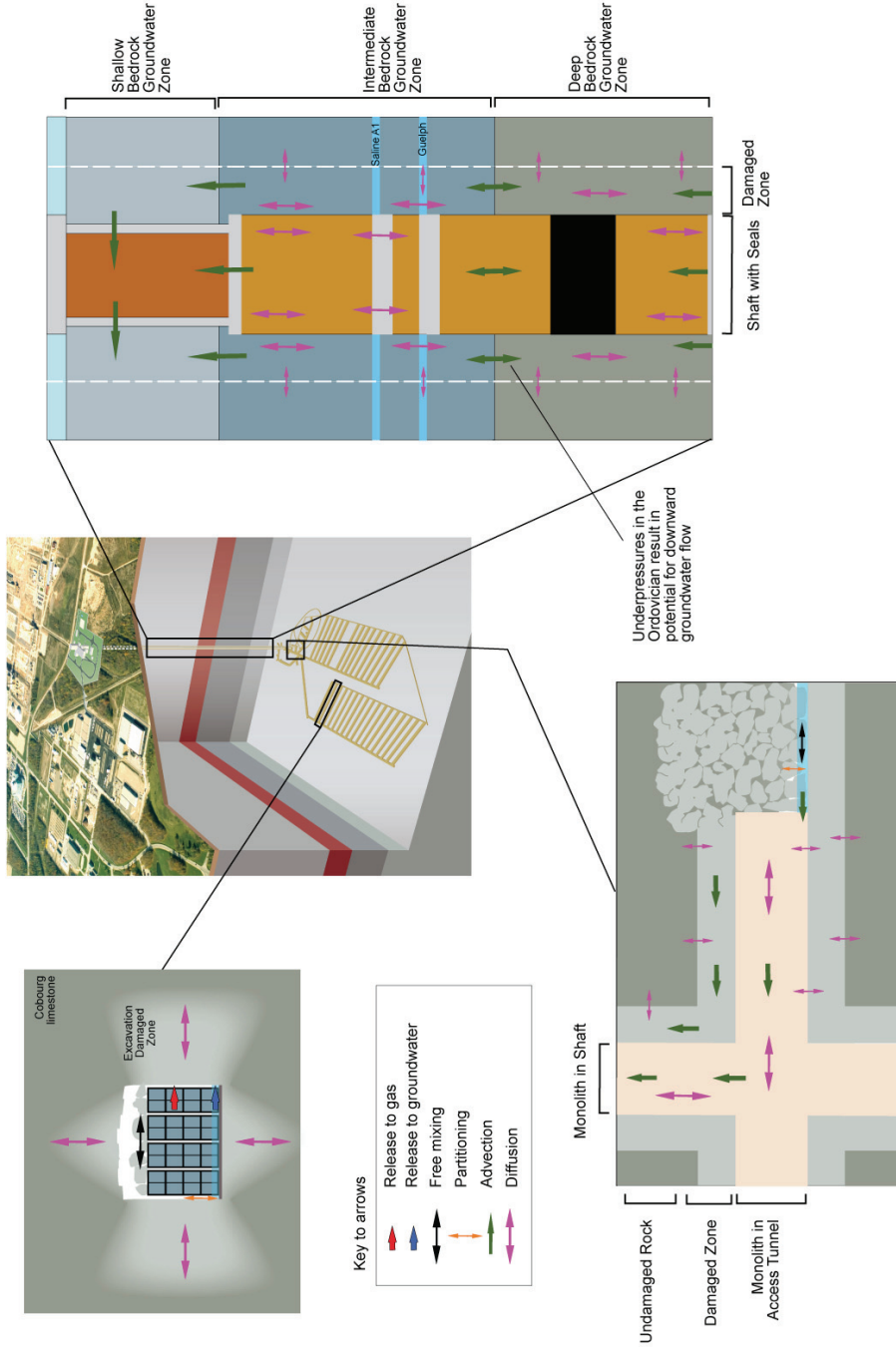
<sup>1</sup> Based on findings presented in the Groundwater Modelling Report (Section 5.2 of GEOFIRMA 2011) and the Gas Modelling Report (Section 5.1 of GEOFIRMA and QUINTESSA 2011).



**Figure 2.2: Timeframes for Key Processes Considered in the Normal Evolution Scenario**







Note: See Figure 2.11 for shaft seal materials.

**Figure 2.4: Detailed Representation of Potential Transport Pathways in the Repository and Geosphere for the Normal Evolution Scenario**

## 2.3.1 Waste and Repository

### 2.3.1.1 Evolution of Repository Conditions

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

On closure (taken to be in 2062), each waste emplacement room is expected to be dry, with little or no standing water, but a relative humidity of around 100% (Section 5.1.1.7 of the Gas Modelling report, GEOFIRMA and QUINTESSA 2011). The rate of water inflow, and hence resaturation, is slow due to the very low permeability of the host rock (see below). Both the wastes and their packaging degrade under the humid conditions. Initially conditions in the DGR will be aerobic, but corrosion and microbial degradation<sup>2</sup> consume oxygen with the formation predominantly of rust on steel packaging and generation of CO<sub>2</sub> from organic wastes. The chemical conditions in the repository rapidly become anaerobic - initially in localized areas within packages, and then across the entire repository.

Under anaerobic conditions, metallic wastes and packaging corrode, generating H<sub>2</sub> gas as a by-product (Figure 2.5). The radioactivity in the waste may locally enhance corrosion in some packages, but overall it is too low to generate appreciable radiolytic gases. Organic materials are subject to microbial degradation, generating a variety of intermediate products (mostly CH<sub>4</sub> and CO<sub>2</sub>) depending on the microbe and other factors (Section 4.2 of QUINTESSA and GEOFIRMA 2011b), but ultimately converting the organics into predominantly CH<sub>4</sub> (Figure 2.5). CO<sub>2</sub> formed from the degradation of organics is microbially metabolized to CH<sub>4</sub> by reaction with H<sub>2</sub> gas. Some CO<sub>2</sub> also reacts with water and iron to form siderite (FeCO<sub>3</sub>) and H<sub>2</sub> gas. Consequently, in the long term, the repository will contain mostly methane gas, consistent with natural gas reservoirs in sedimentary rocks.

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

These corrosion/degradation reactions usually require water. There is a small amount of water initially present in the wastes, but continued corrosion/degradation will depend on water seeping into the DGR from the host rock and/or shafts. Since the surrounding host rock and the shaft seals have low permeability, the rate of water supply may limit the corrosion /degradation rate.

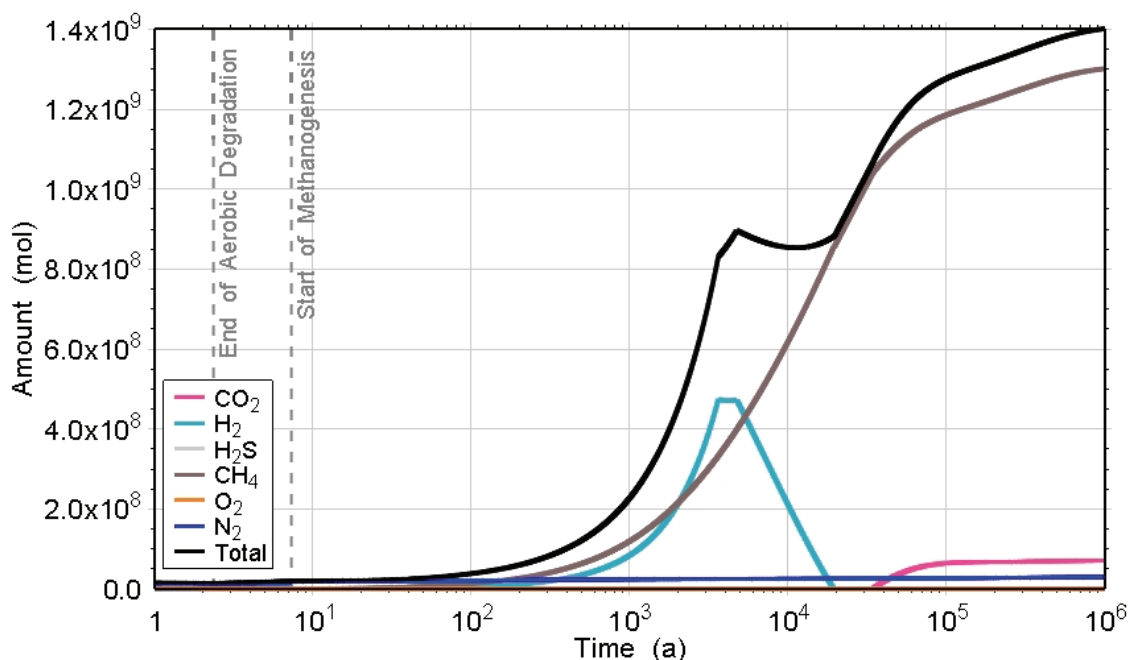
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<sup>2</sup> The degradation of the organics (but not the corrosion of steel) requires the presence of an active anaerobic microbial community. However, the rock porewater around the repository is highly saline and not favourable for microbes, and tests of the host rock formations do not exhibit appreciable microbial activity. Furthermore, locally the presence of concrete could lead to high values of pH which are not favourable to microbial development. Nevertheless, the safety assessment assumes that microbial waste degradation occurs.

As the wastes and their packaging corrode and degrade, the gas pressure inside the repository begins to rise (Figure 2.6), with the rate of increase dependent on:

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

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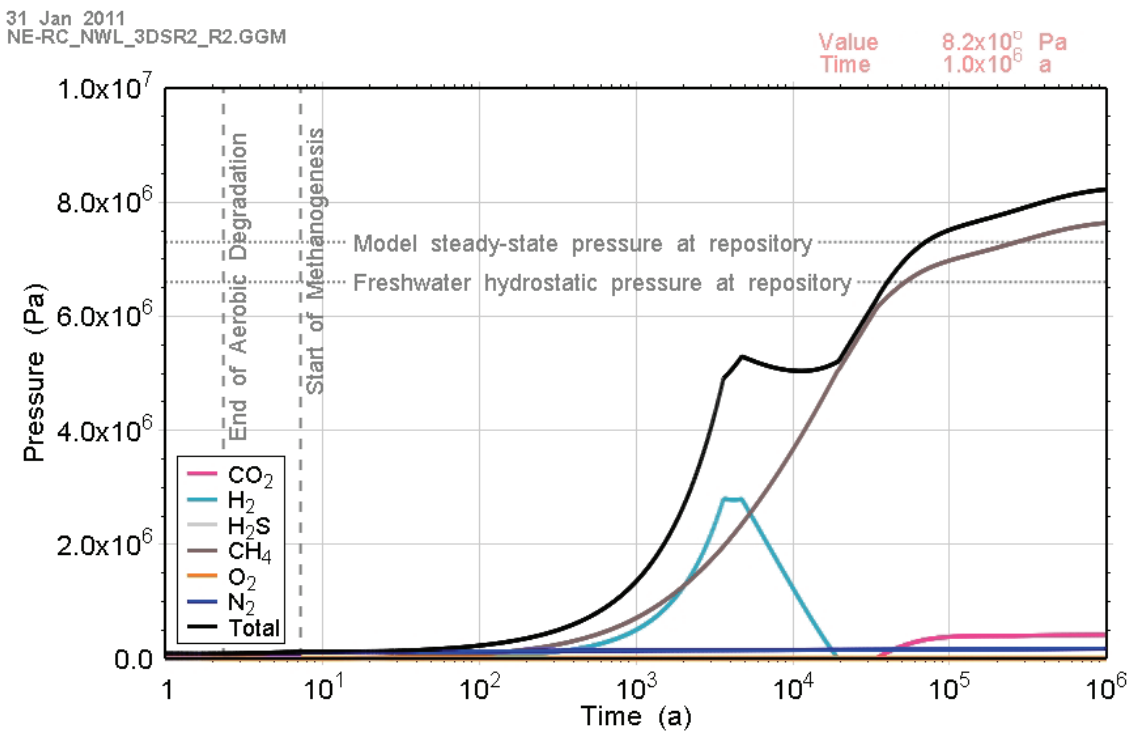
Note: Figure 5.4 in GEOFIRMA and QUINTESSA (2011).

**Figure 2.5: Gas Amounts in the DGR for the Normal Evolution Scenario's Reference Case**

The free gas pressure is important, because it affects both the repository water resaturation time (and hence the water level in the repository) and the potential for migration of gaseous radionuclides from the repository. Due to the very low permeability of the host rock, most of the gases are retained within the repository void space and hence the gas pressure in the repository can rise to levels of around 8 MPa at around a million years for the reference conditions (Figure 2.6). This peak pressure is about 0.8 MPa above the steady-state hydraulic pressure in the host rock, and reflects the presence of a higher pressure free formation gas phase in the geosphere, which flows from the host rock into the lower pressure repository at long times. This pressure is well below the 17 MPa rock lithostatic pressure and the 20-30 MPa horizontal rock stresses. Geomechanical modelling of the DGR with peak gas pressures of 7 MPa shows no fracturing. Even if gas pressures were to reach 15 MPa, there would only be

formation of several metres long horizontal fractures (Section 6.4 of the Geosynthesis report, NWMO 2011a).

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

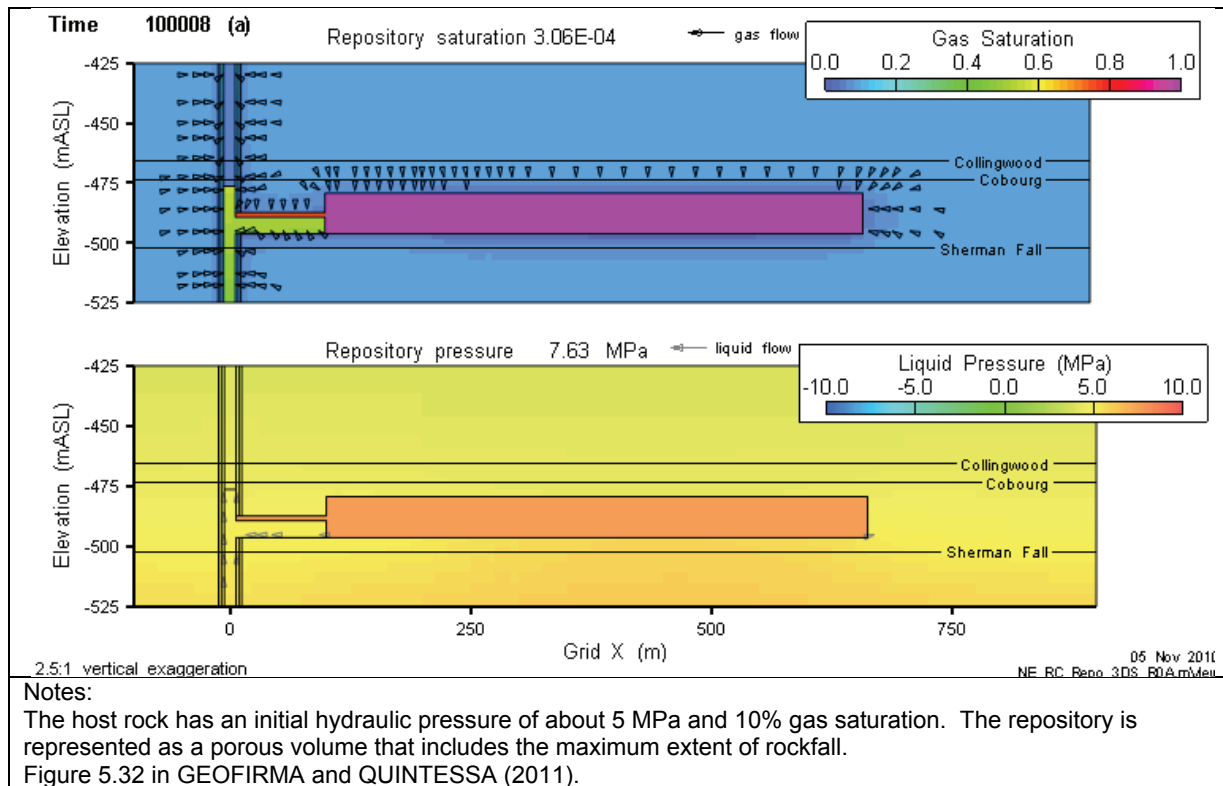


Note: Figure 5.7 in GEOFIRMA and QUINTESSA (2011).

**Figure 2.6: Repository Gas Pressures for the Normal Evolution Scenario's Reference Case**

Figure 2.7 shows the saturation profile and pressures in the repository and adjacent rock at about 100,000 years after most of the gas generation has occurred (Section 5.1.2.2 of GEOFIRMA and QUINTESSA 2011). At this time the repository is virtually 100% gas, while the shaft and surrounding rock are at around 10% gas saturation (within the rock porosity of 1-10%), the initial estimated gas content of these rocks. The concrete monolith at the shaft base and a small region of rock above the monolith are largely unsaturated. There is slow gas movement from the surrounding rock into the repository and eventually through the monolith area and into the shaft.

The quantities of cementitious materials employed in the repository are relatively small (about 15% of the total volume) and are not expected to have a large effect on the average pH conditions within the DGR, which are expected to be around pH 6 to 8 (see discussion of chemical and biological evolution of the DGR in Section 4.5 of the System and Its Evolution report, QUINTESSA 2011). However, these materials might locally affect the pH of repository water significantly (e.g., in the vicinity of cementitious waste packages). Any conditioning of repository water pH by cement will be greatest during this initial period, when pore fluids having pH >13 are likely to be present within the cementitious materials. However, in general, it is expected that the high solute concentrations in the water entering the repository limit significant chemical changes due to the strong buffering reactions associated with the high carbonate concentrations in the water which will balance the tendency to high pH from the cement and the tendency to low pH from CO<sub>2</sub> gas. Calculations indicate that only a small amount of carbonate rock will dissolve under these conditions (Appendix G of QUINTESSA 2011). Within the porewater in the surrounding rocks, it is likely that SO<sub>4</sub> is the dominant S species, and Fe(II) is the dominant aqueous Fe-species (Section 4.5.1 of QUINTESSA 2011).

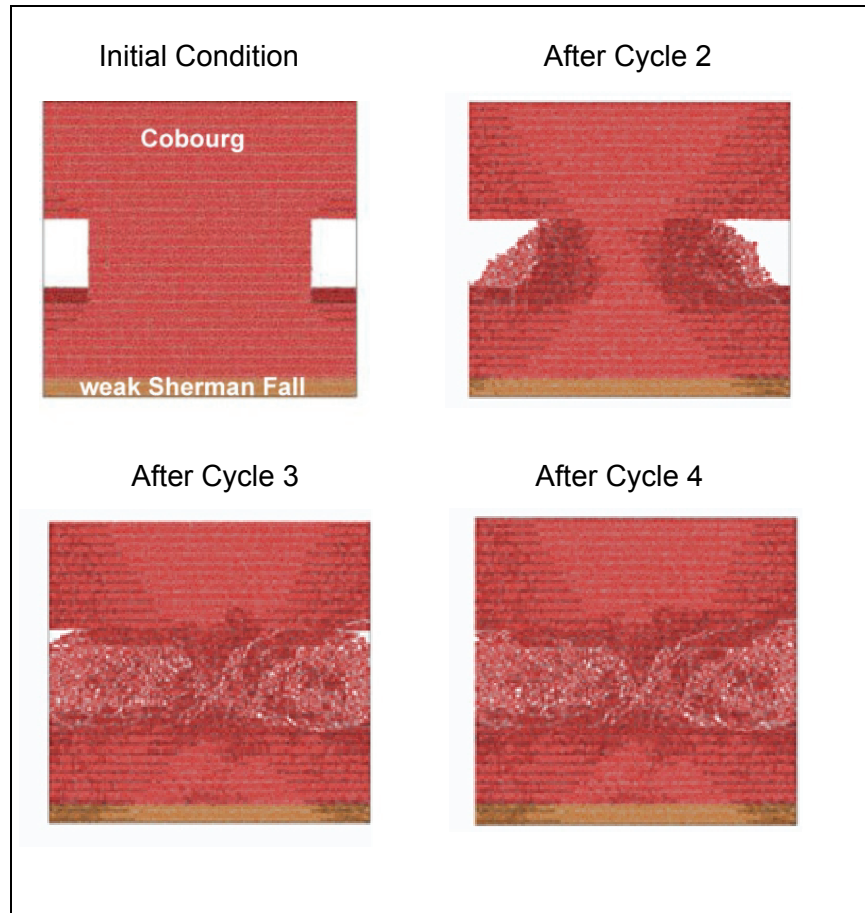


**Figure 2.7: Saturation, Flows and Pressures around the Repository for the Normal Evolution Reference Case after about 100,000 Years**

Some localized thermal gradients exist initially due to cement curing (e.g., the concrete monoliths at the base of the shafts) and radiogenic heat from some ILW wastes, but they are not spatially or temporally extensive. Corrosion of waste metals, and decomposition or

degradation of organic materials will not emit significant heat. Overall, no significant thermal effects are expected given the limited heating power of the repository (maximum 2 kW at closure) relative to the 10 kW natural geothermal flux through the DGR’s panel footprint (see Section 4.2 of the System and Its Evolution report, QUINTESSA 2011).

Over the assessment timescale, it is expected that, in addition to the release of rock stresses resulting from the excavation of DGR rooms and tunnels, external events such as earthquakes and ice-sheet advances and retreats could induce loads on the rock. These events could lead to rockfall in the DGR rooms and tunnels. Geomechanical modelling shows that after three to four cycles of ice-sheet loading and unloading the excavations will become mechanically stable as material that falls from the roof and room pillars between the rooms becomes self-supporting (Section 6.4 of the Geosynthesis report, NWMO 2011a) (Figure 2.8). The modelling shows that the rockfall zone would propagate about 10 m into the repository roof before it stabilizes, and therefore would not affect the overlying geological formations. For the purposes of the safety assessment, the full rockfall is assumed to occur quickly after closure in the present assessment, and is assumed to affect all tunnels and rooms (i.e., it is not “patchy”).

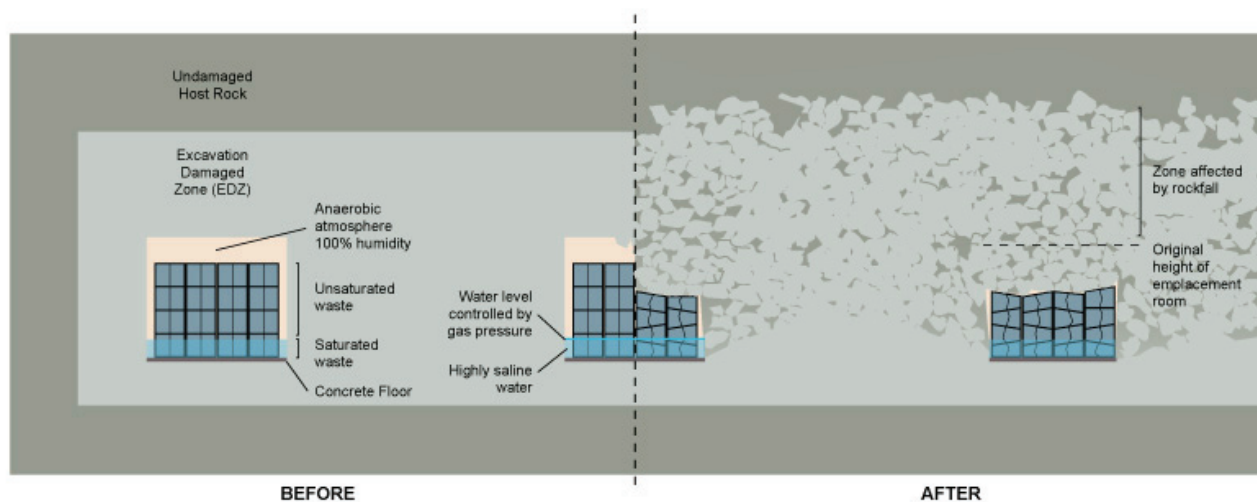


Notes: Adapted from Section 6.4 of NWMO (2011a).

**Figure 2.8: Rockfall within and around the Emplacement Rooms after Four Glacial Cycles**

### 2.3.1.2 Release of Contaminants

Figure 2.9 provides a general illustration of a partially resaturated repository with the lower waste packages standing in water. Contaminants are released from wastes into water or gas, depending on the fraction of wastes that are saturated, and the nature and form of each contaminant. As the waste packages degrade over time, there is some collapse of the stacked packages into the void space that originally existed between and around the containers. The collapse is conservatively taken to occur at closure, minimizing the stack height and maximizing the amount of waste in contact with the water<sup>3</sup>. This is consistent with the assumption of full rockfall at closure, which would damage the containers and promote collapse.



**Figure 2.9: General Illustration of Repository Conceptual Model before and after Rockfall**

#### **Contaminant Releases to Repository Water**

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

The two processes considered for releases to water are instant release and congruent release. Table 2.3 indicates the release processes to water that are considered for each waste category.

The majority of the contaminants associated with LLW are expected to be released quickly on contact with water. This is because the wastes are in 'light' packaging that is likely to degrade

<sup>3</sup> In the assessment calculations, collapsed stack heights are calculated for each waste type (see Appendix J.5).



relatively rapidly postclosure, for example, through corrosion of the carbon steel drums. Also the contamination is generally present on the surfaces of the wastes, such that, once it comes in contact with repository water, it is rapidly transferred into the water.

Many of the ILW wastes are packaged more heavily for operational reasons (i.e., with additional containment and shielding), including the use of steel and concrete packaging (see Chapters 2 and 3 of the Reference L&ILW Inventory report, OPG 2010). For these wastes, the packaging could form a barrier to water-waste interaction and contaminant release to repository water. However, the potential effect of ILW packaging is conservatively ignored for the assessment modelling.

**Table 2.3: Contaminant Release Models from Waste to Repository Water**

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

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

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

### **Gaseous Contaminant Releases**

Radioactive trace gases are also generated in the form of:

- C-14 labelled CH<sub>4</sub> and CO<sub>2</sub>;
- H-3 released as tritiated hydrogen gas and tritiated water vapour;
- Rn-222 produced by radioactive decay of actinides in the wastes; and
- I-129, Cl-36 and Se-79 which may be volatilized.

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

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

**C-14** is present as surface contamination on wastes particularly as C-14 labelled carbonate/bicarbonate ions on exchange sites on ILW resins, and as an activation product in the matrix of irradiated metals. ILW resins are the major source of C-14 in the wastes. C-14 present as surface contamination is released from unsaturated wastes as radiolabelled CO<sub>2</sub> gas. The release rates used in the assessment are the measured rates for ILW resins in storage (Chapter 7 of OPG 2011b). C-14 labelled CH<sub>4</sub> and CO<sub>2</sub> gases are also generated from C-14 present as carbides in metal wastes, with release congruently controlled through corrosion of both saturated and unsaturated metals.

C-14 released as radiolabelled CO<sub>2</sub> gas is expected to be subsequently microbially metabolized to CH<sub>4</sub> by reaction with H<sub>2</sub> gas. C-14 will be redistributed by the CO<sub>2</sub> processes. These include reaction of CO<sub>2</sub> with metals, resulting in some C-14 trapped in siderite precipitates. It includes

CH<sub>4</sub> and CO<sub>2</sub> gas dissolved in water in the repository in accordance with Henry's law, precipitation or exchange with carbonate minerals and cement, and incorporation into microbial biomass.

A specific activity model is used in the assessment calculations to describe the partitioning of C-14 between aqueous and gaseous phases. This model assumes that the partitioning of C-14 mirrors the behaviour of bulk stable carbon (i.e., C-12). It does not consider precipitation as calcite or exchange with carbonate rocks. Further information on the conceptual model of the behaviour of C-14 and the associated mathematical models is provided in Appendix E.

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

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

### 2.3.1.3 Migration of Contaminants

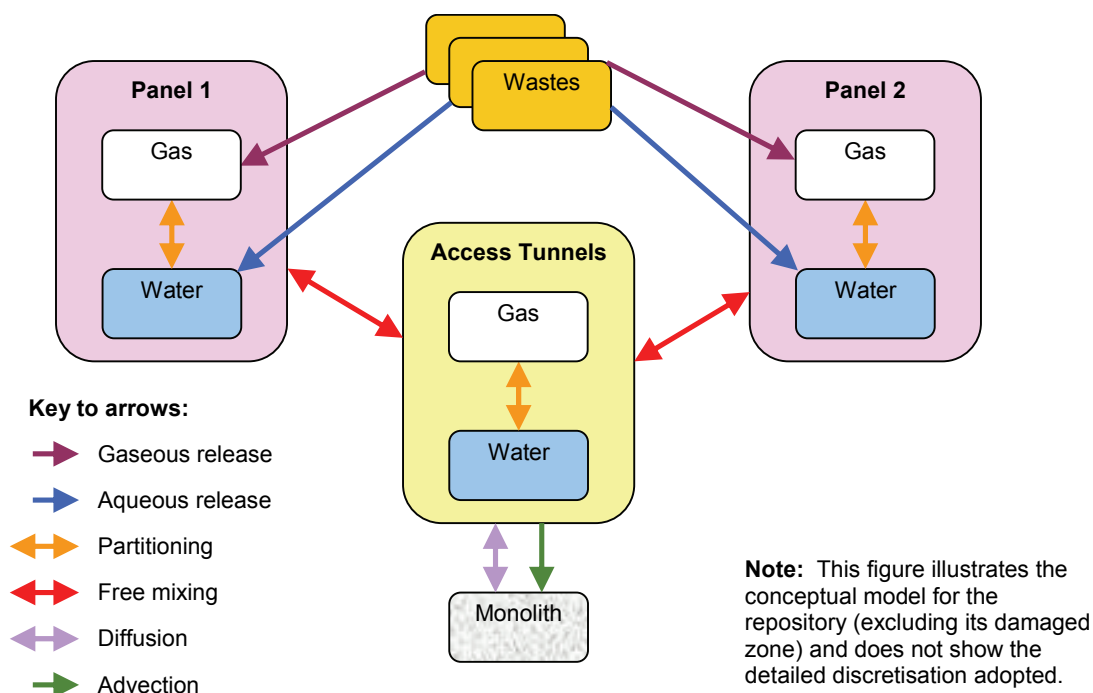
The preliminary design has two waste panels joined by connecting access tunnels. **Water** within the DGR is assumed to equilibrate to a common (time-dependent) depth and contaminants within the water can mix freely through diffusion. No credit is taken for the role of any walls at the ends of the emplacement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

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

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

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

The processes discussed above are illustrated in Figure 2.10, which shows how they apply to and between specific waste and repository components.



**Figure 2.10: Conceptual Model for the Repository - Contaminant Release and Migration Processes**

## 2.3.2 Geosphere and Shafts

### 2.3.2.1 Evolution of Geosphere and Shaft Conditions

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

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

The shafts are backfilled using a combination of sealing materials, some of which intersect the inner EDZs (Figure 2.11). The hydraulic conductivities of these sealing materials are low to

restrict the migration of contaminants up the shafts (see Section 4.5 of the Data report, QUINTESSA and GEOFIRMA 2011a). The concrete monolith and bulkheads are affected by some degradation due to chemical reactions (such as carbonation and sulphate attack) and stresses (see Section 4.5.3 of the System and Its Evolution report, QUINTESSA 2011), which is conservatively taken to occur at closure, and the bulkheads are conservatively taken not to be keyed into the EDZ around the shafts. In light of system-specific calculations presented in Appendix E of the System and Its Evolution report (QUINTESSA 2011), it is concluded that limited alteration/degradation of the bentonite-sand and asphalt seals will occur over the timescales of interest and this has been incorporated into the parameterization of the seal properties (Section 4.5 of the Data report, QUINTESSA and GEOFIRMA 2011a). The effect of ice-sheet loading and unloading on the shaft EDZ was assessed and found to be a small additional effect (Section 6.4 of the Geosynthesis report, NWMO 2011a), and incorporated into its parameterization (Section 5.2.1 of the Data report, QUINTESSA and GEOFIRMA 2011a).

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

The primary impacts of glacial cycles on the Deep and Intermediate Bedrock Groundwater Zones are changes in the hydraulic heads and the stress regime resulting from ice-sheet loading and unloading (see Chapter 5 of the System and Its Evolution report, QUINTESSA 2011). Based on evidence from site characterization and regional groundwater modelling (Sections 5.4.6 and 6.4 of the Geosynthesis report, NWMO 2011a) and a study of glacial erosion (Hallet 2011), these changes will not significantly affect the overall low permeability of the host rock and shaft materials. For example, Figure 2.12 shows the effect of a full glacial cycle on hydraulic head and groundwater concentrations. The results show very little effect in the Deep Bedrock Groundwater Zone.

In contrast, significant changes are likely to occur in the Shallow Bedrock Groundwater Zone (e.g., changes in recharge, development of permafrost, and changes in groundwater chemistry). However, as explained in Appendix B.2.3.1, the current assessment adopts a stylized approach to representing this zone and the biosphere<sup>4</sup>. Specifically, the Shallow Bedrock Groundwater Zone and the surface environment are treated as time-invariant, supporting a water well and self-sufficient farming family in a temperate environment. A time-invariant tundra environment with a hunter-gatherer family is also considered.

The geosphere hydraulic heads measured in the DGR site investigation boreholes show significant overpressures and underpressures in the deep rock formations (Chapter 5 of the Geosynthesis report, NWMO 2011a). These underpressures and overpressures provide the basis for the Reference Case calculation, consistent with the detailed groundwater modelling (GEOFIRMA 2011). The causes of these over- and underpressures are not certain, although there are plausible explanations. They are represented in two ways in the conceptual model.

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<sup>4</sup> A stylised representation is a representation that has been simplified to reduce the natural complexity of a system 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.

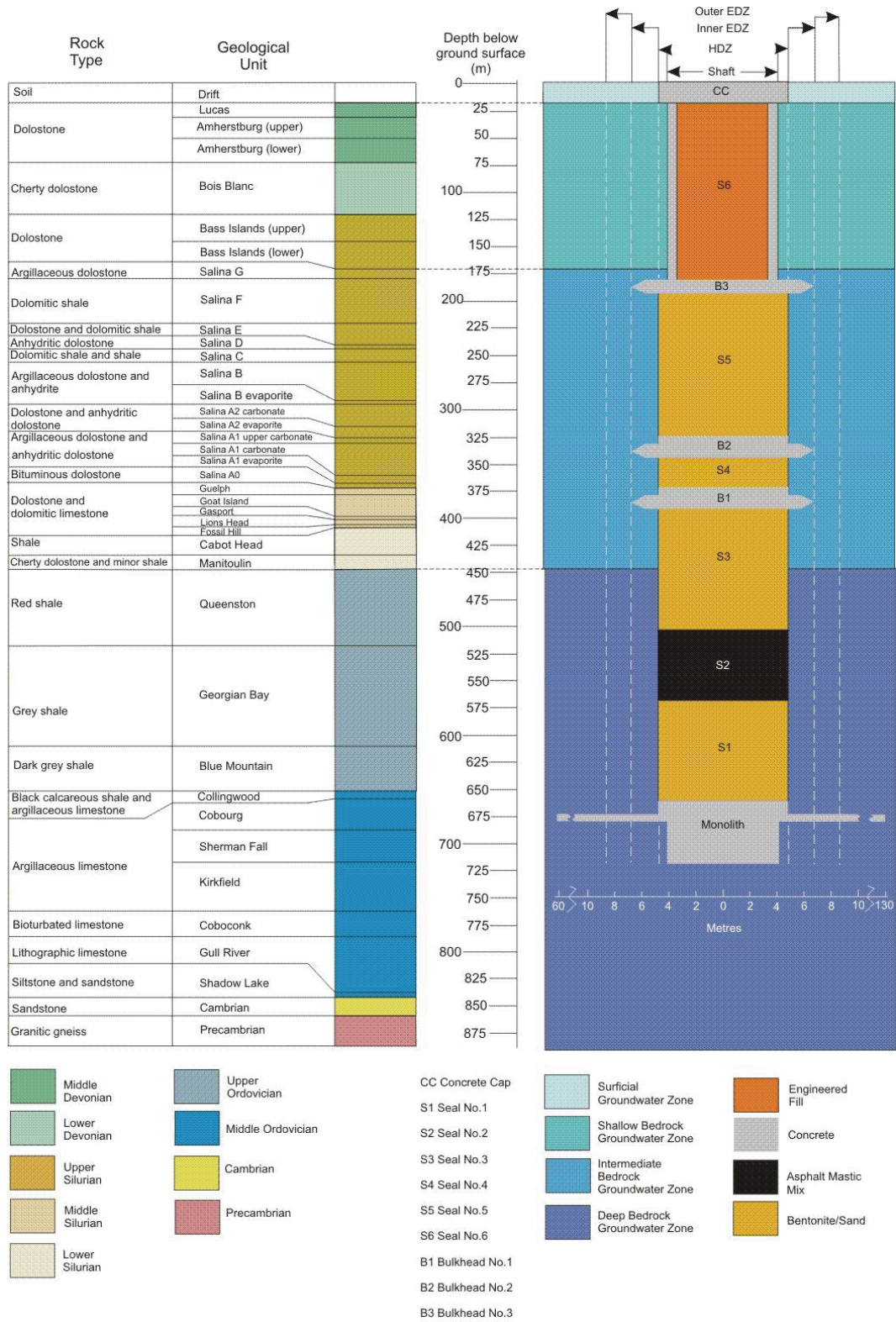
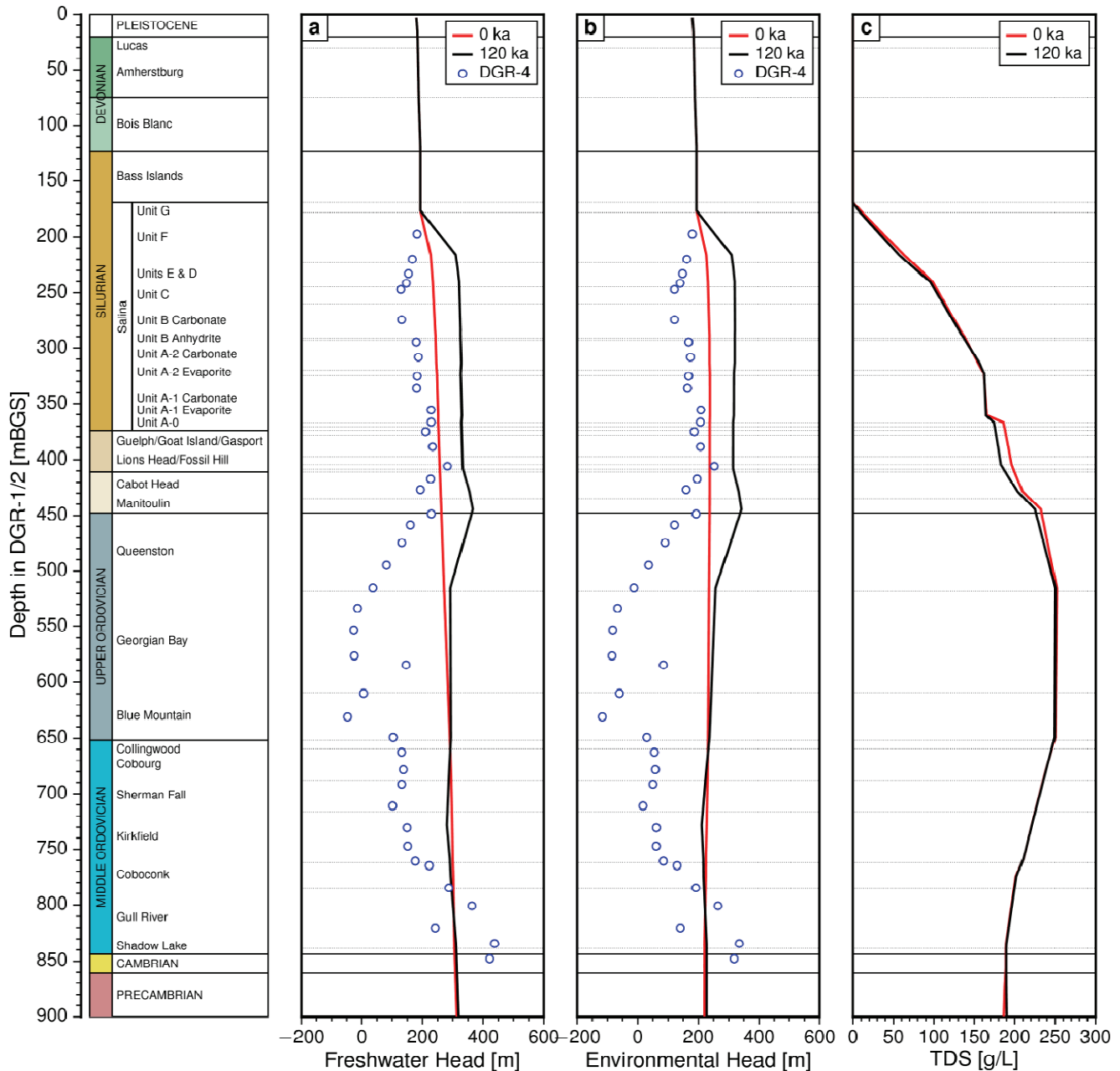


Figure 2.11: Geological Stratigraphy, Hydrogeological Zones, Shaft Seals and Shaft EDZ



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

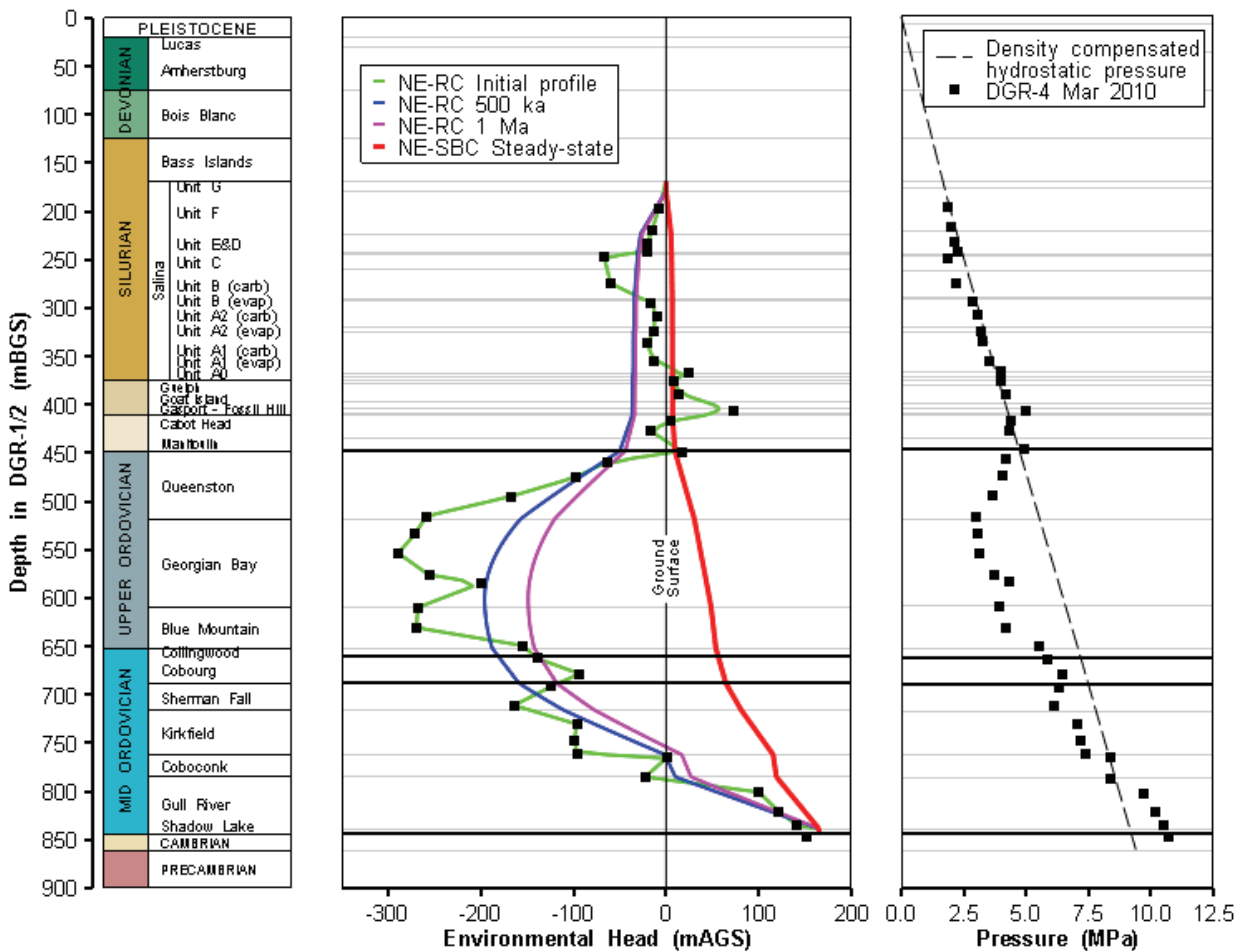
**Figure 2.12: Effect of One Glacial Cycle on Hydraulic Heads and Salinity Profile**

In the Reference Case, the existing measured conditions are adopted as initial conditions. The overpressure in the Cambrian is conservatively assumed to remain constant (i.e., it does not dissipate) over the assessment timeframe. However, the underpressure is allowed to naturally dissipate. The resulting head profile at the shaft centerline (coincident with DGR-4) calculated from detailed groundwater modelling is shown in Figure 2.13, which shows that significant

underpressures still exist in the Ordovician rocks even after a million years. The results of the detailed groundwater modelling (see Figure 2.14) for the Reference Case indicate very low advective groundwater flow in the shafts above the DGR (around 0.1 mm/a) towards the Blue Mountain formation (i.e., groundwater flow in the shaft at the top of the Ordovician is downwards because of the underpressure).

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

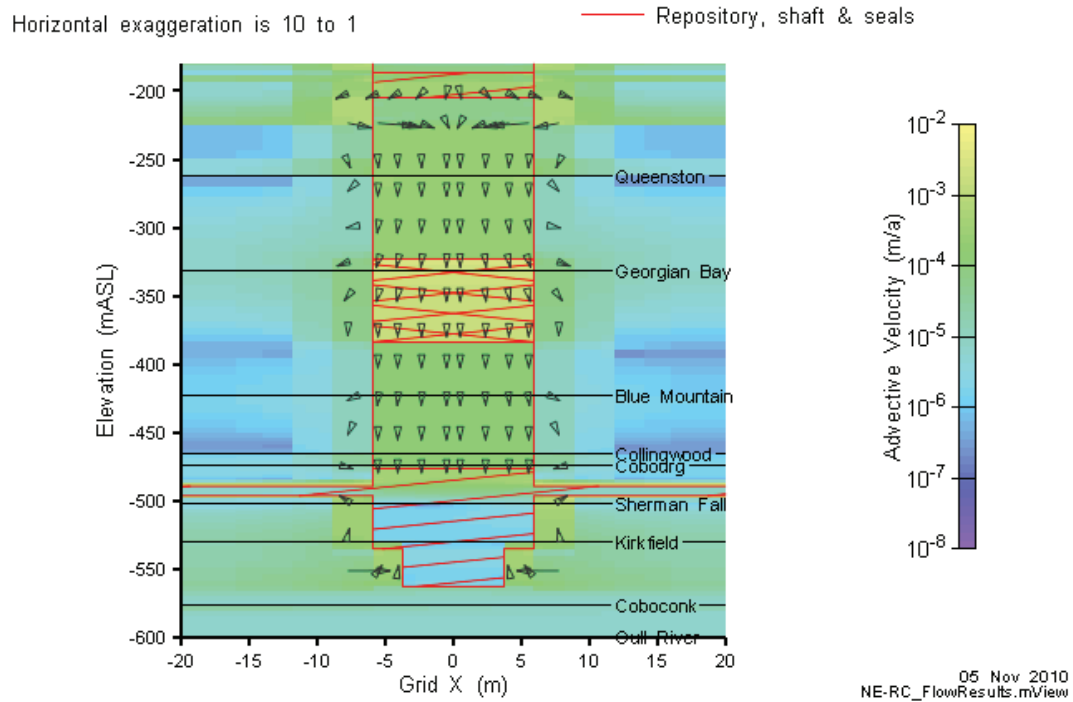
Further details describing the thermal, hydraulic, mechanical, chemical and biological evolution of the geosphere are provided in Chapter 5 of the System and Its Evolution report (QUINTESSA 2011).



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

**Figure 2.13: Hydraulic Heads and Pressure Profiles for the Reference Case (NE-RC-F3) and Simplified Base Case (NE-SBC-F3) from Detailed Groundwater Modelling**



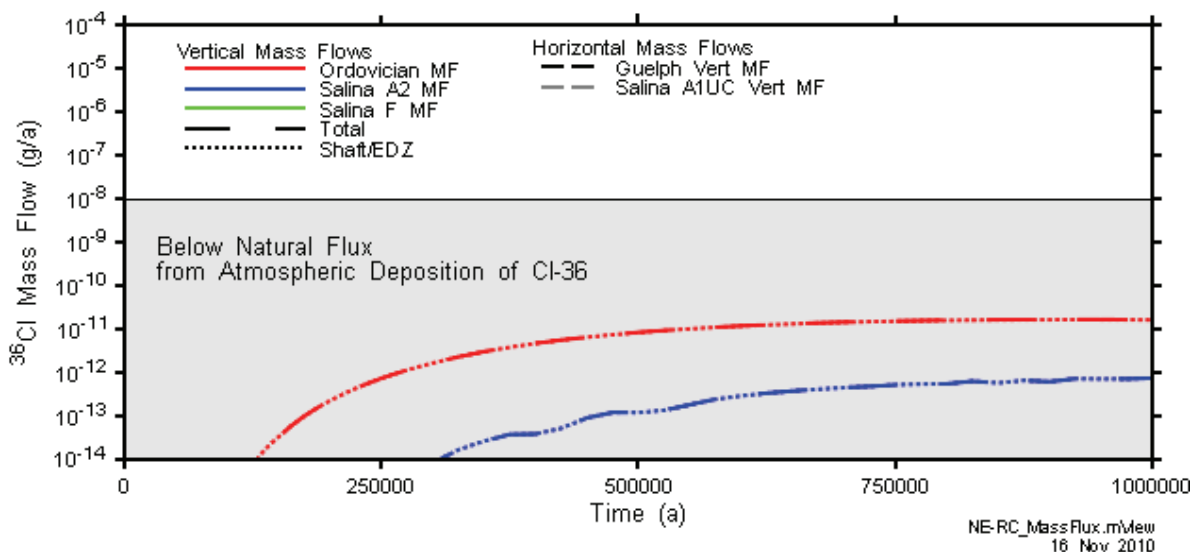


Notes: Figure 5.7 in GEOFIRMA (2011). Also, note horizontal exaggeration.

**Figure 2.14: Advective Velocities in the Lower Shaft for the Reference Case (NE-RC-F3) at 1,000,000 Years from the Detailed Groundwater Modelling**

**2.3.2.2 Migration of Contaminants**

Detailed groundwater modelling for the Reference Case (Section 5.2 of GEOFIRMA 2011) has shown that transport for contaminants in **groundwater** in the host rock is dominated by diffusion in the Deep and Intermediate Bedrock Groundwater Zones. Contaminant transport in the shaft and its associated EDZs is also diffusion dominated, with transport towards the Shallow Bedrock Groundwater Zone being against the very low downward advective groundwater velocities in the shaft at the top of the Ordovician. The primary pathway for any contamination reaching the shallow system is via the shafts and their EDZs rather than the geosphere, although the amounts are very low (Figure 2.15). Furthermore, certain elements will be retarded by sorption in the geosphere and shafts (see Appendix D of the Data report, QUINTESSA and GEOFIRMA 2011a). Transport of any contaminants reaching the Shallow Bedrock Groundwater Zone is advective towards Lake Huron with discharge to the biosphere in the near-shore region (see Figure 2.1).



Notes: Adapted from Figure 5.13 in GEOFIRMA (2011). The FRAC3DVS-OPG model assumes instantaneous resaturation of the repository and release of Cl-36 at closure. The time profiles should be seen as illustrative, since the conceptual model for the assessment calculations assumes different resaturation and release profiles (see Section 2.3.1.1 and 2.3.1.2, respectively). MF= mass flow. No line on the chart indicates that the result is below  $10^{-14}$  g/a throughout. See Figure 2.11 for geologic stratigraphy.

**Figure 2.15: Mass Transport Results for Cl-36 for the Reference Case Plus Instant Resaturation and Release (NE-RC-F3) from the Detailed Groundwater Modelling**

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

The Guelph and Salina A1 upper carbonate formations are more permeable than the surrounding formations in the Intermediate Bedrock Groundwater Zone (Section 2.3.6.2 of QUINTESSA 2011b). Some topographically driven flow occurs within these formations, but it is limited by the low hydraulic gradients under normal conditions. Under glacial conditions, there may be movement in these formations, although only the Salina A1 upper carbonate shows signs of glacial meltwater penetration at the DGR site. However, any groundwater flow in these formations would divert contaminant transport from the shafts/EDZs laterally and reduce the amount of contamination migrating to the Shallow Bedrock Groundwater Zone above the repository. These horizontal flows would further provide dispersion, dilution and time for decay of contaminants. Therefore, horizontal groundwater flow in the Guelph and Salina A1 upper carbonate is ignored in the Reference Case. Even without flow, these formations provide a more porous and permeable path into which some of the contaminants that reach this level can

diffuse (horizontally), especially free gas. (An alternative case with horizontal gradients is also evaluated.)

The low hydraulic gradient in the Cambrian (Section 5.4.1.1 of the Data report, QUINTESSA and GEOFIRMA 2011) will also limit migration of any contaminants that might have diffused down from the repository. Migration in the Cambrian will be further limited by the long distance to outcrop discharge points (in excess of 100 km).

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

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

Under glacial conditions, the site characterization and regional modelling evidence indicates that transport in the deep geosphere remains diffusion controlled (see Figure 2.12). The main effect of the ice-sheet is to transiently increase and decrease the hydraulic pressures across the vertical cross-section at the DGR site. Therefore, for the postclosure safety assessment, the effects of ice-sheets on contaminant transport within the deep geosphere are expected to be small and are not explicitly modelled.<sup>5</sup>

The effects of ice-sheet on contaminant transport within the shallow geosphere will be significant; however, there is very little contaminant release to this system. Since no continuous extended permafrost is anticipated at the DGR site (Section 5.2.3 of System and Its Evolution, QUINTESSA 2011), the main effect of ice-sheets will be to increase or decrease the shallow

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<sup>5</sup> Also, since reversion towards glacial conditions is not likely for at least 60,000 a, most of the C-14 will have decayed. Since C-14 is the primary radionuclide in the gas phase, any effects of glaciation on gas movement will be less important as a release pathway.

geosphere flow rates, but in any event these are represented in the conceptual model (which uses current flow rates) as leading to rapid release to the nearby lake.

### **2.3.3 Biosphere**

#### **2.3.3.1 Evolution of Biosphere Conditions**

Climate change can have a major impact on the biosphere system through the modification of temperature, precipitation, biota, water bodies, sediment/soil, and human activities (see Chapter 6 of the System and Its Evolution report, QUINTESSA 2011). For example, global warming could cause changes in lake level or water table levels. In the longer term, it is assumed that glacial cycles will resume. A stylized climate sequence has been identified in the System and Its Evolution report based on the results of the University of Toronto Glacial Systems Model (Peltier 2011) and is represented in Figure B.1 and Figure B.2 of Appendix B.

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

#### **2.3.3.2 Migration of Contaminants**

For potential groundwater releases, the biosphere features into which contaminants may be released are:

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

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

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

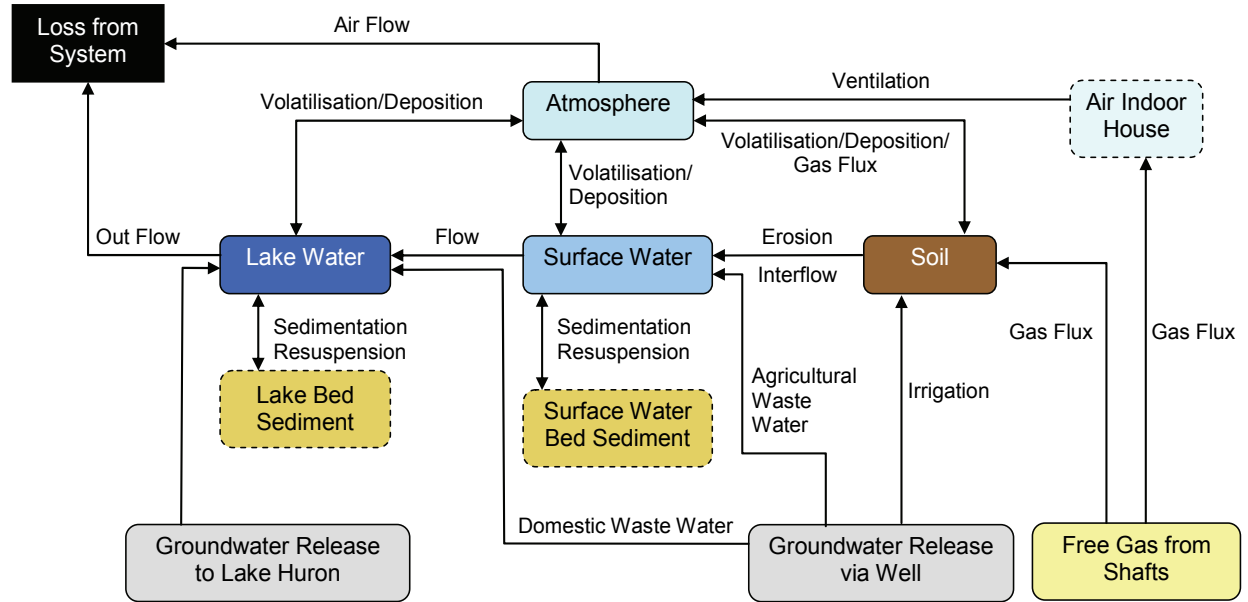
Subsequent migration of any contaminants in the biosphere results in the contamination of the following media.

- Surface waters and associated sediment (and associated wetlands) - due to interflow (lateral flow of groundwater in surface sediments) and erosion from contaminated soil. They provide a source of fish for humans.
- Lake water and associated sediment - by the discharge of contaminated surface water (as well as being contaminated by the direct discharge of groundwater) and atmospheric deposition.
- Biota (plants and animals) - from uptake of contaminants from irrigation water, soils, water bodies and associated sediments and atmospheric deposition.
- The atmosphere - due to volatilization from irrigated soil and from surface water, free gas flux from the soil and ventilation of free gas from the house.
- Soil - contaminated by atmospheric deposition (pasture used for grazing is not irrigated, so atmospheric deposition is the only route considered for it to become contaminated).

The migration and exposure pathways considered in the biosphere model are based on those identified in the Canadian Standards Association's (CSA) N288.1 guidelines for calculating derived release limits for radioactive material in airborne and liquid effluents for normal operations of nuclear facilities (CSA 2008). N288.1 includes recommended approaches for calculating potential exposures in the biosphere and has been developed in collaboration with the Canadian Nuclear Safety Commission and Environment Canada. Although developed for operational releases, the migration and exposure pathways considered are relevant to long-term releases and are, therefore, used as the basis of the migration and exposure model for the DGR biosphere assessment.

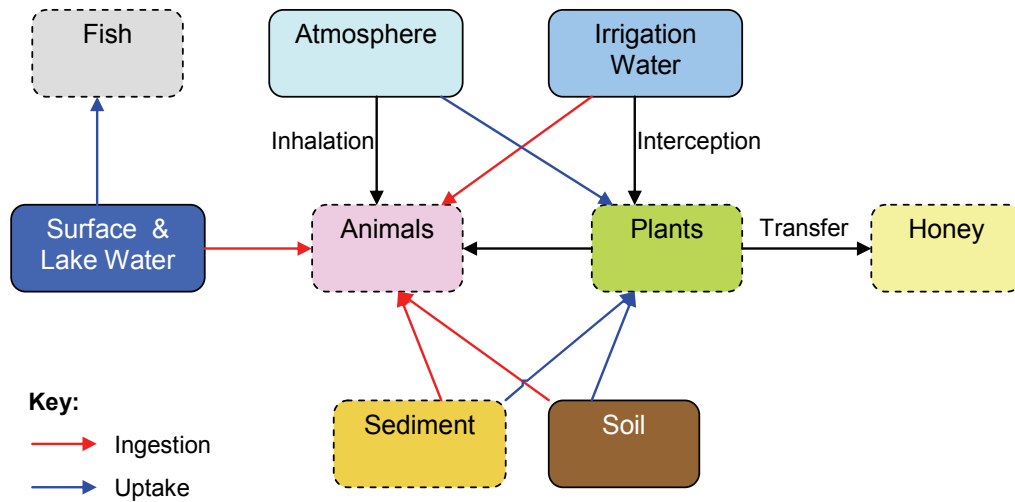
The conceptual model for contaminant migration in the biosphere is illustrated in Figure 2.16. For clarity, biota are not explicitly represented in Figure 2.16, because they are associated with all surface media, as illustrated in Figure 2.17. Well water abstracted as drinking water for animals, and for domestic purposes is directed to the Surface Water and to Lake Huron, respectively, to ensure that all of the water abstracted from the well enters the biosphere model.

Humans are exposed due to the potential release of contaminants into the biosphere and their subsequent migration. Human exposure to the features in Figure 2.16 and Figure 2.17 occur by a variety of pathways, as illustrated in Figure 2.18. Contaminants in soil, water and the atmosphere are assimilated by plants and animals (that may in turn be ingested by humans) and expose humans by external irradiation. Inhalation exposure and external irradiation occur if contaminants are volatilized and released from soil and water or if there is release of contaminated free gas to the atmosphere. The pathways modelled are consistent with recommendations of CSA N288.1 for biosphere modelling (CSA 2008).



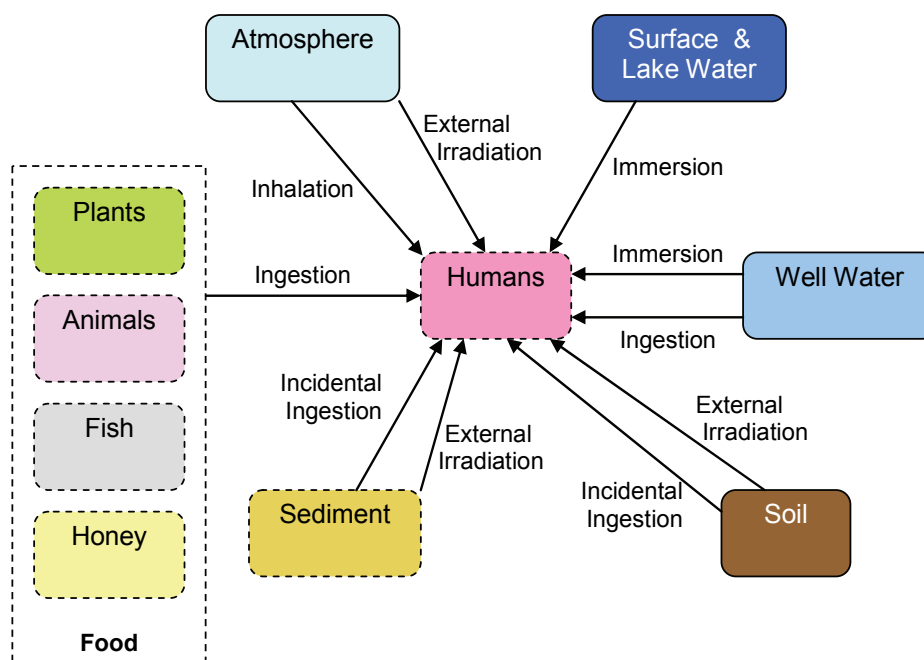
Notes: The figure illustrates the conceptual model and not the detailed discretization. Dotted borders indicate equilibrium treatment.

**Figure 2.16: Conceptual Model for the Biosphere – Contaminant Migration Processes**



Notes: Dotted borders indicate equilibrium treatment.

**Figure 2.17: Conceptual Model for the Biosphere – Transfers to Plants, Animals, Fish and Honey**



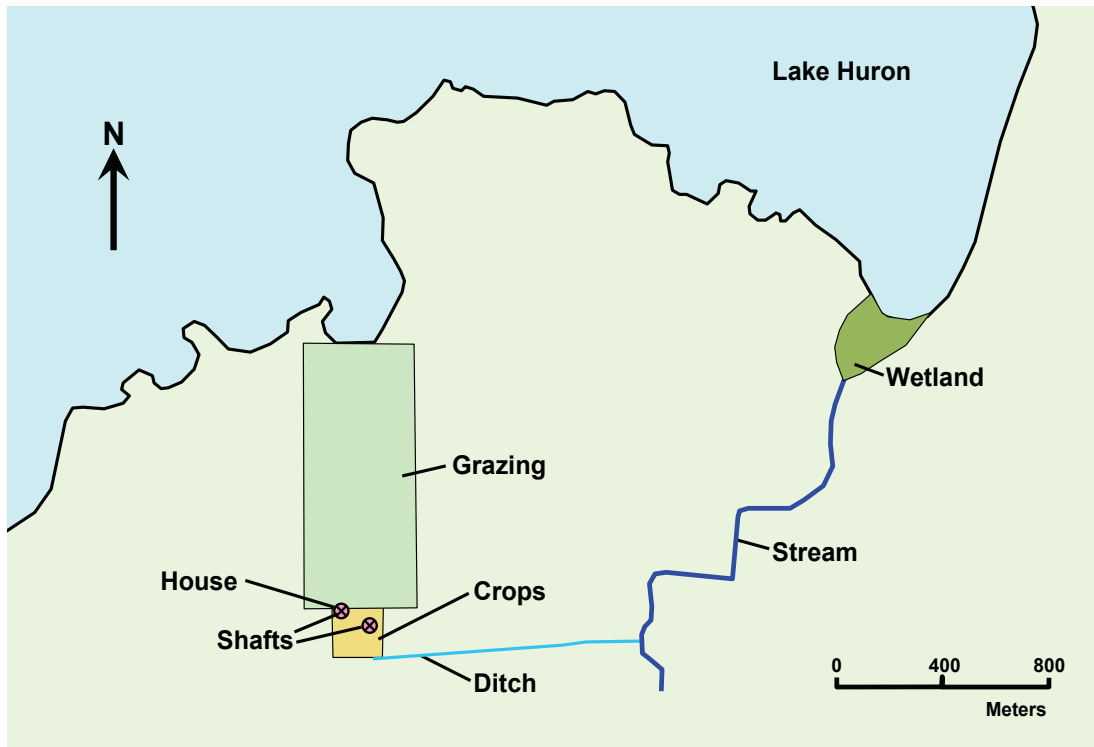
Notes: Dotted borders indicate equilibrium treatment.

**Figure 2.18: Conceptual Model for the Biosphere – Human Exposure Pathways**

In order to assess potential impacts, a hypothetical critical group (the “Site Resident” Group) is defined that is exposed, via the potential exposure pathways illustrated in Figure 2.18, to any repository-derived contaminants released from the geosphere. This conservatively-defined hypothetical family lives a self-sufficient lifestyle on a farm on the repository site. Their house is over the main shaft. They grow their own grain, fruit and vegetables from fields that are located above the repository, and in particular on the ventilation shaft. They pump water from a well drilled into the Shallow Bedrock Groundwater Zone at a location that maximizes capture of any contaminants released from the shafts, for drinking, domestic use, watering animals and irrigating crops for human and animal consumption. The family comprises two adults, a child and an infant. The livestock include dairy and beef cattle, pigs, lambs, goats and chickens. They hunt locally for deer and rabbits, catch fish from the stream and from Lake Huron, and consume local honey. They swim recreationally in the lake.

The house is further assumed to cover the main shaft and part of its EDZ, which means that a proportion of any free gas released through the shaft and EDZ goes directly into the house. Any gas released into the house subsequently migrates outside, where it is subject to transport and dilution in the local atmosphere, along with gas released into the soil directly from the shafts/EDZs.

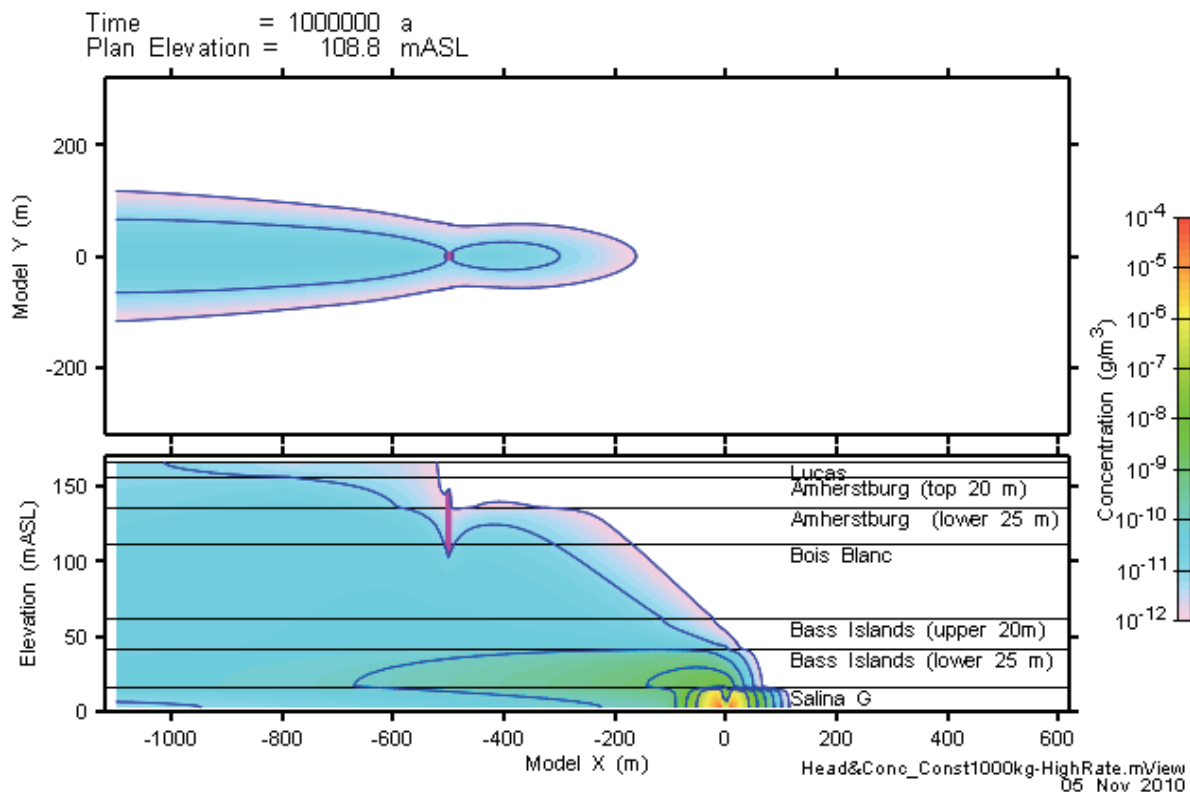
Figure 2.19 illustrates the conceptual layout for the biosphere system in the vicinity of the DGR. While the current safety assessment addresses long timescales, the stylized biosphere system is based on the present-day environment, which provides a firm basis for the parameterization and helps to ensure internal consistency. The irrigated crops are grown close to a ditch, such that the water infiltrating through the soil is directed to the surface water system.



**Figure 2.19: Conceptual Layout of the Biosphere System**

Groundwater flow in the Shallow Bedrock Groundwater Zone means that any dissolved contaminants reaching the Zone will be transported towards Lake Huron. The well is taken to be 80 m deep and 500 m down gradient from the shafts, based on consideration of the local aquifer depth, the depth of potable water and typical practice for wells in the area. The groundwater becomes increasingly brackish at greater depths (see Section 4.5.1.1 of the Descriptive Geosphere Site Model, INTERA 2011). The well captures some of the contaminant plume by drawing water and by vertical dispersion of the plume in flowing groundwater. Therefore, the well is conservatively located down gradient from the area around shafts, which is expected to be the key potential groundwater pathway from the repository (Figure 2.20).





Notes: Figure 5.14 in GEOFIRMA (2011). Shaft is located at  $x = 0$ . The well is shown as a pink dot or pink line.

**Figure 2.20: Calculated CI-36 Concentration in the Shallow Bedrock Groundwater Zone Resulting from a Constant Source at the Shaft Location from the Detailed Groundwater Modelling**

## 2.4 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 as to whether it has been included or excluded 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.

## 2.5 Key Conceptual Model Uncertainties

Now that the conceptual model has been developed, there is a need to consider the various sources of uncertainties associated with it. These conceptual model uncertainties arise from incomplete knowledge of the DGR system and the processes and events that will affect the system and the release and migration of contaminants. Consideration of conceptual model uncertainties, together with consideration of future and parameter uncertainties, allows the calculation cases to be identified in Chapter 3. The calculation cases can then be used to investigate the significance of the various sources of conceptual model uncertainty through the

use of alternative conceptual models and alternative model parameterization. Uncertainties that are purely associated with parameter uncertainty are not discussed in detail in this section (except where the parameterization itself can constitute an alternative conceptual model), but are documented in the Data report (QUINTESSA and GEOFIRMA 2011a).

The conceptual model uncertainties identified below are managed in the current assessment through: the adoption of conservative assumptions that are expected to over-estimate the impacts of any contaminant releases; the analysis of a range of different conceptual models; and the use of stylized biospheres.

### **2.5.1 Repository Design**

One class of conceptual model uncertainty is associated with alternative options for the engineered components of the system: the wastes, waste packages, backfill and engineered structures. A preliminary design has been adopted for the assessment that is described in Sections 2.1 and 2.2 of the System and Its Evolution report (QUINTESSA 2011). The design is based on the Reference L&ILW Inventory report (OPG 2010) for the waste and waste packaging and Chapter 6 of the Preliminary Safety Report (OPG 2011b) for the repository design. This design will be subject to review and optimization before it is finalized. Indeed, it has been revised from the design assessed in the previous postclosure safety assessment (QUINTESSA et al. 2009). Therefore, the effects of modifications to the design should be considered.

### **2.5.2 Waste and Repository Evolution**

The waste and repository are a complex element of the system model, comprising a wide range of processes of potential importance, together with a diverse range of materials, all of which evolve with time. Reflecting this, a range of conceptual model uncertainties associated with repository evolution can be identified.

#### **2.5.2.1 Waste Package Degradation and Contaminant Release**

Waste package degradation and contaminant release are affected by the hydraulic, chemical and physical evolution of the repository. While broad assumptions concerning contaminant release can be derived consistent with the resaturation profile and chemical and physical conditions, there remains uncertainties due to the uncertainties in the resaturation profile and the chemical and physical conditions (see below), and due to the nature of the release mechanisms themselves (Section 2.3.1.2). The Reference Case gives no credit to the waste packaging as a chemical or physical barrier and considers instant and congruent models (Table 2.3), while a variant case considers instant release for all wastes.

#### **2.5.2.2 Availability of Water and Resaturation**

The availability of water in the repository and the rate of repository resaturation are influenced by the evolution of repository gas pressure and groundwater conditions.

Coupled gas and groundwater modelling using the T2GGM code has indicated that the availability of water can be limited (see Chapters 5 and 7 of the Gas Modelling report, GEOFIRMA and QUINTESSA 2011). Corrosion and degradation reactions are dependent on the availability of water in the repository (see Chapter 4 of the T2GGM software documentation, QUINTESSA and GEOFIRMA 2011b). The Reference Case conservatively ignores the effect of the consumption of water by corrosion and degradation reactions on the water balance in the

repository, thereby allowing corrosion and degradation reactions to proceed so long as there is a sufficient supply from the geosphere and shafts. (An alternative case takes account of the removal of water consumed in gas generation reactions on the repository water balance.)

T2GGM has indicated that the repository can be expected to resaturate at a very slow rate (see, for example, Figure 7.1 of the Gas Modelling report, GEOFIRMA and QUINTESSA 2011). However, there may be processes not represented in the current model which might result in faster resaturation of the repository (e.g., elevated hydraulic heads associated with an ice-sheet). Therefore, the effects of shorter resaturation periods on both groundwater and gas releases are considered.

### **2.5.2.3 Repository Chemistry**

Chemical conditions in the repository can be expected to evolve with time as metals and other materials degrade and interact with the local saline groundwater in a manner that may vary between parts of the repository. While the main processes of interest can be anticipated and are discussed and evaluated in Section 4.5 of the System and Its Evolution report (QUINTESSA 2011), it is recognised that uncertainties remain relating to the detailed evolution of chemical conditions in the repository and so the Reference Case conservatively assumes that, with the exception of C-14, all contaminants are neither sorbed nor precipitated in the repository, once released from the waste packages. A variant calculation assumes instantaneous release and no sorption/precipitation for all contaminants.

### **2.5.2.4 Rockfall**

There are also uncertainties with the evolution of the physical conditions in the repository, especially relating to the impact of rockfall. Geomechanical modelling indicates that, after three to four cycles of ice-sheet loading and unloading, a rockfall zone would propagate about 10 m into the repository roof (Section 2.3.1.1). However, there are uncertainties over the timing, extent and impact of rockfall in the repository and in all calculation cases rockfall is conservatively taken to occur at closure, affect all tunnels and rooms, damage waste packages and remove 10 m of geosphere barrier.

## **2.5.3 Geosphere**

On a regional scale, the geosphere is currently reasonably well defined in terms of structure and groundwater conditions (see Chapters 2 and 5 of the Geosynthesis report, NWMO 2011a). The findings from the deep boreholes, which have been drilled at the site, have provided site-specific data regarding material properties and hydrogeological conditions. While the findings are largely in line with expectations from the regional data, a number of uncertainties have been identified. Further information on the geology will be obtained through further measurements and analyses conducted during construction as part of the Geoscientific Verification Plan (NWMO 2011b).

### **2.5.3.1 Over- and Underpressures**

Data from the DGR boreholes indicate that the Cambrian sandstone and the Middle and Upper Silurian are overpressured relative to the ground surface, while the Ordovician limestone and shale are significantly underpressured (Section 5.2 of the Geosynthesis report, NWMO 2011a) (Figure 2.13).

Considerable work has been undertaken to understand the causes of these underpressures and overpressures (Chapter 5 of the Geosynthesis report, NWMO 2011a). This work indicates that ice-sheet advance/retreat scenarios and osmosis are not likely mechanisms. However, the overpressures observed in the Cambrian and Middle and Upper Silurian are consistent with a density-dependent saturated flow analyses of the Michigan Basin cross-section. The observed underpressures in the Ordovician can be reproduced by assuming the presence of a non-wetting immiscible gas phase in the rock (Section 5.4.9 of the Geosynthesis report, NWMO 2011a).

The conceptual model for the Reference Case is that the underpressures and overpressures are ancient and are not of ice-sheet origin and will equilibrate gradually. A conservative variant case with Cambrian overpressure maintained indefinitely and Ordovician underpressure immediately dissipated is also considered.

### **2.5.3.2 Intermediate Bedrock Permeable Zones**

The thin, permeable, Guelph and Salina A1 upper carbonate formations within the Intermediate Bedrock Groundwater Zone might act as preferential pathways for contaminant transport in groundwater. There is a small topographic gradient that could drive flow in the formations. Groundwater from the Salina A1 upper carbonate is expected to discharge to the lake waters tens of kilometres to the northwest of the DGR site (Section 2.3.6.2 of QUINTESSA 2011). Groundwater flow in the Guelph is in an easterly direction; while it is unclear where it discharges, it is expected to be tens of kilometres or more from the DGR. These formations will act to intercept some of the contaminant flux being transported vertically upwards from the DGR via the rock and shaft and divert it laterally on this longer pathway.

The anticipated flow velocities in the Guelph and Salina A1 upper carbonate formations are so low that it is unlikely that a long, purely advective pathline will ever be realized. Contaminants will diffuse and disperse (and decay) into the adjacent formations. The discharge of any contaminants transported through the formations to Lake Huron would be subject to dilution and dispersion in the lake waters.

Horizontal groundwater flows in these formations are, therefore, conservatively ignored in the Reference Case, although the potential for these to receive contaminants in groundwater diffused from the shaft and gas is included. However, a variant case studies the impact of horizontal flows in these formations.

## **2.5.4 Biosphere**

The biosphere system is itself a stylized representation of the physical surface environment that intentionally focuses on regions in which the highest contaminant concentrations may occur. As such, the conceptualization is conservative. Therefore, while uncertainties are present, the conservative nature of the conceptual model for the biosphere serves to ensure that the impacts that are calculated are not under-estimated.

### **2.5.4.1 Biosphere Evolution**

The main uncertainty associated with the biosphere is associated with the evolution of the surface environment over long timescales in response to climate change (i.e., glacial cycling). As discussed in Section 2.3.3.1 and Appendix B, rather than explicitly representing the sequence of climate states (temperate, tundra, glacial and post-glacial), the conceptual model for the Reference Case considers stylized, constant temperate conditions which are comparable

with those found at present at the site. A variant case considers a constant tundra climate with appropriately modified migration and exposure pathways, and critical group (the Tundra Resident Group).

#### **2.5.4.2 Geosphere-Biosphere Interface**

It is particularly important to characterize the location and nature of discharges of any contaminated water and gas from the geosphere appropriately. In this assessment, conservative locations are adopted so as to ensure dilution of contaminant concentrations is limited and potential impacts are not under-estimated.

Two potential points of groundwater discharge are considered – groundwater discharge to the lake and groundwater abstraction via a well sunk into the Shallow Bedrock Groundwater Zone (Section 2.3.3.2).

There is uncertainty associated with the location and character of the groundwater release from the Shallow Bedrock Groundwater Zone into the lake. The conceptual model assumes that discharge from the Shallow Bedrock Groundwater Zone occurs close to the lake margins. Such a region will offer the least potential for dilution and dispersion, and is more directly accessible than a point of discharge that is well submerged within the body of the lake. The tundra climate variant case considers discharge to a stream rather than the lake.

However, the importance of discharges to surface water bodies is overshadowed by the adoption of a conservative well model. The abstraction of contaminated groundwater from a well is adopted in the conceptual model on the basis that such practices are common in the region (Section 2.4.4 of QUINTESSA 2011), and since this is conservative as it exposes the local receptors directly to contaminated groundwater. Only the upper regions of the Shallow Bedrock Groundwater Zone provide potable water and would be pumped. The conceptual model assumes that the well is located 500 m downstream from the shafts – this is a conservative assumption as a much closer location would see lower concentrations due to less vertical dispersion into the well region, while a much farther location would see lower concentrations due to greater dilution and dispersion in the Shallow Bedrock Groundwater Zone (Figure 2.20).

Two potential points of gas discharge from the shafts and their EDZs are considered – gas discharge to the house (conservatively located on top of one shaft), and to the soil overlying the other shaft (Section 2.3.3.2). These are conservative locations that minimize the dilution of any contaminated gas that might reach the biosphere.

#### **2.5.4.3 Critical Groups**

The Reference Case considers a conservatively-defined critical group (the Site Resident Group) that has been defined so as to maximize potential impacts. The group lives a self-sufficient lifestyle on a farm and pumps water from a well drilled into the Shallow Bedrock Groundwater Zone for drinking, domestic use, watering animals and irrigating garden and feed crops (Section 2.3.3.2). A variant case considers two alternative critical groups: Site Shore Resident and Downstream Resident Groups exposed via consumption of lake fish and water from the near shore and South Basin of Lake Huron, respectively.

### 3. CALCULATION CASES

Uncertainties can be accounted for using various strategies (see Section 3.6 of the Postclosure Safety Assessment report, QUINTESSA et al. 2011a) including the evaluation of an appropriate range of calculation cases with the aim of demonstrating that the DGR system is robust to the uncertainties and that the range of cases bounds the uncertainties. A range of calculation cases can be developed to explore the conceptual model and data uncertainties associated with the Normal Evolution Scenario.

The principal **conceptual model uncertainties** have been identified in Section 2.5. These can be summarized as:

- The design of the DGR, including the option of backfilling of the repository;
- The degradation of waste packages and the release of contaminants;
- The hydraulic, chemical, physical and biological evolution of the repository;
- The overpressures and underpressures in the geosphere;
- The gradients in the Guelph and Salina A1 upper carbonate; and
- The evolution of the biosphere (primarily due to glacial cycling), its interface with the geosphere, and its associated critical groups.

In addition, there are uncertainties associated with data values for use in the models. **Data uncertainties** are described in the Data report (QUINTESSA and GEOFIRMA 2011a) through the definition of ranges and, in certain cases, associated probabilistic density functions, in addition to best estimate values. The following sources of data uncertainties are considered as the basis for specific variant cases.

- Contaminant inventories - concentrations of contaminants are subject to a degree of uncertainty as they are based on waste-type-specific sampling and scaling factors rather than direct measurement of each waste package.
- Waste package characteristics - OPG's waste packages are mostly well defined and reference assumptions based on information in the Reference L&ILW Inventory report (OPG 2010) have been adopted. However, a variant case with increased use of overpacks resulting in an increase in the inventory of metals is also considered.
- Waste corrosion and degradation rates - these rates are affected by the hydraulic, chemical, physical and biological evolution of the repository and the characteristics of the waste packages. There is uncertainty associated with the rates, and variant cases are considered with up to an order of magnitude increase in corrosion and degradation rates, and up to an order of magnitude reduction in degradation rates.
- Shaft seal performance - some degradation of the seals is expected and has been incorporated into the Normal Evolution Scenario (Section 4.4.2 of the System and Its Evolution report, QUINTESSA 2011). A variant case is considered that assumes an order of magnitude increase in the permeability of the bentonite-sand seal.
- Damaged zone properties - the reference properties used in the current assessment are based on geomechanical modelling informed by site information and literature review (Section 6.4 of the Geosynthesis report, NWMO 2011a). There is uncertainty associated with these properties (see Section 5.4.2 of the Data report, QUINTESSA and GEOFIRMA

2011a). A variant case is considered with increased hydraulic conductivity for shaft and repository damaged zones by up to three orders of magnitude.

- Gas transport parameters - as noted in Sections 4.7 and 5.6 of the Data report (QUINTESSA and GEOFIRMA 2011a), the gas transport parameters in the shaft seals and rock (in particular capillary pressure and relative permeability) are uncertain. A representative set of values has been adopted (see Section 4.2 of the Gas Modelling report, GEOFIRMA and QUINTESSA 2011). A variant case is considered with decreased van Genuchten air-entry pressures and a less steep air-entry curve.
- Retardation of contaminants - there are currently no sorption data measured specifically for rock, shaft seal and groundwater conditions at the Bruce nuclear site. Conservative (i.e., lower than likely) sorption values have been specified for certain elements in light of a literature review (Appendix D of the Data report, QUINTESSA and GEOFIRMA 2011a). Variant cases with no sorption of contaminants in the geosphere and shafts are considered.

Through the consideration of these conceptual model and data uncertainties, a total of 22 assessment modelling calculation cases have been identified for evaluation in the current assessment of the Normal Evolution Scenario (see Table 3.1 and Figure 3.1). As noted in Table 3.1, many of these cases are supported by the results of associated detailed groundwater and gas modelling cases which are described in the associated reports (GEOFIRMA 2011; GEOFIRMA and QUINTESSA 2011).

The uncertainties that each case addresses are summarized in Table 3.1.

**Table 3.1: Assessment Modelling Calculation Cases**

Case ID	Case Description	Associated Detailed Modelling Cases	Uncertainties Which Case Can Be Used To Addressed
<b>NE-RC-A</b>	<p>Reference case parameters based on reference inventory, original preliminary design and site characterization data.</p> <p>Considers:</p> <ul style="list-style-type: none"> <li>• instantaneous and congruent contaminant release;</li> <li>• source terms with release for certain radionuclides partitioned between gas and water;</li> <li>• no sorption or solubility limitation in repository (except for carbon solubility limitation);</li> <li>• gas generation and gradual repository resaturation;</li> <li>• no consumption (or production) of water by corrosion and degradation reactions;</li> <li>• 10 m rockfall at closure;</li> <li>• sorption of limited number of contaminants in shaft and geosphere;</li> <li>• steady state Cambrian overpressure (+165 m);</li> <li>• initial Ordovician underpressures with subsequent transient evolution towards equilibrium;</li> <li>• initial and residual gas saturations in the Ordovician;</li> <li>• no salinity gradient in the geosphere;</li> <li>• no horizontal groundwater flow in the Cambrian, Guelph or Salina A1 upper carbonate;</li> <li>• no explicit representation of glacial cycling; and</li> <li>• self-sufficient farming family.</li> </ul> <p>See Section 4.3 and Table 4.1 for summary of data.</p>	<p>NE-RC-T2 NE-RC-F3</p>	<ul style="list-style-type: none"> <li>• Reference Case for radioactive contaminants.</li> </ul>
<b>NE-PD-RC-A</b>	<p>As NE-RC-A, but adopting the final preliminary design, including:</p> <ul style="list-style-type: none"> <li>• additional ventilation drifts;</li> <li>• ILW filters &amp; elements, irradiated core components, and IX columns disposed in ILW shield containers rather than concrete arrays.</li> </ul>	<p>NE-PD-RC-T2 NE-PD-RC-F3</p>	<ul style="list-style-type: none"> <li>• Repository design and engineering (alternative layout, alternative waste emplacement).</li> </ul>
<b>NE-SBC-A</b>	<p>As NE-RC-A, but with no underpressures or initial gas saturation in the Ordovician.</p>	<p>NE-SBC-T2 NE-SBC-F3</p>	<ul style="list-style-type: none"> <li>• Hydrogeological conditions in the geosphere and the associated processes and properties.</li> </ul>



Case ID	Case Description	Associated Detailed Modelling Cases	Uncertainties Which Case Can Be Used To Addressed
<b>Water-Limited Reactions</b>			
<b>NE-RC-WL-A</b>	As NE-RC-A, but with consumption (or production) of water by corrosion and degradation reactions.	NE-RC-WL-T2	<ul style="list-style-type: none"> <li>Availability of water for corrosion and degradation reactions.</li> </ul>
<b>NE-SBC-WL-A</b>	As NE-SBC-A, but with consumption (or production) of water by corrosion and degradation reactions.	NE-SBC-WL-T2	<ul style="list-style-type: none"> <li>Availability of water for corrosion and degradation reactions.</li> </ul>
<b>Repository Resaturation</b>			
<b>NE-RS-A</b>	As NE-RC-A, but with: <ul style="list-style-type: none"> <li>immediate water resaturation of repository (including shafts); and</li> <li>no gas generation in repository.</li> </ul>	NE-RC-F3	<ul style="list-style-type: none"> <li>Timing of resaturation of repository (instant resaturation).</li> <li>Partitioning of contaminants between water and gas (all in water).</li> </ul>
<b>Contaminant Release and Transport Model</b>			
<b>NE-RT1-A</b>	As NE-RC-A, but with: <ul style="list-style-type: none"> <li>immediate water resaturation of repository;</li> <li>no gas generation in repository;</li> <li>instantaneous release of radionuclides to repository water; and</li> <li>no radionuclides sorbed or solubility limited in repository or geosphere.</li> </ul>	NE-RC-F3	<ul style="list-style-type: none"> <li>Timing of resaturation (instant resaturation).</li> <li>Partitioning of contaminants between water and gas (all in water) and water and solid (no sorption).</li> <li>Contaminant release and migration (instantaneous release and no sorption/solubility limitation).</li> </ul>
<b>NE-RT2-A</b>	As NE-SBC-A, but with: <ul style="list-style-type: none"> <li>immediate water resaturation of repository;</li> <li>no gas generation in repository;</li> <li>instantaneous release of radionuclides to repository water; and</li> <li>no radionuclides sorbed or solubility limited in repository or geosphere.</li> </ul>	NE-SBC-F3	<ul style="list-style-type: none"> <li>Timing of resaturation (instant resaturation).</li> <li>Partitioning of contaminants between water and gas (all in water) and water and solid (no sorption).</li> <li>Contaminant release and migration (instantaneous release and no sorption/solubility limitation).</li> </ul>
<b>Gas Generation Rates</b>			
<b>NE-GG1-A</b>	As NE-SBC-A, but with: <ul style="list-style-type: none"> <li>increased metal inventory by about 25%; and</li> <li>corrosion and degradation rates increased to maximum rates in the Data report (Tables 3.20 and 3.21 of QUINTESSA and GEORIMA 2011a) (up to an order of magnitude increase).</li> </ul>	NE-GG1-T2 NE-SBC-F3	<ul style="list-style-type: none"> <li>Packaging options (increased used of overpacks).</li> <li>Gas generation (increased gas generation rates).</li> </ul>

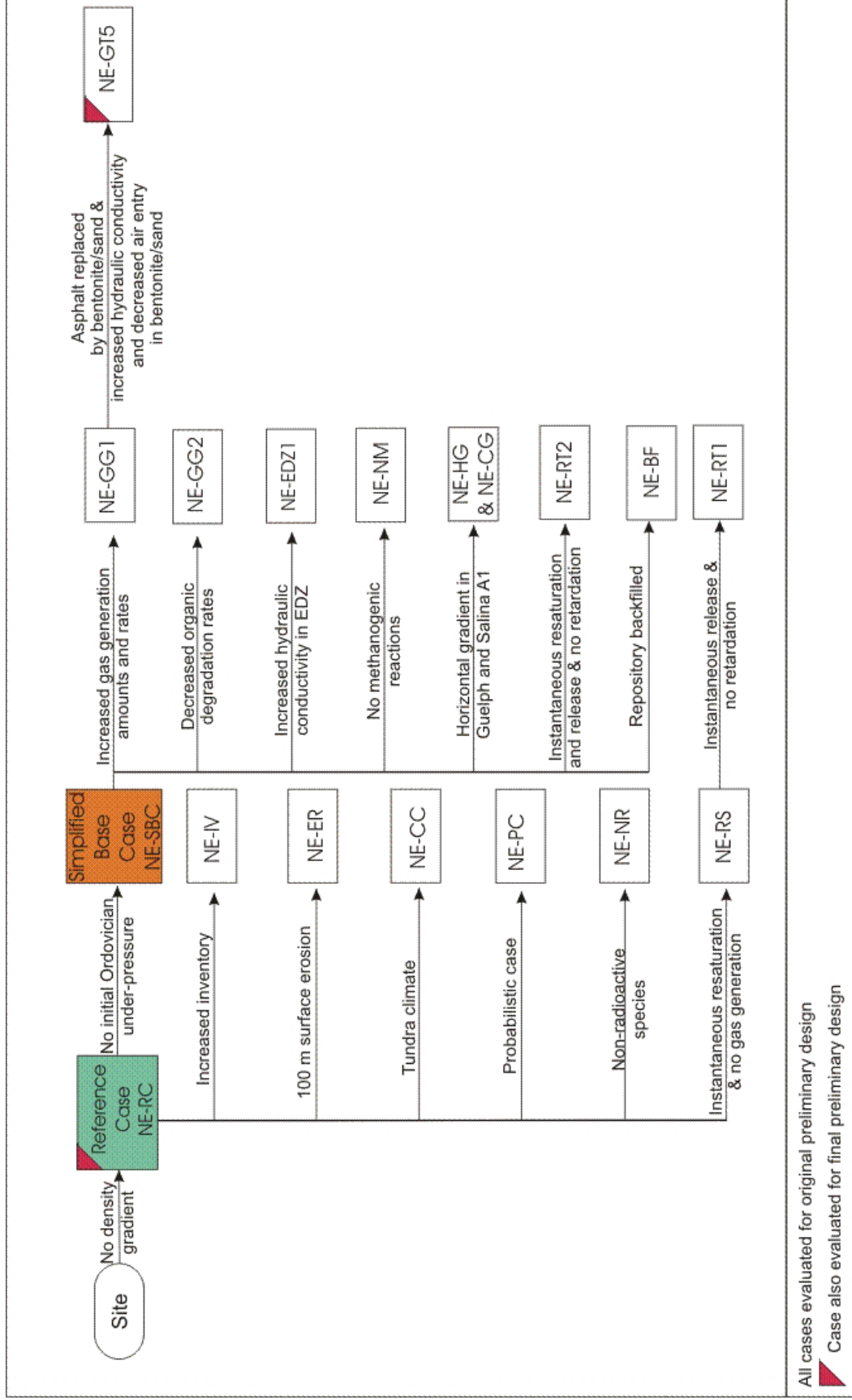
Case ID	Case Description	Associated Detailed Modelling Cases	Uncertainties Which Case Can Be Used To Addressed
<b>NE-GG2-A</b>	As NE-SBC-A, but with organic degradation rates decreased to minimum rates in the Data report (Table 3.21 of QUINTESSA and GEOFIRMA 2011a) (by up to an order of magnitude decrease).	NE-GG2-T2 NE-SBC-F3	<ul style="list-style-type: none"> <li>Gas generation (reduced gas generation rates).</li> </ul>
<b>NE-NM-A</b>	As NE-SBC-A, but with no methanogenic reactions, which includes both methane generation from organic degradation and also the conversion of H <sub>2</sub> and CO <sub>2</sub> to CH <sub>4</sub> .	NE-NM-T2 NE-SBC-F3	<ul style="list-style-type: none"> <li>Gas generation (conditions unfavourable for methanogens).</li> </ul>
<b>Waste Inventory</b>			
<b>NE-IV-A</b>	As NE-RC-A, but with radionuclide inventory increased by a factor of ten.	NE-RC-T2 NE-RC-F3	<ul style="list-style-type: none"> <li>Waste inventory.</li> </ul>
<b>Repository Design and Engineering</b>			
<b>NE-BF-A</b>	As NE-SBC, but with repository backfilled with coarse aggregate material with a porosity of 0.3.	NE-BF-T2 NE-SBC-F3	<ul style="list-style-type: none"> <li>Repository design and engineering (backfilled repository).</li> </ul>
<b>NE-GT5-A</b>	As NE-GG1-A, but with: <ul style="list-style-type: none"> <li>asphalt seal in shaft replaced by bentonite/sand;</li> <li>gas entry pressure for shaft materials reduced by factor of two to <math>5 \times 10^6</math> Pa; and</li> <li>bentonite/sand hydraulic conductivity increased by an order of magnitude to <math>10^{-10}</math> m/s.</li> </ul>	NE-GT5-T2 NE-GT5-F3	<ul style="list-style-type: none"> <li>Repository design and engineering (no asphalt seal).</li> <li>Shaft seal performance (reduced performance).</li> <li>Gas flow parameter values (reduced gas entry pressures).</li> </ul>
<b>NE-PD-GT5-A</b>	As NE-GT5-A, but with final preliminary design (as for NE-PD-RC-A).	NE-PD-GT5-T2 NE-PD-GT5-F3	<ul style="list-style-type: none"> <li>Repository design and engineering (alternative layout, alternative waste emplacement, no asphalt seal).</li> <li>Shaft seal performance (reduced performance).</li> <li>Gas flow parameter values (reduced gas entry pressures).</li> </ul>

Case ID	Case Description	Associated Detailed Modelling Cases	Uncertainties Which Case Can Be Used To Addressed
<b>Excavation Damaged Zone</b>			
<b>NE-EDZ1-A</b>	<p>As NE-SBC-A, but with repository and shaft EDZ hydraulic conductivity increased to maximum values in the Data report (Tables 5.7 and 5.8 of QUINTESSA and GEOFIRMA 2011a), i.e.:</p> <ul style="list-style-type: none"> <li>• increased by two orders of magnitude for shaft inner EDZ to be four orders of magnitude greater than rock mass;</li> <li>• increased by an order of magnitude for shaft outer EDZ to be two orders of magnitude greater than rock mass; and</li> <li>• increased by an order of magnitude for repository EDZ to be four orders of magnitude greater than rock mass.</li> </ul>	NE-EDZ1-T2 NE-EDZ1-F3	<ul style="list-style-type: none"> <li>• The evolution of the repository, shafts and their EDZs, and their impact on contaminant migration.</li> <li>• The gas and groundwater flow and transport characteristics of the shaft sealing materials and repository and shaft EDZs.</li> </ul>
<b>Groundwater Transport in the Intermediate Bedrock Groundwater Zone</b>			
<b>NE-HG-A</b>	<p>As NE-SBC-A, but with:</p> <ul style="list-style-type: none"> <li>• horizontal groundwater flow in the Guelph (gradient of 0.0026) and Salina A1 upper carbonate formations (gradient of 0.0077) (Section 5.4.1.1 of the Data report, QUINTESSA and GEOFIRMA 2011a); and</li> <li>• 1.25 km travel path along Guelph and Salina A1 upper carbonate to lake.</li> </ul>	NE-SBC-T2 NE-HG-F3	<ul style="list-style-type: none"> <li>• Hydrogeological conditions in the geosphere and the associated processes and properties.</li> <li>• Hydraulic characteristics of the Guelph and Salina A1 upper carbonate formations.</li> </ul>
<b>Critical Group</b>			
<b>NE-CG-A</b>	As NE-HG-A, but with dose evaluated to a Site Shore Resident Group and a Downstream Resident Group exposed via consumption of lake fish and water from the near shore and the South Basin of Lake Huron, respectively.	NE-SBC-T2 NE-HG-F3	<ul style="list-style-type: none"> <li>• Alternative critical groups.</li> </ul>
<b>Climate Change</b>			
<b>NE-CC-A</b>	As NE-RC-A, but with alternative constant state biosphere (i.e., tundra rather than temperate).	NE-RC-T2 NE-RC-F3	<ul style="list-style-type: none"> <li>• Biosphere evolution due to glacial cycling.</li> <li>• Alternative geosphere-biosphere interface (discharge to stream rather than lake).</li> </ul>
<b>NE-ER-A</b>	As NE-RC-A, but with removal of 100 m of geosphere due to erosion over 1 million years.	NE-RC-T2 NE-RC-F3	<ul style="list-style-type: none"> <li>• Biosphere evolution due to glacial cycling.</li> </ul>

Case ID	Case Description	Associated Detailed Modelling Cases	Uncertainties Which Case Can Be Used To Addressed
<b>Non-radioactive Contaminants</b>			
<b>NE-NR-A</b>	As NE-RC-A, but with non-radioactive elements and chemical species identified in Table 1.1 employed in the repository.	NE-RC-T2 NE-RC-F3	<ul style="list-style-type: none"> <li>Reference case for non-radioactive elements and chemical species</li> </ul>
<b>Parameter Uncertainties</b>			
<b>NE-PC-A</b>	As NE-RC-A, but with probabilistic treatment of certain parameters.	NE-RC-T2 NE-RC-F3	<ul style="list-style-type: none"> <li>Parameter uncertainties.</li> </ul>

Notes:

NE – Normal Evolution Scenario; RC – reference case; PD – final preliminary design; SBC – simplified base case; RS – repository saturation; GG – gas generation; NM – no methanogens; RD – repository design; RT - radionuclide transport; EDZ- excavation damaged zone; HG - horizontal gradient; CC – climate change; CG – critical group; ER - surface erosion; NR – non-radioactive contaminants; PC – probabilistic case; WL- water-limited case; A – AMBER; F3 – FRAC3DVS-OPG code; T2 – T2GGM code.



All cases evaluated for original preliminary design  
 Case also evaluated for final preliminary design

Figure 3.1: Assessment Modelling Cases for the Normal Evolution Scenario

## **4. MATHEMATICAL MODELS, SOFTWARE IMPLEMENTATION AND DATA**

### **4.1 Mathematical Models**

The mathematical modelling approach for representing the calculation cases is based on the use of a system-level assessment model incorporating all key processes relevant to contaminant release, contaminant transport and associated potential impacts, supported by detailed models for the groundwater and gas generation and transport processes. The mathematical models for the assessment model are described in Appendix D and Appendix E, while the detailed models for groundwater and gas generation and transport are described in the associated reports (GEOFIRMA 2011; GEOFIRMA and QUINTESSA 2011).

The assessment-level models describe the following.

- The spatial discretization of the repository, geosphere and biosphere (see Appendix H):
  - The repository includes explicit representation of each of the 21 distinct wastes, which reflect OPG's LLW and ILW waste categories, together with distinct components representing water and gas in the panels, access tunnels and concrete monolith;
  - 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 in shafts/shaft EDZ and in geological media; and
  - The biosphere represents distinct surface features explicitly, such as soils, streams and distinct regions of the lake.
- Fundamental physical properties of media (including density, porosity, saturation and effective diffusivity) and chemical properties of media (including consequential effects such as capacity for sorption and elemental solubility).
- General contaminant processes including radioactive decay and degradation, sorption, advection (of water and gas), dispersion and diffusion.
- Repository-specific processes, primarily related to waste package saturation as a result of repository resaturation, and contaminant release – including instant and congruent releases.
- Diffusion, advection and dispersion in the repository, shafts, EDZs and geosphere.
- Biosphere processes associated with contaminant transport in surface water, soils and atmosphere.
- Exposure models, considering external irradiation, inhalation (gas and dust), and ingestion (soil, water, plants, animal products and fish).

### **4.2 Software Implementation**

The assessment-level modelling needs to represent:

- The potential release of a large number of contaminants (both radionuclides and non-radioactive species) from a range of different waste packages that comprise the L&ILW within the repository;
- The behaviour of released contaminants within the repository and their subsequent potential migration into the associated shafts, EDZ or host rock;
- The migration of contaminants along the shafts/EDZ and within the host rock towards the surface environment;
- The potential release of contaminants to the surface environment and their subsequent migration; and

- The potential impact of released contaminants on humans and biota.

The assessment-level modelling therefore needs to represent a wide variety of different features together with complex time-dependent events and processes. A wide range of potential calculation endpoints is of interest. These requirements are fulfilled by the AMBER compartment modelling code and so the mathematical model for the Normal Evolution Scenario has been implemented in AMBER 5.3 (QUINTESSA 2009a). The code allows users to implement their own mathematical models to represent contaminant transport within a compartment model approach, and provides powerful tools for representing relevant processes and for undertaking time-dependent calculations. AMBER has a proven track record for postclosure safety assessment of deep geologic radioactive waste disposal facilities in a 'total systems' manner, together with a strong quality assurance status (see Box 2 and Appendix G). The implementation is described in Appendix H, Appendix I and Appendix J.

The assessment-level calculations have been undertaken within QUINTESSA's quality management system, which has been audited against the requirements of the ISO 9001:2008 and TickIT standards.

#### **BOX 2: OVERVIEW OF THE AMBER SOFTWARE TOOL**

##### **Description:**

AMBER is a graphical-user interface based software tool that allows users to build their own dynamic compartment models to represent the migration, degradation and fate of radioactive and non-radioactive contaminants in environmental systems. AMBER was originally developed for modelling contaminants from radioactive waste repositories and this remains its core area of application and development.

AMBER also allows text-based editing, auditing and 'future-proof' recording of case files, with in-built parameter checking and 'units awareness'. The code has full probabilistic capabilities (Monte Carlo or Latin Hypercube sampling) and includes a range of probability density functions. It has two fast solvers that permit complex time-varying source terms, environmental properties and transfer processes, which may be linear or non-linear, to be represented.

The code allows any number of contaminants, compartments and transfers to be represented. The user can define complex algorithms and data sets and allows the import/export of data to facilitate its integrated use with other software tools and databases.

AMBER's capabilities are fully described in a Reference Guide (QUINTESSA 2009a).

##### **Quality Assurance Status:**

AMBER is managed and developed under QUINTESSA's ISO 9001:2008 registered QA system that incorporates the requirements of TickIT software quality system ([www.TickIt.org](http://www.TickIt.org)).

Each release is extensively tested against a broad set of verification tests (e.g., QUINTESSA 2009b).

AMBER has a wide international user base, with over 85 organizations in more than 30 countries owning licences. There are in excess of 75 publications describing assessments in which AMBER has been applied (QUINTESSA 2009c), including several international code intercomparison exercises.

AMBER cases are defined in text-based case files:

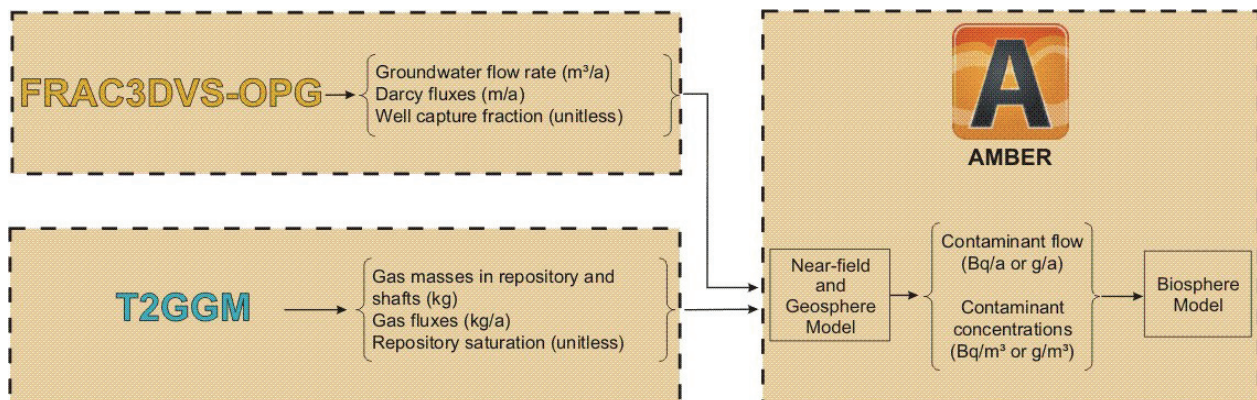
- A case file for the repository, shafts and geosphere model – AMBER\_V2\_NF&geov1.cse;
- A case file for the biosphere model – AMBER\_V2\_biov1.cse; and
- A variant of each of these in which the radionuclides are replaced with non-radioactive contaminants.

The implementation of the models and data within each of these case files has been audited against the specification of the mathematical model and data included in this report and in the Data report (QUINTESSA and GEOFIRMA 2011a). The selection of calculation cases is managed by using 'drop down' options to choose which calculation case is being modelled. The whole suite of assessment calculations can be run in batch mode using a series of commands in a control file to create a specific case file for each calculation case and run each case. The control file has also been audited to ensure that the specification for each calculation case and associated outputs matches that required.

Charts for the assessment-level results are generated by exporting the results into Microsoft Excel. Each of the workbooks used to generate the charts have also been audited to check that that correct set of outputs have been used.

Each of the auditing stages is recorded on a project-specific form designed for checking calculations. More details concerning the quality assurance of the AMBER case files developed for the current assessment are provided in Appendix I.

AMBER has been developed to solve for contaminant movement, with detailed water and gas flows being given rather than calculated. Other codes are used to calculate the detailed groundwater and gas flow within the modelled system, with the results then being imported into the AMBER model. Here, the groundwater and gas flow models have been implemented in the FRAC3DVS-OPG and T2GGM codes, respectively (Figure 4.1). The implementation of these models is described in Chapter 4 of the Groundwater Modelling report for FRAC3DVS-OPG (GEOFIRMA 2011) and Section 4.3 of the Gas Modelling report for T2GGM (GEOFIRMA and QUINTESSA 2011). The inputs from these detailed modelling are given in Appendix J.



**Figure 4.1: Information Flow between the Detailed Groundwater (FRAC3DVS-OPG) and Gas (T2GGM) Codes and the Assessment Model (AMBER)**



### 4.3 Data

A data report has been developed to support the postclosure safety assessment (QUINTESSA and GEOFIRMA 2011a). This comprises reference data that describe the wastes, repository, geosphere and biosphere for the Normal Evolution Scenario. The data used in the AMBER model for the Reference Case are summarized in Table 4.1. Note that there is a degree of simplification between the detailed description provided in the Data report (QUINTESSA and GEOFIRMA 2011a) and the representation of that system in AMBER, which is described in Appendix D to Appendix J of this report.

Some model-specific data are required. These data are presented in Appendix J and have been derived from:

- The general information provided in the Data report (e.g., dimensions of geosphere compartments) (QUINTESSA and GEOFIRMA 2011a); and
- The results of the detailed FRAC3DVS-OPG and T2GGM modelling (e.g., groundwater flow rates, repository saturation and gas fluxes) (GEOFIRMA 2011; GEOFIRMA and QUINTESSA 2011).

The AMBER model is, therefore, informed by both:

- T2GGM results are used to provide the repository resaturation profile, the composition of gas in the DGR, the partial gas pressures and the time at which groundwater can flow away from the DGR; and
- FRAC3DVS-OPG results are used to define the groundwater flow rates.

T2GGM can provide groundwater flow rates; however, the resolution of this model is not as detailed as the FRAC3DVS-OPG model. The results of the two models have been compared for similar cases and the groundwater results are in good agreement (Section 9.2.1 of GEOFIRMA and QUINTESSA 2011).

The postclosure safety assessment was initiated based on the original preliminary design for the repository shown in Figure 4.2 and described in NWMO (2010). The repository data summarized in Table 4.1 are for this original preliminary design. The preliminary design was finalized after the present assessment was largely complete. The final preliminary design is shown in Figure 4.3 and described in Chapter 6 of the Preliminary Safety Report (OPG 2011b) (data of relevance to the postclosure safety assessment are provided in Chapter 4 of the Data report, QUINTESSA and GEOFIRMA 2011a). The key changes from the original to the final preliminary design are summarized in Table 4.3. It should be noted that these changes have been made for operational safety and reliability reasons rather than postclosure safety reasons.

**Table 4.1: Key Parameter Values for the Normal Evolution Scenario Reference Case**

PARAMETER	VALUE(S)
<b>Repository</b>	
Repository depth	680 m
Number of emplacement rooms	Panel 1: 14; Panel 2: 17
Volume of emplacement rooms	Panel 1: $1.7 \times 10^5 \text{ m}^3$ ; Panel 2: $2.5 \times 10^5 \text{ m}^3$
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	$2.4 \times 10^5 \text{ m}^2$
Excavated volume	Excavated: $5.3 \times 10^5 \text{ m}^3$ ; Void: $4.2 \times 10^5 \text{ m}^3$
Waste volume (as emplaced)	Panel 1: $6.8 \times 10^4 \text{ m}^3$ ; Panel 2, $1.3 \times 10^5 \text{ m}^3$
Waste inventory	$8.8 \times 10^2$ TBq LLW, $1.6 \times 10^4$ TBq ILW at 2062
Mass of organics (waste, packages & engineering)	$2.2 \times 10^7 \text{ kg}$
Mass of concrete (waste, packages & engineering)	$2.1 \times 10^8 \text{ kg}$ (includes monolith)
Mass of metals (waste, packages & engineering)	$6.6 \times 10^7 \text{ kg}$
Backfilling of rooms and tunnels	None except monolith in immediate vicinity of shafts
Monolith properties	$K_h$ and $K_v$ $1 \times 10^{-10} \text{ m/s}$ ; porosity 0.1; effective diffusion coefficient $1.25 \times 10^{-10} \text{ m}^2/\text{s}$ (degraded from closure)
Repository HDZ	$K_h$ $1 \times 10^{-6} \text{ m/s}$ , $K_v = K_h$ ; porosity 4 x rock mass Emplacement rooms and tunnels: 0.5 m thick above/below and sides Supported tunnels: 2 m thick above/below, 0.5 m thick sides
Repository EDZ	$K_h$ $10^3$ x rock mass, $K_v = K_h$ ; porosity 2 x rock mass Emplacement rooms and tunnels: 8 m thick above/below and sides Supported tunnels: 3 m thick above/below and sides
Rockfall	Rockfall affects all rooms and tunnels, extending 10 m into ceiling immediately after closure
Resaturation profile	Variable – depends on calculation case
Corrosion rates	Un-passivated carbon steel and galvanized steel: $1 \times 10^{-6} \text{ m/a}$ (unsaturated), $2 \times 10^{-6} \text{ m/a}$ (saturated), Passivated carbon steel, stainless steel and Ni-alloys: $1 \times 10^{-7} \text{ m/a}$ Zr-alloys: $1 \times 10^{-8} \text{ m/a}$
Degradation rates	Cellulose: $5 \times 10^{-4} /\text{a}$ IX resins, plastics and rubber: $5 \times 10^{-5} /\text{a}$
Solubility and sorption in repository	Solubility limitation only considered for aqueous C releases ( $0.6 \text{ mol/m}^3$ ). No sorption considered
<b>Shaft</b>	
Internal diameter (lower section)	Main: 9.15 m; Ventilation: 7.45 m; Combined: 11.8 m (concrete lining and HDZ removed)
Length (lower section)	483.5 m (top of monolith to top of bulkhead at top of Intermediate Bedrock Groundwater Zone)
Internal diameter (upper section)	Main: 6.5 m; Ventilation: 5.0 m
Length (upper section)	178.6 m (top of upper bulkhead to ground surface)
Backfill and seals	Sequence of bentonite-sand, asphalt, LHHPC and engineered fill – see Figure 2.11. LHHPC bulkheads (degraded from closure) keyed across the inner EDZ
Vertical and horizontal hydraulic conductivity	Bentonite-sand: $1 \times 10^{-11} \text{ m/s}$ ; Asphalt: $1 \times 10^{-12} \text{ m/s}$ ; LHHPC: $1 \times 10^{-10} \text{ m/s}$ ; Engineered fill: $1 \times 10^{-4} \text{ m/s}$
Diffusion and transport porosity	Bentonite-sand: 0.3; Asphalt: 0.02; LHHPC: 0.1; Engineered fill: 0.3

PARAMETER	VALUE(S)
Effective diffusion coefficient	Bentonite-sand: $3 \times 10^{-10} \text{ m}^2/\text{s}$ ; Asphalt: $1 \times 10^{-13} \text{ m}^2/\text{s}$ ;
EDZ	LHHPC: $1.25 \times 10^{-10} \text{ m}^2/\text{s}$ ; Engineered fill: $2.5 \times 10^{-10} \text{ m}^2/\text{s}$
Sorption in shaft and EDZ	Inner EDZ, 0.5 x shaft radius thick, $K_v \times 100$ rock, $K_h = K_v$ ; porosity 2 x rock mass Outer EDZ, 0.5 x shaft radius thick, $K_v \times 10$ rock, $K_h = K_v$ ; porosity = rock mass See Table 4.2
<b>Geosphere</b>	
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;
Hydraulic heads	Eh: reducing +165 m at top of the Cambrian sandstone Observed head profile with underpressures in the Ordovician (up to -290 m) 0 m at the top of Lucas formation (top of the Shallow Bedrock Groundwater Zone)
Deep Bedrock Groundwater Zone:	
horizontal hydraulic conductivity	$8 \times 10^{-15}$ to $4 \times 10^{-12}$ m/s ( $1 \times 10^{-9}$ in the Shadow Lake and $3.0 \times 10^{-6}$ 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	$2.2 \times 10^{-13}$ to $2.4 \times 10^{-11} \text{ m}^2/\text{s}$ (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	$5 \times 10^{-14}$ to $2 \times 10^{-7}$ m/s
vertical hydraulic conductivity	10% of horizontal hydraulic conductivity for all formations other than Guelph and Salina A1 upper carbonate which are isotropic
transport porosity	0.007 to 0.2
effective diffusion coefficient	$3 \times 10^{-14}$ to $6.4 \times 10^{-11} \text{ m}^2/\text{s}$ (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	$1 \times 10^{-7}$ to $1 \times 10^{-4}$ m/s
vertical hydraulic conductivity	10% of horizontal hydraulic conductivity for all formations
transport porosity	0.057 to 0.077
effective diffusion coefficient	$6 \times 10^{-12}$ to $2.6 \times 10^{-11} \text{ m}^2/\text{s}$
horizontal hydraulic gradient	0.003
Sorption in geosphere	See Table 4.2
<b>Biosphere</b>	
Average annual surface temperature	8.2 °C
Average total precipitation	1.07 m/a
Ecosystem	Temperate
Groundwater release paths	1) 80 m deep well located 500 m down gradient of combined shaft Well demand of 6388 m <sup>3</sup> /a for self-sufficient farm with crop irrigation (Section 6.2.3 of the Data report, QUINTESSA and GEOFIRMA 2011a) 2) near shore lake bed (for discharge from Shallow Bedrock Groundwater Zone)
Gas release paths	Soil and House located above repository
Sorption in biosphere	For all elements except for B, Li, Tl and W
Land use	Agriculture, recreation, forestry
Critical group	Site resident, living on repository site and farming (habit data provided in Section 7.1 of the Data report, QUINTESSA and GEOFIRMA 2011a)
Abbreviations used in the table:	TDS: Total Dissolved Solids
LLW: Low Level Waste	L: Length
ILW: Intermediate Level Waste	W: Width
IX: Ion exchange	H: Height
$K_v$ : vertical hydraulic conductivity	HDZ: Highly Damaged Zone
$K_h$ : horizontal hydraulic conductivity	EDZ: Excavation Damaged Zone
LHHPC: Low Heat High Performance Cement	

**Table 4.2: Repository and Geosphere Sorption Coefficients (m<sup>3</sup>/kg)**

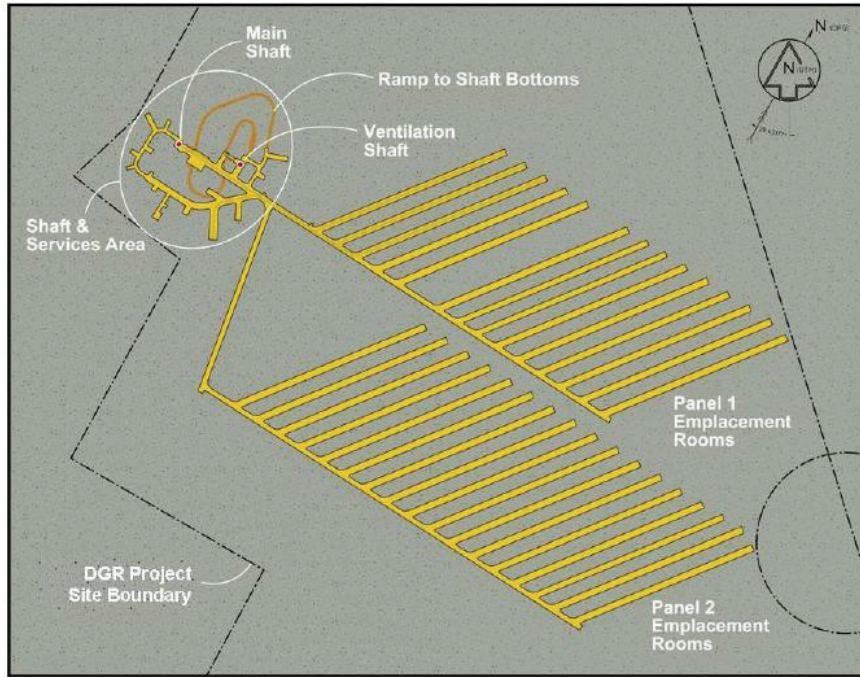
<b>Element/ Substance</b>	<b>Bentonite/Sand</b>	<b>Other Engineered Materials</b>	<b>Limestone and Dolostone</b>	<b>Shale<sup>(1)</sup></b>
Zr	0.05	0	0	0.01
Nb	0.1	0	0	0.05
Cd	0	0	0	0.05
Pb	0.001	0	0	0.03
U	0.01	0	0.001	0.001
Np	0.004	0	0.001	0.03
Pu	0.5	0	0.02	0.2
All other elements/organic substances	0	0	0	0

Notes:

1. Salina C and F, Cabot Head, Manitoulin, Queenston, Georgian Bay and Blue Mountain formations.

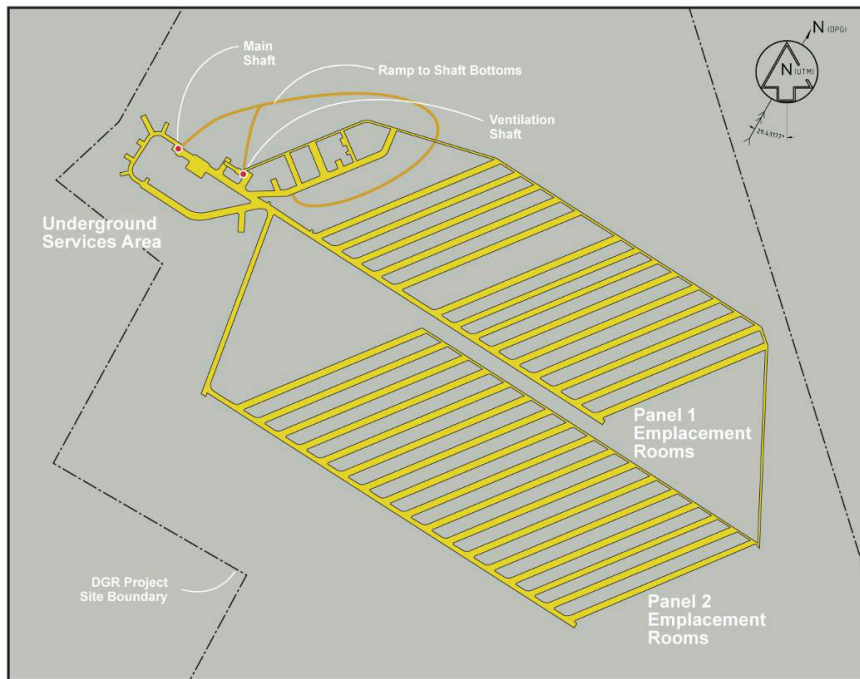
**Table 4.3: Summary of Changes from the Original to the Final Preliminary Design for the DGR**

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



Notes: Figure from NWMO 2010.

**Figure 4.2: General Layout of the Original Preliminary Repository Design**



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

**Figure 4.3: General Layout of the Final Preliminary Repository Design**

#### 4.4 Variant Calculation Cases

The implementation of the variant calculation cases is generally through the input data changes as described in Table 3.1. Only the calculation cases with significant model changes are described below.

##### 4.4.1 Calculation Case NE-PD-RC-A (Reference Case, Final Preliminary Design)

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

- Added ventilation drifts and service areas, resulting in the increase in the repository void volume from  $4.18 \times 10^5 \text{ m}^3$  to  $4.49 \times 10^5 \text{ m}^3$ ; and
- Disposal of ILW filters and elements, irradiated core components, and IX columns in ILW shield containers rather than concrete T-H-E (tile hole equivalent) arrays.

The change in overall repository volume is the main change from a postclosure safety perspective. The added ventilation drift provide another path for contaminants to reach the concrete monolith; however this path was not rate limiting in the original design. The height of access tunnels and shaft stations has been reduced, and the specific connections to the shafts have been changed. However this level of geometric detail around the shafts is not represented in the models as it is not a rate limiting pathway due to the assumed permeable HDZ along the monolith.

Detailed groundwater and gas modelling shows lower calculated fluxes via the shafts when the key features of the final preliminary design are included in the model (see Section 5.11 of GEOFIRMA 2011 and Section 5.15 of GEOFIRMA and QUINTESSA 2011).

Therefore, the AMBER model for the final preliminary design maintains the same dimensions and layout to represent the repository volume and path to a single combined shaft as used for the draft preliminary design. However, the AMBER model takes input from the detailed gas and groundwater calculations undertaken with T2GGM and FRAC3DVS-OPG, respectively for the final preliminary design. The T2GGM model for the final preliminary design keeps with the original preliminary design layout, but increases the volume of the repository (see Section 2.5 of GEOFIRMA and QUINTESSA 2011), while the FRAC3DVS-OPG model explicitly represents the additional drifts and final dimensions (see Section 4.3.3.1 of GEOFIRMA 2011).

The concrete T-H-E arrays represented in the Reference Case are replaced with stacked ILW shield containers that hold the ILW filters and elements, irradiated core components, and IX columns. Unlike the large concrete T-H-E arrays, the stacked ILW shield containers are subject to failure on roof fall (see Appendix J.5) and water can access these wastes as soon as there is standing water in the repository. The total emplaced waste package volume are also slightly larger than in the original preliminary design, resulting in an increase in the total emplaced volume to about  $204,000 \text{ m}^3$ .

##### 4.4.2 Calculation Case NE-CG-A (Alternative Critical Groups)

This case is the same as for NE-HG-A but with two extra critical groups that are exposed through the consumption of fish and water from Lake Huron. A Site Shore Resident Group is assumed to obtain all its fish and water from the near-shore compartment in the lake, while a Downstream Resident Group is assumed to obtain them from the South Basin of Lake Huron.

The fish consumption rate for adults is conservatively taken to be 100 g/d – a value that is five times the value for the Site Resident Group given in the Data report (Table 7.2 of the Data report, QUINTESSA and GEOFIRMA 2011a) and twice the maximum value given in the survey of fish consumption by the Chippewas of Nawash (Nawash Fishes 2002). Fish consumption rates for children and infants are taken to be 50% and 25% of the adult rate, based on the ratio of adult to child to infant consumption rates given in Nawash Fishes (2002).

The consumption rates for drinking water are the same as those for the Site Resident Group, which are given in Table 7.2 of the Data report (QUINTESSA and GEOFIRMA 2011a).

#### 4.4.3 Calculation Case NE-CC-A (Tundra Climate State)

The data for this case are the same as for the Reference Case (NE-RC-A) but with contamination being released to a tundra biosphere. The tundra biosphere state is illustrated in Figure 4.4.

In tundra climate conditions, changes in precipitation may lead to the lake retreating and therefore relocation of the lake margin. Therefore, groundwater discharge from the Shallow Bedrock Groundwater Zone is assumed to enter the stream rather than the lake; the dimensions and flow rates of the stream are taken to be the same as for the Reference Case. Although there is likely to be reduced demand for water (due to reduced agricultural activity), it is likely that water will continue to be pumped from a well in the Shallow Bedrock Groundwater Zone.

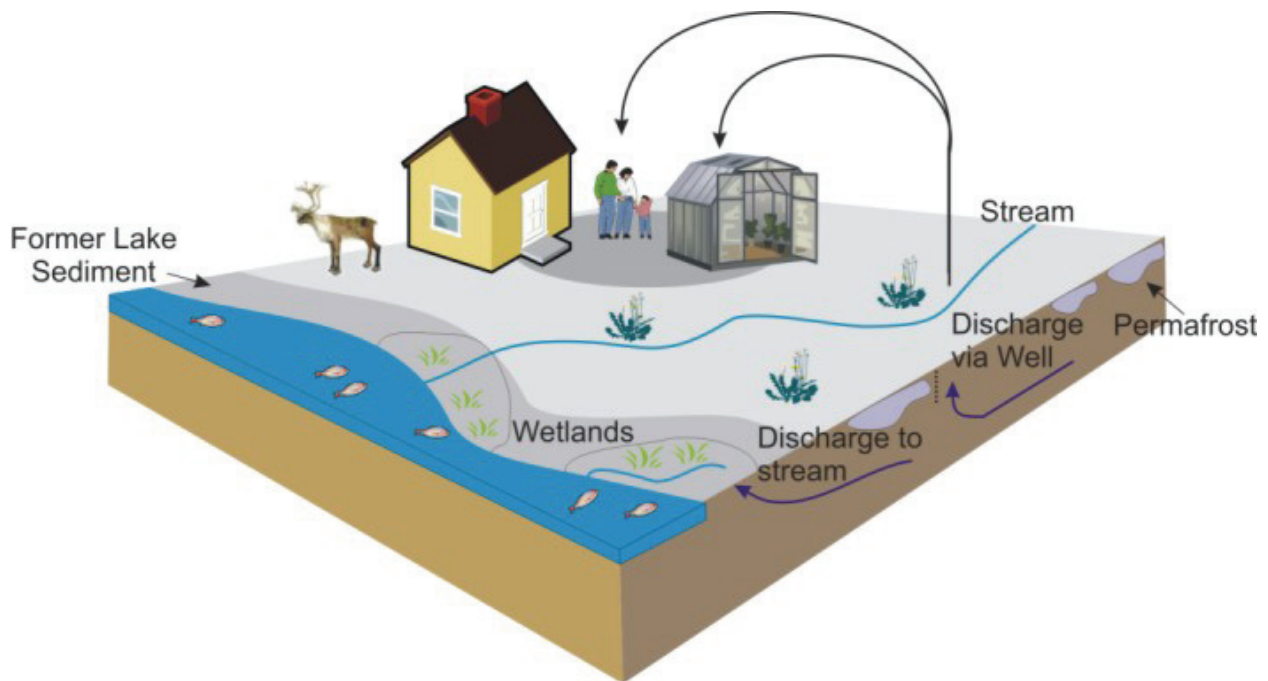


Figure 4.4: Illustration of the Tundra Biosphere State

#### 4.4.3.1 Surface Water, Atmosphere, Soil and Sediment

The lake may retreat as a result of reduced precipitation, exposing former lake sediments. Other soils may become peaty in nature due to the slow decomposition of organic matter in the cold climate; sorption coefficients for an organic soil are, therefore, used (Table 6.6 of the Data report, QUINTESSA and GEOFIRMA 2011a). Any permafrost that might be present would likely be discontinuous and limited to less than a few tens of metres (Section 3.6.3 of Peltier 2011). Its effects are, therefore, disregarded in the present calculations. There is a reduction in the area of land used for farming, from 302,000 m<sup>2</sup> to 1,275 m<sup>2</sup> due to the reduced number of crops that are assumed to be grown resulting from the harsher climatic conditions. The combined effect of a reduction in the use of land for farming and the change of livestock to caribou is a reduction in demand for well water (from 6,400 m<sup>3</sup>/a to 970 m<sup>3</sup>/a). All other water flow rates are assumed to remain the same as for the temperate climate (see Section 6.1 of the Data report, QUINTESSA and GEOFIRMA 2011a).

#### 4.4.3.2 Plants and Animals

Biota are assumed to be similar to those found in present-day tundra environments. The key large herbivore considered is caribou, which is assumed to spend 25% of their time grazing vegetation growing on the former lake bed sediment exposed by the retreating lake. It is conservatively assumed that the caribou obtain 100% of their drinking water from the stream. Ingestion and inhalation rates for caribou are presented in Table 4.4. In the absence of specific information, the forage to meat/milk transfer factors for deer given in Table 6.13 of the Data report (QUINTESSA and GEOFIRMA 2011a) are taken as representative for caribou.

**Table 4.4: Caribou Characteristics**

Parameter	Caribou	Note
Body mass at age of use, kg	135	(1)
Consumption rate of forage, kg·dw/d	3.9	(2)
Soil load on grazed feed, kg·dw/(kg·dw)	0.01	(3)
Consumption rate of soil, kg·dw/d	0.2	(4)
Consumption rate of water, L/d	8.2	(2)
Inhalation rate, m <sup>3</sup> /d	27	(2)

Notes:

1. Based on Table 2 of Garisto et al. (2008).
2. Calculated on the basis of allometric expressions, consistent with default recommendations for animals in Table G6 of CSA (2008).
3. Value for deer and rabbits, which also graze mixed vegetation, in Table G6 of CSA (2008).
4. Value for dairy cattle from Table G6 of CSA (2008).

#### 4.4.3.3 Human Lifestyle Data

Human habitation is expected to continue to be feasible, but reduced temperature and precipitation means that agriculture is limited to growing of crops under cover and there is greater reliance on subsistence hunting, fishing and trapping.



In the absence of detailed habit data specifically associated with tundra lifestyles, characteristics are drawn from the generic Canadian data presented in Section 7.1 of the Data report (QUINTESSA and GEOFIRMA 2011a), but adapted with consideration of potential tundra lifestyles. Like the 'local' group for present-day conditions, the Tundra Resident Group is conservatively assumed to spend all of their time in the DGR area. The environment is not suitable for growing grain, but vegetables, fruit, berries and potatoes are assumed to be grown under cover for human consumption and irrigated with well water. The group are assumed to obtain all of their meat and milk requirement from the caribou that they farm (similar to reindeer currently herded in northern Scandinavia). The adult's time outdoors is split between the time spent near the covered vegetables, and former lake-bed sediment exposed by the retreating lake, on which the caribou spend some of their time grazing, with some time being spent by the stream and by Lake Huron. No recreational swimming is assumed due to the colder climate.

Assumed occupancies are summarized in Table 4.5, while ingestion rates are provided in Table 4.6. Based on these assumptions, the water demand from the well during tundra periods is 970 m<sup>3</sup>/a, and the area of land required for the irrigated crops is 1275 m<sup>2</sup>.

**Table 4.5: Occupancies for Tundra Resident Group**

Activity/Location	Hours: Minutes			Fractional		
	Adult	Child	Infant	Adult	Child	Infant
Outdoors, in irrigated area <sup>(1)</sup>	3:00	1:00	0:30	0.125	0.042	0.021
Outdoors, on former lake bed sediment <sup>(1)</sup>	3:00	1:00	0:30	0.125	0.042	0.021
Outdoors, by Lake Huron <sup>(2)</sup>	0:30	-	-	0.021	0.010	-
Outdoors, by stream <sup>(2)</sup>	0:15	-	-	0.010	-	-
Taking a bath <sup>(3)</sup>	0:20	0:20	0:20	0.014	0.014	0.014
Indoors, in contaminated area <sup>(4)</sup>	17:15	22:00	23:00	0.719	0.916	0.958

Notes:

1. Generally less time spent outside than for present-day conditions due to colder climate.
2. Adults still spend some time by Lake Huron and the stream to catch fish.
3. All age groups are assumed to spend 20 minutes bathing every day, consistent with Clause 6.16.1.3 of CSA (2008).
4. Accounts for all remaining time. Includes time taking a bath.

**Table 4.6: Ingestion Rates for Tundra Resident Group**

Parameter		Local Fraction	Farming Group			Notes
			Infant	Child	Adult	
Ingestion rates, g/d						
	Lake fish	1	1.25	4.25	10.2	(1)
	Stream fish	1	1.25	4.25	10.2	(1)
	Caribou Milk	1	1016	836	727	(2)
	Caribou Meat	1	50.5	139	318	(3)
	Fruit and berries	1	181	255	478	(4)
	Vegetables	1	120	311	642	(4)
	Potatoes	1	64.3	173	285	(4)
Incidental soil ingestion, g-dw/d			0.12	0.33	0.33	(4)
Drinking water, L/d			0.98	1.4	2.3	(4)

## Notes:

1. Conservative default values recommended for temperate conditions in Table 7.2 of the Data report (QUINTESSA and GEOFIRMA 2011a) and total consumption for adults is within the range for Baker Lake Inuit reported in OPG (2005).
2. Conservative default recommended for cow's milk consumption in temperate conditions in Table 7.2 of the Data report (QUINTESSA and GEOFIRMA 2011a). Jokelainen (1966) reports values of 280 g/d for nomadic Lapps and 900 g/d for settled Lapps, which is consistent with the recommended value.
3. Combined conservative default intake of beef, offal, pork, lamb, poultry, deer and rabbits for temperate conditions in Table 7.2 of the Data report (QUINTESSA and GEOFIRMA 2011a); adult value is within the range for Baker Lake Inuit reported in OPG (2005) and within the average range for the Canadian North reported in Arctic Monitoring and Assessment Programme (AMAP) (2004).
4. Conservative default recommended for temperate conditions in Table 7.2 of the Data report (QUINTESSA and GEOFIRMA 2011a).

**4.4.4 Calculation Case NE-ER-A (Surface Erosion)**

This case is the same as for the Reference Case (NE-RC-A), but consideration is given to the removal of 100 m of geosphere due to erosion over 1 million years. Over the timescales of the assessment, the Bruce nuclear site is likely to be affected by a series of ice-sheet advances and retreats resulting in the erosion and deposition of material. Hallet (2011) notes that the subglacial conditions that control erosion are likely to vary with time and space in complex ways and the magnitude of erosion cannot be assessed with precision. However, many lines of evidence point to a conclusion that bedrock erosion on the timescale of 100,000 years is likely to range between a few metres and a few tens of metres. Furthermore, the data and model results collectively point to a broad range of values for the erosion that is plausible for the Bruce nuclear site on a 1,000,000 year timescale of between a few metres up to a maximum of 200 m. In view of the absence of topographic features or other known factors that would tend to localize erosion by ice or water over the Bruce nuclear site, and the absence of evidence of preferential past erosion over the site, a more realistic but still quite conservative site-specific estimate of 100 m over the 1,000,000 year period is given by Hallet (2011).

The stylized approach to the representation of the evolution of the surface and near-surface system over the assessment timescales has assumed that there is no net erosion or deposition at the Bruce nuclear site over the assessment timescales for the Reference Case. The NE-ER-A variant case evaluates the dose consequences of ice-sheet erosion on the safety of the DGR. It assumes that 100 m of the Surficial Groundwater Zone and Shallow Bedrock Groundwater Zone is eroded by ice-sheet advance and retreat, and that the remaining 80 m of the zone contains potable water which is pumped via a well. This is conservatively represented in the associated AMBER model by assuming that the entire flux of each radionuclide discharged from the shafts (and geosphere) at the top of the Intermediate Bedrock Groundwater Zone is immediately captured by a water well and is abstracted at a rate of 6,400 m<sup>3</sup>/a - the rate required to meet all the domestic and agricultural the demands of the self-sufficient critical group.

#### 4.4.5 Calculation Case NE-NR-A (Non-radioactive Contaminants)

This case is the same as for the Reference Case (NE-RC-A), but with non-radioactive elements and chemical species identified in Table 1.1 present in the DGR (waste, packaging and other sources<sup>6</sup>) being modelled rather than radionuclides. The inventory of metals present in the DGR from packaging and other sources is given in Table 4.7. Organic contaminants are modelled conservatively with no degradation.

The end points of interest for non-radioactive contaminants are calculated concentrations in environment media, which are compared against environmental quality standards given in Table 7.12 of the Data report (QUINTESSA and GEOFIRMA 2011a). Therefore, soil sorption coefficients are the only element-dependent biosphere parameters that are required (see Table 6.6 of the Data report, QUINTESSA and GEOFIRMA 2011a).

**Table 4.7: Inventory of Metallic Elements in Sources Other than Waste in the DGR for the Non-radioactive Assessment (NE-NR-A)**

Element	Carbon Steel		Stainless Steel		Total (kg)
	Chemical Composition (% weight)	Mass (kg)	Chemical Composition (% weight)	Mass (kg)	
Mn	1.65	6.56E+05	2	2.57E+05	9.13E+05
Cu	0.6	2.39E+05	-	-	2.39E+05
Cr	-	-	17	2.18E+06	2.18E+06
Ni	-	-	12	1.54E+06	1.54E+06
Mo	-	-	2.5	3.21E+05	3.21E+05

<sup>6</sup> Other sources of metals within the DGR include rails, rock bolts and concrete reinforcement.

#### 4.4.6 Calculation Case NE-PC-A (Probabilistic Case)

This case is the same as the Reference Case (NE-RC-A), but with key parameters being sampled using a Monte Carlo approach. The probabilistic calculations were undertaken for key radionuclides (C-14, Cl-36, Zr-93 and I-129) with 500 samples. The purpose of this work is to investigate sensitivity of consequences to the release and transport parameters, and not to test compliance against a risk criterion. The sensitivity analysis is constrained within the Reference Case geosphere assumptions; in particular repository saturation, gas and groundwater flows are not sampled as they are drawn directly from the detailed T2GGM and FRAC3DVS-OPG models, which are deterministic in nature.

The specification for the parameter distributions is given below.

- Radionuclide inventories – best estimates (i.e., peaks) given in Section 3.5.2 of the Data report (QUINTESSA and GEOFIRMA 2011a) with range of plus/minus one order of magnitude using a log triangular distribution.
- Corrosion rates – as Table 3.20 of the Data report (QUINTESSA and GEOFIRMA 2011a).
- Waste thickness:
  - Core hardware uses a triangular distribution with a minimum and peak of 1 mm and a maximum of 5 mm.
  - Retube wastes use a triangular distribution with a minimum of 2 mm, a peak of 5 mm and a maximum of 10 mm.
- Gas-water partition coefficients:
  - Chlorine uses a log-triangular distribution, with a minimum and peak of  $1 \times 10^{-6}$  and a maximum of  $1 \times 10^{-4}$ .
  - Iodine uses a log-triangular distribution, with a minimum of  $1 \times 10^{-5}$ , a peak of  $1 \times 10^{-4}$  and a maximum of  $1 \times 10^{-3}$ .
- Sorption coefficients use the values given in Table 4.2 with range of plus/minus one order of magnitude using a log triangular distribution.
  - C and Zr in the repository use a peak value of  $0.001 \text{ m}^3/\text{kg}$  and  $1 \text{ m}^3/\text{kg}$ , respectively and the distribution given above.
- Effective diffusion coefficients in the geosphere, use the distributions given in Table 5.14 of the Data report (QUINTESSA and GEOFIRMA 2011a).
- Effective diffusion coefficients for shaft materials are given in Table 4.8.

**Table 4.8: Distributions for Effective Diffusion Coefficients ( $\text{m}^2/\text{s}$ ) for Shaft Materials for Use in Probabilistic Calculations (NE-PC-A)**

Material	Lower Limit	Peak	Upper Limit	Distribution
Degraded structural concrete	5E-11	1.25E-10	3E-10	Triangular
Degraded LHHPC	5E-11	1.25E-10	1.5E-10	Triangular
Bentonite/sand	2E-11	3E-10	6E-10	Triangular
Asphalt	1E-15	1E-13	1E-11	Log triangular

## **5. REFERENCE CASE RESULTS**

The results of the safety assessment modelling for the Reference Cases (NE-RC-A and NE-PD-RC-A) are presented in this chapter. The results are analyzed in order to better understand the safety functions of the different features of the system. In addition, the relative contributions from the shafts/shaft EDZ and host rock to potential contaminant migration are studied. In addition, the relative importance of the lake and well pathways for groundwater release is considered.

The Reference Case (NE-RC-A) is based on the original preliminary design, and the results are presented in Sections 5.1 to 5.3. The Reference Case results based on the final preliminary design (NE-PD-RC-A) are presented in Section 5.4.

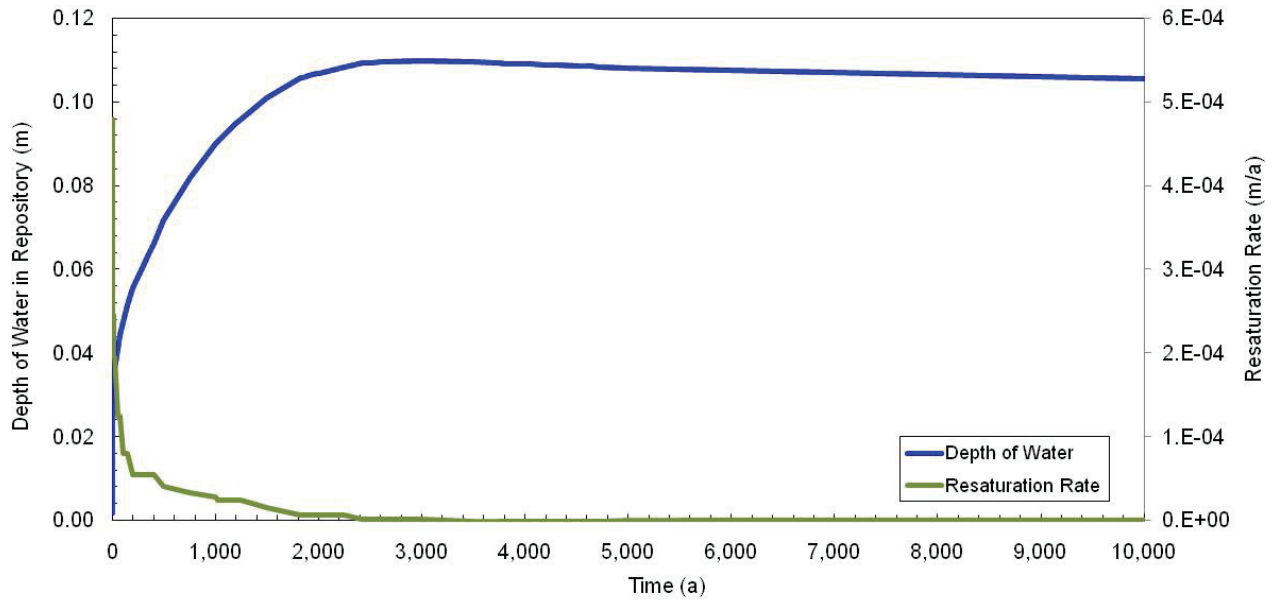
The results of the additional variant calculation cases, provided in Chapter 6, further inform this analysis and enable the key uncertainties to be identified. Chapter 6 also includes comparisons between the assessment and detailed modelling results (GEOFIRMA 2011; GEOFIRMA and QUINTESSA 2011).

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.

### **5.1 Release from the Wastes and Repository Rooms and Tunnels**

#### **5.1.1 Releases from the Wastes**

Radionuclide releases from the wastes are strongly controlled by the water resaturation behaviour of the repository. Radio-labelled gases are released from both the saturated and unsaturated wastes, but radionuclide releases to groundwater in the repository are only possible once the waste comes into contact with water. Figure 5.1 shows that the water level in the repository does not exceed 12 cm for the Reference Case, compared with the average repository height of 7 m; the decline in the water level in the repository continues beyond 10,000 years to beyond a million years. This means that the majority of the waste remains unsaturated.

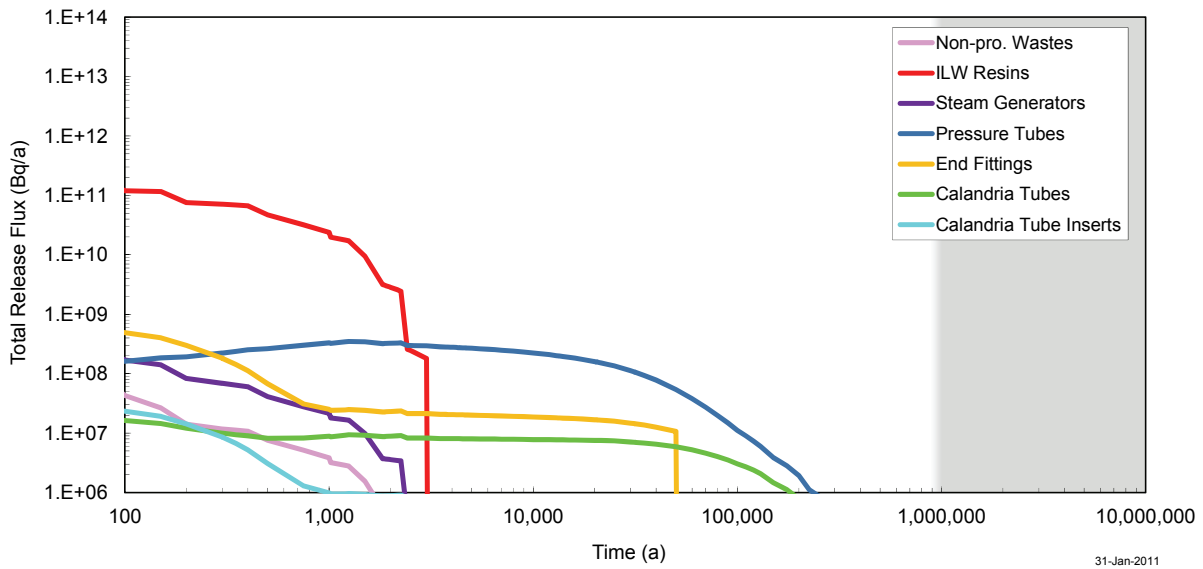


**Figure 5.1: Depth of Water in the Repository and Resaturation Rate for the Reference Case (NE-RC-A)**

For radionuclides that cannot be released in the gas phase (i.e., everything other than H-3 and C-14), the content of the waste that is not exposed to water decays without entering the groundwater in the repository.

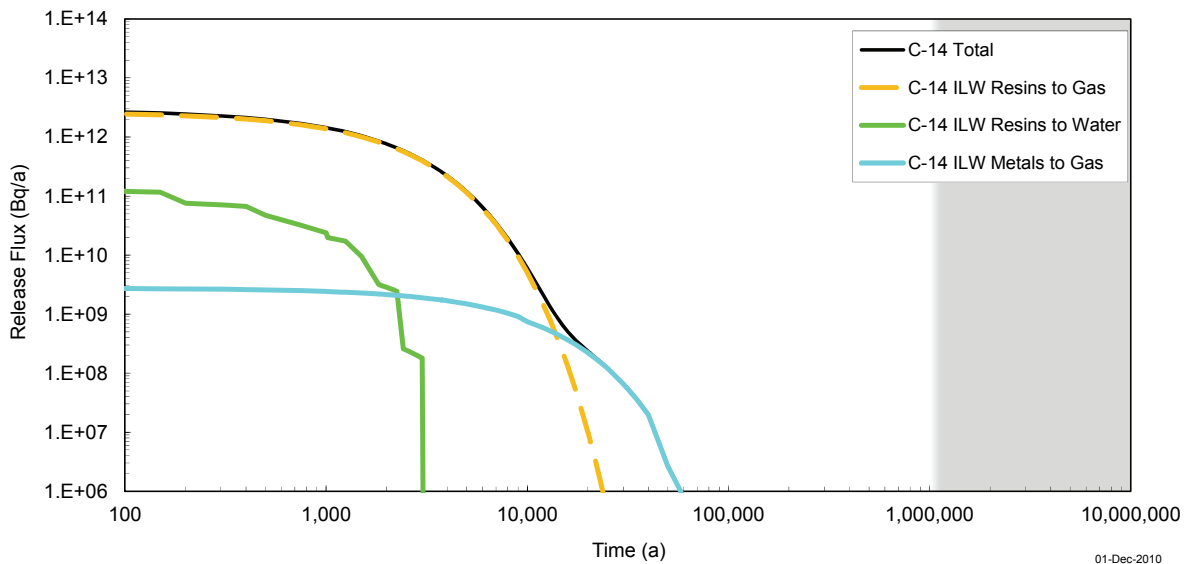
Figure 5.2 shows the radionuclide releases from the waste to the repository water for the Reference Case for some example wastes (the release models are summarized in Table 2.3). Radionuclides can be released to water as soon as the repository is closed and there is standing water, as no account is taken of waste containers and overpacks in preventing the access of water to the wastes. As the water level rises, more wastes are contacted by water and more radioactivity is released. If the water level begins to fall, no new waste is exposed to repository water and releases to water from the waste categories decline and cease if there is no water in the repository.

The contamination in the retube wastes is contained within the waste metals and is released congruently as the waste that has been exposed to repository water corrodes. The complete corrosion of the stainless steel end fittings and calandria tube inserts takes about 50,000 years, while the corrosion of the more resilient Zircaloy pressure tubes and calandria tubes takes about 500,000 years.



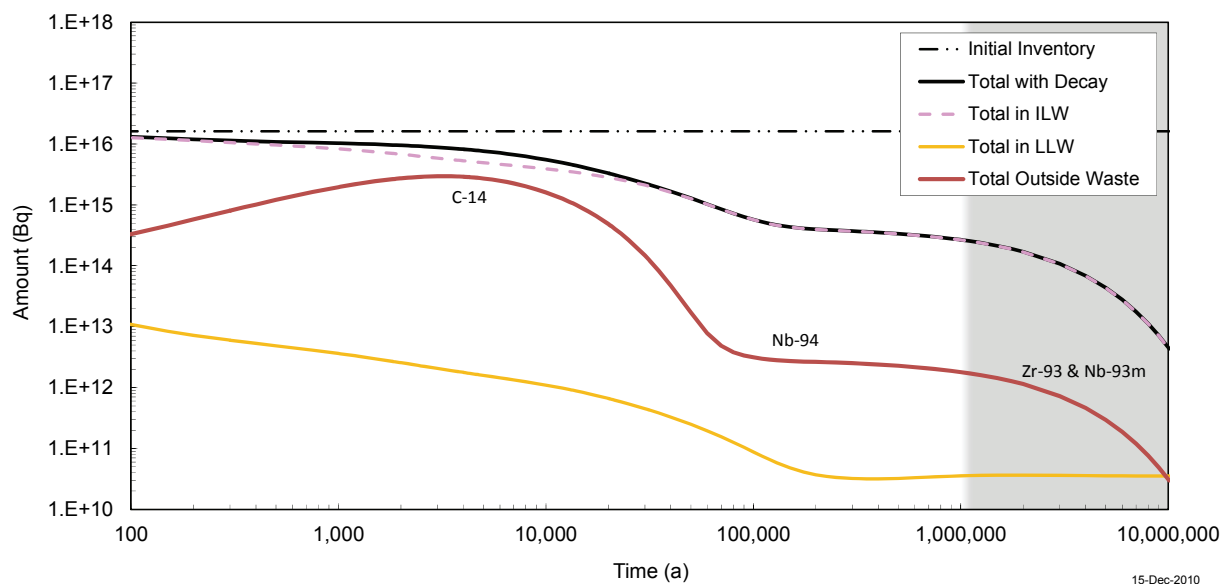
**Figure 5.2: Total Radionuclide Releases from Example Waste-Streams to Repository Water for the Reference Case**

Figure 5.3 shows the calculated releases from the wastes for C-14, which can be released from both saturated and unsaturated waste to repository gas and water (see Appendix E). The figure shows that, the release flux for C-14 is dominated by releases from ILW resins to gas, which itself is dominated by release from moderator resins. Note that H-3 conservatively is taken to be rapidly released to repository gas before 100 years; its relatively short half-life (12.3 years) means that it is of limited importance to postclosure safety.



**Figure 5.3: C-14 Releases to Gas and Groundwater for the Reference Case (NE-RC-A)**

Figure 5.4 summarizes the total amount of radioactivity in the initial inventory remaining in the wastes and released from the wastes over time. The figure shows that the low degree of repository saturation means that most of the initial inventory remains within the waste during the modelled period, with less than 20% of the initial inventory having been released at any time. Most of this is H-3 and C-14 released as gas, more than 99.9% of the initial inventory for other radionuclides is retained in wastes.

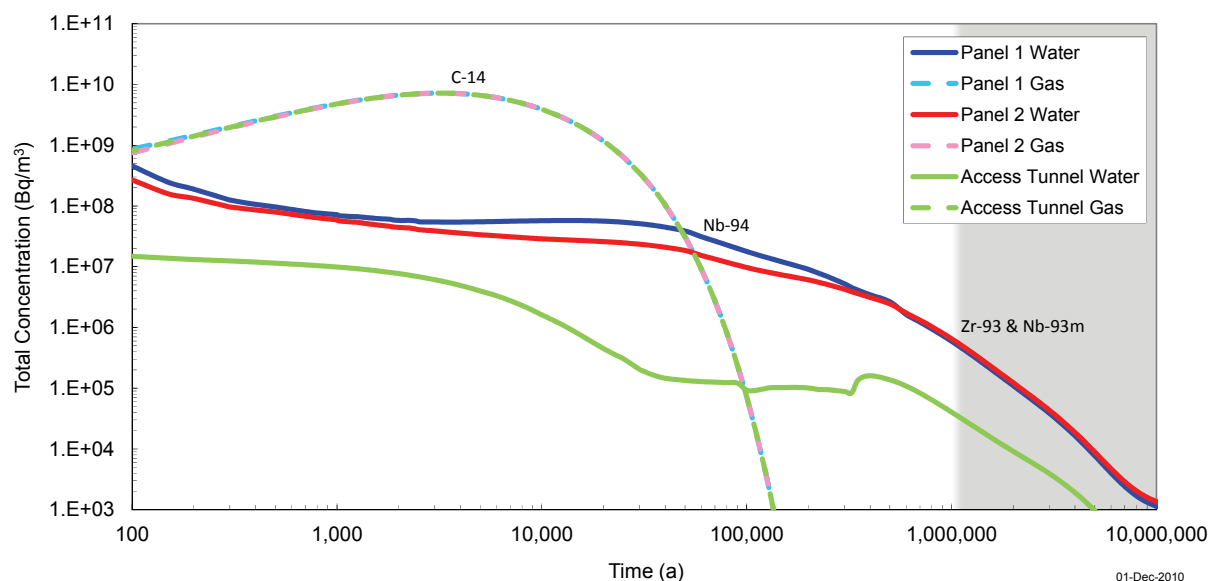


**Figure 5.4: Total Radionuclide Inventory for the Reference Case (NE-RC-A)**

Figure 5.5 shows the total radionuclide concentrations in the gas and water within the DGR (as represented in the AMBER model) with time for the Reference Case. Aqueous radionuclide concentrations are relatively similar in both panels due to similar wastes being disposed in each. The need for radionuclides to diffuse into the access tunnels in the relatively small amount of repository water means that the aqueous concentrations in the tunnels are always lower than those in the emplacement rooms. Calculated concentrations in the gas phase equilibrate relatively quickly around the repository.

Aqueous concentrations in the repository are dominated by C-14 to about 100,000 years. C-14 is released from both saturated and unsaturated waste, so the relatively small degree of water resaturation does not limit its release. Once released, C-14 partitions between the water and gas in the repository. Once C-14 has decayed, repository concentrations become dominated by radionuclides that have leached from the wastes directly into the groundwater. The decline in concentrations beyond 500,000 years coincides with the cessation of releases from the corroding retube waste categories.





Note: Access tunnel concentrations are based on the section of tunnel between Panel 1 and the concrete monolith.

**Figure 5.5: Total Radionuclide Concentrations in Gas and Groundwater within the DGR for the Reference Case (NE-RC-A)**

The waste releases and repository concentrations show that there are two important near-field barriers to radionuclide release to the groundwater pathway. First the slow repository saturation rate, and second the corrosion-resistant Zircaloy waste themselves, with a significant proportion of the long-lived activity. This is also confirmed by variant calculations presented in Chapter 6. Note that no credit is being taken for additional retention within waste containers and overpacks.

### 5.1.2 Releases from the DGR to the Shafts and Geosphere

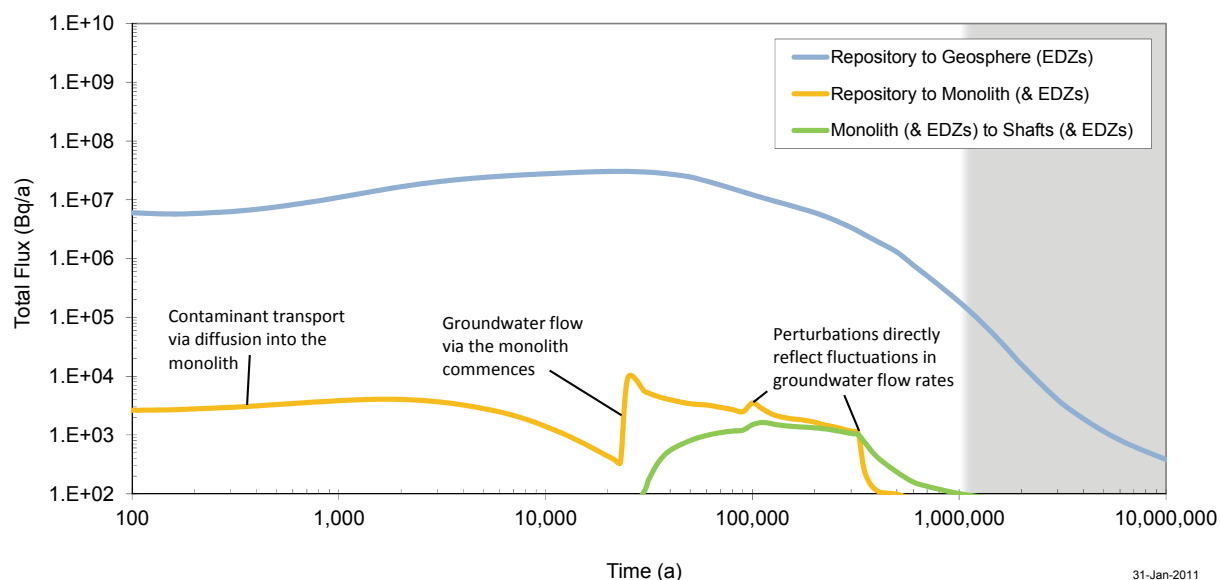
Figure 5.6 shows the total aqueous radionuclide flux from the repository to the geosphere around the repository, to the monolith and surrounding EDZ rock at the base of the shafts, and via the monolith to the shafts (including the shaft EDZs), for the Reference Case. The figure shows that the dominant pathway from the DGR is into the host rock, with fluxes being more than three orders of magnitude higher than those into the shafts, due to the significantly greater interfacial area.

The profile of the total groundwater flux into the shafts and geosphere broadly reflects the activity in the groundwater in the DGR with time (Figure 5.5). T2GGM results for the NE-RC-T2 case for the 3DSRS model (Section 5.1 of the Gas Modelling report, GEOFIRMA and QUINTESSA 2011) indicate that flow away from the repository via the monolith and upwards from the base of the shafts commences after about 25,000 years<sup>7</sup>, which is the time at which the

<sup>7</sup> As repository gas pressures increase, the repository ceases to be the lowest pressure location in the system, and liquid flow in the shaft is directed towards the maximum formation underpressure, near the bottom of the Georgian Bay formation (see Figure 5-38 of the Gas Modelling report, GEOFIRMA and QUINTESSA 2011).

potential for advective flow via the monolith is initiated in the AMBER model. The discontinuities in the transfer flux to the monolith after this time reflect the groundwater flow rates.

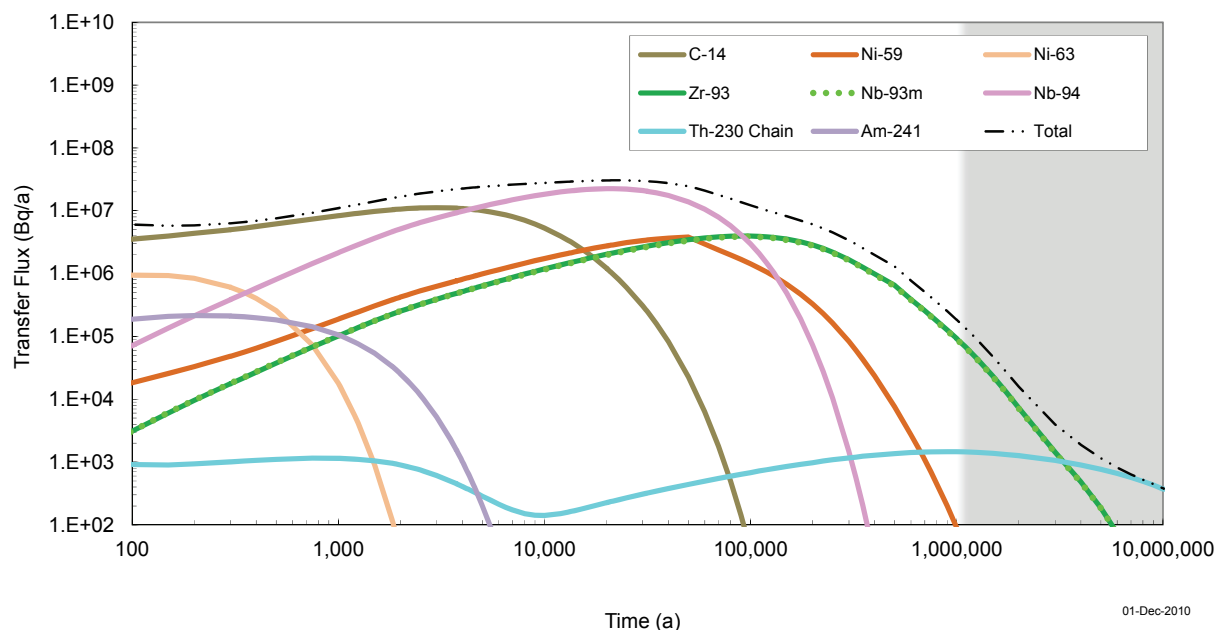
Releases to the geosphere (repository EDZs) and shafts fall beyond about 500,000 years, once congruent releases for resilient metals have completed.



**Figure 5.6: Total Aqueous Radionuclide Fluxes from Repository to the Shafts and Geosphere for the Reference Case (NE-RC-A)**

The detailed gas modelling (Section 5.1 of GEOFIRMA and QUINTESSA 2011) shows that there is no migration of free gas from the DGR into either the host rock or the shafts for the NE-RC-T2 case. Therefore, there is no gas release pathway for the NE-RC-A case. However, radiolabelled gases can dissolve in the groundwater within the DGR and then enter the groundwater pathway.

Figure 5.7 shows the contributions of individual radionuclides to the total groundwater flux from the repository to the geosphere for the Reference Case. The figure shows the significant contributions from Ni-63 (from ILW resins), C-14 (from ILW moderator resins), Nb-94 (from the ILW pressure tubes), Zr-93 (from the ILW pressure tube and calandria tube wastes) and Nb-93m (in-grown from Zr-93). In the extremely long-term (after four million years) the U-238 chain dominates (Th-230, Ra-226, Pb-210 and Po-210), which are in-grown via U-234 from disposed U-238.



**Figure 5.7: Radionuclide Fluxes in Groundwater to the Geosphere for the Reference Case (NE-RC-A)**

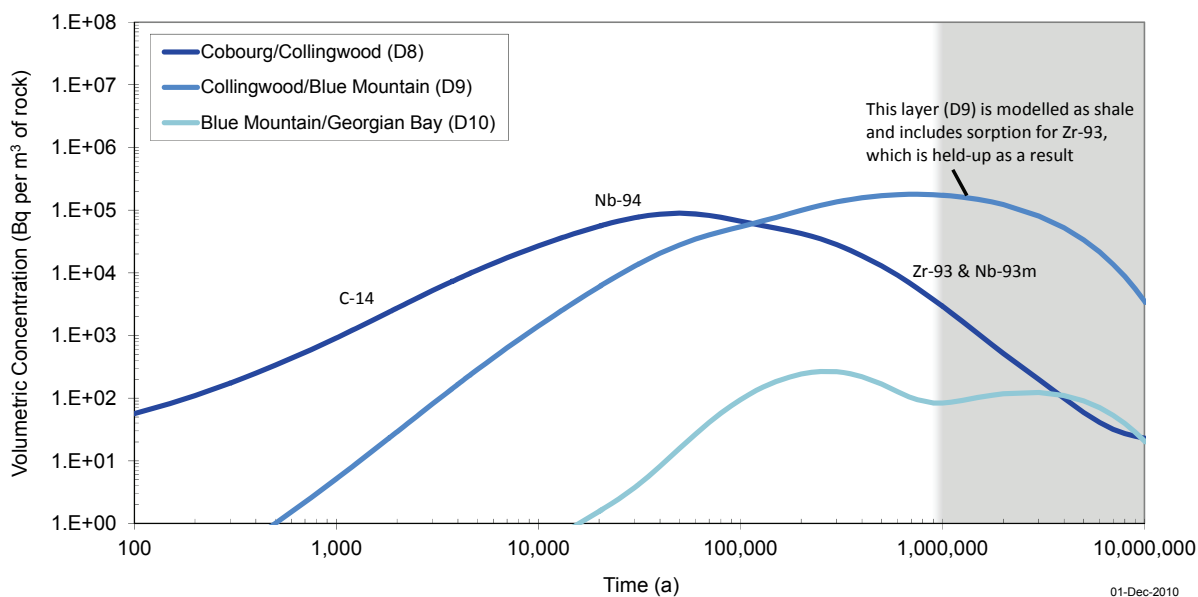
## 5.2 Migration via the Shafts and Geosphere

Detailed gas modelling calculations undertaken with T2GGM indicate that any free gas being released from the repository does not reach the shallow system or biosphere for the Normal Evolution Scenario cases (Section 5.1 of the Gas Modelling report, GEOFIRMA and QUINTESSA 2011). Any free gas that reaches the Intermediate Bedrock Groundwater Zone is diverted laterally into the relatively high permeability Guelph and Salina A1 upper carbonate formations. However, free gas in this region is uncontaminated formation gas seeping in to the shaft in this Reference Case (Section 8.2 of GEOFIRMA and QUINTESSA 2011). Discussion of potential contaminant migration via the shafts and geosphere, therefore, appropriately focuses on contaminants transported in groundwater (including any dissolved gases).

### 5.2.1 Groundwater Transport via the Host Rock

Figure 5.8 shows the total radionuclide concentration in successive host rock compartments above the DGR (and away from the shaft) for the Reference Case (the radioactivity is predominantly in the pores in the rock, but the concentration is averaged over the rock volume). Note that, although the repository does not resaturate throughout the modelled period, radionuclides are able to diffuse into the saturated rock above and below the DGR. The figure shows that the very low permeability of the host rock limits radionuclide migration. Calculated concentrations remain extremely small (below  $1 \text{ Bq/m}^3$ ) beyond the Georgian Bay formation above the DGR. Diffusion of contaminants down into the Cambrian results in a peak

concentration of around 240 Bq/m<sup>3</sup> of rock in the Cambrian for the Reference Case after about 1.5 million years<sup>8</sup>.



Note: The concentrations represent the host rock furthest from the shafts (the 'Panel B' compartments) to minimise the influence of lateral diffusion from the shafts. The model layer numbers are indicated in brackets; see Appendix H for a description of the model discretization.

**Figure 5.8: Volumetric Concentrations in Host Rock Compartments above the DGR (Bq per m<sup>3</sup> of Rock) for the Reference Case (NE-RC-A)**

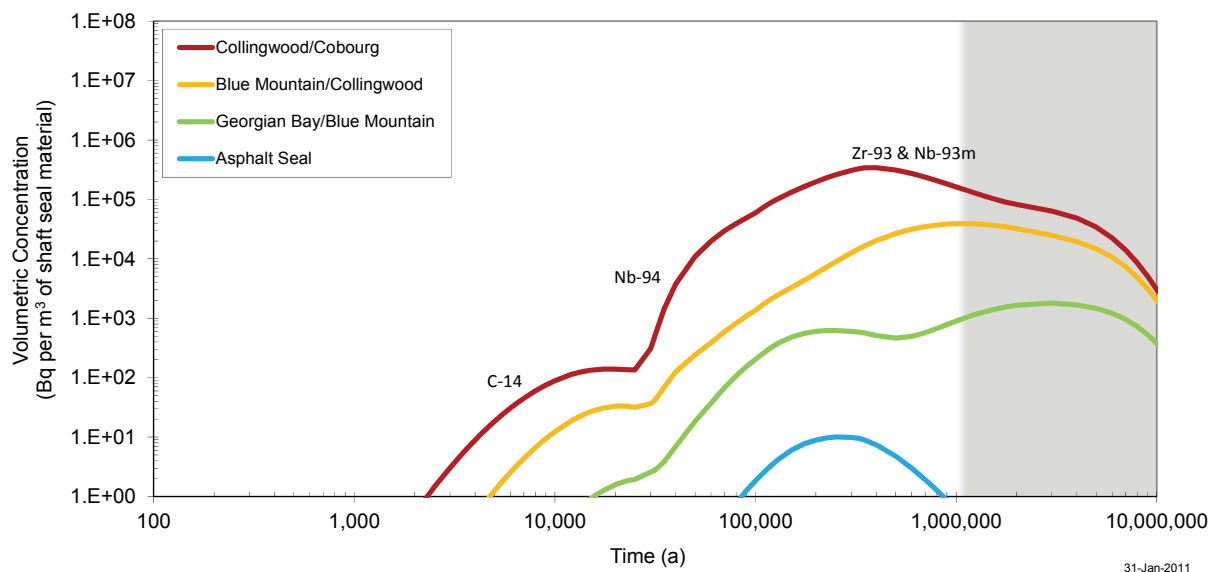
## 5.2.2 Groundwater Transport via the Shafts and their Associated EDZs

Figure 5.9 shows radionuclide concentrations in successive compartments representing the shafts for the Reference Case. The figure shows that the shaft seals provide an effective barrier to radionuclide migration for the Reference Case, with no concentrations greater than 1 Bq/m<sup>3</sup> in the shaft beyond the top of the Ordovician formations. Contaminant transport is dominantly via the shaft seal materials rather than via the EDZ.

The groundwater flows calculated by both FRAC3DVS-OPG and T2GGM for the Reference Case (e.g., see Section 5.2.1 of GEOFIRMA 2011) indicate that groundwater flows downwards via the shafts into the underpressured upper regions of the Ordovician in the shafts to beyond a million years. Therefore, contaminant transport towards the Shallow Bedrock Groundwater

<sup>8</sup> This corresponds with a peak calculated concentration in groundwater of about 3.3 Bq/L. Consumption of water with this concentration would result in a dose of around 0.002 mSv/a, if it were assumed that water was pumped directly from the Cambrian and used without any treatment. This is not possible since the salinity of Cambrian water is around 200 g/L, a factor of 7 higher than seawater.

Zone beyond the middle of the shales in the shafts is predominantly against the direction of groundwater flow, and therefore very slow.



**Figure 5.9: Volumetric Concentration in Successive Shaft Compartments (Bq per m<sup>3</sup> of Shaft Seal Material) for the Reference Case (NE-RC-A)**

The AMBER model for the Reference Case calculates the total radionuclide transfer flux to the Shallow Bedrock Groundwater Zone via the shafts to be essentially zero, peaking at  $3 \times 10^{-6}$  Bq/a beyond one million years. The radionuclide transfer flux to the shallow system is dominated by I-129, with the C-14 having decayed (half-life 5700 years) and Nb-93m, Nb-94 and Zr-93 retarded by sorption onto the bentonite/sand seals.

### 5.3 Biosphere Concentrations and Doses

The amount of radionuclides that reach the biosphere for the Reference Case is effectively zero, with a maximum calculated amount in the biosphere of only 6 Bq, which occurs long after one million years. The resulting concentrations in the surface water, sediment, soil and groundwater are at much lower than the 'no effect concentrations' for non-human biota (Table 7.11 of QUINTESSA and GEOFIRMA 2011). The highest calculated concentrations remain well below  $1 \times 10^{-10}$  Bq/L and  $1 \times 10^{-10}$  Bq/kg in well water, surface water, soils and sediments throughout the assessment; the main contributing radionuclides are Cl-36 and I-129.

Maximum calculated doses to an adult member of the Site Resident Group are  $2 \times 10^{-15}$  mSv/a, much lower than the dose criterion of 0.3 mSv/a. The highest calculated doses occur at the end of the calculation period and arise from I-129 from the consumption of drinking water, plant and animal produce. Maximum calculated doses to children and infants are a factor of 1.7 and 1.6 higher, respectively, and also remain much lower than the dose criterion.

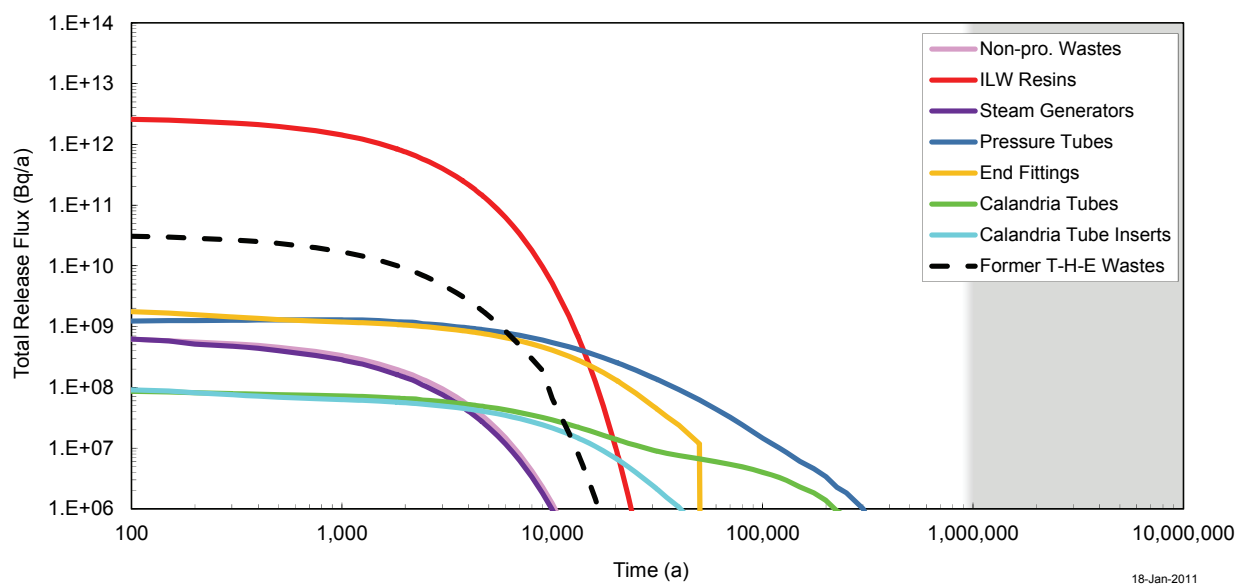
### 5.4 Results for the Final Preliminary Design (NE-PD-RC-A)

This case is the same as the Reference Case, but with the final preliminary design being represented.

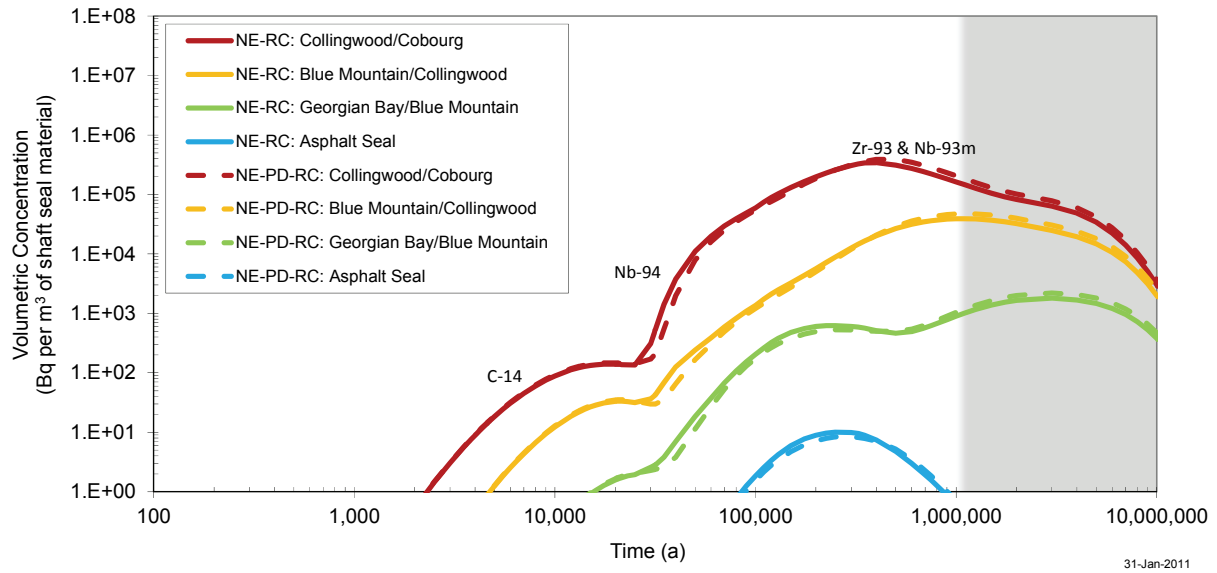
The ILW filters and elements, irradiated core components, and IX columns waste categories are taken to be disposed in ILW shield containers in the final preliminary design, whereas they were raised off the repository floor in large concrete T-H-E arrays in the Reference Case above the water level in the repository. As with other containers, the ILW shield containers are conservatively assumed to fail (see Appendix J.5) from the start of the calculations, allowing contaminants to be released. Figure 5.10 shows the calculated radionuclide release for the ILW filters and elements, irradiated core components, and IX columns waste categories (labelled “Former T-H-E Wastes”) for the NE-PD-RC-A case. The figure highlights that total releases are dominated by those from the ILW resins, which are about two orders of magnitude higher than the releases from the “former T-H-E wastes”.

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

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



**Figure 5.10: Total Radionuclide Releases from the Disposed Waste for the Final Preliminary Design Case (NE-PD-RC-A)**



**Figure 5.11: Volumetric Concentration in Successive Shaft Compartments (Bq per m<sup>3</sup> of Shaft Seal Material) for the Reference Case (NE-RC-A) and Final Preliminary Design Case (NE-PD-RC-A)**

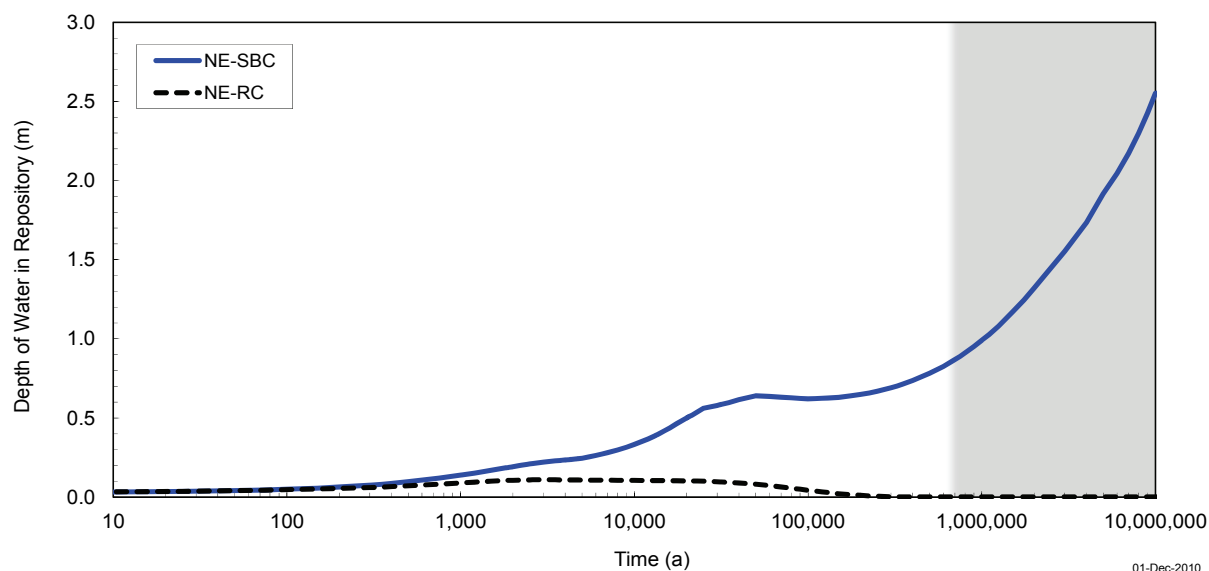
## 6. VARIANT CASES

Variant calculations have been undertaken to investigate both conceptual model uncertainty and data uncertainty in the Normal Evolution Scenario. These cases are described in Table 3.1 and their results are presented below.

### 6.1 NE-SBC-A: Simplified Base Case (No Ordovician Underpressure and Partial Gas Saturation)

This variant case represents steady-state conditions in the geosphere, with the overpressure in the Cambrian sandstone being dissipated over the Deep and Intermediate Bedrock Groundwater Zones; i.e., the case does not include the underpressures observed in Ordovician formations above the DGR. This is a conservative case in relation to the Reference Case (NE-RC-A), as the steady-state conditions have a hydraulic head gradient favouring groundwater flow from the DGR towards the Shallow Bedrock Groundwater zone. The case also assumes no partial gas saturation in the Ordovician.

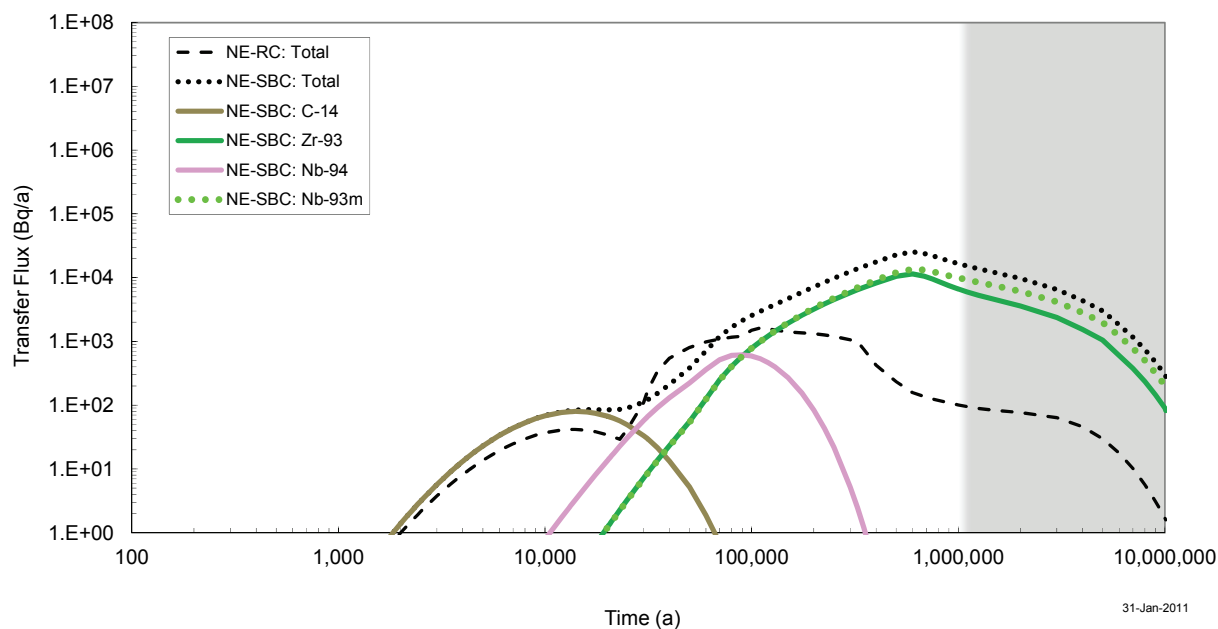
The AMBER model draws the saturation profile, time of initial groundwater flow away from the DGR and the groundwater flow rates directly from the T2GGM NE-SBC-T2 case (Section 5.2 of GEOFIRMA and QUINTESSA 2011), and the FRAC3DVS-OPG NE-SBC-F3 case (Section 5.3 of GEOFIRMA 2011). The depth of water in the repository derived from the T2GGM results is illustrated in Figure 6.1 (note that the average repository height is 7 m). The higher water level in the DGR means that more of the waste becomes saturated and releases contamination to the groundwater than is seen for the NE-RC-A case. T2GGM results indicate that there is no groundwater flow away from the DGR via the monolith and shafts before 50,000 years and that there is no transport of free gas from the repository (Figures 5.48 to 5.53 of GEOFIRMA and QUINTESSA 2011).



**Figure 6.1: Depth of Water in the Repository for the Simplified Base Case (NE-SBC-A), in Comparison to the Reference Case (NE-RC-A)**



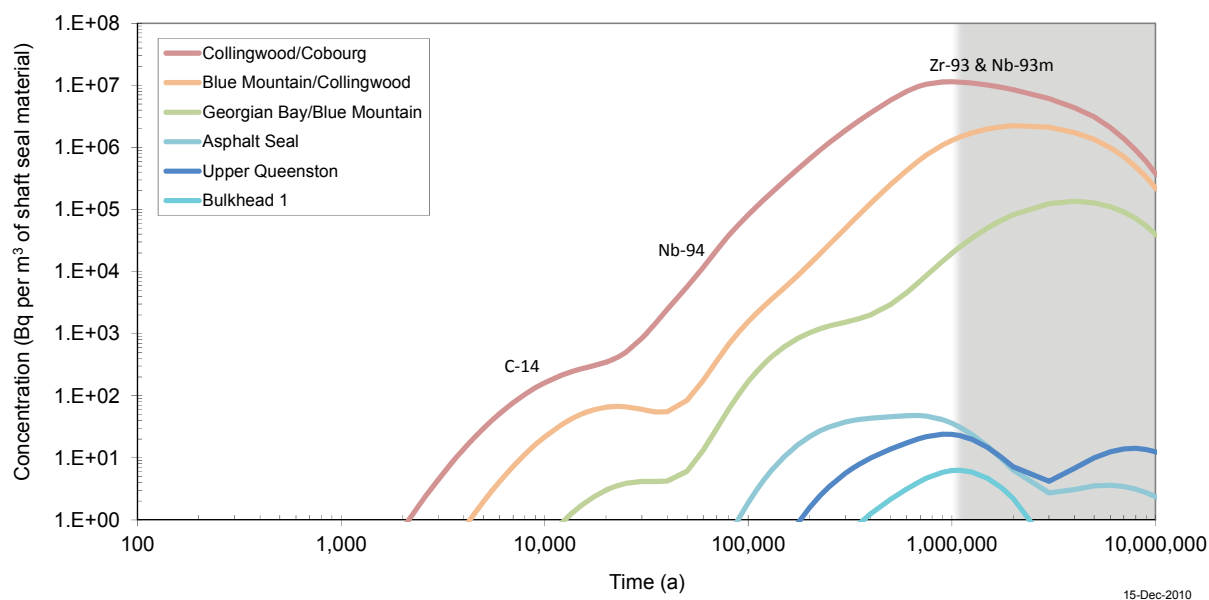
The calculated radionuclide transfer fluxes past the monolith to the base of the shafts are shown in Figure 6.2 and compared against the total for the Reference Case. The figure shows that the greater release of radionuclides into the repository water and the greater magnitude of groundwater flows at the base of the shafts mean that the radionuclide flux to the shafts are mostly greater for the Simplified Base Case. The exception is a period between 25,000 and 50,000 years due to earlier groundwater flow away from the DGR in the Reference Case.



**Figure 6.2: Radionuclide Flux to the Base of the Shafts for the Simplified Base Case (NE-SBC-A)**

The greater radionuclide flux into the shafts and the consistent groundwater flow in the shafts towards the Shallow Bedrock Groundwater Zone means that there is greater migration of radionuclides up the shaft than in the Reference Case (compare Figure 6.3 with Figure 5.9). However, the shaft seals continue to provide an effective barrier, such that calculated radionuclide fluxes to the Shallow Bedrock Groundwater Zone are effectively zero, being less than 1 Bq/a throughout the calculation period.

The calculated release to the biosphere is similarly small with the maximum calculated dose to an adult member of the Site Resident Group being  $1 \times 10^{-13}$  mSv/a at the end of the calculation period. The calculated doses to all age groups remain much less than the dose criterion of 0.3 mSv/a.

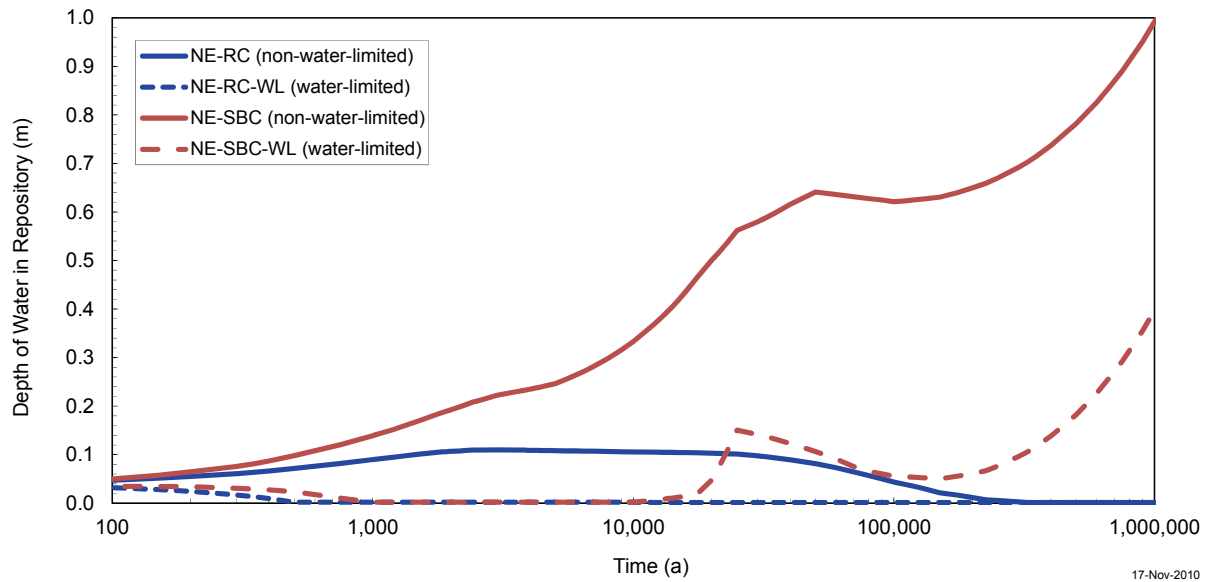


**Figure 6.3: Total Volumetric Concentration in Successive Shaft Compartments for the Simplified Base Case (NE-SBC-A)**

## 6.2 NE-RC-WL-A and NE-SBC-WL-A: Water-Limited Reactions

The Reference Case and Simplified Base Case ignore the effect of the consumption (or production) of water by corrosion and degradation reactions. “Water-limited” variants to the Reference Case and Simplified Base Case have been run which account for the effect of the consumption (or production) of water by these reactions. Since the water-limited cases allow for water consumption by corrosion and degradation reactions, these cases result in even lower levels of repository saturation (see Figure 6.4).

The lower water levels in the DGR mean that even less contamination is released into the repository water, which results in lower contaminant transport via the shafts. The maximum calculated dose for the NE-RC-WL-A case is  $4 \times 10^{-16}$  mSv/a, while that for the NE-SBC-WL-A case is  $6 \times 10^{-14}$  mSv/a, representing a reduction in comparison to the associated non-water-limited cases of about 70% and 35%, respectively.

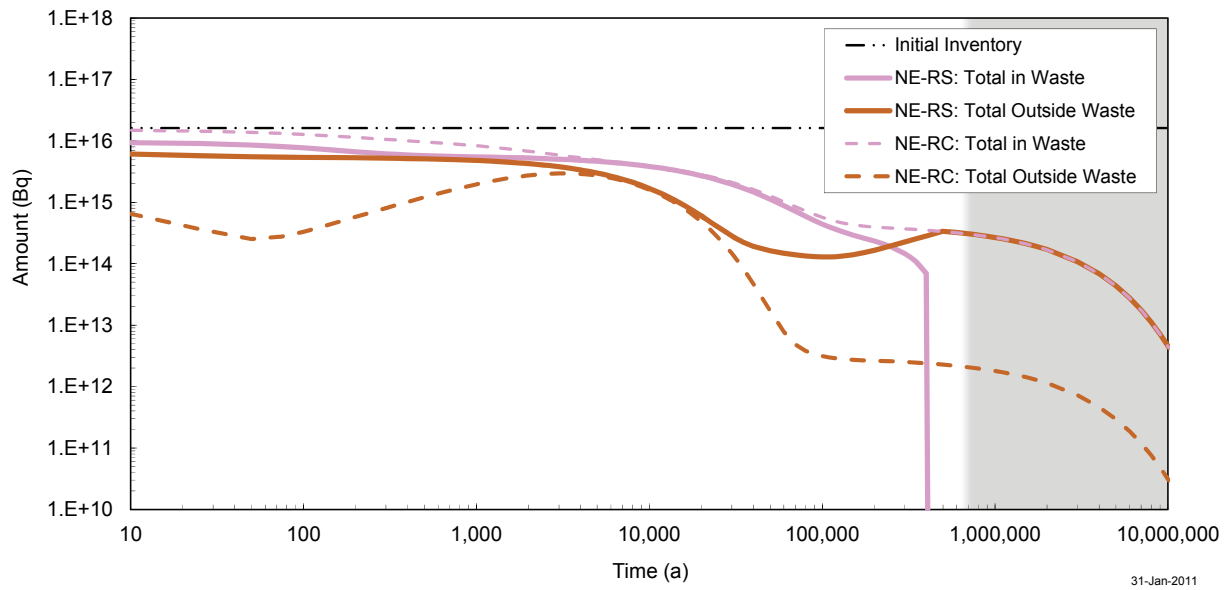


**Figure 6.4: Height of Water in the DGR for the Reference Case (NE-RC) and Simplified Base Case (NE-SBC) with and without Water-Limited Corrosion/Degradation Reactions**

### 6.3 NE-RS-A: Resaturated Repository

The NE-RS-A case conservatively considers the repository to be fully resaturated from closure and there is no gas generation. This maximizes the release of radionuclides from the wastes into repository water and therefore the groundwater pathway. The gas pathway is not modelled in this limiting “what if” case. The AMBER model for this case adopts groundwater flow rates from the reference FRAC3DVS-OPG case (NE-RC-F3); i.e., including the observed underpressures in the Ordovician formations above the DGR.

The amount of radioactivity remaining in the waste and released into repository water is shown in Figure 6.5 for the NE-RS-A case. The figure shows that the full inventory is released by the time that the Zircaloy wastes have completely corroded, after 500,000 years. This differs from the Reference Case, in which most of the radioactivity remains within the disposed wastes due to the very low level of repository resaturation (e.g., much of the corroded Zircaloy remains unsaturated).

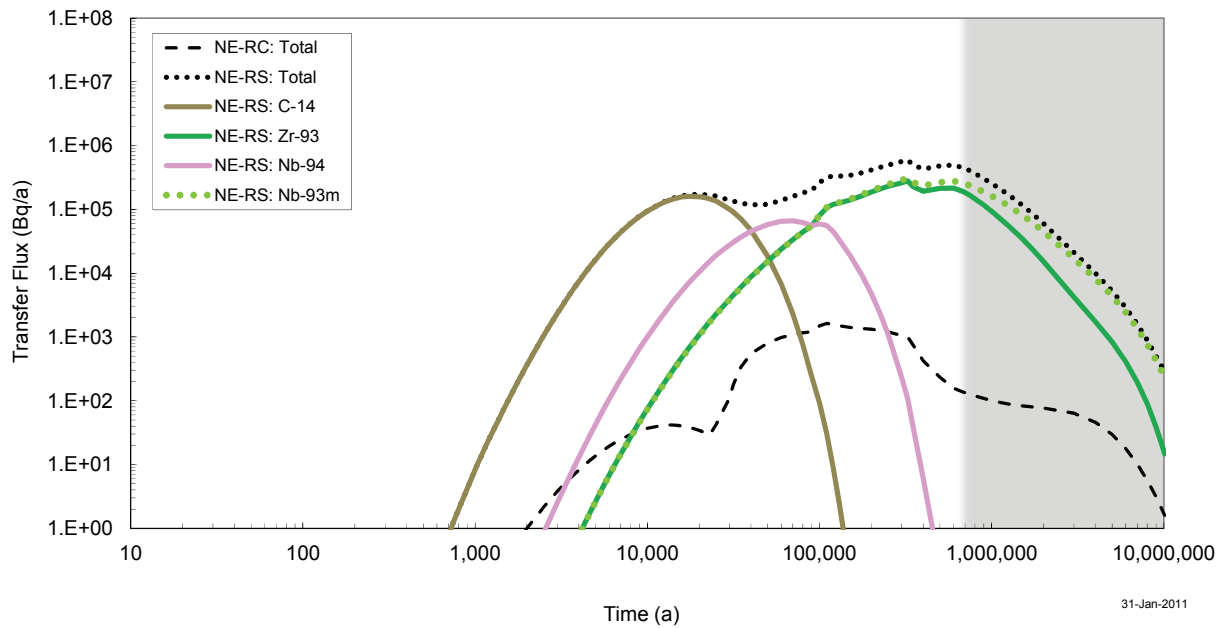


**Figure 6.5: Total Radioactivity in Waste and Released for the NE-RS-A Case**

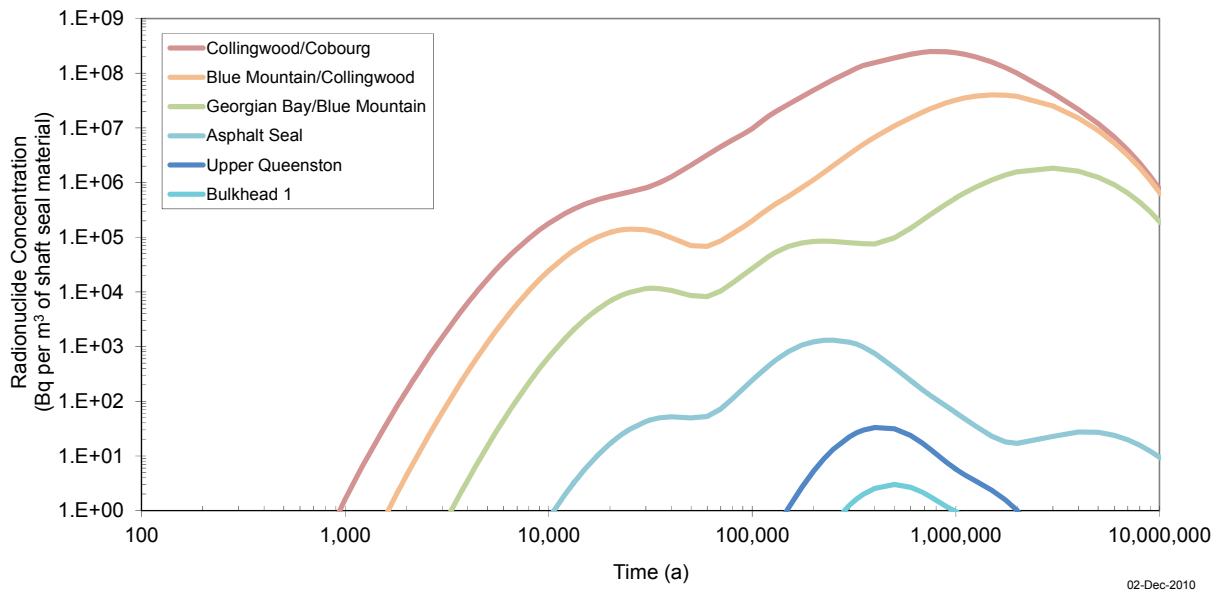
The calculated radionuclide transfer fluxes from the monolith and its EDZs to the base of the shafts and their EDZs are shown in Figure 6.6 and compared against the total for the Reference Case. The figure shows that the greater amount of water in the repository and the associated greater release of radionuclides from the wastes results in higher calculated radionuclide fluxes to the base of the shafts.

The greater radionuclide flux into the shafts means that there is greater migration of radionuclides up the shaft than in the Reference Case (compare Figure 6.7 with Figure 5.9). However, the shaft seals continue to provide an effective barrier, such that calculated radionuclide fluxes to the Shallow Bedrock Groundwater Zone are effectively zero, being less than 1 Bq/a throughout the calculation period.

The calculated release to the biosphere is similarly small with the maximum calculated dose to an adult member of the Site Resident Group being  $4 \times 10^{-14}$  mSv/a at the end of the calculation period. The calculated doses to all age groups remain much less than the dose criterion of 0.3 mSv/a.



**Figure 6.6: Radionuclide Flux to the Base of the Shafts for the NE-RS-A Case**



**Figure 6.7: Radionuclide Concentration in Successive Shaft Compartments (Bq per m<sup>3</sup> of Shaft Seal Material) for the NE-RS-A Case**

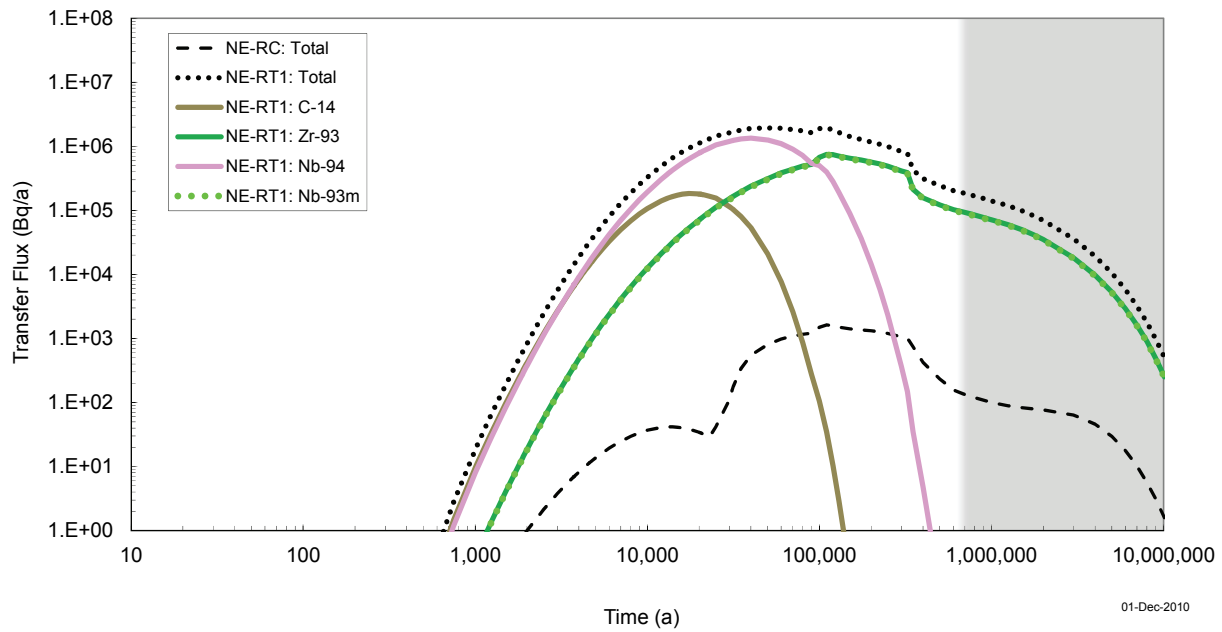
#### **6.4 NE-RT1-A: Reference Case with Conservative Radionuclide Release and Transport**

The NE-RT1-A case is based on the Reference Case (i.e., including initial underpressures in the Ordovician above the DGR), but adopts instant resaturation, instant contaminant releases from waste packages, no solubility limitation or sorption for all radionuclides, and no gas generation. It is not a physically plausible case for the DGR closure option being assessed, but provides an insight into the role of waste releases and sorption in the calculated results by comparison with the Reference Case results.

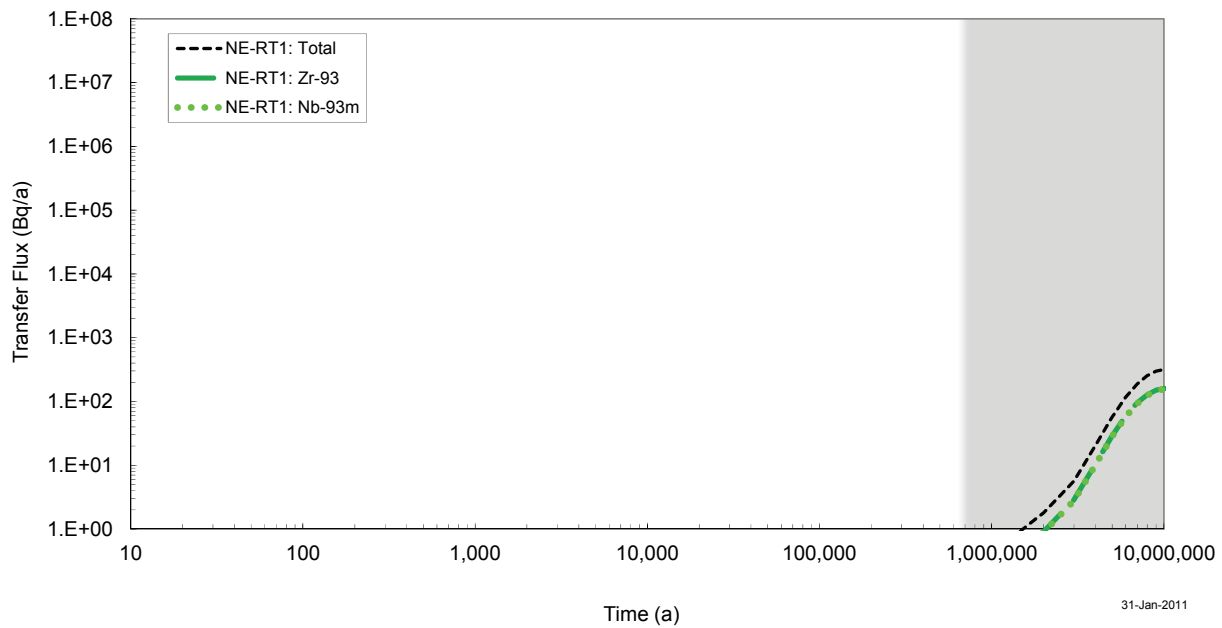
Figure 6.8 shows the calculated transfer fluxes to the base of the shafts for the NE-RT1-A case in comparison to the Reference Case results. The figure shows that instant resaturation and instant releases (there is no sorption in the repository model) results in a more than two order of magnitude increase in the peak calculated groundwater fluxes to the shafts compared to the Reference Case. The results indicate that the gradual resaturation of the repository and the Zircaloy waste forms provide a notable degree of retention for releases to water for the Reference Case.

Although the calculated radionuclide flux to the base of the shafts peaks at about 2 MBq/a, the calculated flux to the Shallow Bedrock Groundwater Zone peaks at only 300 Bq/a, due to the effectiveness of the shaft seals (Figure 6.9). The peak calculated flux into the shallow system is dominated by Zr-93 and its progeny Nb-93m. The peak calculated flux of Zr-93 to the base of the shaft is 0.7 MBq/a after about 110,000 years, while the peak calculated flux into the shallow system occurs after one million years.

In the absence of sorption in the Shallow Bedrock Groundwater Zone, the horizontal groundwater flow in the shallow system means that any contaminant that reaches the bottom of this Zone is discharged to the lake with a travel time of about 750 years. The detailed groundwater flow modelling indicates that the well intercepts about 1.15% of the plume. The small calculated release to the biosphere results in extremely small calculated doses, with the maximum calculated dose to an adult member of the Site Resident Group being  $4 \times 10^{-9}$  mSv/a at the end of the calculation period. The calculated doses to all age groups remain much less than the dose criterion of 0.3 mSv/a.



**Figure 6.8: Radionuclide Flux to the Base of the Shafts for the NE-RT1-A Case**



**Figure 6.9: Radionuclide Flux into the Shallow Bedrock Groundwater Zone for the NE-RT1-A Case**

### 6.5 NE-RT2-A: Simplified Base Case with Conservative Radionuclide Release and Transport

The NE-RT2-A case is based on the Simplified Base Case (i.e., steady-state system excluding the initial underpressures in the Ordovician above the DGR), but adopts instant resaturation, no gas generation, instant contaminant releases from waste packages, and no solubility limitation or sorption for all radionuclides. It is not a physically plausible case, but provides an insight into the role of waste releases and sorption in the calculated results by comparison with the Simplified Base Case results.

Figure 6.10 shows the calculated transfer fluxes to the base of the shafts for the NE-RT2-A case in comparison to the Simplified Base Case results. The figure shows that instant resaturation and instant releases (there is no sorption in the repository model) results in a more than an order of magnitude increase in the peak calculated radionuclide fluxes to the shafts compared to the Simplified Base Case.

Although the calculated radionuclide flux to the base of the shafts peaks at about 0.5 MBq/a, the calculated flux to the Shallow Bedrock Groundwater Zone peaks at only 300 Bq/a, due to the effectiveness of the shaft seals (Figure 6.11). The peak calculated flux into the shallow system is dominated by Zr-93 and its progeny Nb-93m. The peak calculated flux of Zr-93 to the base of the shaft is 0.7 MBq/a after about 200,000 years, while the peak calculated flux into the shallow system does not occur until long after one million years.

The small calculated release to the biosphere for this case results in extremely small calculated doses, with the maximum calculated dose to an adult member of the Site Resident Group being  $5 \times 10^{-9}$  mSv/a at the end of the calculation period. The calculated doses to all age groups remain much less than the dose criterion of 0.3 mSv/a.

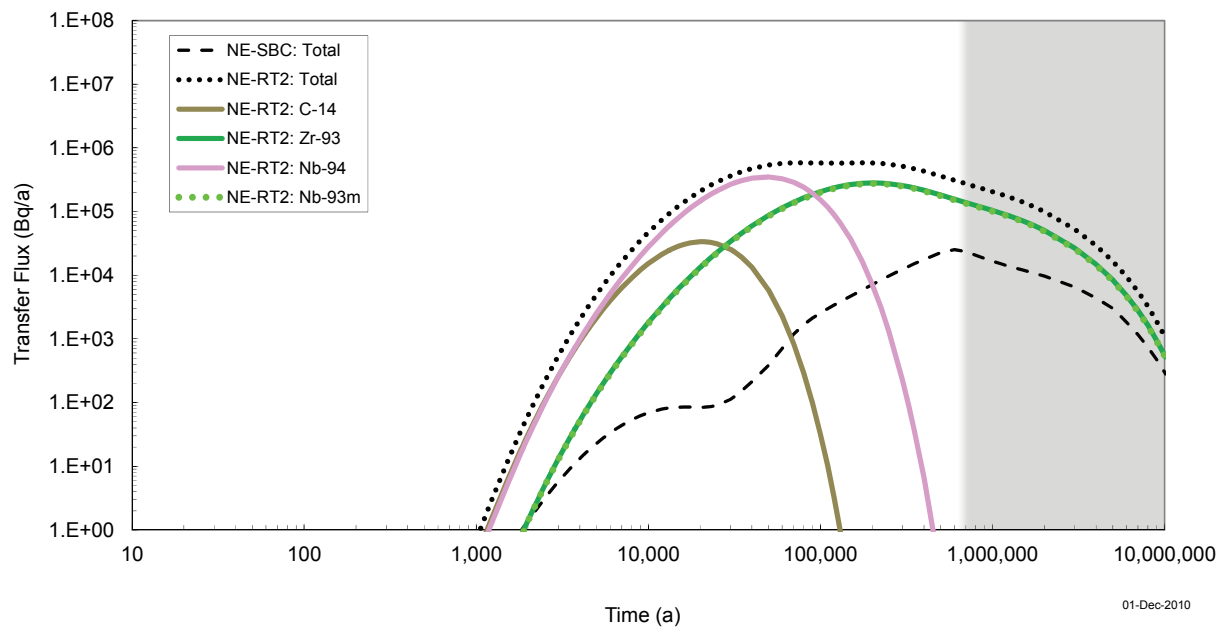
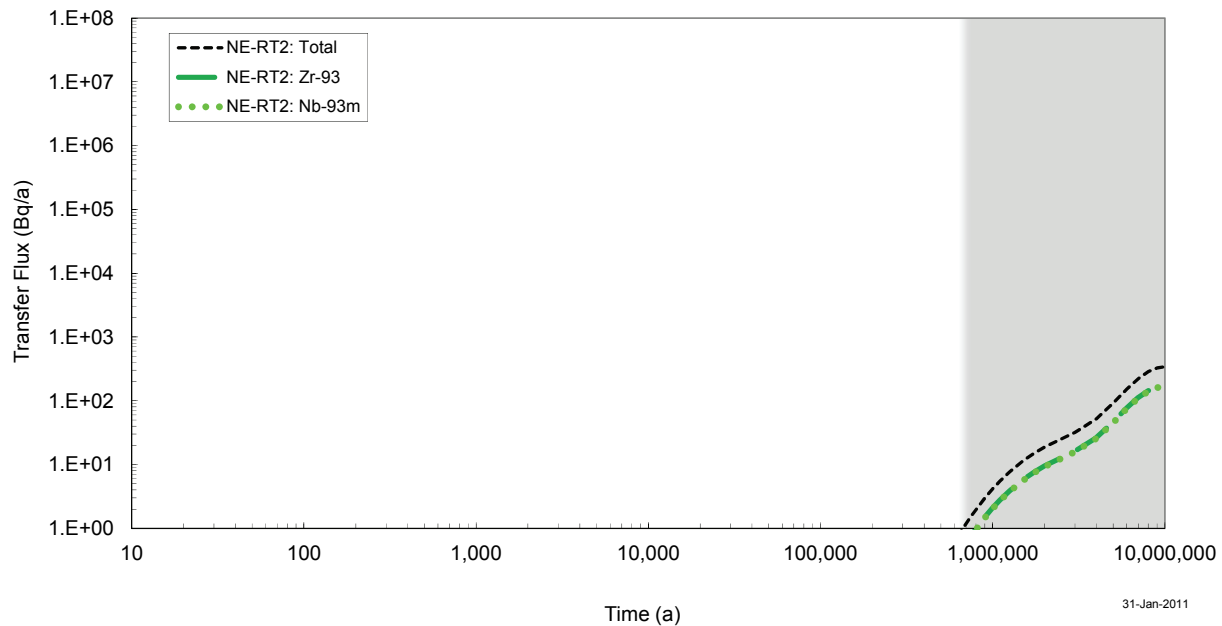


Figure 6.10: Radionuclide Flux to the Base of the Shafts for the NE-RT2-A Case





**Figure 6.11: Radionuclide Flux into the Shallow Bedrock Groundwater Zone for the NE-RT2-A Case**

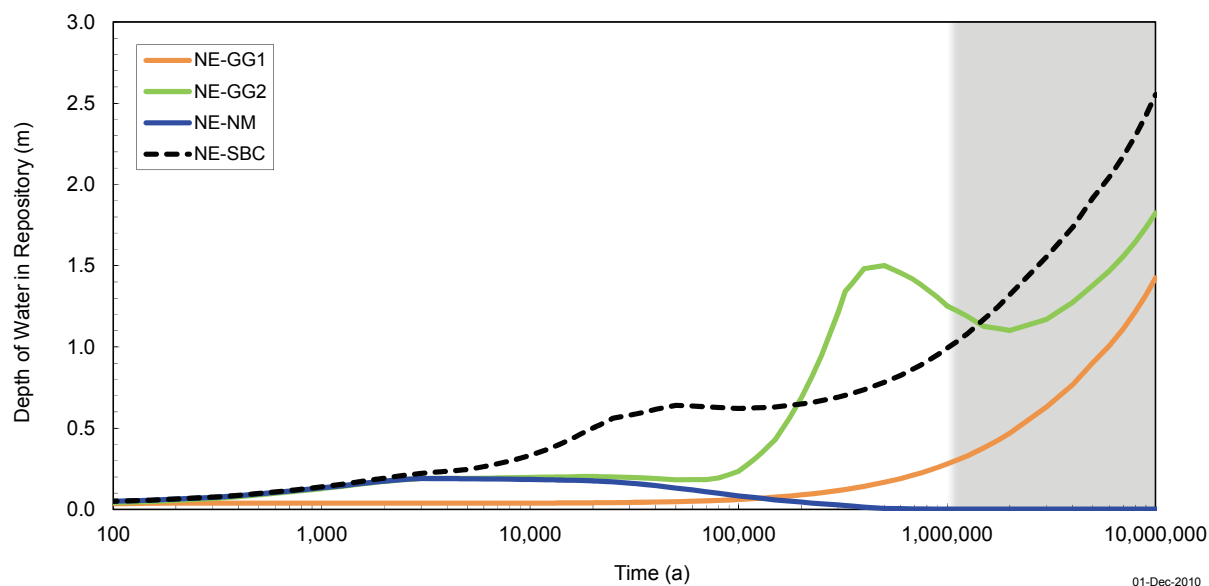
## 6.6 Gas Generation Variants

Three variant cases investigate the potential influence of uncertainties surrounding the gas generation model (see Table 3.1).

- NE-GG1-A considers increased gas generation in comparison to the Reference Case due to an increased metal inventory and increased corrosion and degradation rates.
- NE-GG2-A represents reduced organic degradation rates in comparison to the Reference Case.
- NE-NM-A excludes methanogenic gas reactions from the gas generation model.

In each case, the saturation profile for the repository and the time of initial groundwater flows away from the DGR are taken from the associated T2GGM cases (Sections 5.5, 5.6 and 5.11 of GEOFIRMA and QUINTESSA 2011).

Figure 6.12 shows that the water level in the repository for these variant cases in comparison to that for the Simplified Base Case (NE-SBC-A). The figure shows all three cases result in a lower degree of repository water resaturation for at least 100,000 years, which results in lower potential for releases from the waste to the repository water. The water level for the NE-GG1-A and NE-GG2-A cases reaches up to 1.5 m after one million years, whereas the NE-NM case remains almost completely unsaturated.



**Figure 6.12: Depth of Water in the Repository for the NE-GG1-A, NE-GG2-A and NE-NM-A Cases, in Comparison to the Simplified Base Case (NE-SBC-A)**

The detailed gas modelling undertaken with T2GGM indicates that the gas pressure in the repository is sufficient in both the NE-GG1-A and NE-NM-A cases to force free gas to migrate from the DGR into the shafts, but not for NE-GG2-A. However, although the calculations show the potential for free gas to travel more than 200 m up the shafts, in both cases the gas is captured by the permeable Guelph and Salina A1 upper carbonate formations and does not extend beyond the Salina A2 formation. T2GGM therefore shows that there is no free gas pathway to the Shallow Bedrock Groundwater Zone for these cases<sup>9</sup>. Nonetheless, radiolabelled gases can be transported in the gas phase via the shafts and then partition into groundwater in the shafts within the Intermediate Bedrock Groundwater Zone.

The transfer of C-14 in gas dominates the transfer of contaminants from the repository to the shafts in the NE-GG1-A and NE-NM-A cases and is shown in Figure 6.13. The fluctuations in the C-14 gas fluxes from the DGR reflect variations in the gas flow rates calculated by T2GGM. The figure also shows the flux of C-14 to groundwater in the shafts level with the Guelph formation, which is initiated when gas flow reaches the Guelph formation.

<sup>9</sup> If the free gas is conservatively assumed to reach the Shallow Bedrock Groundwater Zone, then the peak calculated doses would be  $3 \times 10^{-3}$  mSv/a after 9000 years and  $2 \times 10^{-6}$  mSv/a after 35,000 years for the NE-GG1-A and NE-NM-A cases, respectively, due to consumption of plant and animal produce contaminated with C-14.

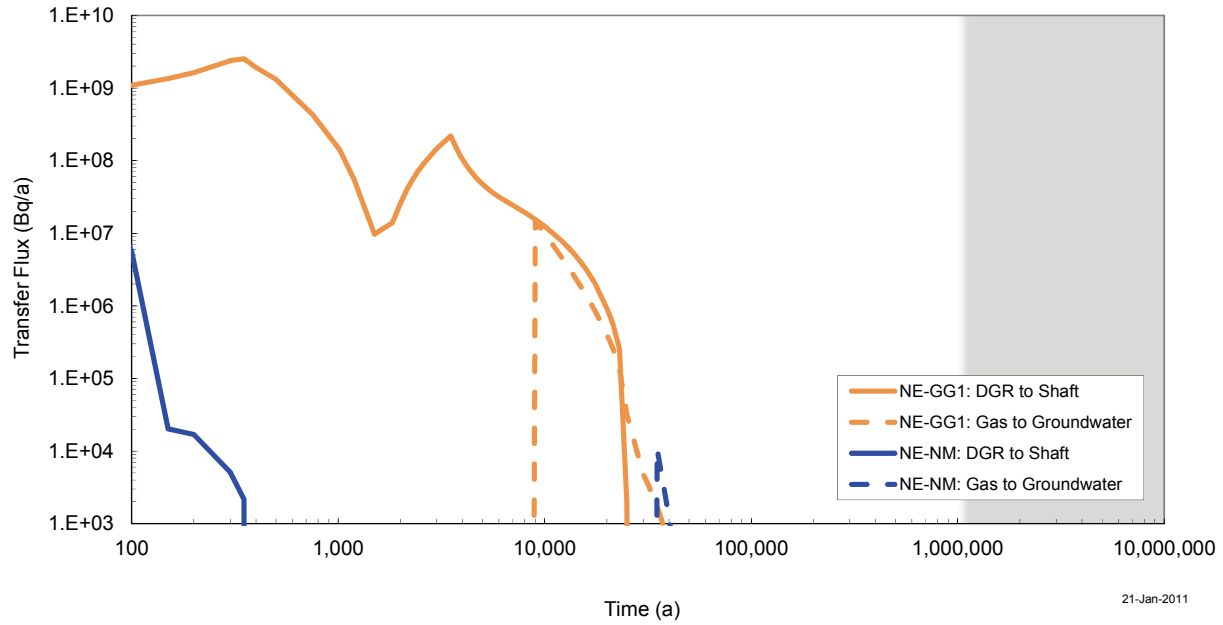
The calculated radionuclide fluxes in groundwater to the base of the shafts are shown in Figure 6.14 for the NE-GG1-A, NE-GG2-A and NE-NM-A cases, in comparison to the results for the NE-SBC-A case, on which the groundwater flow rates are based. The figure shows that while there are some differences in the timescale of releases to the shaft, which reflect the water level in the repository and the time at which groundwater starts to flow away from the DGR via the monolith, the overall magnitude of the fluxes is similar to the NE-SBC-A case.

The calculated radionuclide transfer flux to the Shallow Bedrock Groundwater Zone remains extremely small (less than 1 Bq/a) for the NE-GG1-A, NE-GG2-A and NE-NM-A cases. This indicates that much of the C-14 gas that enters groundwater within the shafts level with the Guelph formation in the NE-GG1-A and NE-NM-A cases decays and/or diffuses into the host rock before reaching the shallow system via diffusion and groundwater advection within the shaft.

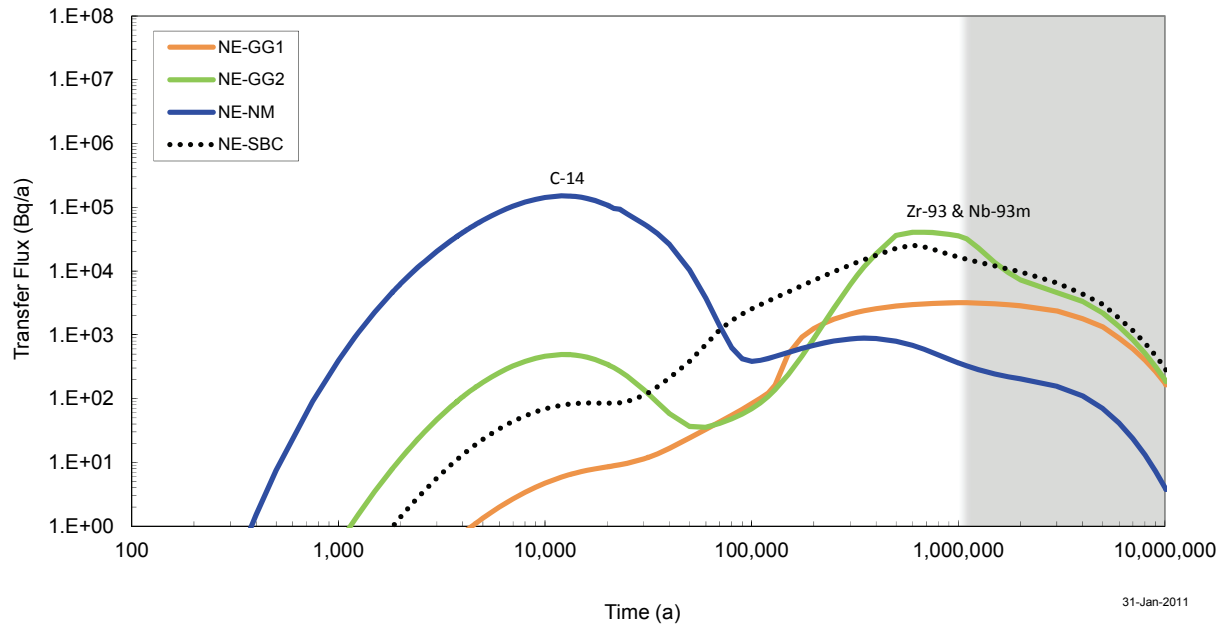
The calculated releases to the biosphere for the NE-GG1-A, NE-GG2-A and NE-NM-A cases remain extremely small.

- NE-GG1-A: The maximum calculated dose to an adult member of the Site Resident Group is  $9 \times 10^{-11}$  mSv/a after 40,000 years due to C-14.
- NE-GG2-A: The maximum calculated dose to an adult member of the Site Resident Group is  $9 \times 10^{-14}$  mSv/a at the end of the calculation period due to I-129.
- NE-NM-A: The maximum calculated dose to an adult member of the Site Resident Group is  $5 \times 10^{-14}$  mSv/a after 70,000 years due to C-14.

In all of these cases, the calculated doses to all age groups remain much less than the dose criterion of 0.3 mSv/a.



**Figure 6.13: C-14 Gas Flux to the Shafts and to Groundwater within the Shafts at the Level of the Guelph Formation for the NE-GG1-A and NE-NM-A Cases**



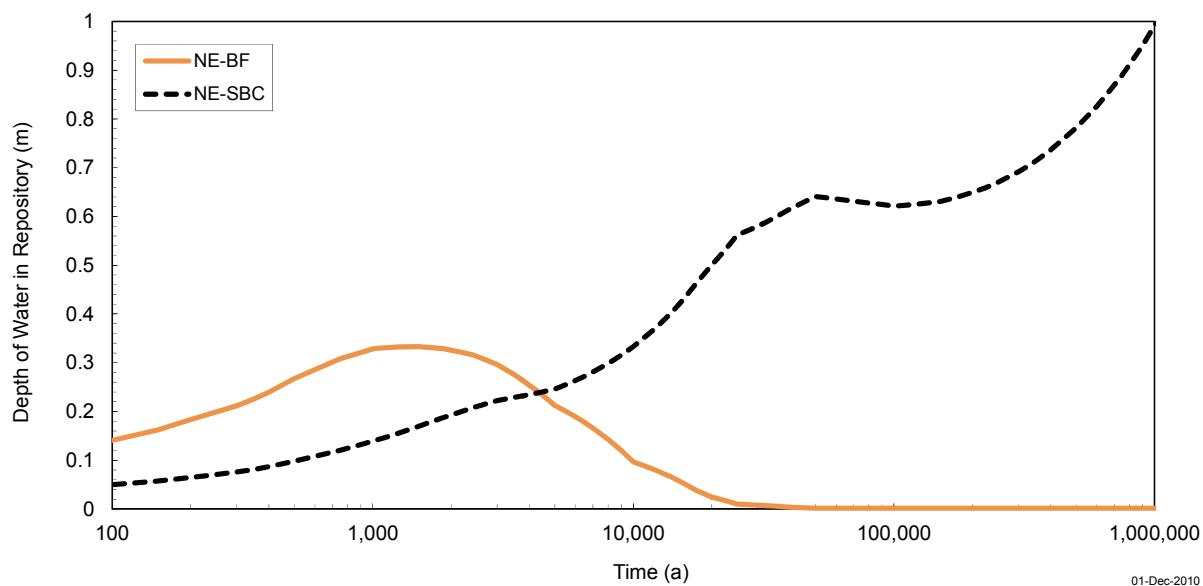
**Figure 6.14: Radionuclide Flux in Groundwater to the Base of the Shafts for the NE-GG1-A, NE-GG2-A and NE-NM-A Cases**

## 6.7 NE-IV-A: Increased Radionuclide Inventory

A factor of ten increase in the initial radionuclide inventory results in an equivalent increase in the calculated results for the NE-IV-A case. Peak biosphere concentrations and doses therefore remain effectively zero, with the maximum calculated doses to an adult member of the Site Resident Group being  $2 \times 10^{-14}$  mSv/a at the end of the calculation period. The calculated doses to all age groups remain much less than the dose criterion of 0.3 mSv/a.

## 6.8 NE-BF-A: Backfilled Repository

This case explores a design alternative; it is not the preliminary design. This case is based on the Simplified Base Case, but with the access tunnels and emplacement rooms backfilled with coarse aggregate material. The T2GGM results from NE-BF-T2 case (Section 5.14 of GEOFIRMA and QUINTESSA 2011) indicate that this will result in higher gas pressures in the repository, which results in the water level in the repository remaining low, and with the repository essentially unsaturated after 10,000 years (see Figure 6.15).



**Figure 6.15: Depth of Water in the Repository for the NE-BF-A Case, in Comparison to the Simplified Base Case (NE-SBC-A)**

The detailed gas modelling undertaken with T2GGM indicates that the gas pressure in the repository is sufficient in the NE-BF-A case to force free gas to migrate from the DGR into the shafts (as for the NE-GG1-A and NE-NM-A cases). However, although the calculations show the potential for free gas to travel more than 200 m up the shafts, the gas is captured by the permeable Guelph and the Salina A1 upper carbonate formations and does not extend beyond

the Salina A2. T2GGM, therefore, shows that there is no free gas pathway to the Shallow Bedrock Groundwater Zone for these cases<sup>10</sup>. Nonetheless, radiolabelled gases can be transported in the gas phase via the shafts and then partition into groundwater in the shafts within the Intermediate Bedrock Groundwater Zone.

The transfer of C-14 in gas dominates the transfer of contaminants from the repository to the shafts and is shown in Figure 6.16. The fluctuations in the C-14 gas fluxes from the DGR reflect variations in the gas flow rates calculated by T2GGM. The figure also shows the flux of C-14 to groundwater in the shafts level with the Guelph formation, which is initiated when gas flow reaches the Guelph.

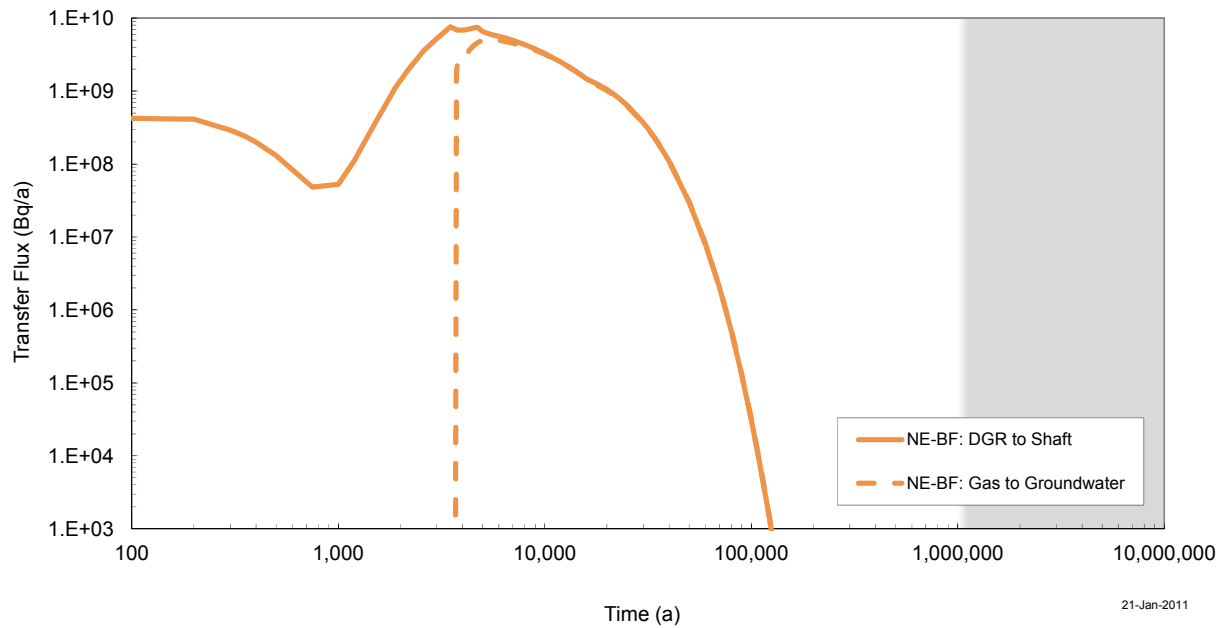
Figure 6.17 shows the calculated radionuclide flux in groundwater to the base of the shafts for the NE-BF-A case in comparison to the NE-SBC-A case. The figure shows that while the release of C-14 in groundwater to the shafts is greater for the NE-BF-A case, the lower level of repository saturation beyond 5,000 years effectively prevents the release of other radionuclides via the groundwater pathway (notable for Zr-93 and Nb-93m on longer timescales in the figure).

While there is a notable transfer of C-14 in gas to the shafts level with the Guelph formation (peaking at about 8 GBq/a after 3,500 years), the effectiveness of the shaft seals means that only a relatively small amount reaches the Shallow Bedrock Groundwater Zone (peaking at about 400 Bq/a after 40,000 years) due to diffusion and groundwater advection in the shafts. Calculated biosphere concentrations therefore remain low, and the maximum calculated dose to an adult member of the Site Resident Group is  $8 \times 10^{-8}$  mSv/a after 40,000 years due to C-14. The calculated doses to all age groups remain much less than the dose criterion of 0.3 mSv/a.

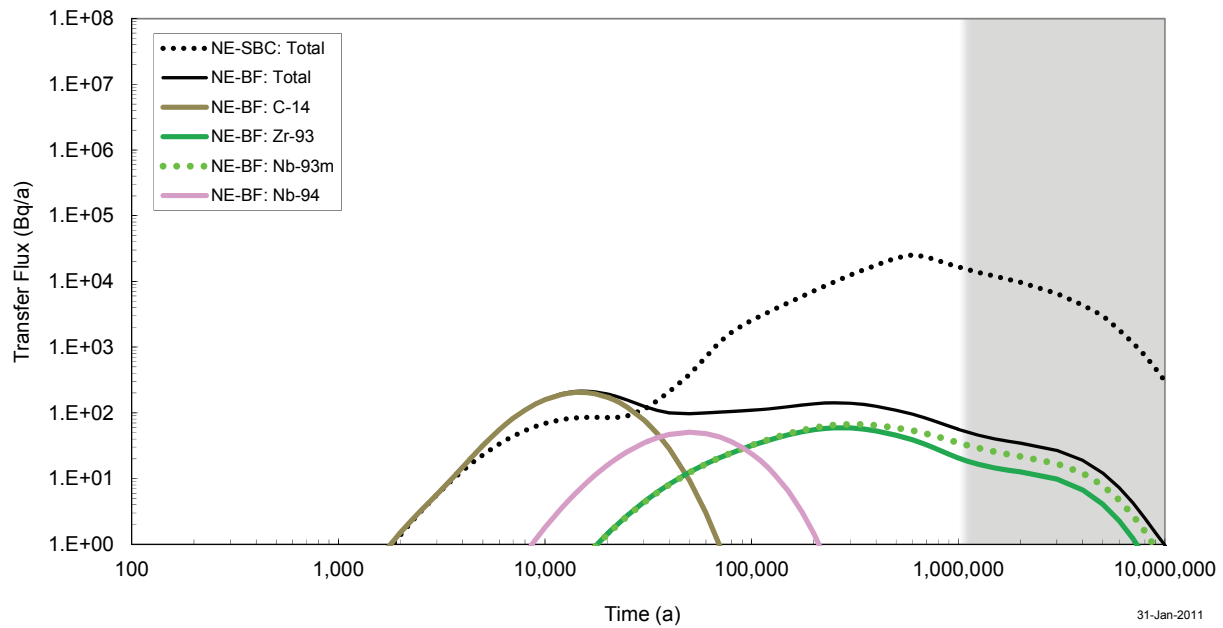
The mechanical effects of the high repository pressure (16 MPa) calculated for the non-water-limited version of this case were not assessed. If a pressure of 16 MPa were to cause the shaft seals to fail, then much higher dose rates would result. However, the pressure for the water-limited version of the backfill case is lower at 7.5 MPa and the use of backfill is not currently the design basis.

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<sup>10</sup> If the free gas is conservatively assumed to reach the Shallow Bedrock Groundwater Zone directly via the shafts, then the peak calculated dose would be 2 mSv/a after 5000 years due to consumption of plant and animal produce contaminated by C-14.



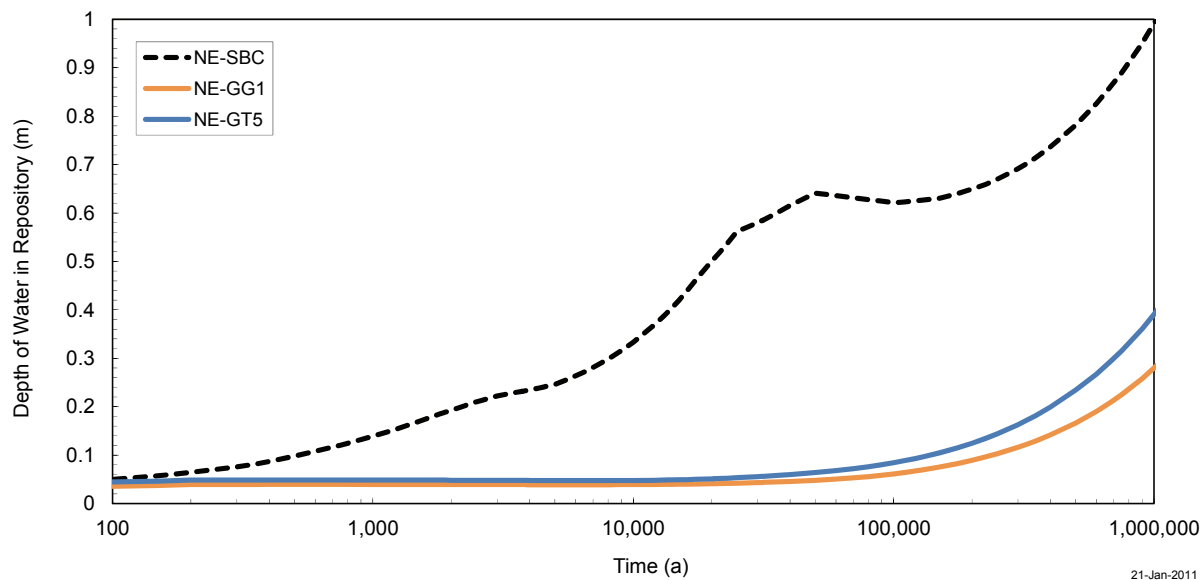
**Figure 6.16: C-14 Gas Flux to the Shafts and to Groundwater within the Shafts at the Level of the Guelph Formation for the NE-BF-A Case**



**Figure 6.17: Radionuclide Flux in Groundwater to the Base of the Shafts for the NE-BF-A Case**

## 6.9 NE-GT5-A: Increased Gas Generation and Reduced Shaft Seal Performance

This case is the same as NE-GG1-A but with a factor of two reduction in gas entry pressure for shaft materials to  $5 \times 10^6$  Pa and an order of magnitude increase in hydraulic conductivity of bentonite/sand to  $10^{-10}$  m/s. In addition, the asphalt seal in the shaft is replaced by bentonite/sand. These modifications result in a greater degree of repository saturation in comparison to the NE-GG1-A case, while the water level in the DGR remains lower than for the Simplified Base Case (see Figure 6.18).



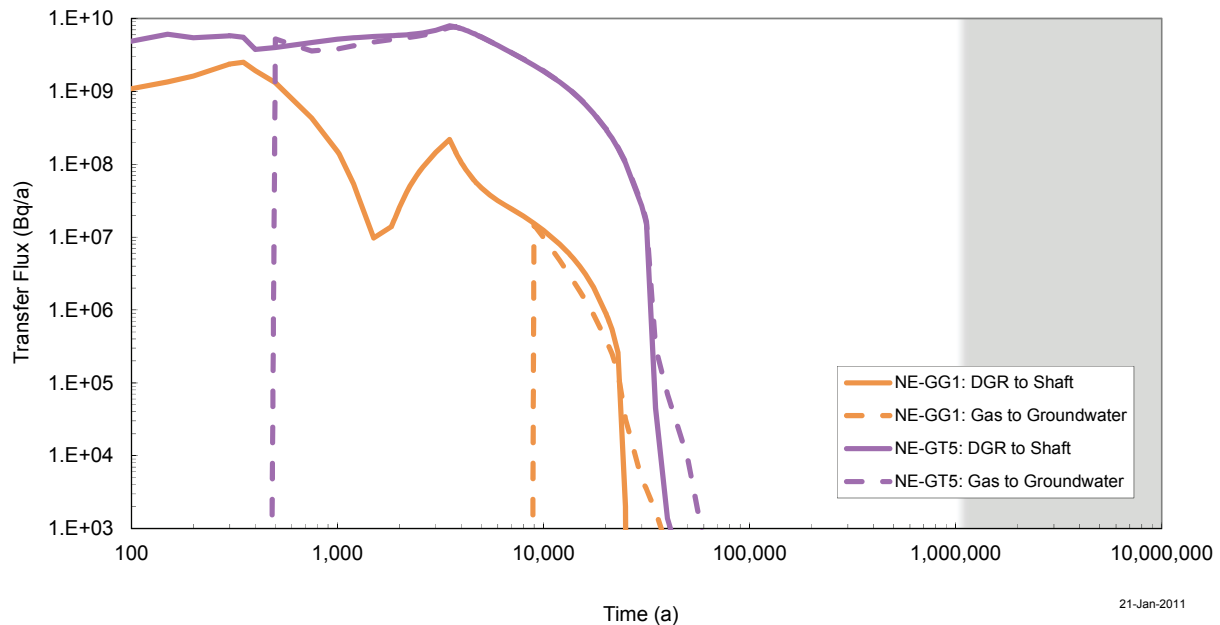
**Figure 6.18: Depth of Water in the Repository for the NE-GT5-A Case, in Comparison to the Simplified Base Case (NE-SBC-A) and NE-GG1-A**

As for the NE-GG1-A case, the detailed gas modelling undertaken with T2GGM indicates that the gas pressure in the repository is sufficient in the NE-GT5-A case to force free gas to migrate from the DGR into the shafts (Section 5.8 of GEOFIRMA and QUINTESSA 2011). However, although the calculations show the potential for free gas to travel more than 200 m up the shafts, the gas is captured by the permeable Guelph and the Salina A1 upper carbonate formations and does not extend beyond the Salina A2. T2GGM, therefore, shows that there is no free gas pathway to the Shallow Bedrock Groundwater Zone for this case<sup>11</sup>. Nonetheless, radiolabelled gases can be transported in the gas phase via the shafts then partition into groundwater in the shafts within the Intermediate Bedrock Groundwater Zone.

<sup>11</sup> If the free gas is conservatively assumed to reach the Shallow Bedrock Groundwater Zone directly via the shafts, then the peak calculated dose would be 4 mSv/a after 3,500 years due to consumption of plant and animal produce contaminated with C-14.



The transfer of C-14 in gas dominates the transfer of contaminants from the repository to the shafts and is shown in Figure 6.19 in comparison to that for the NE-GG1-A case from which the NE-GT5-A case is derived. The figure also shows the flux of C-14 to groundwater in the shafts level with the Guelph formation, which is initiated when gas flow reaches the Guelph formation. The reduced performance of the shaft seals result in a higher flux of C-14 gas to the shaft and earlier breakthrough at the Intermediate Bedrock Groundwater Zone.



**Figure 6.19: C-14 Gas Flux to the Shafts and to Groundwater within the Shafts at the Level of the Guelph Formation for the NE-BF-A Case**

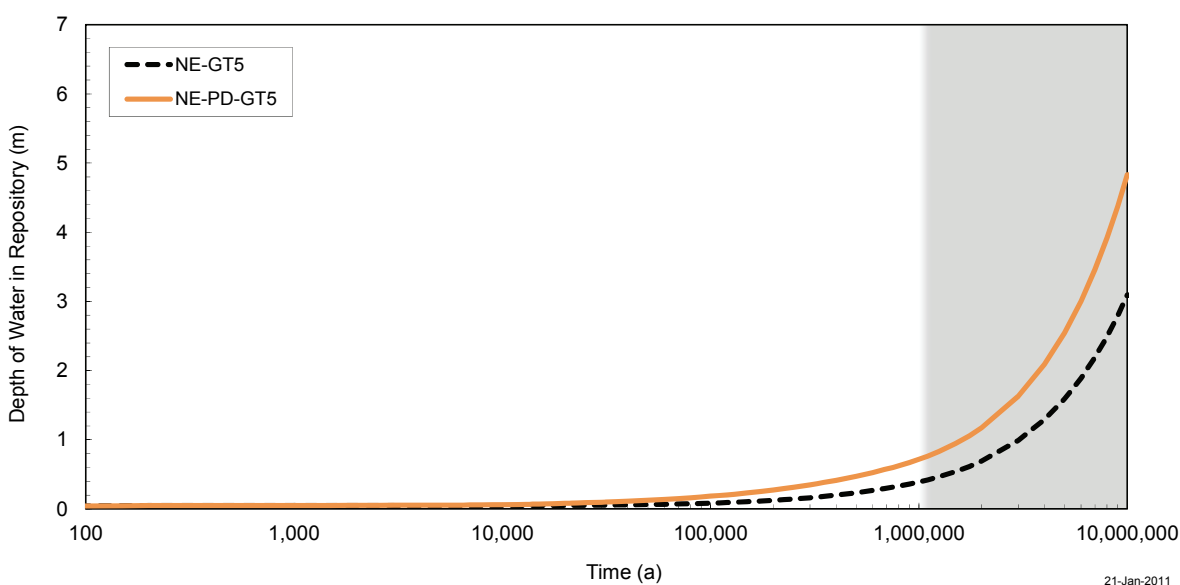
While there is a notable transfer of C-14 in gas to the shafts level with the Guelph formation (peaking at about 8 GBq/a after 3,500 years), the effectiveness of the shaft seals means that only a relatively small amount reaches the Shallow Bedrock Groundwater Zone (peaking at about 2,000 Bq/a after 35,000 years) due to diffusion and groundwater advection in the shafts.

The maximum calculated dose to an adult member of the Site Resident Group is higher than that for either the Simplified Base Case or the NE-GG1 case. However it remains very small, at  $5 \times 10^{-7}$  mSv/a after 35,000 years due to ingestion of plant and animal produce contaminated with C-14. The calculated doses to all age groups remain much less than the dose criterion of 0.3 mSv/a.

### 6.10 NE-PD-GT5-A: Increased Gas Generation and Modified Shaft Seal Properties for Final Preliminary Design

This case is the same as the NE-GT5-A case, but with the final preliminary design being represented.

The calculated water level in the repository for the NE-PD-GT5-A case is shown in Figure 6.20 in comparison to the NE-GT5-A case, based on the T2GGM calculations. The figure shows that the water level in the calculation case based on the final preliminary design (NE-PD-GT5-A) is higher, once the repository starts to resaturate due to lower gas pressure (see Section 5.16 of GEOFIRMA and QUINTESSA 2011).



**Figure 6.20: Water Level in the Repository for the Case with Increased Gas Generation and Reduced Seal Performance with the Final Preliminary Design (NE-PD-GT5-A)**

The T2GGM modelling results indicate that, although the gas pressure in the repository is reduced compared with the NE-GT5-A case, it is still sufficient to force some free gas to migrate from the DGR into the shafts. Similarly, the calculations show that, as with the NE-GT5-A case, the gas in the shaft is captured by the relatively permeable Guelph and Salina A1 upper carbonate formations so there is no free gas pathway to the Shallow Bedrock Groundwater Zone for this case<sup>12</sup>. Nonetheless, radiolabelled gases can be transported in the gas phase via

<sup>12</sup> If the free gas is conservatively assumed to reach the Shallow Bedrock Groundwater Zone directly via the shafts, then the peak calculated dose would be 1 mSv/a after 4,000 years due to consumption of plant and animal produce contaminated with C-14.

the shafts and then partition into groundwater in the shafts within the Intermediate Bedrock Groundwater Zone.

The calculated flux of C-14 as gas to the shafts is lower than for the NE-GT5-A case (peaking at 6 GBq/a in comparison to 8 GBq/a for the NE-GT5-A case). While the free gas flow reaches the shafts at the level of the Guelph formation at the same time as in the NE-GT5-A case (after about 500 years), the calculated flux of C-14 from gas to groundwater in the shafts is about 40% lower.

The reduction in the C-14 gas flux to the groundwater in the shafts within the Guelph formation is reflected in a reduction in the calculated radionuclide flux to the Shallow Bedrock Groundwater Zone, which is dominated by C-14 and peaks at about 1,000 Bq/a after 32,000 years (in comparison to 2,000 Bq/a for the NE-GT5-A case). Consequently, the maximum calculated dose to the adult member of the Site Resident Group is also lower, at  $3 \times 10^{-7}$  mSv/a after 32,000 years due to ingestion of plant and animal produce contaminated with C-14. The calculated doses to all age groups remain much less than the dose criterion of 0.3 mSv/a.

### **6.11 NE-EDZ1-A: Enhanced EDZ Permeability**

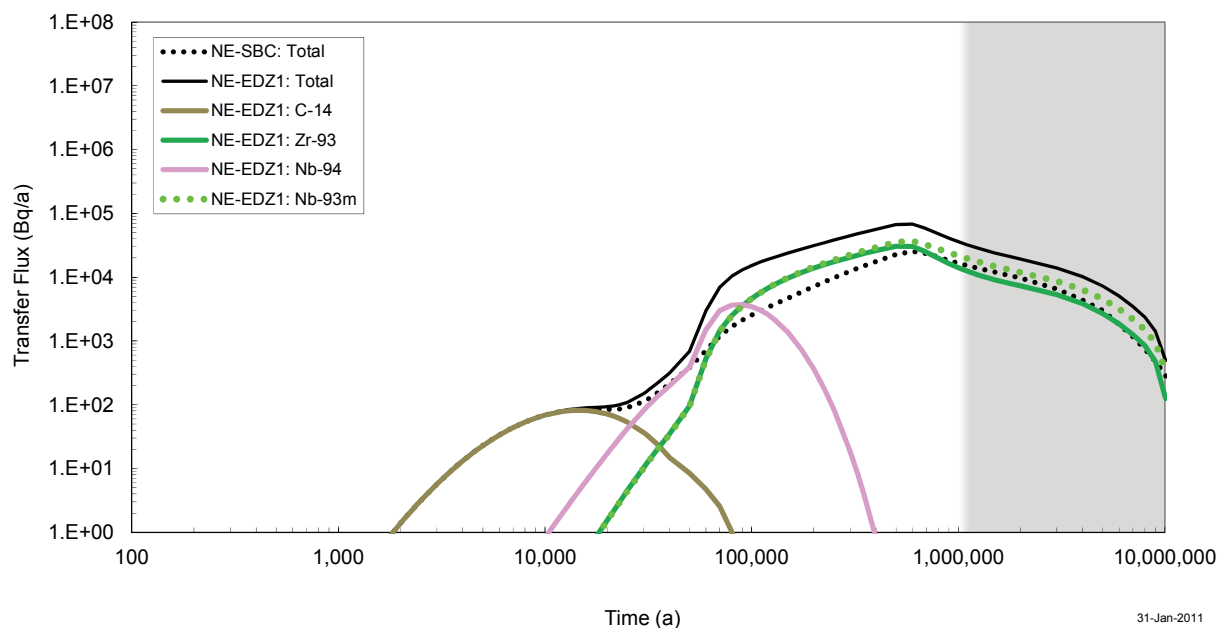
This case investigates the impact of greater than expected permeability in the EDZ around the shafts and repository (see Table 3.1).

T2GGM results (NE-EDZ1-T2) show relatively little difference in the saturation profiles for the repository between the NE-EDZ1-A case and the NE-SBC-A case on which it is based (see Section 5.4 of GEOFIRMA and QUINTESSA 2011). The FRAC3DVS-OPG results (NE-EDZ-F3) indicate a greater magnitude of groundwater flow towards the base of the shafts (Section 5.7 of GEOFIRMA 2011).

The greater groundwater flow from the DGR results in a greater release of radionuclides to the base of the shafts (Figure 6.21).

The FRAC3DVS-OPG results show that groundwater flow towards the Shallow Bedrock Groundwater Zone focuses on the inner EDZ around the shaft rather than flowing through the shaft sealing materials, which is the case for the NE-SBC-A and NE-RC-A cases. However, the slow travel time up the shafts still means that C-14 has decayed before reaching the shallow system. As for the Simplified Base Case, sorption onto the bentonite/sand shaft seals and onto shale formations means that the Zr-93 and Nb-94 do not reach the shallow system. Therefore, the fluxes to the Shallow Bedrock Groundwater Zone remain extremely small for the NE-EDZ1-A case, peaking at only 1 Bq/a after 1.1 million years due to Cl-36.

The small release of radionuclides to the Shallow Bedrock Groundwater Zone translates into equivalently small calculated releases to the biosphere and associated doses. The maximum calculated doses to an adult member of the Site Resident Group is  $2 \times 10^{-11}$  mSv/a, associated with Cl-36 after 1.2 million years. The calculated doses to all age groups remains much less than the dose criterion of 0.3 mSv/a.



**Figure 6.21: Radionuclide Flux to the Base of the Shafts for the NE-EDZ1-A Case**

## 6.12 NE-HG-A: Horizontal Gradients in Guelph and Salina A1 Upper Carbonate Formations

The DGR site investigation boreholes indicate that the permeable Guelph and Salina A1 upper carbonate formations include slow horizontal groundwater flow due to small horizontal gradients in the formations. This flow is conservatively ignored in the Reference and Simplified Base Cases (NE-RC-A and NE-SBC-A) on the basis that groundwater flow in these formations will laterally divert a proportion of any contamination migrating up the shafts away from a potential discharge to the Shallow Bedrock Groundwater Zone. Ignoring this groundwater flow is, therefore, conservative in that this assumption maximizes the potential exposure of a Site Resident Group living on the repository site.

However, in the present variant case, based on the Simplified Base Case, the hydraulic gradients and, therefore, groundwater flow in the Guelph and Salina A1 upper carbonate formations are included. Based on the formations and the current direction of the gradients, the surface discharge would be several tens of kilometres away from the repository. The nearest surface expression is also several tens of kilometres distant, even if the flow direction were to change as a result of glaciation. For this case, both formations are assumed to discharge after a relatively short distance (1.25 km from the repository) to the near shore of the lake.

The saturation profile for the repository and the time of initial groundwater flow away from the DGR via the monolith and its EDZ are taken from the same T2GGM case as used for Simplified Base Case. Groundwater flow rates are drawn from the FRAC3DVS-OPG (NE-HG-F3) case with horizontal groundwater flow in the Guelph and Salina A1 upper carbonate (Section 5.4 of GEOFIRMA 2011). The detailed NE-HG-F3 model shows that the groundwater flow rates around the monolith and via the shaft are almost identical to those for the NE-SBC-F3

FRAC3DVS-OPG case, so releases to the shaft and transport to the Guelph formation are very similar to those for the Simplified Base Case.

The radionuclide flux reaching the Guelph formation is extremely small, such that the peak calculated flux that is captured by the horizontal groundwater flow is less than 1 Bq/a. This occurs after about a million years and represents more than 80% of the flux that reaches the Guelph via the shafts. The calculated flux reaching the Salina A1 upper carbonate is even smaller.

By diverting the flow from the Shallow Bedrock Groundwater Zone, the horizontal groundwater flow reduces the potential for radionuclides to reach the well that is used by the Site Resident Group and is the main source of exposure for the Reference and Simplified Base Cases. Radionuclides discharging to the lake are subject to significant dilution within the water of the lake before exposure may occur, e.g., from eating fish from the lake. The maximum calculated doses to an adult member of the Site Resident Group for the NE-HG-A case is  $5 \times 10^{-16}$  mSv/a. The calculated doses to all age groups remain much less than the dose criterion of 0.3 mSv/a.

### **6.13 NE-CG-A: Alternative Critical Groups**

This case considers potential exposures to two extra groups that are exposed through the consumption of high-fish diets and water from Lake Huron. A “shore” group is assumed to obtain all its fish and water from the near-shore compartment in the lake, while a “downstream” group is assumed to obtain them from the South Basin of Lake Huron. The calculations are based on the NE-HG-A case, which includes horizontal groundwater flow in the Guelph and Salina A1 upper carbonate formations and maximizes the amount of contamination reaching the lake.

The maximum calculated dose to an adult member of the Site Shore Resident Group is  $6 \times 10^{-16}$  mSv/a, whereas the maximum to the Downstream Resident Group is  $3 \times 10^{-17}$  mSv/a. The ingestion of fish and water from the lake contribute about equally to the calculated dose, which is dominated by I-129 and reaches its maximum at the end of the calculation period. The calculated doses to all age groups remain much smaller than the dose criterion of 0.3 mSv/a.

### **6.14 NE-CC-A: Climate Change – Tundra Biosphere**

This variant calculation considers the effect of exposure to people living at the site in a future cold climate state, to illustrate the importance of alternative biospheres on the impacts. Otherwise, the model is based on the Reference Case for the repository and geosphere. In the tundra biosphere, the boundary of Lake Huron is assumed to be further away, so that fluxes from the Shallow Bedrock Groundwater Zone that had previously entered the near-shore lake compartment now enter a nearby stream instead. Also human activities and diet are assumed to change. A full description of these changes is given in Section 4.4.3.

The extremely small calculated release to the Shallow Bedrock Groundwater Zone for the NE-RC-A case means that calculated doses for the NE-CC-A case are similarly small. The colder climate means that a more limited range of exposure pathways are relevant, e.g., through more limited agricultural use of the land. However, the main exposure pathway is the ingestion of contaminated well water, with the contaminant flux to the well being intercepted by a smaller volume of abstracted well water. This results in calculated well water concentrations that are about a factor of six higher than those for the Reference Case. The maximum calculated dose to an adult member of the Tundra Resident Group is  $7 \times 10^{-15}$  mSv/a. The calculated doses to all age groups remain much smaller than the dose criterion of 0.3 mSv/a.

### **6.15 NE-ER-A: Surface Erosion**

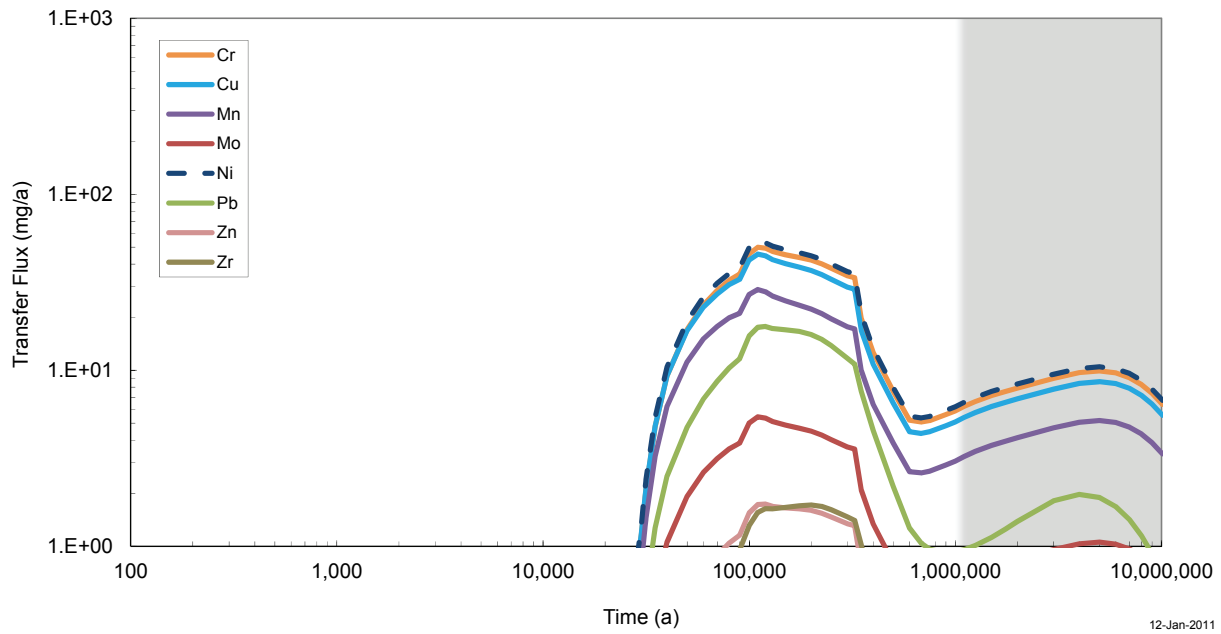
This case is the same as for Reference Case but consideration is given to the removal of 100 m of geosphere due to erosion over 1 million years. It is represented with the entire contaminant flux from the top of the Intermediate Bedrock Groundwater Zone being captured by the groundwater well.

Calculated contaminant fluxes to the biosphere via the well are about two orders of magnitude greater than for the Reference Case, although they remain extremely small, well below 1 Bq/a. Calculated doses to an adult member of the Site Resident Group are similarly small, with a maximum of  $1 \times 10^{-13}$  mSv/a at the end of the calculation period. The calculated doses to all age groups remain much smaller than the dose criterion of 0.3 mSv/a.

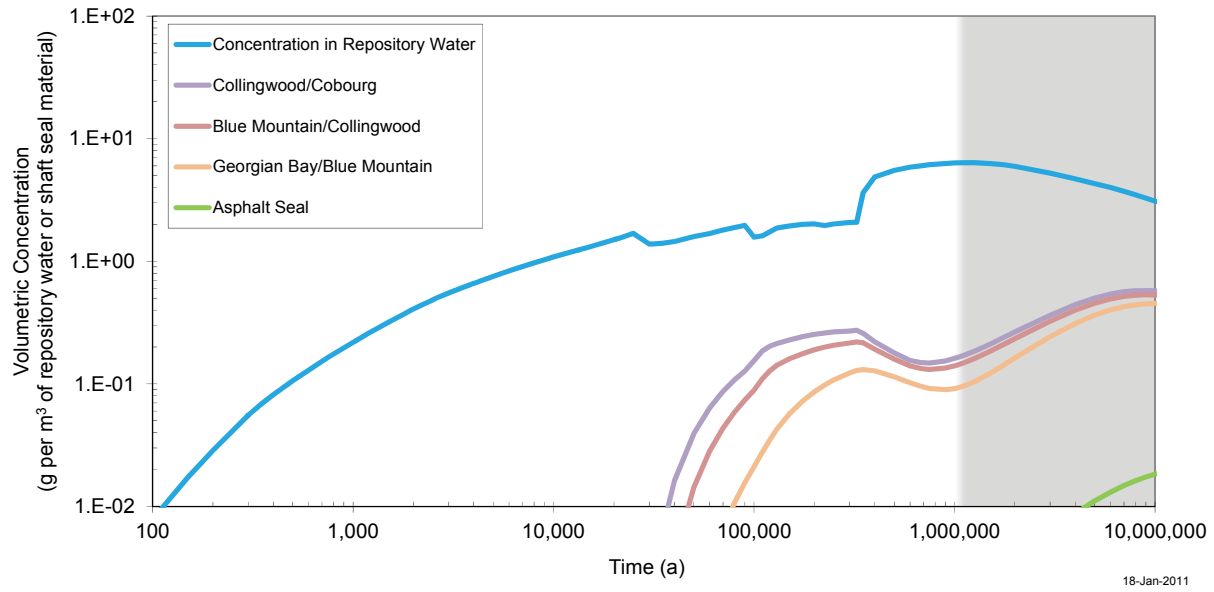
### **6.16 NE-NR-A: Non-radioactive Contaminants**

This case models the release and migration of non-radioactive contaminants, including non-radioactive contaminants (present in the waste packaging and other sources) from the DGR for the Reference Case. As for the radionuclides, the very low degree of repository saturation means that only a very small fraction (2%) of the inventory is released from the repository. Figure 6.22 shows the calculated flux of non-radioactive contaminants from the monolith to the shaft, which peaks at less than 0.1 g/a after about 100,000 years and is dominated by Ni and Cr (over 50% of which comes from non-waste sources) and Cu (which is dominated by non-processible LLW). Figure 6.23 shows how the shaft seals effectively limit the migration of contaminants from the DGR, with very small concentrations that decrease with distance from the repository.

The effectiveness of the shaft seals means that the calculations show only a very small amount of contamination reaching the Shallow Bedrock Groundwater Zone (less than 1 g in total). Consequently, the maximum calculated concentrations in groundwater, soils, surface water and surface water sediments are extremely small (they do not exceed  $2 \times 10^{-5}$  µg/L in well water or surface water, or  $6 \times 10^{-8}$  µg/g in soils or sediments) and very much smaller than the associated environmental quality standards (see Table 6.1).



**Figure 6.22: Contaminant Transfer Flux from the Monolith to the Shafts for the Non-radioactive Case (NE-NR-A)**



**Figure 6.23: Concentration of Ni in Repository Water and in Shaft Seals (g per m³ of Repository Water or per m³ of Sealing Material) for the Non-radioactive Case (NE-NR-A)**

**Table 6.1: Ratio of Calculated Maximum Concentration of Non-radioactive Contaminants in Biosphere Media to Environmental Quality Standards for the Normal Evolution Scenario (NE-NR)**

Contaminant	Well Water	Irrigated Soil	Sediment	Surface Water
Ag	<1E-10	<1E-10	<1E-10	<1E-10
As	1E-10	<1E-10	<1E-10	<1E-10
B	<1E-10	<1E-10	-	<1E-10
Ba	<1E-10	<1E-10	-	<1E-10
Be	1E-09	<1E-10	-	<1E-10
Br	-	-	-	<1E-10
Cd	9E-08	<1E-10	<1E-10	4E-09
Co	8E-10	<1E-10	<1E-10	<1E-10
Cr	1E-06	<1E-10	1E-10	3E-08
Cu	3E-06	<1E-10	4E-09	2E-08
Gd	-	-	-	<1E-10
Hf	-	-	-	<1E-10
Hg	3E-09	<1E-10	<1E-10	1.E-10
I	-	-	-	<1E-10
Li	-	-	-	<1E-10
Mn	-	-	-	<1E-10
Mo	7E-08	<1E-10	-	<1E-10
Nb	-	-	-	<1E-10
Ni	1E-06	<1E-10	2E-09	1E-09
Pb	<1E-10	<1E-10	<1E-10	<1E-10
Sb	8E-09	<1E-10	-	<1E-10
Sc	-	-	-	<1E-10
Se	<1E-10	<1E-10	-	<1E-10
Sn	-	-	-	<1E-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	4E-09	<1E-10	<1E-10	<1E-10
Zr	-	-	-	<1E-10
Chlorobenzene	1E-09	<1E-10	<1E-10	<1E-10
Dioxins/Furans	2E-08	<1E-10	-	<1E-10
PAH	1E-10	<1E-10	<1E-10	<1E-10
PCB	<1E-10	<1E-10	<1E-10	<1E-10

Notes: Environmental quality standards are given in Table 7.12 of the Data report (QUINTESSA and GEOFIRMA 2011a). '-' indicates that no environmental quality standard applies.



### 6.17 NE-PC-A: Probabilistic Case

Probabilistic calculations have been undertaken for key radionuclides (C-14, Cl-36, Zr-93 and I-129) with 500 simulations. The purpose of this work is to investigate sensitivity of consequences to the release and transport parameters, and not to test compliance against a risk criterion. The sensitivity analysis is constrained within the Reference Case geosphere assumptions; in particular, repository saturation, gas and groundwater flows are not sampled as they are drawn directly from the detailed T2GGM and FRAC3DVS-OPG models, which are deterministic in nature.

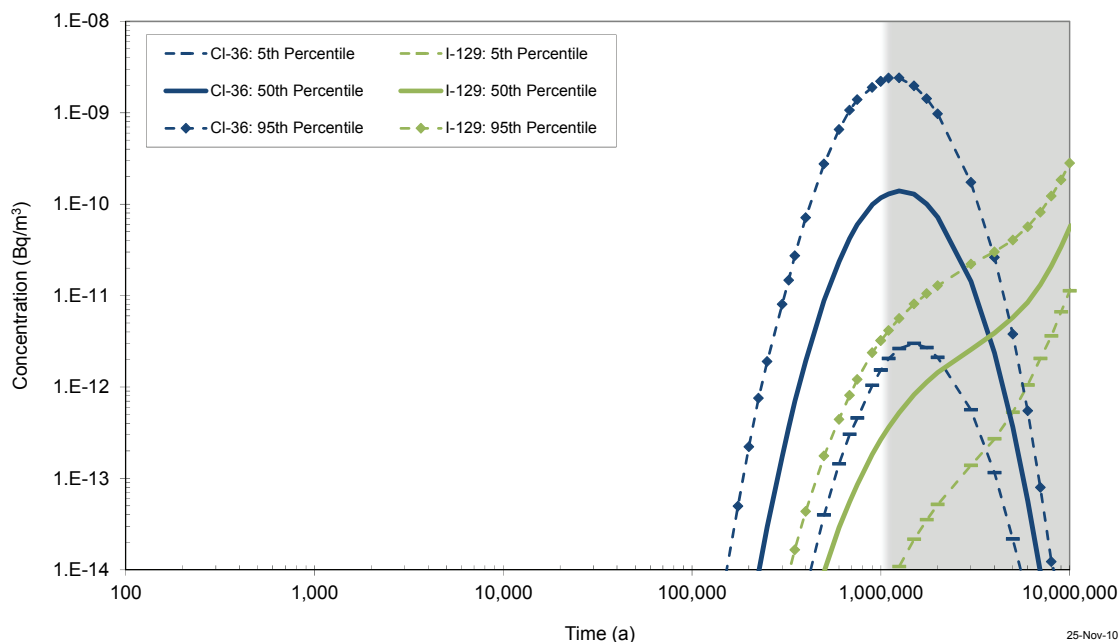
Sampled parameters include the initial inventory, thicknesses and corrosion rates for metallic wastes, effective diffusion coefficients and sorption coefficients (see Section 4.4.19). The effect of varying the sampled parameters on the maximum calculated concentration in well water have been considered, as this is a key factor in determining calculated dose rates in the biosphere (see Table 6.2). The results show that even with a range of parameters sampled, the maximum calculated concentrations remain extremely small.

**Table 6.2: Maximum Calculated Well Water Concentrations from Probabilistic Sensitivity Calculations (NE-PC) Based on the Reference Case**

Radionuclide	Maximum Concentration (Bq/m <sup>3</sup> )			Range
	5 <sup>th</sup> Percentile	50 <sup>th</sup> Percentile	95 <sup>th</sup> Percentile	
C-14	$1.2 \times 10^{-24}$	$1.8 \times 10^{-21}$	$1.2 \times 10^{-19}$	$1 \times 10^5$
Cl-36	$3.0 \times 10^{-12}$	$1.4 \times 10^{-10}$	$2.4 \times 10^{-9}$	$8 \times 10^2$
Zr-93	$2.1 \times 10^{-28}$	$7.0 \times 10^{-20}$	$2.0 \times 10^{-11}$	$1 \times 10^{17}$
I-129	$1.2 \times 10^{-11}$	$5.8 \times 10^{-11}$	$2.9 \times 10^{-10}$	$2 \times 10^1$

Although C-14 and Zr-93 are most sensitive to the parameters varied in the NE-PC case, C-14 released from the DGR decays before it reaches the groundwater well, while Zr-93 is retarded through sorption onto shaft seal materials. Cl-36 and I-129 are, therefore, the main radionuclides that reach the groundwater well and also contribute most to the extremely small calculated doses. Figure 6.24 shows the calculated well water concentrations for Cl-36 and I-129. The figure shows a range in initial breakthrough times of between 175,000 to 500,000 years for Cl-36 and from 325,000 to 1.25 million years for I-129 at the smallest concentration indicated on the chart.

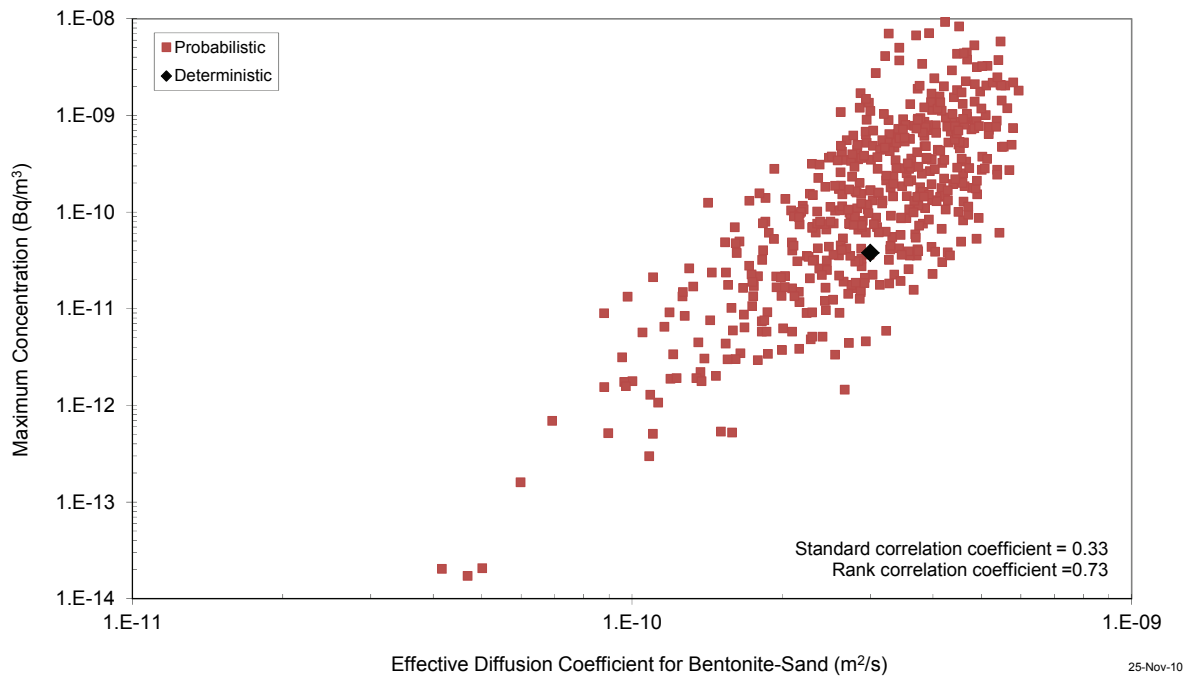
Analysis of correlation coefficients between the sampled parameters and the peak calculated concentration in the groundwater well (see Table 6.3) indicate that, out of the parameters sampled, Cl-36 is most sensitive to the effective diffusion coefficient of Cl-36 in bentonite-sand and I-129 is most sensitive to the initial inventory of I-129. The correlations are illustrated in the scatter charts shown in Figure 6.25 and Figure 6.26, respectively.



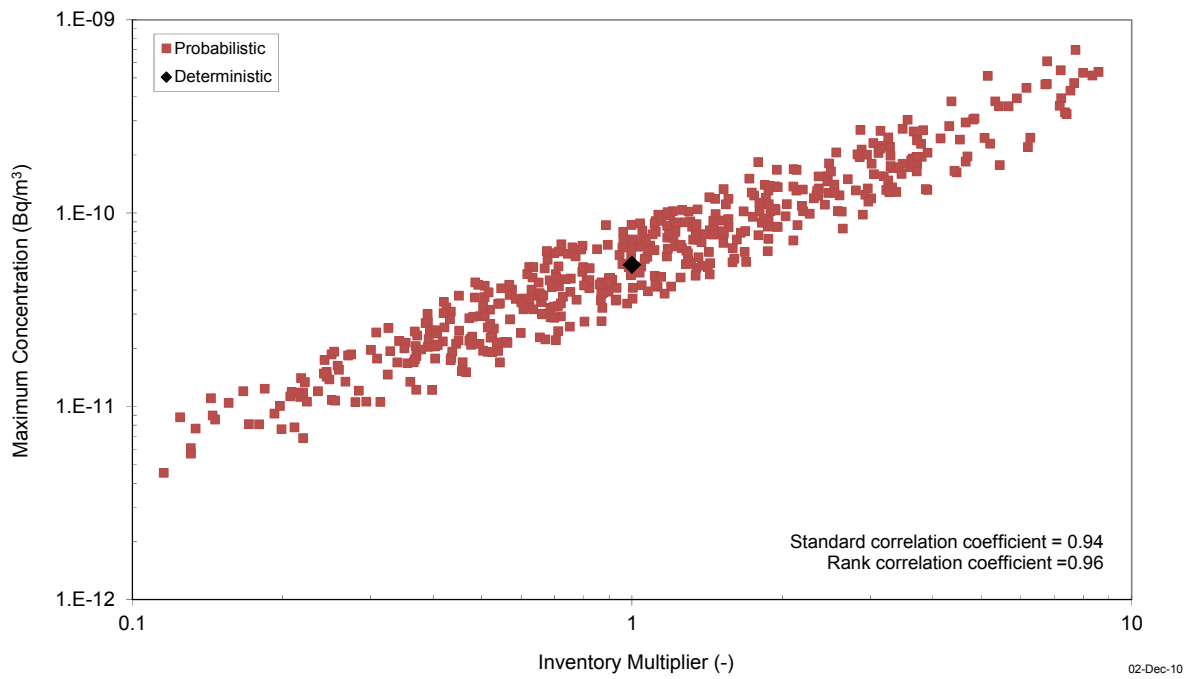
**Figure 6.24: Calculated Well Water Concentrations for Cl-36 and I-129 from Probabilistic Sensitivity Calculations (NE-PC) Based on the Reference Case**

**Table 6.3: Rank Correlation Coefficients for Varied Parameters against the Maximum Flux to the Shaft and the Maximum Concentration in Well Water**

Parameter	Monolith to Shaft Fluxes				Well Concentration			
	C-14	Cl-36	Zr-93	I-129	C-14	Cl-36	Zr-93	I-129
Kd	-0.10	-0.04	-0.04	-0.10	-0.07	-0.05	-0.98	-0.09
Corrosion rate of steel	0.05	-0.02	0.04	0.05	-0.05	-0.06	0.01	0.04
Corrosion rate of Zircaloy	0.03	0.52	0.56	0.02	-0.01	0.30	0.05	0.01
Inventory	0.98	0.69	0.77	1.00	0.32	0.48	0.17	0.96
Thickness of core metals	-0.04	-0.01	-0.01	-0.03	0.01	0.01	0.00	-0.02
Thickness of retube	0.00	-0.20	-0.23	0.01	0.02	-0.10	0.05	0.02
Deff asphalt	0.00	-0.01	0.01	0.01	0.17	0.09	0.15	0.03
Deff bentonite/sand	0.11	0.05	0.03	0.07	0.91	0.73	0.08	0.29
Deff concrete	-0.03	-0.10	-0.02	-0.02	-0.14	-0.17	-0.03	-0.05
Deff rock	0.03	0.05	0.06	0.04	-0.05	0.00	-0.03	0.04
Deff LHHPC	0.12	0.05	0.06	-0.04	0.10	0.09	0.06	0.00
Gas/water partition for I	-	-	-	-0.10	-	-	-	-0.02
Gas/water partition for Cl	-	0.50	-	-	-	0.31	-	-



**Figure 6.25: Sensitivity of the Maximum Calculated Well Water Concentrations for CI-36 to the Effective Diffusion Coefficient for CI-36 in Bentonite-Sand (NE-PC)**



**Figure 6.26: Sensitivity of the Maximum Calculated Well Water Concentrations for I-129 to the I-129 Inventory (NE-PC)**

## 7. SUMMARY AND CONCLUSIONS

This report provides an analysis of the Normal Evolution Scenario, which represents the expected evolution of the DGR system and its degradation (gradual loss of barrier function) over time. The analysis is undertaken by systematically developing and implementing models of the system and its evolution over time, running calculations and exploring the results.

The conceptual model covers the entire system, including waste packages, releases into the repository, subsequent transport from the repository into the host rock and via the shafts to potential release to the biosphere, along with subsequent impact assessment. The conceptual model is informed by detailed gas (GEOFIRMA and QUINTESSA 2011) and groundwater (GEOFIRMA 2011) calculations that provide information concerning the repository saturation, gas pressures and flow rates, and groundwater flow rates.

Assessment-level mathematical models have been developed to represent the expected evolution of the system and are fully described in Appendix D. These models are implemented in the compartment modelling code AMBER (Appendix H) and informed by the results of the detailed groundwater and gas calculations of FRAC3DVS-OPG and T2GGM, respectively. The results of the assessment-level calculations for the Reference Case and a range of variant cases are presented and analyzed.

### 7.1 Summary Results

The key results from the Reference Case dose calculations are as follows.

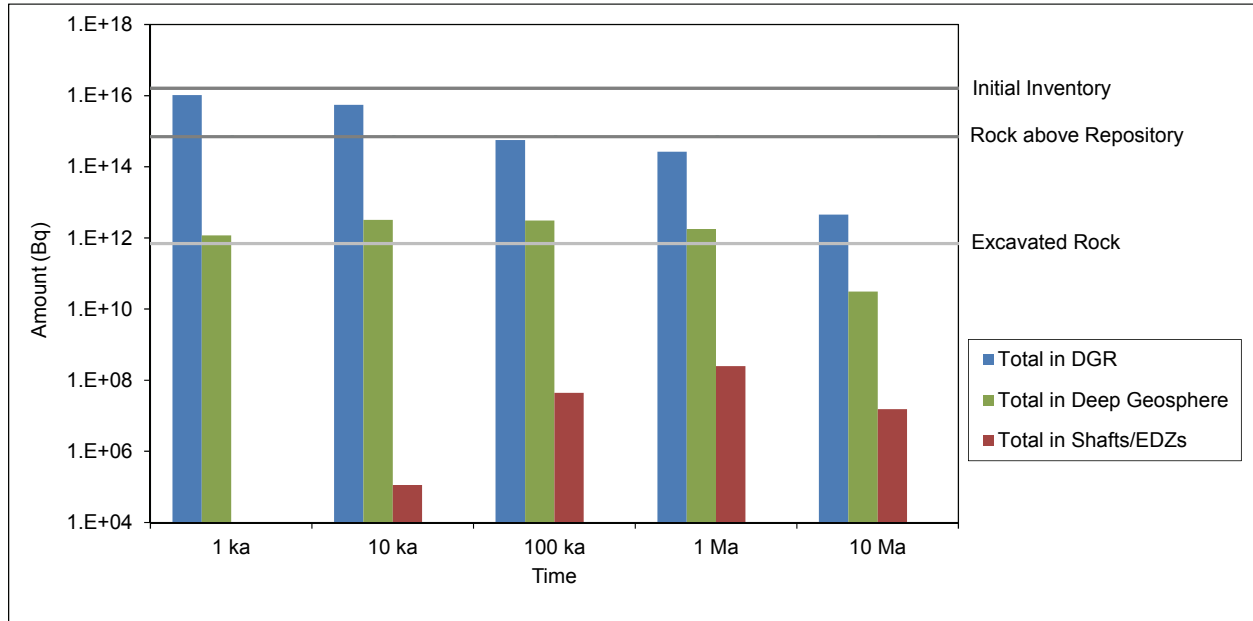
- The repository isolates and contains the wastes, and protects groundwater and Lake Huron. Most radionuclides decay within the repository or the deep geosphere (Figure 7.1).
- The 0.3 mSv/a dose criterion is not exceeded for the Site Resident Group. Calculated maximum effective dose for the Reference Case (NE-RC-A) is much smaller than the criterion. The maximum calculated effective dose does not occur until after one million years.
- C-14, Nb-93m, Nb-94 and Zr-93 represent the greatest releases from the repository; however, the host rock and shaft seals prevent these radionuclides from reaching the surface.
- I-129 and Cl-36 are the main dose contributors due to their mobility and longevity.

The maximum calculated adult effective doses for the Reference Case and variant cases are summarized in Table 7.1 and Figure 7.2. The maximum calculated doses to child or infant were generally within a factor of three of the adult dose.

The variant case calculations have been used to investigate model and data uncertainties through the adoption of alternative assumptions to those adopted for the Reference Case. The findings are summarized below.

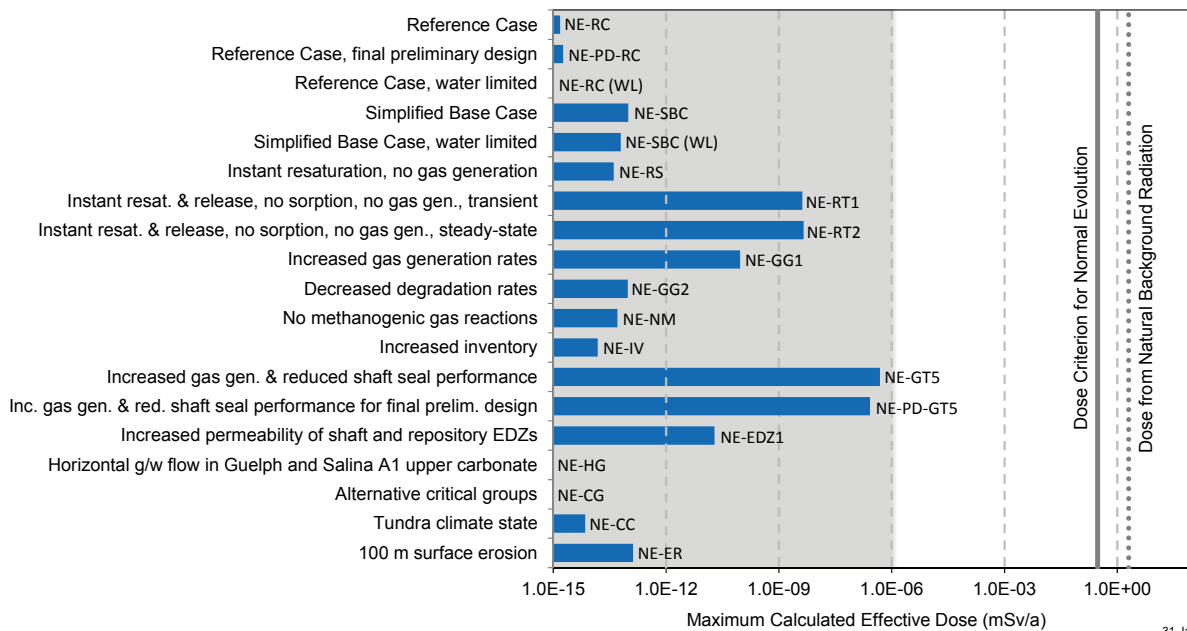
**Table 7.1: Summary of Maximum Calculated Doses to Adults for All Calculation Cases for the Normal Evolution Scenario**

<b>Case</b>	<b>Brief Description</b>	<b>Maximum Calculated Dose (mSv/a)</b>
NE-RC-A	Reference case	2E-15
NE-PD-RC-A	Final preliminary design	2E-15
NE-RC-WL-A	Reference case, water-limited gas reactions	4E-16
NE-SBC-A	Simplified base case	1E-13
NE-SBC-WL-A	Simplified base case, water-limited gas reactions	6E-14
NE-RS-A	Instant resaturation, no gas generation	4E-14
NE-RT1-A	Instant resaturation and release, no sorption, no gas generation, transient	4E-09
NE-RT2-A	Instant resaturation and release, no sorption, no gas generation, steady-state	5E-09
NE-GG1-A	Increased gas generation	9E-11
NE-GG2-A	Reduced degradation rates	9E-14
NE-NM-A	No methanogenic gas reactions	5E-14
NE-GT5-A	Increased gas generation, reduced shaft seal performance	5E-07
NE-PD-GT5-A	Increased gas generation, reduced shaft seal performance with the final preliminary design	3E-07
NE-IV-A	Increased inventory	2E-14
NE-EDZ1-A	Increased permeability of shaft and repository EDZs	2E-11
NE-HG-A	Horizontal gradients in Guelph and Salina A1 upper carbonate	5E-16
NE-CG-A	Alternative critical groups	6E-16
NE-CC-A	Tundra climate state	7E-15
NE-ER-A	100 m surface erosion	1E-13



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

**Figure 7.1: Distribution of Activity in System at Different Times for the Normal Evolution Scenario Reference Case**



**Figure 7.2: Maximum Calculated Doses to Adults for All Calculation Cases for the Normal Evolution Scenario**

- A conservative Simplified Base Case is considered (NE-SBC-A) in which the measured overpressure in the Cambrian sandstone remains but the measured underpressures in the Ordovician above the DGR are assumed quickly dissipated, resulting in a steady-state vertical upwards hydraulic gradient. The variant case results in an increase in the maximum calculated dose compared to the Reference Case, which remains well below the dose criterion.
- Strictly limiting the gas generation reactions within the DGR based on the amount of water that is available reduces the maximum calculated doses for both the Reference Case (NE-RC-WL-A) and Simplified Base Case (NE-SBC-WL-A).
- Instant resaturation of the repository (NE-RS-A) releases more radionuclides into the groundwater and results in an increase in calculated doses, although they remain much smaller than the dose criterion.
- Conservative variants to the Reference Case (NE-RT1-A) and Simplified Base Case (NE-RT2-A) are considered where the DGR is resaturated immediately after closure, radionuclides are instantly released to groundwater, with zero sorption on engineering or geosphere media. The results are dominated by Zr-93, which increases calculated doses, but they remain well below the dose criterion.
- Increased gas generation within the DGR (NE-GG1-A), in combination with an absence of initial underpressures in Ordovician formations, are sufficient for contaminated gas from the DGR to reach the Intermediate Bedrock Groundwater Zone. Subsequent transport in groundwater via the shafts enables C-14 to reach the Shallow Bedrock Groundwater Zone and then the biosphere, where calculated doses increase, although they remain well below the dose criterion.
- Decreased degradation rates (NE-GG2-A) decrease calculated doses in comparison to the Simplified Base Case, on which the variant is based, due to a predominantly lower degree of repository saturation (and, therefore, less contaminant release to groundwater).
- An absence of methanogenic gas reactions (NE-NM-A) results in higher gas pressures in the repository, lower repository water levels (and, therefore, lower releases to groundwater) and causes gas to be released from the DGR into the shafts. However, the gas release to the shafts is relatively small and free gas does not reach the shallow system. Consequently calculated doses are slightly lower than those for the Simplified Base Case, on which the variant is based.
- Increasing the radionuclide inventory by a factor of ten (NE-IV-A) results in an equivalent increase in the calculated dose rate, which remains well below the dose criterion.
- Results for the final preliminary design are very similar to those calculated for the original preliminary design (NE-PD-RC-A and NE-PD-GT5-A, compared with NE-RC-A and NE-GT5-A).
- Increased gas generation within the DGR, combined with removal of the asphalt shaft seal, reduced performance of the bentonite/sand seal within the shaft and an absence of initial underpressures in some Ordovician formations (NE-GT5-A) results in a free gas pathway

being established to the Intermediate Bedrock Groundwater Zone after 500 years. Subsequent transport in groundwater via the shafts enables C-14 to reach the Shallow Bedrock Groundwater Zone and then the biosphere where calculated doses increase, although they remain well below the dose criterion.

- Increased permeability of the shaft Excavation Damaged Zones (EDZs) results in an increase in the calculated doses due to greater groundwater flow via the EDZs (NE-EDZ1-A), while the results remain well below the dose criterion.
- Horizontal groundwater flow in the Guelph and Salina A1 upper carbonate formations of the Intermediate Bedrock Groundwater Zone (NE-HG-A) results in much of the contaminant flux via the shafts being diverted into the lake, and significantly reduces calculated doses to the Site Resident Group.
- If the Guelph and Salina A1 upper carbonate formations include horizontal groundwater flow and are assumed to discharge to the lake close to the site, then the calculated dose to an alternative Site Shore Group that drinks water and eats fish from the lake close to the site (NE-CG-A) is smaller than that for the Site Resident Group evaluated in the Reference Case or Simplified Base Case and well below the dose criterion.
- Release to a potential future tundra biosphere (NE-CC-A) rather than the reference present-day biosphere results in a small increase in calculated doses (due to increased well water concentrations), which remain well below the dose criterion.
- Erosion of 100 m of the Surficial and Shallow Bedrock Groundwater Zone (e.g., by glacial erosion) would reduce the depth of the DGR and increase calculated doses due to reduced cross section area of the Shallow Bedrock Groundwater Zone (NE-ER-A). However, the maximum calculated dose remains well below the dose criterion.

In addition to the above specific variant cases, probabilistic calculations (NE-PC-A) were conducted based on the Reference Case gas generation, groundwater and gas transport rates, but with radionuclide release and transport parameters varying. In the Reference Case, the most important radionuclides were Cs-137 and I-129. In the probabilistic run, calculated well water concentrations for Cs-137 ranged over about six orders of magnitude, whereas those for I-129 ranged over about two orders of magnitude. The probabilistic doses remained much less than the dose criterion.

The main radionuclides that contribute to calculated effective doses for the Reference Case and Simplified Base Case are Cs-137 (mostly from ILW pressure tubes) and I-129 (mostly from ILW PHT resins), due to their longer half-life and their mobility. While C-14 dominates initial liquid and gaseous releases to the shafts from the repository, the effectiveness of the shaft seals means that it decays (half-life 5700 a) before reaching the surface. Nb-94 and Zr-93 (and its daughter Nb-93m) dominate liquid release to the shafts at later times but are mostly retained within the shafts and so are not significant contributors to the calculated doses.

Calculations have been undertaken to assess the potential impact of radionuclides on non-human biota for the Reference Case. The results indicate that potential impacts of radionuclides on biota are below the relevant criteria. The highest calculated concentrations remain well below  $1 \times 10^{-10}$  Bq/L and  $1 \times 10^{-10}$  Bq/kg in well water, surface water, soils and sediments throughout the assessment; the main contributing radionuclides are Cs-137 and I-129.



Calculations of the potential impacts of non-radioactive contaminants on human and biota (NE-NR-A) also are well below the relevant criteria (they do not exceed  $2 \times 10^{-5}$  µg/L in well water or surface water, or  $6 \times 10^{-8}$  µg/g in soils or sediments).

The results indicate that the deep limestone and shale host rock, and the shaft seals provide effective barriers to isolate and contain the contaminants in the waste. The low rate of resaturation and the permeable Silurian formations (Guelph and Salina A1 upper carbonate) also contribute.

The long timescales under consideration mean that there are uncertainties about the way in which the system will evolve. The key uncertainties in terms of their importance to potential impacts are as follows.

- **Gas pressure and repository water saturation** are important in determining the release of radioactivity into repository water, and the potential for C-14 release through gas in the first 60,000 years. The uncertainties in the gas pressure and groundwater saturation modelling are discussed in the detailed Gas and Groundwater Model reports (GEOFIRMA and QUINTESSA 2011; GEOFIRMA 2011). They were approached in this safety assessment through use of a range of calculation cases to test the importance of uncertainties in the processes that control gas pressure and groundwater saturation.
- **Shaft seal and EDZ properties** and their evolution with time. Variant calculation cases presented here consider the effects of greater permeability in the shaft seals and repository EDZs, and if the asphalt shaft seal is replaced with bentonite/sand seal. However, the maximum dose remains many orders of magnitude below the dose criterion.
- **Glaciation effect.** Although geological evidence at the site indicates that the deep geosphere has not been affected by past glaciation events and that the associated groundwater system has remained stagnant, glaciation is expected to have a major effect on the surface and near-surface environment, and it is not entirely predictable. It should, however, be noted that ice-sheet coverage of the site is likely to occur only after 60,000 to 100,000 years, at which point the primary remaining hazard will be long-lived radionuclides in groundwater rather than gaseous C-14. Calculations have shown that the deep groundwaters are stable and transport is diffusion-dominated, so dissolved radionuclides in groundwater will be contained in the deep geosphere with large safety margins.
- **Chemical reactions.** Under the highly saline conditions of the deep geosphere at the DGR site, several aspects of the chemistry are uncertain due to the limited database. In particular, this includes the sorption of contaminants on seal materials and host rocks, as well as mineral precipitation/dissolution reactions. Generally, conservative values have been adopted in this assessment

The Geoscientific Verification Plan (NWMO 2011b) outlines plans to initiate tests of important processes and materials in the rock during the repository construction, for example, EDZ measurements. Also, the shaft seal design will not be finalized until the decommissioning application several decades from now, and will take advantage of these tests and knowledge gained over the intervening period. While these tests plus further modelling work will improve confidence in these Normal Evolution Scenario results, the results presented here show that the DGR system's safety is robust (i.e., the system will maintain its integrity and reliability under a range of conditions). The uncertainties should be interpreted in the context of the low calculated

impacts; for example, calculated doses for all variant cases are more than five orders of magnitude below the dose criterion.

## **7.2 Conclusions**

The assessment calculations for the Normal Evolution Scenario indicate that the DGR system provides effective containment of the emplaced contaminants. Most radionuclides decay within the repository or the deep geosphere. The release of contaminants from the waste packages is limited by the slow rate of repository resaturation (due to the low permeability of geosphere and shafts, and eventually the repository gas pressure), and the slow corrosion rate of the higher activity metallic wastes. The low permeability of the geosphere and the shaft seals further limit the migration of contaminants in water or as free gas. The amount of contaminants reaching the surface is extremely small, such that the calculated maximum impacts for the Reference Case are far below the relevant criteria for humans and biota, including people who may live on the site in the far future.

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**9. ABBREVIATIONS AND ACRONYMS**

2D	2-Dimensional
A	AMBER code
ALW	Active Liquid Waste
BSI	British Standards Institution
CNSC	Canadian Nuclear Safety Commission
CSA	Canadian Standards Association
DGR	Deep Geologic Repository
DGR-4	DGR Site Characterization Borehole #4
EDZ	Excavation Damaged Zone
Eh	Reduction potential
EIS	Environmental Impact Statement
F3	FRAC3DVS-OPG code
FEPs	Features, Events and Processes
GGM	Gas Generation Model
HDZ	Highly Damaged Zone
HTO	Tritiated Water
IAEA	International Atomic Energy Agency
ILW	Intermediate Level Waste
ISO	International Standards Organization
IX	Ion Exchange
L&ILW	Low and Intermediate Level Waste
LHHPC	Low-Heat High-Performance Cement
LLW	Low Level Waste
NEA	Nuclear Energy Agency
NE	Normal Evolution Scenario
NE-BF	Normal Evolution Scenario - Repository Backfill Case
NE-CC	Normal Evolution Scenario - Climate Change Case

NE-CG	Normal Evolution Scenario - Critical Group Case
NE-EDZ1	Normal Evolution Scenario - Increased EDZ Permeability case
NE-ER	Normal Evolution Scenario - Surface Erosion Case
NE-GG1	Normal Evolution Scenario - Increased Gas Generation Case
NE-GG2	Normal Evolution Scenario - Reduced Degradation Rate Case
NE-GT5	Normal Evolution Scenario - Gas Transport Case with increased gas generation and reduced shaft seal performance
NE-PD-GT5	Normal Evolution Scenario - Final Preliminary Design Gas Transport Case with increased gas generation and reduced shaft seal performance
NE-HG	Normal Evolution Scenario - Horizontal Gradient Case
NE-IV	Normal Evolution Scenario - Increased Inventory Case
NE-NM	Normal Evolution Scenario - No Methanogenic Gas Reactions Case
NE-NR	Normal Evolution Scenario - Non-radioactive Contaminants
NE-PC	Normal Evolution Scenario - Probabilistic Case
NE-PD-RC	Normal Evolution Scenario - Final Preliminary Design Reference Case
NE-RC	Normal Evolution Scenario - Reference Case
NE-RC-WL	Normal Evolution Scenario - Water-Limited Reference Case
NE-RS	Normal Evolution Scenario - Repository Resaturation Case
NE-RT1	Normal Evolution Scenario - Radionuclide Transport Case (Instant Release, No Sorption, Transient)
NE-RT2	Normal Evolution Scenario - Radionuclide Transport Case (Instant Release, No Sorption, Steady-State)
NE-SBC	Normal Evolution Scenario - Simplified Base Case
NE-SBC-WL	Normal Evolution Scenario - Water-Limited Simplified Base Case
NWMO	Nuclear Waste Management Organization
OBT	Organically Bound Tritium
OPG	Ontario Power Generation Inc.
PHT	Primary Heat Transport
PSR	Preliminary Safety Report
SA	Safety Assessment

T2	T2GGM code
T-H-E	Tile Hole Equivalent
WL	Water-Limited
WWMF	Western Waste Management Facility



## **APPENDICES**

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## APPENDIX A: MODEL DEVELOPMENT APPROACH

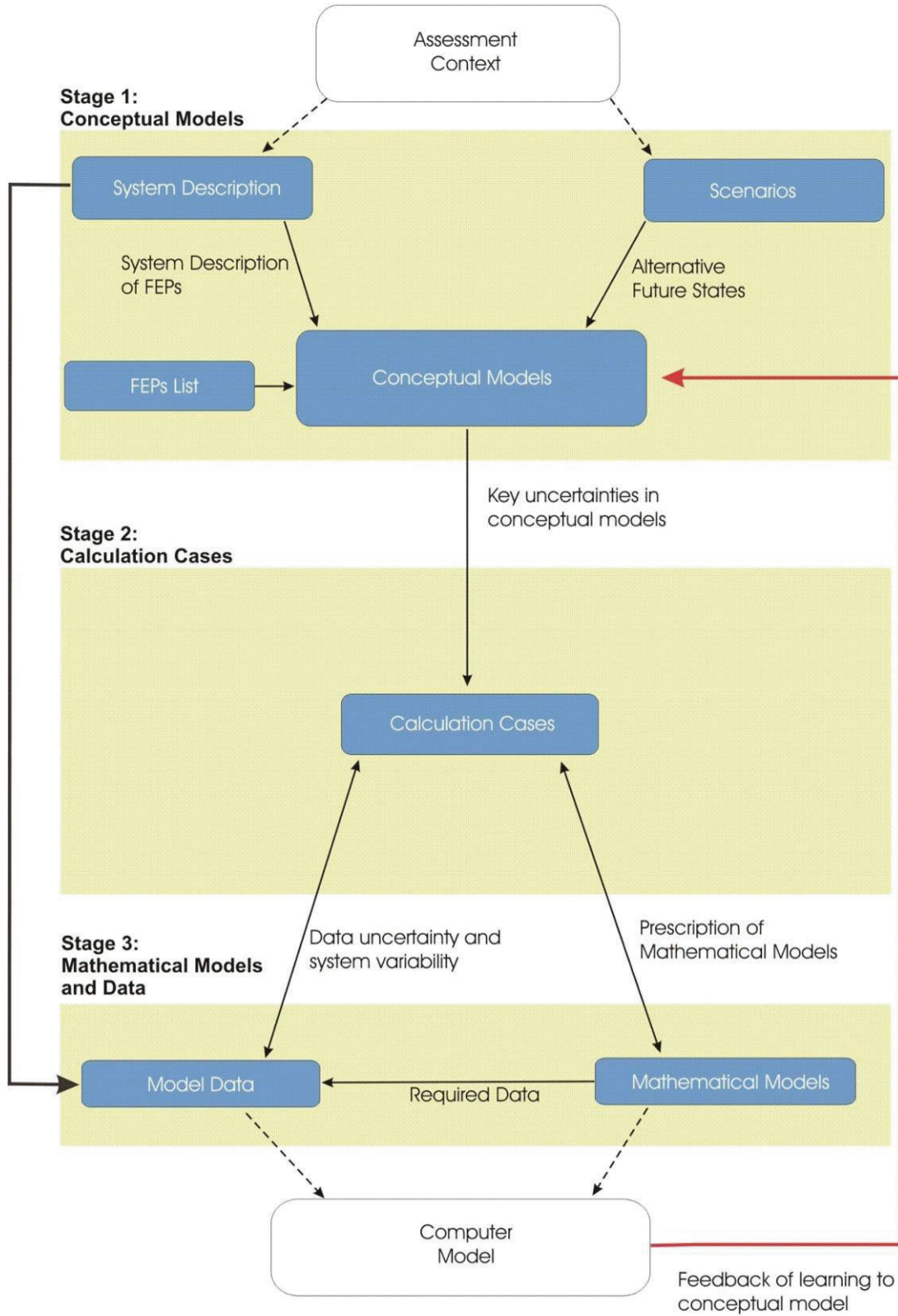
The approach used for the development of conceptual and mathematical models is illustrated in Figure A.1 and described below. It is consistent with model formulation and implementation processes described in International Atomic Energy Agency (IAEA) (2004 and 2010).

First, the conceptual models are developed for each scenario using input from the assessment context (documented in Chapter 3 of the Postclosure SA 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 Normal Evolution 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 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**

**REFERENCES FOR APPENDIX A**

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- QUINTESSA, GEOFIRMA and SENES. 2011a. Postclosure Safety Assessment. Quintessa Ltd., Geofirma Engineering Ltd. and SENES Consultants Ltd. report for the Nuclear Waste Management Organization NWMO DGR-TR-2011-25 R000. Toronto, Canada.
- QUINTESSA, SENES and GEOFIRMA. 2011b. 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 R000. Toronto, Canada.

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## APPENDIX B: KEY FEATURES, EVENTS AND PROCESSES

### B.1 KEY FEATURES

#### B.1.1 Waste and Repository Features

**Waste Packages:** OPG's wastes have been characterized into 21 reference waste plus container and overpack categories (Section 3.1 of QUINTESSA and GEOFIRMA 2011). Although for safety assessment purposes some waste categories could be further grouped together due to similar contaminant release characteristics, distinguishing these categories provides information on their relative contribution to the overall impact from contaminant releases, and also permits the flexibility to represent the waste characteristics in detail.

**Water:** On closure, the repository will have a relative humidity of up to 100%. After closure, groundwater will begin to seep into the repository and it will begin to resaturate, albeit at a slow rate due to the low permeability of the host geology at depth and the generation of gas from the degradation of the repository contents. Indeed, results from detailed gas modelling indicate that the repository will remain relatively unsaturated throughout the assessed period (GEOFIRMA and QUINTESSA 2011). Water will contact the wastes and allow the release and subsequent migration of contaminants from the waste packages.

A distinction is made in the conceptual model between repository water in **Panel 1 emplacement rooms**, **Panel 2 emplacement rooms** and the **access tunnels** that connect the emplacement rooms to the main and ventilation shafts. This is on the basis that different amounts of contaminants in groundwater will be present.

**Gas:** The wastes will degrade under the humid conditions, and gas will be generated. Under anaerobic conditions, metallic wastes will corrode generating H<sub>2</sub> gas, while degradable organic materials will be subject to microbial degradation generating CO<sub>2</sub> and CH<sub>4</sub>. The gases will impact upon the resaturation rate of the repository, and will act as a potential medium for the migration of gaseous contaminants from the repository. In common with the approach to the repository water, a distinction is made between the gas in **Panel 1 emplacement rooms**, **Panel 2 emplacement rooms** and the **access tunnels**. The rate of diffusive mixing of gases between these areas of the repository will be faster than that for water.

**Engineered Structures:** The engineered structures consist of the **concrete floors**, the **end and closure walls** at the entrance/exit to each emplacement room, the **main and ventilation shafts**, the **concrete monolith** at the base of the main and ventilation shafts, the **shaft seals** (concrete, bentonite-sand and asphalt) **and backfill** (engineered fill) along the length of the shafts, and any **concrete lining** in upper parts of the shafts. The engineering structures will provide a material into which contaminants can migrate and potentially sorb. The structures also have different physical and chemical characteristics from the rock and most of the wastes. Residual engineering structures such as **rock bolts** and **rails** are expected to be left postclosure and are also part of the engineered structures. These structures, especially in the shallower parts of the geosphere, have the potential to be affected by changes in stress regimes caused by ice-sheet advance and retreat (see Chapter 5 of the System and Its Evolution report, QUINTESSA 2011).

### B.1.2 Geosphere Features

Given the potential role of groundwater in transporting contaminants through the geosphere, a hydrogeological classification is used for the purpose of developing the conceptual model for the geosphere since each zone has its own hydrogeological (and geochemical) characteristics that will influence the migration of contaminants through the geosphere (see Table 5.2 of QUINTESSA and GEOFIRMA 2011).

**EDZ:** The EDZ around the emplacement rooms, tunnels/drifts and shafts requires modelling as this portion of the host rock has distinct characteristics (it has higher porosity and permeability than the rock mass). The shaft EDZ can be further divided into an inner and outer EDZ, while the repository EDZ can be further divided into a HDZ and the remaining EDZ, with the extent of damage and enhancement of porosity and hydraulic conductivity being greatest in the inner EDZ around the shafts and the HDZ around the repository (see Section 5.4.2 of the Data report, QUINTESSA and GEOFIRMA 2011).

**Deep Bedrock Groundwater Zone:** This zone is located within the Ordovician shale and limestone sequences and contains the repository. The zone also includes the Cambrian sandstones and Precambrian granitic gneiss. The Ordovician shale and limestone sequences have very low rock mass permeability and the porewater is saline (150 to 350 g/L). Site characterization results show elevated environmental heads in the Cambrian sandstones and underpressured conditions throughout the Ordovician sequence, indicating that the system is not in hydrodynamic equilibrium. The zone is over 400 m thick.

**Intermediate Bedrock Groundwater Zone:** This zone consists of Silurian sediments from the Salina G down to the Manitoulin (inclusive). Some zones of medium permeability exist in this sequence (in particular the Guelph, and Salina A1 upper carbonate), but the formations are primarily low-permeability shales and dolostones, with some low permeability anhydrite beds. Regional groundwater flow is posited to exist in the medium permeability units, albeit under very low horizontal gradients. Groundwater in the zone is saline (100 to 310 g/L). The zone is approximately 280 m thick.

**Shallow Bedrock Groundwater Zone:** This includes the dolostone sequence of the Lucas, Amherstburg, Bois Blanc and Bass Island Formations. The upper portions of this sequence contain fresh water (where shallow wells are drilled) while at greater depths, saline water occurs (2.5 g/L). Groundwater flow is primarily horizontal, driven by topographic features with near-shore discharge to Lake Huron. Gradients in this zone are sufficiently high to create advective dominated flow. The zone is approximately 150 m thick.

### B.1.3 Biosphere Features

**Well Water:** Present-day practice is for most of the rural population within the region around the Bruce nuclear site to obtain its domestic, agricultural and industrial water from wells rather than the lake or other surface water sources (see Section 2.4.4 of the System and Its Evolution report, QUINTESSA 2011). The wells, of which there are many in the region, extract water from the Shallow Bedrock Groundwater Zone. Typically, they are sunk into the Amherstburg Formation. It is unlikely that deeper wells would be sunk into the Silurian dolostones of the Intermediate Bedrock Groundwater Zone due to the highly mineralized nature of the water. The Normal Evolution Scenario assumes that a well draws water from the Shallow Bedrock Groundwater Zone. For the purposes of developing the conceptual model, well water need not be explicitly represented as its properties will be the same as those of the freshwater region of



the Shallow Bedrock Groundwater Zone, although an operating well is represented in the detailed groundwater model (GEOFIRMA 2011).

**Surface Water:** Although the conceptual model of the present-day system does not consider the direct discharge of groundwater from the Shallow Bedrock Groundwater Zone into terrestrial surface water systems, it is recognized that such systems could become contaminated with water abstracted via the well. Furthermore, Section 6.3.4 of the System and Its Evolution report (QUINTESSA 2011) notes that discharge might occur to streams in future biosphere states as lake levels and hydrological conditions change in response to climate changes.

In addition, due to the low hydraulic conductivity of the tills that lie close to the surface, there are numerous areas of wetland around the Bruce nuclear site. Notable locations include the wetland on the eastern edge of the WWMF and the Baie du Dore wetland into which Stream C drains, at the edge of the lake to the northeast of the Bruce nuclear site. Biota living in the surface waters may be exposed to contaminants, and/or be consumed and therefore result in human exposure.

The presence and character of surface waters will be dynamic, especially in the periods directly before and after ice-sheet cover occurs.

**Surface Water Sediment:** Water body sediment can interact with the associated water and preferentially accumulate certain contaminants. Sediment characteristics and concentrations may vary; however, it is likely to be appropriate to consider them to be relatively homogeneous, but distinguish between the sediment locations (e.g., those associated with the stream and wetland). The presence and character of surface water sediment will be dynamic, especially in the periods before and after ice-sheet cover occurs.

**Lake Water:** Lake water is generally uniform in characteristics in the vicinity of the Bruce nuclear site, but it can vary over the whole of Lake Huron. The large volume of the lake means that it is necessary to sub-divide the feature for modelling purposes (see Figure 6.2 of the Data report, QUINTESSA and GEOFIRMA 2011). This allows the spatial variation in contaminant concentrations and impacts to be presented. A zone close to the shore is important, as it can represent the initial mixing of contaminated groundwater discharged via the lake sediment with lake water, and it may also be used for drinking water or fishing. Biota living in the lake may also be consumed and therefore result in exposure. As climatic conditions change, lake characteristics (e.g., level, size and flows) can vary (see Section 6.3.4 of the System and Its Evolution report, QUINTESSA 2011). Peltier (2011) indicates that it is likely that a proglacial lake will overlie the site for a period following ice-sheet retreat. This will gradually recede due to changing climatic conditions and crustal uplift.

**Lake Sediment:** Like surface water sediment, lake sediment is likely to preferentially accumulate certain contaminants. Lake sediment interacts with contaminants in lake water and so it is necessary to ensure that each lake water compartment has an associated lake sediment compartment. The zone close to the shore is important since contaminated groundwater from the Shallow Bedrock Groundwater Zone discharges into it and then into the overlying water. The lake sediment includes the lakeshore sediment that is regularly exposed to the atmosphere and provides a mechanism for exposure of humans to potentially contaminated sediment. Furthermore, lake sediment can become exposed due to climate-induced falls in lake level and become soil.

**Soils:** Contaminants can become associated with soil by a variety of transport mechanisms, such as irrigation from the contaminated well. Soil is a key medium for transport of

contaminants into food prior to ingestion; in addition, individuals may be directly exposed to contaminants in the soils. Contaminants in soil may be sorbed onto soil material or be present in pore water. The precise characteristics of soil might vary around the area of interest, but these can be addressed with spatial discretization. In general, the soils are thin and underlain by a thin sand/gravel layer overlying the till, the soil being progressively more sandy towards the lakeshore. Soils will be affected by climate induced changes such as permafrost formation, ice-sheet erosion and deposition and lake enlargement (see Chapter 6 of the System and Its Evolution report, QUINTESSA 2011).

**Biota:** The local environment is characterized by a variety of biota, as described in Section 2.4.8 of the System and Its Evolution report (QUINTESSA 2011). The lake is a source of fish for humans and, although there is no information on the fishing of local streams, such behaviours could potentially occur in the future, providing a pathway for contaminated foodstuffs to humans. Both agricultural and natural terrestrial environments are described in Section 2.4 of the System and Its Evolution report (QUINTESSA 2011). Human cultivation of land is of particular interest, as it offers the possibility for localized use of soil that could become contaminated through irrigation. The soil in the region around the Bruce nuclear site is reported to be fertile, and Bruce County is a leading producer of cattle (along with other animals such as sheep, pigs and chickens). It is also noted for production of barley, oats and canola. The assessment context for the assessment requires the consideration of impacts on non-human biota as well as humans (Section 3.4 of QUINTESSA et al. 2011) and so animals and plants associated with natural environments such as the wetlands also have to be considered. The characteristics of the biota can also be expected to change as a consequence of climate change (see Chapter 6 of the System and Its Evolution report, QUINTESSA 2011).

**Houses and Buildings:** Enclosed environments offer the potential for the accumulation of repository derived gases, and are consequently of interest. The buildings around the site are presently industrial; however, there are a number of residential communities nearby. It is possible to envisage a building being constructed on or near a repository shaft and the associated EDZ once controls are no longer effective.

**Atmosphere:** The general surface atmosphere does not provide a feature in which contaminants can accumulate to high concentrations, owing to its dispersive effects. However, humans, animals and plants interact with the atmosphere, and therefore it offers an alternative pathway of interest from soil and water to biota and directly to humans.

**Permafrost:** Recent work by Peltier (2011) indicates that permafrost development at the site will not be extensive, reaching only a few tens of metres and will likely be discontinuous. Therefore, although present, it will not provide a major restriction on groundwater flow in the Shallow Bedrock Groundwater Zone.

**Ice-sheet:** It is expected that the site will continue to be affected by advancing and retreating ice-sheets over the timescale of the assessment (see Chapter 6 of the System and Its Evolution report, QUINTESSA 2011). It is presently estimated that the maximum thickness of an ice-sheet that would cover the DGR site would be more than 2.5 km (Chapter 1 of Peltier 2011).

## B.2 KEY PROCESSES AND EVENTS

### B.2.1 Processes Internal to Features

**Decay and Degradation:** All radionuclides undergo radioactive decay and some produce radioactive progeny that need to be considered explicitly or implicitly (i.e., treated as separate radionuclides, or assumed to be in secular equilibrium with parent radionuclides). The rate of decay for a given radionuclide is constant; it does not depend on environmental conditions. For the current assessment, all progeny with a half-life of greater than 25 days are explicitly modelled. Those with a half-life of 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 2011). It is conservatively assumed that, for the purpose of health and environmental impact calculations, organic contaminants do not degrade, although their degradation is considered for the purpose of gas generation rates (see below).

**Gas Generation:** Gas generation in the waste packages (saturated or unsaturated) may occur by a variety of mechanisms, e.g., the corrosion of metals and the degradation of organic wastes. Collectively, these processes can act to generate contaminants in a gaseous phase that are subsequently released from the waste package into the surrounding repository environment. In addition, the gaseous element radon can be generated from the decay of certain parent radionuclides (Ra-226 and Ra-224). Radiolysis is not a significant mechanism for gas generation given the decay rates associated with the wastes that will be disposed in the DGR. Gas generation rates have been evaluated through detailed gas modelling work (see the Gas Modelling report, GEOFIRMA and QUINTESSA 2011), and the generation of gaseous radionuclides has been computed based on radionuclide inventories.

**Sorption:** Sorption and desorption describes the distribution of contaminants between solids and liquids within a porous medium. Consideration of sorption enables the quantity of contaminants available for aqueous transport to be determined. The extent and nature of sorption data will depend on the medium and on the groundwater chemistry.

Sorption onto colloids is 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 of the rock and shaft seals.

In the current assessment sorption is conservatively neglected in the repository, Deep and Intermediate Bedrock Groundwater Zones and shafts, for all elements other than seven elements of interest where sorption was plausible under saline conditions (Cd, Zr, Nb, Pb, U, Np and Pu). A review of sorption values for these elements has been undertaken and minimum credible values for conditions at the DGR site have been adopted (see Appendix D of the Data report, QUINTESSA and GEOFIRMA 2011).

**Solubility:** The concentration of some elements in the repository water may be limited by solubility, given the chemical composition of the water. The effects of solubility limits on contaminant dissolution will require consideration in the repository only, since this is where the contaminant concentration should be highest (see Appendix C of the Data report, QUINTESSA and GEOFIRMA 2011). No solubility limitation is considered for elements other than for stable carbon.

**Chemical effects and reactions:** Chemical effects (such as pH and Eh conditions) in a medium can influence the chemical form and therefore the partitioning of contaminants between

phases (solids, liquids or gases). The consequences may therefore be manifest primarily in terms of the degree of solubility and/or sorption exhibited by a particular element. This issue is principally of interest where there is scope for chemical conditions to change, such as may occur in the repository water. In the current assessment, the evolution of repository and geosphere chemistry is considered in Sections 4.5 and 5.4 of the System and Its Evolution report (QUINTESSA 2011), respectively. It is expected that following the initial transition from oxidizing to reducing conditions, there will be no significant changes in groundwater chemistry in the repository other than a slight increase in pH due to leaching of cementitious materials. Meltwater from an ice-sheet could significantly modify the groundwater chemistry in the Shallow Bedrock Groundwater Zone, for example, through the introduction of oxygenated fresh water, but impacts on the deep system are expected to be minimal (see Chapters 4 and 5 of the System and Its Evolution report, QUINTESSA 2011).

**Radiation Dosimetry:** Decay of radioactive species can result in harm to human and non-human biota. The mechanism is damage of DNA by radiation emissions. At high doses, this can result in deterministic effects, however thresholds exist for such effects and for this scenario these will not be exceeded. At lower doses, stochastic effects result in the increased risk of cancer or hereditary defects. For humans, these processes are represented with a semi-empirical measure of exposure, the effective dose. This is a measure that is weighted for the varying sensitivities of organs and the particular bioaccumulation of radionuclides in organs (for internal exposure by radionuclides). Conversion factors relating intake to effective dose have been internationally recommended. Similar values are available in relation to external exposure by radionuclides in representative geometries.

## **B.2.2 Processes Resulting in Transport of Contaminants between Features**

**Gas release from waste packages:** Gas will be released from the corrosion of metal containers and degradation of organic materials in the wastes in the repository. The gas will contain radioactive trace gases such as C-14 labelled CH<sub>4</sub> and CO<sub>2</sub>. The waste containers and overpacks are not considered to be a barrier to gas release. This is consistent with the assumption that they fail immediately post-closure, that LLW is 'lightly' packaged, and that many of the more robust ILW packages have gas vents. It is conservative for ILW retube wastes that are in robust packaging that is expected to be gas tight.

**Gas transport:** Gas can migrate through the repository, shafts and geosphere either in the gas phase (free gas) or through dissolution and subsequent transport in groundwater (dissolved gas). Gaseous radionuclides can be transported within the free gas phase or as dissolved gas.

**Gas dissolution:** Gas can dissolve and exsolve in/from groundwater. Dissolution/exsolution are controlled by changes in pressure (depth), temperature and concentration (due to dilution, dispersion, and biogeochemical reactions). Transport of bulk gas within the shaft and subsequent dissolution within the Shallow Bedrock Groundwater Zone could be a potentially significant transport path.

**Gas Volatilization:** Gaseous and volatile species (e.g., C-14, Cl-36, Se-79, and I-129) can be transported as dissolved species in groundwater but subsequently released as gases upon discharge into the biosphere. This process is most relevant to consider in the context of the potential exposure of humans and biota in the environment and therefore will be considered in the biosphere. Volatilization of these radionuclides can also occur in the repository (see Section 2.3.1.2).

**Resaturation:** Infiltration of porewater into the repository from the surrounding geosphere causes the repository to resaturate following closure. The rate of resaturation depends on the permeability of the host rock and the gas pressure in the repository. The resaturation profile adopted for the current assessment is discussed in Section 2.3.1.1.

**Aqueous Release:** Each of the waste categories has an associated contaminant release function to water. The release processes considered are instant release upon contact with water and congruent release with waste corrosion, depending on the physical characteristics of the waste and how the contaminant occurs within the waste (see Table 2.3).

**Groundwater Transport - Advection:** Advective flow can occur in a variety of features, some within which the water flow is predominantly via the pores, and some within which water flow is predominantly via fractures and bedding planes. Advective flow only occurs in rock if there is a head gradient. Advective flow in porous media is therefore relevant to the saturated overburden sediments and the Shallow Bedrock Groundwater Zone. Some advective flow is also possible in the Intermediate and Deep Bedrock Groundwater Zones due to the pressured heads in the Cambrian, and, in the case of the Intermediate Bedrock Groundwater Zone, the higher permeability horizons such as the Guelph Formation if there is a horizontal gradient. Advective flow may also occur along any discontinuities in otherwise low-permeability rock, potentially including the shafts and their associated EDZ. Head gradients may be ambient groundwater heads, or can result from build-up of gas pressure (for example in the repository as a result of waste degradation).

**Groundwater Transport - Dispersion:** Dispersion is a process that accompanies advective transport of groundwater. The dispersion of a plume of contaminated water in a saturated medium is a result of the inhomogeneities in the medium, that are small compared with the length over which transport is being observed. Effectively, there are a variety of different paths available to the moving water, with the net result that over a defined pathlength, a distribution of water travel times may be observed. The process is important in influencing the time profile and spatial distribution of contaminants following transport in such a medium.

**Groundwater Transport - Diffusion:** Diffusion processes are most significant when the permeability of media is low and/or there is an absence of or limited head gradients. Contaminants migrate diffusively according to the concentration gradient existing from one location to another. The transport process is important in the repository (e.g., the concrete monolith) and the Deep and Intermediate Bedrock Groundwater Zones, as well as potentially in the EDZ and shafts due to the low permeability of the associated rocks.

**Surface Water Transport:** Surface water can provide a mechanism for transporting contaminants in surface soils into other media, and is therefore an important consideration, especially immediately before/after ice-sheet advance/retreat when the site might be affected by large volumes of meltwater. Periodic flooding of terrestrial water courses can also result in water infiltrating soil and provides a mechanism for the transport of contaminants in the surface water to the soil. Bulk water flows in the terrestrial environment (through streams and lakes) are important mechanisms that redistribute contaminants in the biosphere. These are driven by the local and regional hydrology and, in the lake environment, by lake currents.

**Infiltration:** The advective flow of water percolating from the surface is necessary for consideration in all unsaturated surface media, and results in vertically downward advective transport of contaminants in solution. Advective transport is affected by the characteristics of the medium through which the water flows, including its capacity for sorption. As infiltration is

principally of interest for soils and overburden sediments, it is represented in terms of transport through a porous medium.

**Interflow:** The lateral movement of water through the soil into surface water courses can occur during or following significant precipitation events when the rate of infiltration of water at the top of the soil profile exceeds the exfiltration rate from the base of the soil profile. It will result in advective transport of contaminants in solution. As interflow is only of relevance for the overburden sediments, it is represented in terms of transport through a porous medium.

**Resuspension and Sedimentation:** Soil dust can be suspended into the atmosphere and dispersed with the action of the wind on the soil surface. Suspended particles ultimately settle out due to gravity (sedimentation). Resuspension and sedimentation of solid material can also occur in aquatic environments, as a result of the action of shear forces on sediments. Over a long period, the processes of resuspension and sedimentation can lead to net erosion of some surface features and the redistribution of contaminated soil or sediments over a wide area.

**Erosion and Deposition:** Erosion/deposition includes all mechanisms by which there is a net movement of solid material from one surface medium to another. The resuspension/sedimentation process described above can result in erosion/deposition; however, erosion/deposition may also occur by the movement of solid material by surface water, or the 'rolling' of particles over surfaces, without suspension. Soil and other material can also be redistributed by the movement of animals. The process of erosion/deposition, therefore, is taken to represent the movement of solid material from one location to another, as distinct from the temporary suspension of solid material in atmosphere or water, which is addressed by resuspension and sedimentation. Future ice-sheets and associated meltwater streams are expected to be significant causes of erosion/deposition at the DGR site.

**Water Pumping:** The Normal Evolution Scenario assumes that a well pumps water from the Shallow Bedrock Groundwater Zone to supply a family living on the site in the future. Only the upper portion of the Shallow Bedrock Groundwater Zone is suitable (deeper waters have too high a mineral content). Water obtained from surface water bodies and Lake Huron can also be pumped but it is assumed that contaminant concentrations will be lower in these waters than in well water due to the effects of dilution. A well would not be present when the site is covered by a lake. A well may also not be practical during periods in which permafrost is present, even if it is discontinuous, because the available water supply may be constrained by the permafrost, and the deeper waters below the permafrost may be too saline. Finally, it is also possible that climate-related limitations on land use may mean wells are not required for other periods, although wells may be used to meet domestic water requirements.

**Uptake by Biota:** Contaminants in soil can be transferred to plants via uptake by roots, interception by leaves and/or direct contamination of plant surfaces (some portion of the contaminants may also be subsequently removed, e.g., by washing). Animals can eat contaminated plants, soil and/or water. Uptake by plants and animals is rapid in comparison with the overall timescale of interest in the assessment and therefore equilibrium transfer factors can be applied. Contamination by/uptake of contaminants in soil and water can be represented according to the mass of soil/water that is on the plant or ingested by the animal.

**Human Ingestion of Contaminated Media:** Humans can be envisaged to ingest a variety of contaminated media. Residents could ingest contaminated animals and crops if contaminated soil were to be farmed. The soil itself could be ingested inadvertently. If drinking water were

obtained from a well or lake, this could also be contaminated. Contaminants are transferred directly at a rate determined by the ingestion rate of the foodstuff/water.

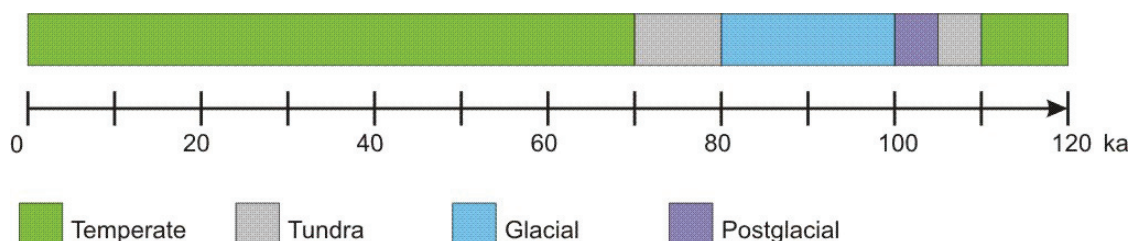
**Human Inhalation of Contaminated Media:** Contaminants may be present in the air that could be inhaled by a resident on the site. For example, contaminated soil can be suspended by the action of the wind or by the ploughing of soil and subsequently inhaled. Gaseous contaminants could be inhaled if released into the biosphere and/or volatilized once in the biosphere, in which case, the most significant exposure situation is likely to be associated with their accumulation and inhalation in indoor air. Contaminants are transferred directly at a rate determined by the inhalation rate and concentration of contaminants in the air.

**External Irradiation of Humans by Contaminated Media:** People in the proximity of media (e.g., soil and sediment) contaminated by radionuclides can be irradiated by gamma emissions. External irradiation can also occur from immersion in contaminated water and air.

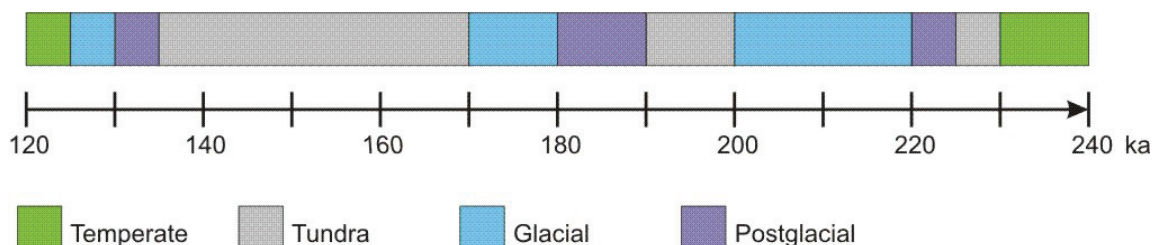
**B.2.3 Events and Processes Changing Features with Time**

**B.2.3.1 Climate Change**

A stylized climate sequence has been identified in Section 6.3.5 of the System and Its Evolution report (QUINTESSA 2011) based on the results of the University of Toronto Glacial Systems Model (Peltier 2011) and is reproduced in Figure B.1 and Figure B.2.



**Figure B.1: Sequence of Climate States for the Next 120,000 a**



**Figure B.2: Sequence of Climate States from 120,000 a to 240,000 a (this sequence is assumed to repeat indefinitely)**

Rather than explicitly representing the sequence of temperate, tundra, glacial and post-glacial climate states identified in Figure B.1 and Figure B.2, the conceptual model considers the evolution of the system assuming constant climate conditions. All but one calculation case assume constant temperate conditions which are comparable with those found at present at the

site; one case considers a tundra climate. In particular, it is assumed that the site is occupied by a self-sufficient farmer living directly above the repository and extracting well water for drinking, domestic water usage, and irrigation. Detailed modelling of the potential impacts of glaciation in a Canadian Shield setting indicate that assuming this type of conservative, stylized constant-climate receptor is a reasonable indicator for the effects of glacial cycles, considering the transient changes in lifestyles, water conditions and geosphere release rates in that hypothetical case study (Garisto et al. 2010).

Although the sequence of climate states is not explicitly represented, the effects of climate change have been evaluated and Table B.1 summarizes their inclusion in/exclusion from the conceptual model.



**Table B.1: Representation of Climate Change Effects in the Normal Evolution Scenario's Conceptual Model**

<b>Effects of Climate Change on the DGR System</b>	<b>Representation in Normal Evolution Scenario's Conceptual Model</b>	<b>Justification/Explanation</b>
<p>Delay in onset of next cooling cycle due to global warming</p>	<p>Temperate conditions assumed. Onset of the next cooling cycle (Figure B.2) assumed to occur after 60,000 a.</p>	<p>Peltier (2011) notes that glacial cycles in the next 60,000 a could be inhibited (in practice, this could be even longer, depending on the rate at which greenhouse gases are removed from the atmosphere). Work on long-term climate modelling using Earth Models of Intermediate Complexity by the BIOCLIM project (BIOCLIM 2004) indicate that no significant glaciations would occur for potentially in excess of 100,000 a.</p>
<p>Consequences of ice-sheet loading/unloading on rock mass, repository and shaft properties</p>	<p>Represented by accounting for rockfall in the repository (Section 2.3.1.1) and the degradation of concrete bulkheads and the monolith (Section 2.3.2.1).</p>	<p>The impact of ice-sheet loading/unloading on DGR system has been evaluated in Chapter 6 of the Geosynthesis report (NWMO 2011). The associated geomechanical modelling has shown that the consequences are limited. Significant degradation of system is evaluated in the Severe Shaft Seal Failure Scenario (QUINTESSA and SENES 2011).</p>
<p>Consequences of substantial land depression during glaciations including inundation of the site by a proglacial lake</p>	<p>Not represented</p>	<p>Land depression expected to be on very large scale, so local effects are small. Only temperate and tundra biosphere states considered in the conceptual model for the current assessment (see Appendix B.2.3.1). These bound the case of site covered by a lake since during a proglacial lake state, there is nobody living on the site and there would be large dilution of any contaminant releases.</p>
<p>Changes in groundwater and gas flow in the geosphere as a consequence of permafrost development, presence of an ice-sheet, and meltwater incursion</p>	<p>Not represented</p>	<p>The permafrost is expected to be discontinuous (Section 5.2.3 of the System and Its Evolution report, QUINTESSA 2011) and so is not expected to significantly affect groundwater and gas flow.</p>

<b>Effects of Climate Change on the DGR System</b>	<b>Representation in Normal Evolution Scenario's Conceptual Model</b>	<b>Justification/Explanation</b>
Changes in groundwater chemistry as a result of the ice-sheet meltwater	Not represented	No evidence from site investigation of meltwater from previous glaciations penetrating the Deep Bedrock Groundwater Zone due to its low permeability and the relatively high permeability of the Shallow Bedrock Groundwater Zone (Section 4.3.2 of the Geosynthesis report, NWMO 2011). Meltwater changes in Shallow Bedrock Groundwater Zone are unlikely to affect the quality of this water with respect to well water extraction when site is not ice covered (Section 2.3.2.1).
Point of discharge of contaminated groundwater into the surface environment	Represented	Conceptual model for tundra biosphere state considers discharge to stream, in addition to the well (see Section 4.4.3).
Changing soil/sediment and biota characteristics	Represented	Different characteristics considered for temperate and tundra biosphere states (see Sections 4.3 and 4.4.3).
Variation in temperature and precipitation rates and the role of infiltrating glacial water	Represented	Different temperature and precipitation rates considered for temperate and tundra biosphere states (see Section 4.4.3). Note that infiltrating glacial water is not considered due to the reasons given above.
Changing human exposure conditions, reflecting the habitability and resources of the surface environment in various climate states	Represented	Different human exposure conditions considered for temperate and tundra biosphere states (see Sections 4.3 and 4.4.3.3).

### B.2.3.2 Repository Changes

The evolution of the waste and repository is described in detail in Chapter 4 of the System and Its Evolution report (QUINTESSA 2011) and summarized below.

**Physical and Chemical Degradation of Waste Packages:** The physical and chemical degradation of waste packages will result in time-dependent aqueous and gas release of contaminants as discussed in Appendix B.2.2. Waste packages will corrode/degrade and fail over time. It is conservatively assumed that packages fail at the start of postclosure period and that in most cases, contaminants will be instantly released on contact with water (Section 2.3.1.2). As the repository resaturates, more contaminants will become available for aqueous release from the saturated waste packages.

**Rockfall in Repository Tunnels and Emplacement Rooms:** Rockfall, induced by seismic events, will fill the void in the emplacement rooms and repository tunnels. The collapse zone will develop progressively until the stress relief has been fully redistributed and the collapse zone (column) becomes self-supporting. The extent of roof collapse is expected to be <10 m above the original ceiling (see Section 6.5 of the Geosynthesis report, NWMO 2011).

**Degradation of Engineered Structures:** Metallic components in the repository (e.g., rock bolts, rails and ventilation ducts) will corrode, with the rate of corrosion depending on the nature of the metal (e.g., carbon vs. stainless steel) and the presence of passivating concrete. Concrete plugs and end walls are assumed not to provide any significant barrier to gas, water or contaminant transport.

**Degradation of Shaft Seals.** The performance of the bentonite-sand and asphalt seals in the repository and shaft in terms of resistance to gas and water flow is not expected to degrade significantly in the Deep and Intermediate Bedrock Groundwater Zone due to the stable geological environment, the selection of suitable seal materials, the low rock permeability and, therefore, slow rate of exchange of chemical reactants, and the low temperature (see Sections 4.5.4 and 4.5.5 of the System and Its Evolution report, QUINTESSA 2011). However, the concrete monolith and bulkheads are expected to degrade more significantly (see Section 4.5.3 of the System and Its Evolution report, QUINTESSA 2011).

### B.2.3.3 Geosphere Changes

The impacts of glacial cycles in the Deep and Intermediate Bedrock Groundwater Zones are likely to be limited to transitory changes in the hydraulic heads, temperature and the stress regime resulting from ice-sheet loading and unloading (see Chapter 6 of the System and Its Evolution report, QUINTESSA 2011). Changes in the stress regime are expected to result in repository rockfall, as described in Appendix B.2.3.2. This will result in the vertical extension of the EDZ into the host rock. This effectively reduces the pathlength for contaminant migration through the geosphere immediately above the repository.

Changes are likely to occur in the Shallow Bedrock Groundwater Zone due to the glacial and interglacial cycling, such as the development of permafrost and the introduction of ice-sheet derived meltwater. However, as explained in Table B.1, the stylized conceptual models developed for the current assessment do not represent these effects.

### B.2.3.4 Biosphere Changes

As discussed in Appendix B.2.3.1, climate change has a significant impact on the biosphere system through the modification of temperature, precipitation, biota, water bodies, sediment/soil, and human activities. All but one calculation case developed for the current assessment assumes constant temperate conditions which are comparable with those found at present at the site; one case considers a tundra climate. For both cases, it is assumed that once controls are no longer effective, land use at the site becomes consistent with the surrounding area and a water well is sunk into the Shallow Bedrock Groundwater Zone. For the temperate system, groundwater discharge from the Shallow Bedrock Groundwater Zone is into the lake's near shore. For the tundra system, it is to a stream.

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**APPENDIX C: FEP AUDIT OF CONCEPTUAL MODEL**

<b>FEP</b>	<b>Included in Conceptual Model for Normal Evolution Scenario</b>
<b>2. REPOSITORY SYSTEM FACTORS</b>	
2.1 Waste, Waste Form & Engineered Components	
2.1.01 Waste inventory	
2.1.01.01 <b>Radionuclide content</b>	<b>Yes</b> , consider - see Table 2.6 of the System and Its Evolution report (QUINTESSA 2011).
2.1.01.02 <b>Chemical content</b>	<b>Yes</b> , consider - see Table 2.6 of the System and Its Evolution report (QUINTESSA 2011).
2.1.02 Waste-form characteristics	
2.1.02.01 <b>Metallic wastes</b>	<b>Yes</b> , consider - see Tables 2.1, 2.2 and 2.7 of the System and Its Evolution report (QUINTESSA 2011).
2.1.02.02 <b>Organic wastes</b>	<b>Yes</b> , consider - see Tables 2.1, 2.2 and 2.7 of the System and Its Evolution report (QUINTESSA 2011).
2.1.02.03 <b>Non-metallic, inorganic wastes</b>	<b>Yes</b> , consider - see Tables 2.1, 2.2 and 2.7 of the System and Its Evolution report (QUINTESSA 2011).
2.1.03 Waste-packaging characteristics	
2.1.03.01 <b>Containers</b>	<b>Yes</b> , consider in materials balance, but not as a transport barrier - see Tables 2.3 and 2.7 of the System and Its Evolution report (QUINTESSA 2011) and Tables 3.3 and 3.4 of the Data report (QUINTESSA and GEOFIRMA 2011a).
2.1.03.02 <b>Overpacks</b>	<b>Yes</b> , consider in materials balance, but not as a transport barrier - see Table 2.3 of the System and Its Evolution report (QUINTESSA 2011) and Tables 3.3 and 3.4 of the Data report (QUINTESSA and GEOFIRMA 2011a).
2.1.04 <b>Emplacement room and access and shaft &amp; services area characteristics</b>	
2.1.04.01 <b>Roofs and walls</b>	<b>Yes</b> , 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).
2.1.04.02 <b>Floors</b>	<b>Yes</b> , 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).
2.1.04.03 <b>Rock bolts</b>	<b>Yes</b> , consider in calculation of mass of steel in the repository (see Table 4.9 of the Data report, QUINTESSA and GEOFIRMA 2011a).



<b>FEP</b>	<b>Included in Conceptual Model for Normal Evolution Scenario</b>
2.1.04.04 <b>Room and closure walls</b>	<b>Yes</b> , consider in mass balance, but not as a transport barrier - see Sections 2.3.1.1 and 2.3.1.3. 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).
2.1.04.05 <b>Backfill</b>	<b>Yes</b> , although no backfill is considered in the preliminary repository design - see Section 2.2.3 of System and Its Evolution report (QUINTESSA 2011), a variant case with backfill has been considered for detailed groundwater and gas calculations (see the Groundwater Modelling report, GEOFIRMA 2011, and the Gas Modelling report, GEOFIRMA and QUINTESSA 2011).
2.1.05 Shaft characteristics	
2.1.05.01 <b>Lining</b>	<b>Yes</b> , but only for shafts in Shallow Bedrock Groundwater Zone since liner removed from repository level up to the start of this zone at closure (see Section 2.2.3.4 of the System and Its Evolution report, QUINTESSA 2011).
2.1.05.02 <b>Backfill</b>	<b>Yes</b> , consider backfill (bentonite/sand mix, asphalt and engineered fill) – see Section 2.2.3.4 of the System and Its Evolution report, QUINTESSA 2011).
2.1.05.03 <b>Plugs</b>	<b>Yes</b> , consider basal monolith, three concrete bulkheads and a surface cap – see Section 2.2.3.4 of the System and Its Evolution report, QUINTESSA 2011).
2.1.05.04 Rock bolts	<b>No</b> , not expected to have a significant impact on long-term postclosure safety (see the FEPs report, Quintessa et al. 2011a).
2.1.06 Mechanical processes and conditions (in wastes and emplacement rooms, tunnels and shafts)	
2.1.06.01 Packaging collapse	
A <b>Steel failure</b>	<b>Yes</b> , consider failure of the steel packaging as a result of corrosion and rockfall (see Section 2.3.1.2).
B <b>Concrete failure</b>	<b>Yes</b> , consider failure of the concrete packaging as a result of rockfall (see Section 2.3.1.2).
2.1.06.02 Material volume changes	
A <b>Concrete shrinkage/ expansion</b>	<b>Yes</b> , see discussion of concrete shrinkage/expansion in Section 4.5.3 of the System and Its Evolution report (QUINTESSA 2011).
B <b>Bentonite swelling</b>	<b>Yes</b> , see discussion of bentonite swelling in Section 4.5.4 of the System and Its Evolution report (QUINTESSA 2011).

<b>FEP</b>	<b>Included in Conceptual Model for Normal Evolution Scenario</b>
C <b>Corrosion products</b>	<b>Yes</b> , see discussion of effects of corrosion in Section 4.5.1 of the System and Its Evolution report (QUINTESSA 2011).
2.1.06.03 <b>Emplacement room/tunnel collapse</b>	<b>Yes</b> , consider rockfall affecting the entire repository (see Section 4.4.1 of the System and Its Evolution report, QUINTESSA 2011).
2.1.06.04 <b>Container movement</b>	<b>Yes</b> , consider collapse of containers (see Section 2.3.1.2).
2.1.06.05 <b>Fracture formation</b>	<b>Yes</b> , consider through effect on the physical degradation of concrete bulkheads and monolith (see Section 2.3.2.1).
2.1.06.06 <b>Stress-corrosion cracking</b>	<b>No</b> , 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.
2.1.06.07 <b>Gas explosion</b>	<b>No</b> , 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.
2.1.06.08 <b>Influence of climate change</b>	<b>Yes</b> , consider mechanical impacts of glacial-interglacial cycling on concrete bulkheads and monolith (Section 2.3.2.1) and rockfall in the repository (Section 2.3.1.1).
2.1.07 <b>Hydraulic/hydrogeological processes and conditions (in wastes, emplacement rooms, tunnels and shafts)</b>	
2.1.07.01 <b>Resaturation/desaturation</b>	<b>Yes</b> , consider various resaturation profiles (see Section 2.3.1.1).
2.1.07.02 <b>Water flow</b>	<b>Yes</b> , consider – see Sections 2.3.1 and 2.3.2.
2.1.07.03 <b>Gas-mediated water flow</b>	<b>Yes</b> , resaturation and desaturation profiles driven by gas pressures (see Section 2.3.1.1).
2.1.07.04 <b>Failure of drainage system</b>	<b>No</b> , no drainage system is operative following closure.
2.1.07.05 <b>Fracturing of repository components due to hydraulic pressure</b>	<b>No</b> , pressure gradients not expected to be sufficient to cause such fracturing (see the FEPs report, QUINTESSA et al. 2011a, also the Geosynthesis report, NWMO 2011).
2.1.07.06 <b>Coupled hydraulic processes including temperature, chemical or</b>	<b>No</b> , no significant gradients expected to develop (see the FEPs report, QUINTESSA et al. 2011a).

<b>FEP</b>	<b>Included in Conceptual Model for Normal Evolution Scenario</b>
electrical gradients	
2.1.07.07 <b>Influence of climate change</b>	<b>Yes</b> , 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 (Section 2.3.2.1).
2.1.08 Chemical/geochemical processes and conditions (in wastes, emplacement rooms, tunnels and shafts)	
2.1.08.01 <b>pH conditions</b>	<b>Yes</b> , 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).
2.1.08.02 <b>Redox conditions</b>	<b>Yes</b> , 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).
2.1.08.03 <b>Chloride and sulphate conditions</b>	<b>Yes</b> , consider impact on corrosion and microbial degradation rates (see Appendix E and F of the Data report, QUINTESSA and GEOFIRMA 2011a) and solubility and sorption values (see Appendix C and D of the Data report, QUINTESSA and GEOFIRMA 2011a).
2.1.08.04 Corrosion	
A <b>General</b>	<b>Yes</b> , consider impact on gas generation rates and failure of packaging (see the FEPs report, QUINTESSA et al. 2011a).
B Localized	<b>No</b> , localized corrosion is expected to occur only during the short (<10 years) aerobic phase (see the FEPs report, QUINTESSA et al. 2011a).
C Galvanic	<b>No</b> , consider impact on gas generation rates will be small (see the FEPs report, QUINTESSA et al. 2011a).
2.1.08.05 <b>Polymer degradation</b>	<b>Yes</b> , consider impact on gas generation rates (see Section 4.2 of the T2GGM software document, QUINTESSA and GEOFIRMA 2011b).
2.1.08.06 Mineralization	
A <b>Leaching</b>	<b>Yes</b> , consider leaching of concrete in the shaft bulkheads and monolith (see Section 4.5.3 of the System and Its Evolution report, QUINTESSA 2011).
B <b>Chloride attack</b>	<b>Yes</b> , consider effect on degradation of concrete (see Section 4.5.3 of the System and Its Evolution report, QUINTESSA 2011).

FEP	Included in Conceptual Model for Normal Evolution Scenario
C Sulphate attack	<b>Yes</b> , consider effect on degradation of concrete (see Section 4.5.3 of the System and Its Evolution report, QUINTESSA 2011).
D Carbonation	<b>No</b> , not represented since calculations indicate that it will be slow and of limited spatial extent (see the FEPs report, QUINTESSA et al. 2011a).
E Illitization	<b>No</b> , calculations indicate that it will be negligible (see Appendix E.3 of the System and Its Evolution report, QUINTESSA 2011).
2.1.08.07 <b>Precipitation reactions</b>	<b>Yes</b> , consider solubility limitation of releases from waste to groundwater but only for C (see Section 2.3.1.1).
2.1.08.08 Chelating agent effects	<b>No</b> , only small amounts of complexing agents and assumed that have no significant effects (see the FEPs report, QUINTESSA et al. 2011a).
2.1.08.09 Colloid formation	<b>No</b> , 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).
2.1.08.10 Osmotic effects	<b>No</b> , not considered to be a significant process (see the FEPs report, QUINTESSA et al. 2011a).
2.1.08.11 Chemical concentration gradients	<b>No</b> , not considered to be a significant process (see the FEPs report, QUINTESSA et al. 2011a).
2.1.08.12 Influence of climate change	<b>No</b> , no significant effects expected (see the FEPs report, QUINTESSA et al. 2011a).
2.1.09 Biological/biochemical processes and conditions (in wastes, emplacement rooms, tunnels and shafts)	
2.1.09.01 <b>Microbial growth and poisoning</b>	<b>Yes</b> , consider through impact on corrosion, degradation and gas generation rates and associated gas and aqueous release rates (see Section 2.3.1.1).
2.1.09.02 <b>Microbially/biologically mediated processes</b>	<b>Yes</b> , consider through impact on corrosion, degradation and gas generation rates and associated gas and aqueous release rates (see Section 2.3.1.1).
2.1.09.03 <b>Microbial/biological effects of evolution on redox (Eh) and acidity/alkalinity (pH)</b>	<b>Yes</b> , consider through accounting for effect on Eh evolution of the repository (see Section 2.3.1.1). Assume that there is no significant microbial/biological effect on repository pH.
2.1.09.04 Influence of climate change	<b>No</b> , no significant effects expected (see the FEPs report, QUINTESSA et al. 2011a).

FEP	Included in Conceptual Model for Normal Evolution 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	<b>No</b> , 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).
2.1.10.02 Heat production from engineered features	<b>No</b> , any heat from concrete hydration will have dissipated prior to closure.
2.1.10.03 Temperature evolution	<b>No</b> , assume no significant temperature evolution (see the FEPs report, QUINTESSA et al. 2011a).
2.1.10.04 Temperature dependence of processes	
A Mechanical	<b>No</b> , assume no significant temperature evolution and so no effect on mechanical processes (see the FEPs report, QUINTESSA et al. 2011a).
B Hydraulic	<b>No</b> , assume no significant temperature evolution and so no effect on hydraulic processes (see the FEPs report, QUINTESSA et al. 2011a).
C Chemical	<b>No</b> , assume no significant temperature evolution and so no effect on chemical processes (see the FEPs report, QUINTESSA et al. 2011a).
D Biological	<b>No</b> , assume no significant temperature evolution and so no effect on biological processes (see the FEPs report, QUINTESSA et al. 2011a).
2.1.10.05 Influence of climate change	<b>No</b> , 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 the evolution of the repository (see the FEPs report, QUINTESSA et al. 2011a).
2.1.11 Gas sources (in wastes, emplacement rooms, tunnels and shafts)	
2.1.11.01 Radioactive decay	<b>No</b> , although Rn-222 is ingrown in the repository through radioactive decay of Ra-226, the gas pathway travel time is very long so that Rn-222 decays before reaching the surface (see Section 2.3.1.2).
2.1.11.02 Metal corrosion	<b>Yes</b> , see Section 2.3.1.1.
2.1.11.03 Organic waste degradation	<b>Yes</b> , see Section 2.3.1.1.

FEP	Included in Conceptual Model for Normal Evolution Scenario
2.1.11.04 Cement degradation	<b>No</b> , 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).
2.1.11.05 Asphalt degradation	<b>No</b> , the volume of CO <sub>2</sub> and CH <sub>4</sub> produced will be small compared with that produced from the microbiological degradation of the wastes (see the FEPs report, QUINTESSA et al. 2011a).
2.1.12 Radiation effects (in wastes, emplacement rooms, tunnels and shafts)	<b>No</b> , this is not expected to be significant due to the low initial amounts of radioactivity and the fall in radiation levels after facility closure (see the FEPs report, QUINTESSA et al. 2011a).
2.1.13 Effects of extraneous materials	<b>No</b> , not considered to be a significant process (see the FEPs report, QUINTESSA et al. 2011a).
2.1.14 Nuclear criticality	<b>No</b> , the concentration of fissile material is substantially lower than could result in a criticality (see the FEPs report, QUINTESSA et al. 2011a).
2.2 Geological Environment	
2.2.01 <b>Stratigraphy</b>	<b>Yes</b> , consider Deep, Intermediate and Shallow Bedrock Groundwater Zones – see Table 2.1, Section 2.3.2 and Appendix B.1.2.
2.2.02 <b>Host rock lithology</b>	<b>Yes</b> , see Box 1 in Section 2.3.1.1.
2.2.03 Disturbed zone (in geosphere)	
2.2.03.01 <b>Emplacement rooms and tunnels</b>	<b>Yes</b> , consider excavation damaged zone around repository – see Table 2.1 Section 2.3.1, Section 2.3.2, Table 4.1 and Appendix B.1.2
2.2.03.02 <b>Shafts</b>	<b>Yes</b> , consider excavation damaged zone around shaft – see Table 2.1 Section 2.3.1, Section 2.3.2, Table 4.1 and Appendix B.1.2.
2.2.04 Large-scale discontinuities (in geosphere)	
2.2.04.01 Faults and shear zones	<b>No</b> , 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 2011).
2.2.04.02 <b>Fractures and joints</b>	<b>Yes</b> , 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).

<b>FEP</b>	<b>Included in Conceptual Model for Normal Evolution Scenario</b>
2.2.04.03 Dykes	<b>No</b> , no evidence of dykes at the site (see Section 2.3 of the System and Its Evolution report, QUINTESSA 2011).
2.2.05 Mechanical processes and conditions (in geosphere)	
2.2.05.01 <b>Geomechanical properties</b>	<b>Yes</b> , consider rockfall in emplacement rooms and tunnels (see Section 5.3.1 of the System and Its Evolution report, QUINTESSA 2011).
2.2.05.02 <b>Current stress regime</b>	<b>Yes</b> , see Section 2.3.9 of the System and Its Evolution report, QUINTESSA 2011).
2.2.05.03 <b>Future stress regime</b>	<b>Yes</b> , consider evolution of stress regime around the repository that causes rockfall (see Section 5.3.1 of the System and Its Evolution report, QUINTESSA 2011) 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 2011).
2.2.06 Hydraulic/hydrogeological processes and conditions (in geosphere)	
2.2.06.01 <b>Hydraulic properties</b>	<b>Yes</b> , see Section 2.3.2 and Table 4.1.
2.2.06.02 <b>Current hydraulic potentials and gradients</b>	<b>Yes</b> , although simplified case with no representation of Ordovician underpressure also assessed (see Table 4.1).
2.2.06.03 <b>Future hydraulic potentials and gradients</b>	<b>Yes</b> , reference case allows initial Ordovician underpressures to equilibrate (see Table 3.1).
2.2.07 Chemical/geochemical processes and conditions (in geosphere)	
2.2.07.01 <b>Mineralogical properties</b>	<b>Yes</b> , properties discussed in Section 2.3.7.2 of the System and Its Evolution report (QUINTESSA 2011).
2.2.07.02 <b>Geochemical properties</b>	<b>Yes</b> , properties given in Section 2.3.7 of the System and Its Evolution report (QUINTESSA 2011) and used to inform selection of sorption coefficients (Appendix D of the Data report, QUINTESSA and GEOFIRMA 2011a).
2.2.07.03 Effects of engineered barriers	<b>No</b> , expect that any effects will be localized.

<b>FEP</b>	<b>Included in Conceptual Model for Normal Evolution Scenario</b>
2.2.07.04 Effects of climate change	<b>No</b> , climate change is expected to alter the geochemical conditions in the Shallow Bedrock Groundwater Zone, for example due to injection of glacial meltwaters (Section 6.2.1.3 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). 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).
2.2.08 Biological/biochemical processes and conditions (in geosphere)	<b>No</b> , not expected to have significant impact on the migration of contaminants through the geosphere.
2.2.09 Thermal processes and conditions (in geosphere)	
2.2.09.01 Thermal properties	<b>No</b> , 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).
2.2.09.02 Effects of waste and repository materials	<b>No</b> , 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.
2.2.09.03 Effects of climate change	<b>No</b> , the system at depth is expected to be isolated from the effects of climate change and so it is assumed to evolve under constant climate conditions.
2.2.10 Gas processes and effects (in geosphere)	
2.2.10.01 <b>Gas sources (excluding waste and repository materials)</b>	<b>Yes</b> , a Normal Evolution Scenario reference case considers residual gas saturation in the Ordovician (see Table 3.1).
2.2.10.02 <b>Gas migration</b>	<b>Yes</b> , consider the migration of repository-derived gases through the geosphere as bulk gas and dissolved groundwater (see Section 2.3.2.2).
2.2.10.03 <b>Gas dissolution</b>	<b>Yes</b> , dissolution of gases considered (see Section 2.3.2.2).
2.2.10.04 Gas-induced fractures	<b>No</b> , gas pressures are likely to be much less than the lithostatic pressure (see Figures 8.1 and 8.2 of the Gas Modelling report, GEOFIRMA and QUINTESSA 2011).



<b>FEP</b>	<b>Included in Conceptual Model for Normal Evolution Scenario</b>
2.2.11 <b>Geological resources (in geosphere)</b>	<b>Yes</b> , 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 2011).
2.2.12 Undetected features (in geosphere)	<b>No</b> , not considered for the Normal Evolution Scenario (although considered in Human Intrusion and Vertical Fault Scenarios) – see QUINTESSA et al. (2011a).
2.3 Surface Environment	
2.3.01 <b>Topography and morphology</b>	<b>Yes</b> , consider by differentiating terrestrial and lacustrine environments (see Section 2.3.3).
2.3.02 <b>Biomes</b>	<b>Yes</b> , consider biome consistent with present-day climate and human (see Section 2.3.3.1).
2.3.03 Soil and sediment	
2.3.03.01 <b>Surface soils</b>	<b>Yes</b> , receptor of contaminants in groundwater and gas (see Section 2.3.3.2, Figure 2.16 and Appendix B.1.3).
2.3.03.02 <b>Overburden</b>	<b>Yes</b> , see Appendix B.1.2.
2.3.03.03 <b>Aquatic sediments</b>	<b>Yes</b> , receptor of contaminants in groundwater (see Section 2.3.3.2, Figure 2.16 and Appendix B.1.3).
2.3.04 <b>Near-surface aquifers and water-bearing features</b>	<b>Yes</b> , contaminated as a result of releases from geosphere (see Section 2.3.3.2, Figure 2.16 and Appendix B.1.3).
2.3.05 Terrestrial surface-water bodies	
2.3.05.01 <b>Wetlands</b>	<b>Yes</b> , contaminated as a result of releases from geosphere (see Section 2.3.3.2, Figure 2.16 and Appendix B.1.3).
2.3.05.02 <b>Lakes and rivers</b>	<b>Yes</b> , contaminated as a result of releases from geosphere (see Section 2.3.3.2, Figure 2.16 and Appendix B.1.3).
2.3.05.03 <b>Springs and discharge zones</b>	<b>Yes</b> , consider groundwater discharge to lake from geosphere (see Section 2.3.3.2, Figure 2.16 and Appendix B.1.3).
2.3.06 Coastal features	<b>No</b> , not considered due to site's inland location.
2.3.07 Marine features	<b>No</b> , not considered due to site's inland location.

FEP	Included in Conceptual Model for Normal Evolution Scenario
2.3.08 Atmosphere	Yes, contaminated as a result of releases in groundwater and gas from geosphere (see Section 2.3.3.2, Figure 2.16 and Appendix B.1.3).
2.3.09 Vegetation	Yes, contaminated as a result of releases in groundwater and gas from geosphere (see Section 2.3.3.2, Figure 2.17 and Appendix B.1.3).
2.3.10 Animal populations	Yes, contaminated as a result of releases in groundwater and gas from geosphere (see Section 2.3.3.2, Figure 2.17 and Appendix B.1.3).
2.3.11 Climate and weather	Yes, consider in atmospheric dispersion calculations for gas release (Equation D30) and water balance calculations (Equation D26).
2.3.12 Hydrological regime and water balance (near-surface)	Yes, consider in conceptual model of biosphere through representation of surface water movements (see Figure 2.16 and Appendix B.2.2).
2.3.13 Erosion and deposition	Yes, see Figure 2.16 and Appendix B.2.2.
2.3.14 Ecological/biological/microbial systems	Yes, see Section 2.3.3.2 and Figure 2.16.
2.3.15 Biotic intrusion	No, not relevant for deep repository (see the FEPs report, QUINTESSA et al. 2011a).
2.4 Human Behaviour	
2.4.01 Human characteristics (physiology, metabolism)	Yes, consider International Commission on Radiological Protection Reference Man (see the FEPs report, QUINTESSA et al. 2011a).
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).
2.4.03 Diet and liquid intake	
2.4.03.01 Farming diet	Yes, the Site Resident Group is exposed via a wide range of pathways associated with the use of the land including farming (see Section 2.3.3.2 and Figure 2.18).
2.4.03.02 Hunter/gatherer diet	Yes. Since the Site Resident Group's diet is 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 GEOFIRMA 2011a), potential impacts for groups that might maximize 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. Furthermore, a variant calculation case considers fishing

<b>FEP</b>	<b>Included in Conceptual Model for Normal Evolution Scenario</b>
	critical groups (Section 4.4.2).
2.4.03.03 Other diets	<b>No</b> , since self-sufficient farming diet usually gives a reasonable or conservative estimate of dose, and since the fisher diet is included in FEP (2.4.03.02), it is not considered necessary to include any other diets.
2.4.04 <b>Habits (non-diet-related behaviour)</b>	<b>Yes</b> , consider habits resulting in inadvertent ingestion, inhalation and external irradiation/dermal exposure (see Section 2.3.3.2 and Figure 2.18).
2.4.05 Community characteristics	
2.4.05.01 <b>Community type</b>	<b>Yes</b> , consider Site Resident Group (see Section 2.3.3.2).
2.4.05.02 <b>Community location</b>	<b>Yes</b> , assume critical group is exposed to contaminated media in the vicinity of the site (see Section 2.3.3.2 and Figure 2.19).
2.4.05.03 <b>Water source</b>	<b>Yes</b> , consider Site Resident Group takes water from well pumping from Shallow Bedrock Groundwater Zone (see Section 2.3.3.2).
2.4.06 Food preparation and water processing	<b>No</b> , conservatively ignored, consistent with CSA (2008) (see the FEPs report, QUINTESSA et al. 2011a).
2.4.07 <b>Dwellings</b>	<b>Yes</b> , consider house dwelling for Site Resident Group (see Section 2.3.3.2 and Appendix B.1.3).
2.4.08 <b>Natural/semi-natural land and water use</b>	<b>Yes</b> , Site Resident Group uses natural/semi-natural land and water (e.g., for fishing and recreation) (see Section 2.3.3.2).
2.4.09 <b>Rural and agricultural land and water use</b>	<b>Yes</b> , Site Resident Group uses rural and agricultural land and water (see Section 2.3.3.2).
2.4.10 Urban and industrial land and water use	<b>No</b> , due to absence of significant urban and industrial land in immediate vicinity of site (see Section 2.4.7 of System and Its Evolution report, QUINTESSA 2011) and the expected lower impacts than for Site Resident Group (see the FEPs report, QUINTESSA et al. 2011a).
2.4.11 <b>Leisure and other uses of environment</b>	<b>Yes</b> , Site Resident Group uses land for recreation (see Section 2.3.3.2).
<b>3. CONTAMINANT FACTORS</b>	
3.1 Contaminant Characteristics	

<b>FEP</b>	<b>Included in Conceptual Model for Normal Evolution Scenario</b>
3.1.01 <b>Radioactive decay and in-growth</b>	<b>Yes</b> , consider progeny with half life 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).
3.1.02 <b>Organics and potential for organic forms</b>	<b>Yes</b> , 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).
3.1.03 <b>Chemical/organic toxin stability</b>	<b>Yes</b> , conservatively assume that, for the purpose of health and environmental impact calculations, organic contaminants do not degrade, although their degradation is considered for the purpose of gas generation rates.
3.1.04 <b>Inorganic solids/solutes</b>	<b>Yes</b> , consider inorganic contaminants (see Sections 3.5.1 and 3.6.1 of the Data report, QUINTESSA and GEOFIRMA 2011a).
3.1.05 <b>Volatiles and potential for volatility</b>	<b>Yes</b> , consider generation of gases in the repository (Section 2.3.1.1) and volatilization in the biosphere (see Section 2.3.3.2).
3.1.06 <b>Noble gases</b>	<b>Yes</b> , consider radon ingrown from Ra-226 in the biosphere (Equation D86).
3.2 Contaminant Release and Migration Factors	
3.2.01 <b>Contaminant release pathways</b>	<b>Yes</b> , consider two release pathways (gas and groundwater) (see Sections 2.3.1.3, 2.3.2.2 and 2.3.3.2).
3.2.02 Water-mediated migration of contaminants	
3.2.02.01 Water-mediated effects (repository)	
A <b>Advection</b>	<b>Yes</b> , consider in the repository (see Section 2.3.1.3 and Figure 2.10).
B <b>Molecular diffusion</b>	<b>Yes</b> , consider in the repository (see Section 2.3.1.3 and Figure 2.10).
C <b>Dispersion</b>	<b>Yes</b> , dispersive transport is considered since advection is considered (see FEP 3.2.02.01.A).
3.2.02.02 Water-mediated effects (geosphere)	
A <b>Advection</b>	<b>Yes</b> , see Section 2.3.2.2.
B <b>Molecular diffusion</b>	<b>Yes</b> , see Section 2.3.2.2.
C <b>Dispersion</b>	<b>Yes</b> , dispersive transport is considered since advection is considered (see FEP

<b>FEP</b>	<b>Included in Conceptual Model for Normal Evolution Scenario</b>
	3.2.02.02.A).
D Matrix diffusion	<b>No</b> , assume no dual porosity systems (see the FEPs report, QUINTESSA et al. 2011a).
3.2.02.03 Water-mediated effects (biosphere)	
A <b>Groundwater discharge to biosphere</b>	<b>Yes</b> , via well and discharge to lake (See Section 2.3.3.2).
B <b>Infiltration</b>	<b>Yes</b> , see Appendix B.2.2.
C Capillary rise	<b>No</b> , not considered to be a significant process for transfer of contaminants (see the FEPs report, QUINTESSA et al. 2011a).
D <b>Transport by surface run-off</b>	<b>Yes</b> , through subsuming it into FEP (3.2.03) – see the FEPs report (QUINTESSA et al. 2011a).
E <b>Transport by interflow</b>	<b>Yes</b> , see Figure 2.16 and see Appendix B.2.2.
F <b>Transport in surface-water bodies</b>	<b>Yes</b> , see Figure 2.16 and see Appendix B.2.2.
3.2.02.04 <b>Multiphase transport processes</b>	<b>Yes</b> , consider movement in gas and water phases (see Sections 2.3.1.3, 2.3.2.2 and 2.3.3.2).
3.2.03 <b>Solid-mediated migration of contaminants</b>	<b>Yes</b> , consider erosion/deposition by water and atmospheric resuspension/deposition in biosphere (see Figure 2.16 and Appendix B.2.2).
3.2.04 <b>Gas-mediated migration of contaminants</b>	<b>Yes</b> , consider gas migration from repository to biosphere via shaft and geosphere (Section 2.3.2.2), degassing from groundwater (see Section 2.3.2.2 and Figure 2.16), atmospheric dispersion of gas released to the biosphere (Section 2.3.3.2 and Figure 2.16), and volatilization in the biosphere (see Section 2.3.3.2 and Figure 2.16).
3.2.05 <b>Atmospheric migration of contaminants</b>	<b>Yes</b> , see Figure 2.16.
3.2.06 <b>Microbial/biological-mediated processes, effects on contaminant release and migration</b>	<b>Yes</b> , consider through impact on corrosion, degradation and gas generation rates and associated gas and aqueous release rates (see Section 2.3.1.1).

FEP	Included in Conceptual Model for Normal Evolution Scenario
3.2.07 <b>Animal, plant and microbe mediated migration of contaminants</b>	<b>Yes</b> , consider animal and plant uptake (see Figure 2.17 and Appendix B.2.2).
3.2.08 <b>Human-action-mediated migration of contaminants</b>	<b>Yes</b> , consider pumping of contaminated water from Shallow Bedrock Groundwater Zone and establishment of agricultural system (Section 2.3.3.2).
3.2.09 Colloids-mediated migration of contaminant	<b>No</b> , 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.
3.2.10 Dissolution, precipitation and mineralization	
3.2.10.01 <b>Dissolution and Precipitation (repository)</b>	<b>Yes</b> , consider aqueous release from wasteform and solubility limitation (see Section 2.3.1.1). Also consider leaching, chloride & sulphate attack and carbonation of concrete (see FEP 2.1.08.06).
3.2.10.02 Dissolution and Precipitation (geosphere)	<b>No</b> , assume no dissolution/precipitation in geosphere (see the FEPs report, QUINTESSA et al. 2011a).
3.2.10.03 Dissolution and Precipitation (biosphere)	<b>No</b> , assume no dissolution/precipitation in biosphere (see the FEPs report, QUINTESSA et al. 2011a).
3.2.10.04 <b>Change in mineralization</b>	<b>Yes</b> , consider mineralization of concrete (see Appendix E.5 of the System and Its Evolution report, QUINTESSA 2011).
3.2.11 Speciation and solubility (contaminant)	
3.2.11.01 <b>Speciation and solubility (solubility limitation, repository)</b>	<b>Yes</b> , consider dissolution of solids and solubility (see Section 2.3.1.1). Speciation considered through solubility limitation but only for C (see the FEPs report, QUINTESSA et al. 2011a).
3.2.11.02 Speciation and solubility (solubility limitation, geosphere)	<b>No</b> , concentrations assumed to be too low for solubility limitation to occur.
3.2.11.03 Speciation and solubility (solubility limitation, biosphere)	<b>No</b> , concentrations assumed to be too low for solubility limitation to occur.
3.2.11.04 <b>Solubility changes caused by chemical interaction between</b>	<b>Yes</b> , but only for C (see the FEPs report, QUINTESSA et al. 2011a).

FEP	Included in Conceptual Model for Normal Evolution Scenario
<b>waste and pore water</b>	
3.2.11.05 Solubility changes caused by change in temperature	<b>No</b> , no significant temperature change expected (see FEP 2.1.10).
3.2.11.06 Species equilibrium change caused by change in temperature	<b>No</b> , no significant temperature change expected (see FEP 2.1.10).
3.2.12 Sorption and desorption (contaminant)	
3.2.12.01 <b>Sorption and desorption (repository)</b>	<b>Yes</b> , consider sorption for certain elements in bentonite/sand (see Section 4.6.3 of the Data report, QUINTESSA and GEOFIRMA 2011a).
3.2.12.02 <b>Sorption and desorption (geosphere)</b>	<b>Yes</b> , consider sorption for certain elements (see Section 5.5.1.3 of the Data report, QUINTESSA and GEOFIRMA 2011a).
3.2.12.03 <b>Sorption and desorption (biosphere)</b>	<b>Yes</b> , see Section 6.2 of the Data report (QUINTESSA and GEOFIRMA 2011a).
3.2.12.04 Chemical reactions caused by adsorption or desorption	<b>No</b> , no need to identify this issue as a separate FEP (see the FEPs report, QUINTESSA et al. 2011a).
3.2.12.05 <b>Anion exclusion effects</b>	<b>Yes</b> , 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).
3.2.12.06 Sorption change caused by change in temperature	<b>No</b> , no significant temperature change expected (see FEP 2.1.10 and FEP 2.2.09).
3.2.13 Complexing agent effects (contaminant)	
3.2.13.01 Organics	<b>No</b> , screened out by use of conservative parameters (see the FEPs report, QUINTESSA et al. 2011a).
3.2.13.02 Inorganic ligands	<b>No</b> , not considered to be a significant process (see the FEPs report, QUINTESSA et al. 2011a).
3.2.13.03 Microbes	<b>No</b> , not considered to be a significant process (see the FEPs report, QUINTESSA et al. 2011a).

<b>FEP</b>	<b>Included in Conceptual Model for Normal Evolution Scenario</b>
3.2.14 <b>Food chains and uptake of contaminants</b>	<b>Yes</b> , the Site Resident Group is exposed via a wide range of pathways associated with the use of the land including farming (see Section 2.3.3.2 and Figure 2.18).
3.3 Exposure Factors	
3.3.01 <b>Contaminant concentrations in drinking water, foodstuffs and drugs</b>	<b>Yes</b> , see Section 2.3.3.2 and Figure 2.18.
3.3.02 Contaminant concentrations in non-food products	<b>No</b> , shown not to be significant in previous assessments (see the FEPs report, QUINTESSA et al. 2011a).
3.3.03 <b>Contaminant concentrations in other environmental media</b>	<b>Yes</b> , see Section 2.3.3.2 and Figure 2.18.
3.3.04 Exposure modes	
3.3.04.01 <b>Exposure of humans</b>	<b>Yes</b> , see Section 2.3.3.2, Figure 2.18 and Appendix B.2.2.
3.3.04.02 <b>Exposure of biota other than humans</b>	<b>Yes</b> , see Section 2.3.3.2 and Figure 2.18.
3.3.05 Dosimetry and biokinetics	
3.3.05.01 <b>Dosimetry and biokinetics for humans</b>	<b>Yes</b> , see Section 7.2 of the Data report, QUINTESSA and GEOFIRMA (2011a).
3.3.05.02 <b>Dosimetry and biokinetics for biota other than humans</b>	<b>Yes</b> , see Section 7.3 of the Data report, QUINTESSA and GEOFIRMA (2011a).
3.3.06 Radiological toxicity/effects	
3.3.06.01 <b>Radiological toxicity/effects for humans</b>	<b>Yes</b> , annual individual effective dose is calculated for adults, children and infants (see Section 3.4 of the Postclosure Safety Assessment report, QUINTESSA et al. 2011b).
3.3.06.02 <b>Radiological toxicity/effects for biota other than humans</b>	<b>Yes</b> , considered using no effect concentrations and if necessary, radiation doses (see Section 3.4 of the Postclosure Safety Assessment report, QUINTESSA et al. 2011b).
3.3.07 Chemical toxicity/effects	



<b>FEP</b>	<b>Included in Conceptual Model for Normal Evolution Scenario</b>
3.3.07.01 <b>Chemical toxicity/effects for humans</b>	<b>Yes</b> , considered using environmental quality standards and if necessary, toxicity calculations (see Section 3.4 of the Postclosure Safety Assessment report, QUINTESSA et al. 2011b).
3.3.07.02 <b>Chemical toxicity/effects for biota other than humans</b>	<b>Yes</b> , considered using environmental quality standards and if necessary, toxicity calculations (see Section 3.4 of the Postclosure Safety Assessment report, QUINTESSA et al. 2011b).
3.3.08 <b>Radon and radon daughter exposure</b>	<b>Yes</b> , consider radon ingrown from Ra-226 in the biosphere (Equation D86 and D108).

**REFERENCES FOR APPENDIX C**

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## APPENDIX D: MATHEMATICAL MODEL

### D.1 MODELLING APPROACH

A compartment modelling approach has been adopted to represent the dynamic parts of the system (e.g., radionuclide transport in the geosphere), and scalar models<sup>13</sup> have been adopted to represent those parts of the system that can be regarded as having a local equilibrium, e.g., the transfer of radionuclides in soil and water to plants.

The approach represents features of interest as compartments of a user defined volume, within which the distribution of contaminants is unimportant (either because the features are well-mixed, or the average concentration within a feature is sufficient for the required transport and/or exposure modelling). These may be assigned a specific spatial location and orientation (e.g., an area of contaminated soil).

Exchanges between compartments ('transfer processes') are described with first-order linear differential equations. These can be used to represent a wide range of physically-based or empirical transport processes. The mathematical representation of the inter-compartment transfer processes takes the form of a matrix of transfer coefficients that allow the compartment amounts to be represented as a set of first order linear differential equations. For the  $i^{\text{th}}$  compartment, the rate at which the compartment inventory changes with time is given by:

$$\frac{dN_i}{dt} = \left( \sum_{j \neq i} \lambda_{ji} N_j + \lambda_M M_i + S_i(t) \right) - \left( \sum_{j \neq i} \lambda_{ij} N_i + \lambda_N N_i \right) \quad (\text{D1})$$

where:

$i$  and  $j$  are indices denoting the  $i^{\text{th}}$  and  $j^{\text{th}}$  compartments;

$N$  and  $M$  are the amounts of contaminants  $N$  and  $M$  in a compartment ( $M$  is the precursor of  $N$  in a decay/degradation chain), mol;

$S(t)$  is a time dependent external source of contaminant  $N$ , mol/a;

$\lambda_M$  and  $\lambda_N$  are the decay constant for contaminants  $M$  and  $N$ , /a, respectively; and

$\lambda_{ji}$  and  $\lambda_{ij}$  are transfer coefficients representing the gain and loss of contaminant  $N$  from compartment  $i$  by transfer from and to compartment  $j$ , /a, respectively.

The solution of the matrix of equations given above provides the time-dependent inventory of contaminant  $N$  in each compartment. From the compartment sizes, estimates of the associated concentrations can then be made.

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<sup>13</sup> Scalar models assume that equilibrium exists instantaneously between two features. A simple radionuclide or elemental 'concentration factor' or 'transfer factor' can then be applied to estimate the concentration in one feature from the other. These factors are generally derived from experimental observations or from more detailed models.

The specific mathematical formulae used to represent the various release and migration processes and the exposure mechanisms identified in the conceptual models considered in the current assessment are documented in the following sections.

## D.2 GENERIC PROCESSES

The following processes are generic to all areas of the model:

- Radioactive decay;
- Sorption;
- Advection of gas and water;
- Dispersion; and
- Diffusion in gas and water.

### D.2.1 Radioactive Decay

The decay rate ( $\lambda$ , /a) is given by:

$$\lambda = \frac{\ln(2)}{t_{1/2}} \quad (D2)$$

where  $t_{1/2}$  is the half life of the radionuclide (a).

### D.2.2 Sorption

The element dependent retardation of the compartment  $R$  (unitless) is calculated using:

$$R = 1 + \frac{\rho K_d}{\theta_w} \quad (D3)$$

where:

$\rho$  is the dry bulk density of the compartment, kg/m<sup>3</sup>;

$K_d$  is the sorption coefficient of the element in the compartment, m<sup>3</sup>/kg; and

$\theta_w$  is the water filled porosity of the compartment (unitless).

The dry bulk density,  $\rho$ , is calculated using:

$$\rho = \rho_g (1 - \theta) \quad (D4)$$

where:

$\rho_g$  is the grain density of the compartment, kg/m<sup>3</sup>; and

$\theta$  is the total porosity of the compartment (unitless).

The water filled porosity,  $\theta_w$ , is calculated using:

$$\theta_w = \varepsilon \theta \quad (D5)$$

where:

$\varepsilon$  is the degree of saturation (unitless) in the compartment.

### D.2.3 Water Advection

Where volumetric water flows are provided, then the advective transfer rate for contaminants in water ( $\lambda_{flow}$ , /a) can be calculated using:

$$\lambda_{flow} = \frac{Q}{V \theta_w R} \quad (D6)$$

where:

$Q$  is the volumetric flow rate from the donor compartment, m<sup>3</sup>/a; and

$V$  is the volume of the donor compartment.

In the case of bulk surface water flows,  $\theta_w$  is unity and retardation does not apply and so the transfer rate can be expressed as  $Q/V$ .

Where Darcy velocities are specified,  $\lambda_{flow}$  is given by:

$$\lambda_{flow} = \frac{q}{L \theta_w R} \quad (D7)$$

where:

$q$  is the annual flow rate through the donor compartment, m/a; and

$L$  is the length of the compartment in the direction of water flow, m.

For fluid flow through porous media, the annual flow rate through the donor compartment,  $q$ , is generally given by:

$$q = -K i \quad (D8)$$

where:

$K$  is the hydraulic conductivity of the donor compartment, m/a; and

$i$  is the hydraulic gradient in the direction of transfer (unitless).

### D.2.4 Dispersion

Dispersion along advective flow paths is represented implicitly through the discretization of the geosphere into a series of compartments. Discretizing a pathway into five compartments, results in mathematical dispersion equivalent to hydrodynamic dispersion with a dispersion length of 10% of the path length (see Appendix E).

### D.2.5 Diffusion in Water

Appendix E describes how diffusion can be represented in donor controlled compartment models with forward and return transfers. The 'forward' diffusive transfer rate,  $\lambda_{DiffD}$ , /a, is given by:

$$\lambda_{DiffD} = \frac{A_d D_{Eff}}{R_U V_U \Delta_d \theta_{wU}} \quad (D9)$$

where:

$A_d$  is the cross-sectional area relevant to the diffusive transfer, m<sup>2</sup>;

$D_{Eff}$  is the average effective diffusion coefficient for transfer, m<sup>2</sup>/a;

$R_U$  is the retardation factor in the upstream compartment for the radionuclide (unitless);

$V_U$  is the volume of the upstream compartment, m<sup>3</sup>;

$\Delta_d$  is the distance between the mid-points of the compartments in the direction of the diffusive flux, m; and

$\theta_{wU}$  is the water-filled porosity of the upstream compartment (unitless).

The effective diffusion coefficient for a transfer,  $D_{Eff}$  (m<sup>2</sup>/a), is determined as the arithmetic average of that for the donor and receptor compartments<sup>14</sup>:

$$D_{Eff} = \frac{D_{EffU} L_U + D_{EffD} L_D}{L_U + L_D} \quad (D10)$$

where:

$D_{EffU}$  is the effective diffusion coefficient for the upstream compartment, m<sup>2</sup>/a;

$D_{EffD}$  is the effective diffusion coefficient for the downstream compartment, m<sup>2</sup>/a;

$L_U$  is the distance from the midpoint of the upstream compartment to the transfer interface, m; and

$L_D$  is the distance from the midpoint of the downstream compartment to the transfer interface, m.

The volume,  $V$ , is given by:

$$V = L A_d \quad (D11)$$

<sup>14</sup> Note that the AMBER model for the host rock amalgamates different formations with relatively similar properties. Harmonic average vertical effective diffusion coefficients are used for these layers, as noted in Appendix J.

where:

$L$  is the length of the compartment in the direction of diffusion.

In addition to this 'forward' diffusive transfer rate, there is a need to represent a corresponding 'return' diffusive transfer rate in the reverse direction,  $\lambda_{DiffU}$ , /a. This transfer rate is given by:

$$\lambda_{DiffU} = \frac{A_d D_{Eff}}{R_D V_D \Delta_d \theta_{wD}} \quad (D12)$$

where:

$R_D$  is the retardation factor for the radionuclide in the downstream compartment (unitless);

$V_D$  is the volume of the downstream compartment, m<sup>3</sup>; and

$\theta_{wD}$  is the water-filled porosity of the downstream compartment (unitless).

### D.3 REPOSITORY PROCESSES

The general conceptual model identifies two distinct functions for the availability of contaminants to water (i.e., the release of contaminants from the waste):

- Instant release/availability – contamination is released immediately on contact with water.
- Congruent release/availability – contamination is available as the waste corrodes/degrades and is released on contact with water.

Because of the long predicted resaturation times, it is necessary to consider the availability of the wastes to release to water with time. Water levels in the repository will vary with time depending on the resaturation profile adopted for the calculation case (Section 2.3.1.1). Contamination in the waste can then be mobilized into the water associated with the waste package via the appropriate processes.

Once released to the repository water, contaminants can freely diffuse around the DGR.

#### D.3.1 Availability of Contaminants as a Result of Resaturation

Each waste category is represented with a single compartment that represents the contaminants that are unavailable for release to repository water, which is both that fraction that is in the unsaturated portion of the waste and the fraction that is 'locked away' in the waste form and unavailable for leaching into the repository water. At initial times all contamination is in the waste compartments and the contaminants are unavailable for release to repository water.

The amount of waste that is 'available' for release to repository water will be a function of the water height versus the height of the waste package stack. The height of the waste package stack is constant and takes into account collapse of the waste stacks from closure, see Appendix J.5. Packaging is not taken to limit the availability of contaminants.

$$F_A = \begin{cases} \left( \frac{h_{water}}{h_{waste}} \right) f_{waste} & h_{water} \leq h_{waste} \\ f_{waste} & h_{water} > h_{waste} \end{cases} \quad (D13)$$

where:

$F_A$  is the fraction of the waste inventory available for transport in water (unitless);

$h_{water}$  is the height of water in the emplacement room, m (time dependent);

$h_{waste}$  is the height of the waste package stack (collapsed), m; and

$f_{waste}$  is the fraction of a waste that is available for release to repository water (unitless).

The rate of contaminant release to the repository water is equal the ratio of the rate of change of availability (i.e., the derivative of  $F_A$ ) divided by the quantity of unavailable waste remaining.

The derivative of  $F_A$  is:

$$\frac{\partial F_A}{\partial t} = \left( \frac{f_{waste}}{h_{waste}} \cdot \frac{\partial h_{water}}{\partial t} \right) + \left( \frac{h_{water}}{h_{waste}} \cdot \frac{\partial f_{waste}}{\partial t} \right) \quad (D14)$$

which has two components, the first relating to the release of available contaminants from unsaturated waste due to resaturation of the repository, and the second relating to the release of unavailable contaminants in the saturated waste due to corrosion of waste packages.

The contaminant release rate is controlled by the rate of change of availability versus the amount of waste remaining to be made available,  $\lambda_{Avail}$ , /a.

$$\lambda_{Avail} = \frac{\left( \frac{f_{waste}}{h_{waste}} \cdot \frac{\partial h_{water}}{\partial t} \right) + \left( \frac{h_{water}}{h_{waste}} \cdot \frac{\partial f_{waste}}{\partial t} \right)}{1 - F_A} \quad (D15)$$

### D.3.1.1 Instant Availability

Contaminants present on waste material surfaces will immediately go into solution when in contact with water – no credit is taken for sorption onto the waste material. The relationship for  $f_{waste}$  is as follows:

$$f_{waste} = 1 \quad (D16)$$

### D.3.1.2 Congruent Availability

Congruent release occurs due to the rate of corrosion or degradation of the waste. Given that wastes corrode due to the presence of high humidity and the presence of a thin film of water everywhere, the degradation of congruent released waste occurs when the waste is both unsaturated and saturated. Degraded waste is available for instant release.



The degradation of the wastes is best accounted for via  $f_{waste}$ , representing the availability of waste as it progressively degrades and becomes available for release to repository water. If a simple 2D 'plate' geometry is adopted, i.e., the degradation rate represents a constant rate at which waste becomes available for release with time, then  $f_{waste}$  becomes a simple linear release model, based on the thickness of the waste and the corrosion rate.

$$\begin{aligned}
 f_{waste} &= 0 & t < t_{degrad\_start} \\
 f_{waste} &= \frac{t - t_{deg\ rad\_start}}{t_{deg\ rad\_finish} - t_{deg\ rad\_start}} & t_{degrad\_start} \geq t < t_{degrad\_finish} \\
 f_{waste} &= 1 & t \geq t_{degrad\_finish}
 \end{aligned} \tag{D17}$$

where:

- $t$  is the elapsed time since repository closure, a;
- $t_{degrad\_start}$  is the time at which corrosion/degradation starts, a; and
- $t_{degrad\_finish}$  is the time at which corrosion/degradation is complete, a.

The duration of a corrosive release is calculated from the corrosion rate ( $c_{rate}$ , m/a) and the thickness of the waste metal ( $W_{thickness}$ , m):

$$t_{deg\ rad\_finish} = t_{deg\ rad\_start} + W_{thickness} / c_{rate} \tag{D18}$$

### D.3.2 Gaseous Contaminants

Gaseous contaminants include H-3, C-14, and potentially volatile contaminants such as Cl-36, Se-79 and I-129. Detailed calculations determine the bulk volumes of gases; however, at an assessment level, it is necessary to adopt simple models that determine the rate of release of gaseous contaminants. Given the potential importance of C-14 to postclosure safety and the complexities associated with modelling carbon within the DGR, the model for C-14 is described separately in Appendix E.

#### D.3.2.1 Tritium

The entire H-3 inventory is assumed to be released from the wastes immediately at closure. This is represented with a rapid transfer rate (see Appendix J.6) for H-3 from the wastes to the repository gas.

In the assessment models H-3 is assumed to be in the form of HT, although as described in Section 2.3.1.2 some H-3 may also be in the form of HTO. H-3 is modelled to partition between water and gas in the DGR in accordance with Henry's law. The assumption that all H-3 is in the form of HT is considered to be appropriate given that H-3 is only of interest very early in the postclosure period due to its short half-life (12.3 a). This assumption maximizes the amount of H-3 in gas because HT is less soluble in water than HTO.

### D.3.2.2 Volatiles

The general conceptual model includes volatilization of I-129 and Se-79, and to a lesser extent Cl-36, in the repository. The number of moles in the gas phase compared with the number of moles in the aqueous phase is specified as a fixed partition coefficient for each radionuclide.

### D.3.2.3 Gas Transport within the Repository

Gases mix rapidly throughout the DGR due to the high porosity of the repository. This is modelled by scaling rapid transfer rates between the gas compartments by their volumes to provide an even concentration throughout the repository gas compartments:

$$\lambda_{GasRep} = \lambda_{Rapid} \frac{V_{Receptor}}{V_{Donor} + V_{Receptor}} \quad (D19)$$

where:

$\lambda_{GasRep}$  is the transfer rate from a donor to a receptor gas compartment (/a);

$\lambda_{Rapid}$  is a rapid rate in relation to other modelled processes (/a) (see Appendix J.6);

$V_{Donor}$  is the volume of the donor gas compartment; and

$V_{Receptor}$  is the volume of the receptor gas compartment.

### D.3.3 Desaturation of the Repository

In some cases (including the Reference Case), there are periods during which the water level in the repository falls as a result of increased gas pressure. During these periods, the water leaving the repository is transferred into the repository floor. The transfer rate,  $\lambda_{Desat}$  (1/a), is given by:

$$\lambda_{Desat} = \frac{U_{Desat}}{H_{Wat}} \quad (D20)$$

where:

$U_{Desat}$  is the rate of desaturation (m/a); and

$H_{Wat}$  is the depth of water in the repository (m).

## D.4 GEOSPHERE AND SHAFT PROCESSES

### D.4.1 Groundwater Transport

The advection, dispersion and diffusion of contaminants in groundwater within the shafts and geosphere are represented with the generic expressions described in Sections D.2.3, D.2.4 and D.2.5, respectively.

#### D.4.2 Gas Transport

As described in Appendix J, the AMBER gas model uses parameters derived from the T2GGM model results (GEOFIRMA and QUINTESSA 2011).

The transfer rate due to gas transport,  $\lambda_{GasFlow}$ , /a, is given by:

$$\lambda_{GasFlow} = \frac{F_{Gas}}{M_{Gas}} \quad (D21)$$

where:

$F_{Gas}$  is the time-dependent flux rate of free gas from the donor compartment (kg/a); and

$M_{Gas}$  is the time-dependent mass of gas in the donor compartment (kg).

The general conceptual model also considers dissolution of CH<sub>4</sub> and CO<sub>2</sub> gases migrating via the shaft. Considering the low water movement in the shaft, it is assumed to saturate quickly. Therefore, dissolution is only modelled in the shallow groundwater system, where there is a flow of water that can continuously remove the dissolved gas. The fraction that dissolves in groundwater is dependent on the rate at which any free gas reaches the shallow groundwater system. The maximum amount of gas that can be dissolved in the shallow system,  $d_{CH_4}$  (mol/a), is determined in Appendix H to the Analysis of Human Intrusion and Other Disruptive Scenarios report (QUINTESSA and SENES 2011). The fraction of gas that dissolves,  $f_{Dissolved}$  (-), is then determined by:

$$f_{Dissolved} = \min \left( \begin{array}{c} \frac{d_{CH_4}}{G_{Flux}} \\ 1 \end{array} \right) \quad (D22)$$

where:

$G_{Flux}$  is the flux of bulk gas to the Shallow Bedrock Groundwater System (mol/a).

The calculated transfer flux of C-14 to the shallow system is therefore split, with the dissolved fraction entering the groundwater, and the remaining fraction being released upward to the biosphere as free gas.

#### D.5 DYNAMIC BIOSPHERE PROCESSES

The input to the biosphere model for the gas pathway is a flux to the atmosphere. The flux provides the basis for calculating the various atmospheric concentrations due to the gas release from the shafts/geosphere. The dynamic model needs the concentrations above the soil and shore compartments. After leaving the house, any plume from the shafts is taken to pass over the farmland and lake.

### D.5.1 Irrigation and Animal Watering

Irrigation and animal watering can be represented with an advective transfer from an appropriate point within the Shallow Bedrock Groundwater Zone. It is important that the balance of advective transfer between the pumped groundwater and that which might continue to flow towards Lake Huron is maintained.

The volume of water pumped from the well,  $Q_{Abs}$  ( $m^3/a$ ), is a key input parameter and, depending on the scenario, will be comprised of that which is applied to the soil as irrigation water,  $Q_{Irrig}$  ( $m^3/a$ ), that which is used to water animals,  $Q_{AnnWat}$  ( $m^3/a$ ) and that which is used for domestic purposes (drinking, bathing etc.),  $Q_{HumWat}$  ( $m^3/a$ ). These can be determined using:

$$Q_{Irrig} = F_{WellIrrig} A_{Crop} D_{Irrig} \quad (D23)$$

where:

$F_{WellIrrig}$  is the proportion of irrigation water provided by the well (unitless);

$A_{Crop}$  is the area of farmland used for irrigated crops,  $m^2$ ; and

$D_{Irrig}$  is the depth of irrigation water required for each crop,  $m/a$ .

$$Q_{AnnWat} = \sum_{Animals} F_{WellAnn} N_{Ann} I_{WatAnn} \quad (D24)$$

where:

$F_{WellAnn}$  is the proportion of the animals' drinking water that is provided by the well (unitless);

$N_{Ann}$  is the number of animals that require watering (unitless); and

$I_{WatAnn}$  is the ingestion rate of water by animals,  $L/d$  converted to  $m^3/a$ .

$$Q_{HumWat} = N_H I_{Wat} \quad (D25)$$

where:

$N_H$  is the number of people using the abstracted water; and

$I_{Wat}$  is the domestic water demand per person ( $m^3/a$ ).

Water pumped for domestic purposes is transferred as waste water to the Lake Shore and can be represented with a similar advective transfer from an appropriate point within the Shallow Bedrock Groundwater Zone, as used for irrigation/watering.

### D.5.2 Infiltration/Percolation and Interflow

These transfer processes adopt the standard advection model. The key inputs defining the volume of infiltration from the soil,  $Q_{Infil}$  ( $m^3/a$ ) and the volume of interflow to the local surface water course from the soil,  $Q_{Inter}$  ( $m^3/a$ ) are provided by a water balance model, where the volume of water leaving the top soil by infiltration and interflow,  $Q_{Soil}$  ( $m^3/a$ ) is given by:

$$Q_{Soil} = A_{Farm} (P_{tn} - R_o - E_{tp}) + Q_{Irrig} \quad (D26)$$

where:

$A_{Farm}$  is the area of the irrigated farmed land, m<sup>2</sup>;

$P_{tn}$  is the depth of annual precipitation, m/a;

$R_o$  is the depth of precipitation that is lost as surface runoff (i.e., does not enter the top soil) m/a; and

$E_{tp}$  is the depth of evapotranspiration, m/a.

All of the water infiltrating through the soil compartment is taken to discharge to a nearby surface water course.

### D.5.3 Surface Water Transport

Surface water flows can be represented by advective transfers, with the volumetric flow rates ( $Q$ , m<sup>3</sup>/a) and water body volumes ( $V$ , m<sup>3</sup>) being provided as inputs.

### D.5.4 Erosion

Erosion of the surface soil is characterized by an erosion rate,  $ER$  (kg dry weight/m<sup>2</sup>/a), and the associated erosive transfer rate,  $\lambda_{er}$  (/a), of contaminants out of the soil layer is characterized by<sup>15</sup>:

$$\lambda_{er} = \frac{ER(1 - f_{wat})}{\rho_b Z_{soil}} \quad (D27)$$

where:

$Z_{soil}$  is the depth of the donor soil compartment, m; and

$f_{wat}$  is the fraction of radionuclide in soil in the water phase (i.e., not sorbed), which is given by:

$$f_{wat} = \frac{\theta_w}{\theta_w + K_d \rho_b} \quad (D28)$$

### D.5.5 Losses due to Crop Removal

The transfer rate due to crop removal,  $\lambda_c$  (/a), is given by<sup>16</sup>:

<sup>15</sup> Clause 6.3.4.1 of CSA (2008).

<sup>16</sup> Based on Clause 6.3.7.1 of CSA (2008).

$$\lambda_c = \sum_{crops} \frac{A_{crop} CR DW_p Y_c NL cf}{hi V_{soil} \rho_b} \quad (D29)$$

where:

$A_{crop}$  is the area used for each crop (m<sup>2</sup>);

$CR$  is the plant/soil concentration ratio (Bq/kg dry weight plant per Bq/kg dry soil);

$DW_p$  is the dry/fresh weight ratio for plant products (kg dry plant/kg fresh or stored plant);

$Y_c$  is the consumable plant yield (kg fresh weight plant/m<sup>2</sup>soil);

$NL$  is the nutrient loss rate (or fraction of crop harvested for food) (unitless);

$cf$  is the cropping frequency (/a);

$hi$  is the harvest index (mass of consumable product divided by the mass of total above ground plant; total below ground plant for root crops) (unitless); and

$V_{soil}$  is the volume of the soil compartment (m<sup>3</sup>).

#### D.5.6 Air Flow

Transfers through the atmosphere compartments due to the flow of air,  $\lambda_{air}$  (/a), are given by:

$$\lambda_{air} = \frac{u}{L} \quad (D30)$$

where:

$u$  is the mean wind speed (m/a); and

$L$  is the length of the atmosphere compartment in the direction of wind flow.

The increasing size of the atmosphere compartments above the cropped soil, grazed soil and shore provide a simple representation of atmospheric dispersion, which is appropriate to the context of the assessment.

#### D.5.7 Deposition of Gaseous Radionuclides onto Soil and Surface Water

The deposition of gaseous radionuclides onto soil and water,  $\lambda_{dep}$  (/a), is provided by:

$$\lambda_{dep} = \frac{v_g}{Z} \quad (D31)$$

where:

$v_g$  is the deposition velocity (m/s); and

$Z$  is the height of the atmosphere compartment (m).

The deposition velocity from the air onto the soil and surface water is given by<sup>17</sup>:

$$v_g = v_d + v_w \quad (D32)$$

where:

$v_d$  is the dry deposition velocity (m/s); and

$v_w$  is the wet deposition velocity (m/s).

The wet deposition velocity is expressed as<sup>18</sup>:

$$v_w = f_p W_r Ptn \quad (D33)$$

where:

$f_p$  is the fraction of time that precipitation falls when wind is blowing from the source to receptor location (unitless/unitless);

$W_r$  is the washout ratio to soil; and

$Ptn$  is the long-term average precipitation rate, m/s.

### D.5.8 Volatilization

Consistent with Clause 6.3.5.1 of CSA (2008), volatilization from the soil is applicable for tritium, C-14, and the radioiodines. The specific activity approach for modelling tritium means that volatilization need not be explicitly represented, while simple volatilization transfer rates,  $\lambda_{vol}$  (/s), are specified for C-14 and radioiodine.

When there is a free gas flux from the ventilation shaft to the soil used for growing crops (note that a house is taken to be above the main shaft), the transfer rate of C-14 from the soil is increased by the volumetric through-flow of gas,  $\lambda_{SoilGas}$ , /a:

$$\lambda_{SoilGas} = \frac{V_{GasFlux[Vent]}}{V_{Soil} (\theta_t - \theta_w)} \quad (D34)$$

The volumetric gas flux from the ventilation shaft,  $V_{GasFlux[Vent]}$ , m<sup>3</sup>/a, is given by:

$$V_{GasFlux[Vent]} = \frac{A_{VentShaft}}{A_{BothShafts}} Q_{Gas} (1 - f_{Dissolved}) \frac{R_{Gas} T}{P_{Atm} m_{CH4}} \quad (D35)$$

<sup>17</sup> Clause 6.3.3.1 of CSA (2008).

<sup>18</sup> Clause 6.3.3.1 of CSA (2008).

where<sup>19</sup>:

$A_{VentShaft}$  is the cross-sectional area of the ventilation shaft (m<sup>2</sup>);

$A_{BothShafts}$  is the combined cross-sectional areas of both shafts (m<sup>2</sup>);

$Q_{Gas}$  is the total flux of free gas to the Shallow Bedrock Groundwater Zone (kg/a); and

$f_{Dissolved}$  is the fraction of the free gas flux to the Shallow Bedrock Groundwater Zone that dissolves in the groundwater (unitless);

$R_{Gas}$  is the ideal gas constant (J/K/mol);

$T$  is the temperature (K);

$P_{Atm}$  is the atmospheric pressure (Pa); and

$m_{CH_4}$  is the molar mass of CH<sub>4</sub> (g/mol).

## D.6 EQUILIBRIUM PROCESSES

Mathematical expressions representing equilibrium relationships are described in the subsections below. The expressions are based on those given in CSA (2008), which represents the relationship with transfer parameters of notation  $P_{\#\#}$ , where ‘##’ are numbers relating to numbered components of the CSA (2008) biosphere model. Given the site-specific nature of the biosphere model developed, the discretization differs from CSA (2008) and, therefore, the numbers are less relevant. Therefore, new transfer parameter names are used, while the equivalent CSA (2008) parameter name is also indicated for cross-reference purposes.

### D.6.1 Volatilization from Irrigated Soil

Volatilization from soil leads to an equilibrium air concentration downwind,  $P_{SoilAir}$  (Bq/m<sup>3</sup>)/(Bq/kg dw), which is applicable to C-14 and I-129 and is given by<sup>20</sup>:

$$P_{SoilAir} = P_{3mass1} = Z_{soil} \rho_b \lambda_{vol} D_{res} C_{res} \quad (D36)$$

where:

$Z_{soil}$  is the depth of the top mixed soil layer (m);

$\rho_b$  is the dry bulk density of the soil (kg dry soil/m<sup>3</sup>);

$\lambda_{vol}$  is the volatilization rate (/s);

$D_{res}$  is the air dilution factor (s/m); and

<sup>19</sup> Note that AMBER will convert between mass units of g and kg.

<sup>20</sup> Clause 7.2.5.1 of CSA (2008)



$C_{res}$  is a correction factor that accounts for the location of the receptor relative to the irrigated field (unitless).

The air dilution factor accounts for dispersion in air from source to receptor, and is the air concentration at the receptor divided by the source strength, as given by<sup>21</sup>:

$$D_{res} = 4.87 A_f^{\frac{1}{8}} - 3.56 \quad (D37)$$

where the receptor is downwind at the end of the field ( $C_{res} = 1$ ) and

$A_f$  is the area of the irrigated field ( $m^2$ ).

Resuspension of tritium from the soil,  $P_{SoilAir\_HTO}$  ( $L/m^3$ ) is provided by<sup>22</sup>:

$$P_{SoilAir\_HTO} = P_{3spw\_1HTO} = R_a H_a C_{res} \quad (D38)$$

where:

$H_a$  is the atmosphere absolute humidity ( $L/m^3$ ); and

$R_a$  is the ratio of the concentration of tritium in air moisture at 1.5 m above ground to concentration of tritium in air moisture at ground level (which is same as in soil moisture).

## D.6.2 Volatilization from Water

Volatilization from water,  $P_{WatAir}$  (unitless), which is applicable to C-14 and I-129, is provided by:

$$P_{WatAir} = Z_{wat} \lambda_{vol} D_{wat} \quad (D39)$$

where:

$Z_{wat}$  is the depth of the water (m);

$\lambda_{vol}$  is the volatilization rate (/s);

$D_{wat}$  is the air dilution factor (s/m).

The air dilution factor accounts for the dispersion in air from source to receptor, and is the air concentration at receptor divided by the source strength, as given by<sup>23</sup>:

$$D_{wat} = e^{\left[5 \ln \left( \ln A_{wat} \right) - 9\right]} \quad (D40)$$

<sup>21</sup> Clause 7.2.5.2 of CSA (2008).

<sup>22</sup> Clause 7.2.5.4 of CSA (2008).

<sup>23</sup> Based on Equation 7.5 and Chapter 7.3.4 of Davis et al. (1993).

where:

$A_{wat}$  is the area of the water compartment (m<sup>2</sup>).

### D.6.3 Contamination of Vegetation Due to Irrigation

The transfer parameter for deposition of radionuclides from spray irrigation to vegetation,  $P_{PlantIrrig}$  (L/kg fresh weight), for radionuclides other than H-3 and C-14 is given by<sup>24</sup>:

$$P_{PlantIrrig} = P_{24} = \frac{LAI I_{wt} \eta_i tf hi [1 - e^{-\lambda_p t_e}]}{\lambda_p Y_c} \quad (D41)$$

where:

$LAI$  leaf area index - leaf area per unit ground surface area (m<sup>2</sup>/m<sup>2</sup>);

$I_{wt}$  the volume of water retained per unit leaf area (L/m<sup>2</sup>);

$\eta_i$  frequency of irrigation events using contaminated water (/s)

$tf$  is the translocation factor from foliage to consumable product;

$\lambda_p$  is the effective removal constant due to physical processes such as wind and rain (/s);

$t_e$  is the effective duration of deposition (s).

For tritiated water (HTO), the transfer from irrigation water to HTO in vegetation,  $P_{PlantIrrig[HTO]}$  (L/kg), is given by<sup>25</sup>:

$$P_{PlantIrrig} [HTO] = P_{24\_HTO} = 1 - DW_p \quad (D42)$$

The transfer of HTO in irrigation water to organically bound tritium (OBT) in vegetation,  $P_{PlantIrrig[OBT]}$  (L/kg fw), is given by<sup>26</sup>:

$$P_{PlantIrrig} [OBT] = P_{24\_OBT} = DW_p ID_p WE_p \quad (D43)$$

where:

$ID_p$  is the isotopic discrimination factor for plant metabolism; and

$WE_p$  is the water equivalent of the plant dry matter (L water/kg dw plant).

<sup>24</sup> Clause 7.3.1.1 of CSA (2008).

<sup>25</sup> Clause 7.3.2 of CSA (2008).

<sup>26</sup> Clause 7.3.3 of CSA (2008).

The transfer from irrigation water to plants for C-14,  $P_{PlantIrrig[C14]}$ , (L/kg fw), is given by<sup>27</sup>:

$$P_{PlantIrrig[C14]} = P_{24\_C14} = \frac{(1 - f_{c\_air}) L' f_{CO2}}{Y_c \left( \left( \frac{TS}{hi} \right) - 1 \right) cf} \quad (D44)$$

where<sup>28</sup>:

$f_{c\_air}$  is the fraction of plant stable carbon derived from air (unitless);

$L'$  is annual average irrigation rate (L/m<sup>2</sup>/s);

$f_{CO2}$  is the fraction of annual input of C-14 leaving the soil surface as CO<sub>2</sub> per annum (unitless);  
and

$TS$  is the ratio of the total plant yield to the above ground yield (total below ground for root crops) (unitless).

The fraction of annual input of C-14 into soil, as CH<sub>4</sub>, that leaves the soil as CO<sub>2</sub>,  $f_{CO2}$ , is given by:

$$f_{CO2} = \frac{f_{CO2[Irrig]} X_{CH4[Irrig]} + f_{CO2[Shaft]} X_{CH4[Shaft]}}{X_{CH4[Irrig]} + X_{CH4[Shaft]}} \quad (D45)$$

where:

$f_{CO2[Irrig]}$  is the fraction of the C-14 gas flux from the irrigated soil that is CO<sub>2</sub> (-);

$X_{CH4[Irrig]}$  is the flux of dissolved CH<sub>4</sub> to the irrigated soil (mg/day).

$f_{CO2[Shaft]}$  is the fraction of the C-14 gas flux from the soil above the shaft that is CO<sub>2</sub> (-); and

$X_{CH4[Shaft]}$  is the flux of CH<sub>4</sub> to the soil above the shaft (mg/day).

The fraction of the C-14 gas flux from the irrigated soil that is CO<sub>2</sub>,  $f_{CO2[Irrig]}$  (-) is given by:

$$f_{CO2[Irrig]} = \min \left( \frac{\chi_{CH4} A_{Soil[Irrig]}}{X_{CH4[Irrig]}}, 1 \right) \quad (D46)$$

where:

<sup>27</sup> Clause 7.3.4.2 of CSA (2008).

<sup>28</sup> Note that AMBER will convert between time units of years and seconds.

$\chi_{CH_4}$  is the oxidation rate for CH<sub>4</sub> to CO<sub>2</sub> in the soil (mg/m<sup>2</sup>/day); and

$A_{Soil[Irrig]}$  is the area of soil receiving the irrigation water (m<sup>2</sup>).

The flux of CH<sub>4</sub> to the irrigated soil,  $X_{CH_4[Irrig]}$  (mg/day) is given by:

$$X_{CH_4} = Q_{Gas} f_{CH_4} f_{Dissolved} f_{Well} \frac{Q_{Irrig}}{Q_{Abs}} \quad (D47)$$

where:

$Q_{Gas}$  is the total flux of free gas to the Shallow Bedrock Groundwater Zone (kg/a)<sup>29</sup>;

$f_{CH_4}$  is the fraction of the total gas flux that comprises CH<sub>4</sub> (unitless).

$f_{Dissolved}$  is the fraction of the free gas flux to the Shallow Bedrock Groundwater Zone that dissolves in the groundwater (unitless);

$f_{Well}$  is the capture fraction of the well (unitless);

$Q_{Irrig}$  is the annual amount of groundwater that is abstracted from the well for irrigation (m<sup>3</sup>/a); and

$Q_{Abs}$  is the total annual amount of groundwater abstracted from the well (m<sup>3</sup>/a).

The fraction of the C-14 gas flux from the soil above the shaft that is,  $f_{CO_2[Shaft]}$  CO<sub>2</sub> (-), is given by:

$$f_{CO_2[Shaft]} = \min \left( \frac{\chi_{CH_4} A_{Soil[Shaft]}}{X_{CH_4[Shaft]}}, 1 \right) \quad (D48)$$

where:

$A_{Soil[Shaft]}$  is the area of soil receiving the gas flux from the ventilation shaft (m<sup>2</sup>).

The flux of CH<sub>4</sub> to the soil above the shafts,  $X_{CH_4[Shaft]}$  (mg/day), is given by:

$$\chi_{CH_4[Shaft]} = Q_{Gas} f_{CH_4} (1 - f_{Dissolved}) \frac{A_{VentShaft}}{A_{BothShafts}} \quad (D49)$$

where:

$A_{VentShaft}$  is the cross-sectional area of the ventilation shaft at the surface (m<sup>2</sup>); and

<sup>29</sup> Note that AMBER will convert between mass units of mg and kg and between time units of years and days.

$A_{BothShafts}$  is the cross-sectional area of both shafts ( $m^2$ ).

#### D.6.4 Crop Plant Uptake from the Soil

Transfer from soil to plants,  $P_{PlantSoil[Crop]}$  (Bq/kg fw)/(Bq/kg dw soil), for radionuclides other than tritium and C-14 is provided by<sup>30</sup>:

$$P_{PlantSoil} = P_{3mass\ 4} = CR\ DW_p \quad (D50)$$

where:

$CR$  is the concentration ratio (Bq/kg dwplant)/(Bq/kg dw soil); and

$DW_p$  is the dry/fresh weight ratio for plant products (kg dw plant/kg fw plant).

The transfer of H-3 and C-14 from soil to plants is incorporated into the transfer from air to plants.

#### D.6.5 Wild Plant Uptake from the Soil

Transfer from soil to wild forage plants,  $P_{PlantSoil[Wild]}$  (Bq/kg fresh plant per Bq/kg dry soil), for radionuclides other than tritium and C-14 is provided by<sup>31</sup>:

$$P_{PlantSoil\ [Wild]} = P_{3mass\ 4} = CR\ DW_p\ DF_s \quad (D51)$$

where:

$CR$  is the concentration ratio (Bq/kg dry weight plant per Bq/kg dry weight soil);

$DW_p$  is the dry/fresh weight ratio for plant products (kg dry plant)/(kg fresh or stored plant);  
and

$DF_s$  is the dilution factor for shoreline deposits.

Note that wild plants are taken to be present in the wetland area, therefore they are taken to be in equilibrium with wetland sediment and, thus, the shoreline factor is required (although this is conservatively set to 1 for this Postclosure SA, see Table 6.7 of the Data report, QUINTESSA and GEOFIRMA 2011). The transfer of H-3 and C-14 from soil to plants is incorporated into the transfer from air to plants.

#### D.6.6 Tritium Transformation from HT to HTO

The transformation of HT to HTO in the air,  $P_{HT\_HTO}$  (unitless), is given by<sup>32</sup>:

<sup>30</sup> Clause 6.8.1 of CSA (2008).

<sup>31</sup> Clause 6.8.1 of CSA (2008).

<sup>32</sup> Clause 6.1.6.2 of CSA (2008).

$$P_{HT\_HTO} = P_{11a} = R_{HT} H_a f_{oxid} \quad (D52)$$

where:

$R_{HT}$  is the ratio of HTO concentration in air moisture to HT concentration in air (B/L per Bq/m<sup>3</sup>);

$H_a$  is the absolute humidity (L/m<sup>3</sup>); and

$f_{oxid}$  fraction of the year when oxidation may occur (unitless).

### D.6.7 Deposition of Gaseous Radionuclides onto Vegetation

Transfer parameter for deposition of gaseous radionuclides from atmosphere to vegetation,  $P_{PlantAir}$  (m<sup>3</sup>/kg fresh weight) for radionuclides other than H-3 and C-14, is given by<sup>33</sup>:

$$P_{PlantAir} = P_{14} = \frac{v_g f_{int} tf hi [1 - e^{-\lambda_p t_e}]}{\lambda_p Y_c} \quad (D53)$$

where:

$v_g$  deposition velocity (m/s);

$f_{int}$  foliar interception fraction (unitless);

$tf$  translocation factor from foliage to consumable product (Bq/kg fw consumable plant product per Bq/kg fw total above ground plant);

$\lambda_p$  effective removal constant from vegetation surfaces due to processes other than radiological decay (/s);

$t_e$  effective duration of the deposition (s); and

$Y_c$  yield of consumable plant product (kg fw/m<sup>2</sup>).

### D.6.8 Plant Uptake of H-3 and C-14 from the Air

The transfer parameter from air HTO (and soil HTO) to HTO in the plant,  $P_{PlantAir[HTO]}$  (m<sup>3</sup>/kg), is given by<sup>34</sup>:

$$P_{PlantAir[HTO]} = P_{14\_HTO} = \frac{RF_p (1 - DW_p)}{H_{a\_g}} \quad (D54)$$

where:

<sup>33</sup> Clause 6.4.1 of CSA (2008).

<sup>34</sup> Clause 6.4.6.2 of CSA (2008).

$RF_p$  is the reduction factor that accounts for the effect of soil water HTO concentrations that are lower than air moisture HTO concentrations (unitless); and

$H_{a\_g}$  is the atmospheric absolute humidity during the growing season ( $L/m^3$ ).

$(1-DW_p)$  is the water content of the plant  $L_{water}/kg$  fw plant.

The transfer parameters from air HTO to OBT in plants,  $P_{PlantAir[OBT]}$ , ( $m^3/kg$  fw), is given by<sup>35</sup>:

$$P_{PlantAir[OBT]} = P_{14\_HTO-OBT} = \frac{RF_p DW_p ID_p WE_p}{H_{a\_g}} \quad (D55)$$

where:

$ID_p$  is the isotopic discrimination factor for plant metabolism (unitless); and

$WE_p$  is the water equivalent of the plant dry matter ( $L$  water/ $kg$  dw plant).

Elemental tritium (HT) in the air is converted to HTO in plants. This process is represented by  $P_{PlantAir[HT]}$  ( $m^3/kg$  fw)<sup>36</sup>:

$$P_{PlantAir [HT]} = P_{14\_HT} = CF_{HT} (1 - DW_p) \quad (D56)$$

where:

$CF_{HT}$  oxidation/re-emission/uptake factor for plants, equal to ratio of HTO concentration in plant water to HT concentration in air ( $Bq/L$  plant HTO per  $Bq/m^3$  air HT).

The transfer parameter from air HT to OBT in the plant,  $P_{PlantAir[HT\_OBT]}$  ( $m^3/kg$ ), is given by<sup>37</sup>:

$$P_{PlantAir [HT\_OBT]} = P_{14\_HT - OBT} = CF_{HT} DW_p ID_p WE_p \quad (D57)$$

For C-14, the transfer parameter from air to vegetation,  $P_{PlantAir[C14]}$  ( $m^3/kg$  fw) is given by<sup>38</sup>:

$$P_{PlantAir[C14]} = P_{14\_C14} = \frac{f_{c\_air} X_{4C} DW_p}{X_{1C}} \quad (D58)$$

where:

$X_{4C}$  is the mass of stable carbon per mass of plant ( $gC/kg$  dw); and

<sup>35</sup> Clause 6.4.8.2 of CSA (2008).

<sup>36</sup> Clause 6.4.7.2 of CSA (2008).

<sup>37</sup> Clause 6.4.8.3 of CSA (2008).

<sup>38</sup> Clause 6.4.9.2 of CSA (2008).

$X_{1C}$  is the concentration of stable carbon in air (gC/m<sup>3</sup>).

### D.6.9 Transfer to Honey

The transfer of radionuclides to honey,  $P_{HonPlant}$  (on a fresh weight honey and fresh weight plant basis), is determined by<sup>39</sup>:

$$P_{HonPlant} = P_{25\ honey} = \frac{CR_h}{DW_p} \quad (D59)$$

where:

$CR_h$  is concentration ratio for honey (Bq/kg fresh weight honey per Bq/kg dry plant); and

$DW_p$  is dry/fresh weight ratio for plant products (kg dry plant/kg fresh or stored plant).

### D.6.10 Contamination of Animal Produce by Radionuclides in the Air

The transfer parameter relating concentrations in animal produce to that in the air,  $P_{AnmInh}$  (m<sup>3</sup>/kg fw), for radionuclides other than H-3 and C-14 is given by<sup>40</sup>:

$$P_{AnmInh} = P_{15} = Q_a F_{inh} \quad (D60)$$

where:

$Q_a$  is the inhalation rate of the animal (m<sup>3</sup>/d); and

$F_{inh}$  is the fraction of animal's daily intake by inhalation that appears in each kg of produce (d/kg fw).

The fraction of animal's daily intake by inhalation that appears in each kg of produce,  $F_{inh}$ , is calculated from the ingestion transfer factor,  $F_{ing}$ , according to:

$$F_{inh} = II F_{ing} \quad (D61)$$

where:

$II$  is the inhalation/ingestion absorption ratio.

The transfer of HTO from air to HTO in animal produce,  $P_{AnmInh[HTO]}$  (m<sup>3</sup>/kg fw), is given by<sup>41</sup>:

$$P_{AnmInh[HTO]} = P_{15\_HTO} = \frac{f_{w\_sw} (1 - DW_a)}{H_a} \quad (D62)$$

<sup>39</sup> Clause 6.10.5.1 of CSA (2008).

<sup>40</sup> Clause 6.12.1.1 of CSA (2008).

<sup>41</sup> Clause 6.12.2.1 of CSA (2008).



where:

$f_{w\_sw}$  is the fraction of animal water intake derived from inhalation and skin absorption (unitless);

$DW_a$  is the dry weight of the animal food product per total fresh weight (kg dw/kg fw); and

$H_a$  is the absolute humidity (L/m<sup>3</sup>).

The transfer parameter for HTO concentration in the air to OBT concentration in the animal,  $P_{AnmInh[OBT]}$  (m<sup>3</sup>/kg), is given by<sup>42</sup>:

$$P_{AnmInh[OBT]} = P_{15\_OBT} = \frac{f_{w\_sw} DW_a ID_a WE_a}{H_a} \quad (D63)$$

where:

$ID_a$  is the isotopic discrimination factor for animal metabolism (unitless); and

$WE_a$  is the water equivalent of the animal dry matter (L water/kg dw product).

Note that animals take up very little gaseous C-14 via inhalation.

#### D.6.11 Transfer from Soil to Animal Produce

Transfer factor from soil to animal product,  $P_{AnmSoil}$  (kg fresh weight/kg dry weight), for radionuclides other than tritium and C-14 is given by<sup>43</sup>.

$$P_{AnmSoil} = P_{3mass\ 5} = \left( k_{af} Q_f f_{sl} + Q_s \right) F_{ing} \quad (D64)$$

where:

$k_{af}$  is the fraction of feed from contaminated sources (unitless);

$Q_f$  is the feed consumption rate by the animal (kg dw/d);

$f_{sl}$  is the soil load on feed as consumed (kg dry soil per kg dry feed);

$Q_s$  is the soil consumption rate of the animal from sources other than feed (kg dw/d); and

$F_{ing}$  is the fraction of animal's daily intake by ingestion that appears in each kg of produce (d/kg fw).

Consistent with CSA (2008), the soil ingestion pathway for contamination of animal produce is expected to be negligible for H-3 and C-14.

<sup>42</sup> Clause 6.12.2.3 of CSA (2008).

<sup>43</sup> Clause 6.11.1.1 of CSA (2008).

### D.6.12 Transfer from Water to Animal Produce

The transfer parameter relating the concentration of all radionuclides other than H-3 in animal produce to that in contaminated water,  $P_{AnnWat}$  (L/kg fresh weight) is given by<sup>44</sup>:

$$P_{AnnWat} = P_{25} = k_{aw} Q_w F_{ing} \quad (D65)$$

where:

$k_{aw}$  is the fraction of the animal's drinking water from the contaminated source;

$Q_w$  is the water consumption of the animal (L/d); and

$F_{ing}$  is the fraction of the animal's daily intake by ingestion that appears in each kg of produce (d/kg fresh weight).

The specific activity model used to represent the transfer of HTO from drinking water to HTO in animal produce,  $P_{AnnWat[HTO]}$  (L/kg fresh weight), is<sup>45</sup>:

$$P_{AnnWat [HTO]} = P_{25 HTO} = k_{aw} f_{w\_w} (1 - DW_a) \quad (D66)$$

where:

$f_{w\_w}$  is the fraction of animal water intake derived from direct ingestion of water; and

$DW_a$  is the dry weight of the animal food product per total fresh weight (kg dw/kg fw).

The transfer parameter from HTO in drinking water to OBT in animal produce on a fresh weight basis,  $P_{AnnWat[OBT]}$  (L/kg) is provided by<sup>46</sup>:

$$P_{AnnWat [OBT]} = P_{25 OBT} = k_{aw} f_{w\_w} DW_a ID_a WE_a \quad (D67)$$

where:

$ID_a$  is the isotopic discrimination factor for animal metabolism; and

$WE_a$  is the water equivalent of the animal product dry matter (L water/kg dry weight product).

### D.6.13 Transfer from Vegetation to Animal Produce

The transfer parameter relating the concentration of radionuclides except H-3 in animal produce to that in dry weight feed,  $P_{AnnPlant}$  (kg fw animal/kg dw feed), is given by<sup>47</sup>:

<sup>44</sup> Clause 6.9.1.1 of CSA (2008).

<sup>45</sup> Clause 6.9.2.1 of CSA (2008).

<sup>46</sup> Clause 6.9.3.1 of CSA (2008).

<sup>47</sup> Clause 6.10.1.1 of CSA (2008).

$$P_{AnnPlant} = P_{45} = \frac{k_{af} Q_f F_{ing} e^{(-\lambda_r t_h)}}{DW_p} \quad (D68)$$

where:

$k_{af}$  is the fraction of feed from contaminated sources (unitless);

$Q_f$  is the feed consumption by the animal (kg dw/d);

$F_{ing}$  is the fraction of animal's daily intake by ingestion which appears in each kg of produce (d/kg fw);

$\lambda_r$  is the radioactive decay constant (/s);

$t_h$  is the hold-up time between plant exposure to contamination and feeding (s); and

$DW_p$  is the dry/fresh weight ratio for plant products (kg dry plant/kg fresh or stored plant).

The transfer of HTO from feed to animal produce,  $P_{AnnPlant[HTO]}$ , is given by<sup>48</sup>:

$$P_{AnnPlant[HTO]} = P_{45\ HTO} = \frac{k_{af} (f_{w\_pw} + ID_p f_{w\_dw}) (1 - DW_a)}{(1 - DW_p)} \quad (D69)$$

where:

$f_{w\_pw}$  is the fraction of the animal water intake derived from water in the plant feed;

$ID_p$  is the isotope discrimination factor for plant metabolism; and

$f_{w\_dw}$  is the fraction of animal water intake that results from the metabolic decomposition of the organic matter in the feed.

The transfer of OBT from plant feed to animal product,  $P_{AnnPlant[OBT]}$ , is provided by<sup>49</sup>:

$$P_{AnnPlant[OBT]} = P_{45\ OBT} = \frac{k_{af} (f_{w\_pw} + ID_p f_{w\_dw}) ID_a DW_a WE_a}{(ID_p DW_p WE_p)} \quad (D70)$$

where:

$WE_p$  is the water equivalent of the plant dry matter (L water/kg fresh or stored plant).

<sup>48</sup> Clause 6.10.2.1 of CSA (2008).

<sup>49</sup> Clause 6.10.3 of CSA (2008).

### D.6.14 Transfer from Surface Water to Aquatic Animals

The transfer parameter from surface water to aquatic animals,  $P_{AqWat}$  (L/kg fresh weight), for radionuclides except H-3 and C-14 is provided by the bioaccumulation factor (BAF), which relates the concentration in the edible portion (Bq/kg fresh weight) to the total concentration (dissolved plus particulate) in the water (Bq/L):

$$P_{AqWat} = BAF \quad (D71)$$

The model for HTO transfer from surface water to aquatic animals,  $P_{AqWat[HTO]}$  (L/kg fresh weight), is provided by<sup>50</sup>:

$$P_{AqWat [HTO]} = P_{26 HTO} = 1 - DW_{aa} \quad (D72)$$

where:

$DW_{aa}$  is the dry weight of the aquatic animal food product per total fresh weight (kg dry weight/kg fresh weight).

The model for HTO transfer from surface water to OBT in aquatic animals,  $P_{AqWat[OBT]}$  (L/kg fresh weight), is provided by<sup>51</sup>:

$$P_{AqWat [OBT]} = P_{26 OBT} = DW_{aa} ID_{aa} WE_{aa} \quad (D73)$$

where:

$ID_{aa}$  is the isotopic discrimination factor for aquatic animal metabolism; and

$WE_{aa}$  is the water equivalent of the aquatic animal dry matter (L/kg dry weight).

The model for C-14 transfer from surface water to aquatic animals,  $P_{AqWat[C14]}$  (L/kg fresh weight), is provided by<sup>52</sup>:

$$P_{AqWat} = P_{26 C14} = \frac{M_{aa}}{M_w} \quad (D74)$$

where:

$M_{aa}$  is the mass of stable carbon in aquatic animals (gC/kg fresh weight); and

$M_w$  is the mass of stable carbon in the dissolved inorganic phase in water (gC/L).

<sup>50</sup> Clause 7.7.4.1 of CSA (2008).

<sup>51</sup> Clause 7.7.4.3 of CSA (2008).

<sup>52</sup> Clause 7.7.5.1 of CSA (2008).

## D.6.15 Equilibrium Concentrations

The CSA (2008) expressions define the relevant source/receptor components in the parameter name, however, the differing discretization in the site-specific biosphere model means that a different naming convention has been used. Therefore, it is helpful to be explicit about the calculation of concentrations in the biosphere components, which are described below.

### D.6.15.1 General Calculation of Concentrations in Biosphere Media

The dynamic model provides amounts of contaminants in compartments as an output, *Amount* (Bq). The amounts can be converted to volumetric or mass concentrations, depending on the compartment properties.

Volumetric concentrations,  $C_V$  (Bq/m), are given by:

$$C_V = \frac{\text{Amount}}{V} \quad (\text{D75})$$

where:

$V$  is the compartment volume ( $\text{m}^3$ ).

The concentration of contaminants in the liquid phase,  $C_L$  (Bq/L), can be calculated with:

$$C_L = \frac{C_V}{(\theta_w + \rho_b K_d)} \quad (\text{D76})$$

The concentration of contaminants on the solid phase,  $C_D$  (Bq/kg dry weight), can be calculated with:

$$C_D = K_d C_L \quad (\text{D77})$$

The wet weight concentration,  $C_W$  (Bq/kg), is provided by:

$$C_W = \frac{C_V}{\theta_w \rho_w + \rho_b} \quad (\text{D78})$$

where:

$\rho_w$  is the density of water,  $\text{kg}/\text{m}^3$ ;

The total concentration (i.e., in solid and liquid phase) by dry mass,  $C_T$  (Bq/kg) is provided by:

$$C_T = \frac{C_V}{\rho_b} \quad (\text{D79})$$

The dry weight concentration in sediment,  $C_{DSed}$  (Bq/kg dry weight), is required for uptake to wild plants and incidental ingestion by wild animals. This is calculated by:

$$C_{DSed} = K_d C_{L[Water]} \quad (\text{D80})$$

The volumetric concentration in bed sediments,  $C_{VSed}$  (Bq/m<sup>3</sup>), is required for external irradiation and is calculated as described below:

$$C_{VSed} = C_{L[Water]} \left( \theta_{w[Sed]} + K_d \rho_{b[Sed]} \right) \quad (D81)$$

where:

$\theta_{w[sed]}$  is the water filled porosity of the sediment; and

$\rho_{b[sed]}$  is the dry bulk density of the sediment (kg/m<sup>3</sup>).

The total concentration in sediment by dry weight,  $C_{TSed}$  (Bq/kg dry weight), is therefore calculated with:

$$C_{TSed} = \frac{C_{VSed}}{\rho_{b[Sed]}} \quad (D82)$$

#### D.6.15.2 Concentrations in Air

The concentration in the air above the soil,  $C_{air[Soil]}$  (Bq/m<sup>3</sup>), is provided by:

$$C_{air [Soil]} = P_{SoilAir} C_{T[Soil]} \quad (D83)$$

The concentration in air above surface water and lake water is,  $C_{air[Water]}$  (Bq/m<sup>3</sup>), is provided by:

$$C_{air [Water]} = P_{WatAir} C_{V[Water]} \quad (D84)$$

The air concentration of Rn-222 above soil,  $C_{air[Rn,Soil]}$ , is given by:

$$C_{air [Rn, Soil]} = \chi_{RnSoil} D_{res} \quad (D85)$$

where:

$\chi_{RnSoil}$  is the flux of Rn-222 released from the soil compartment, Bq/m<sup>2</sup>/a, given by<sup>53</sup>:

$$\chi_{RnSoil} = C_{V[Ra-226]} e_{Rn} \sqrt{\frac{\lambda_{Rn} D_{Rn}}{\theta_t}} \quad (D86)$$

where:

$C_{V[Ra-226]}$  is the concentration of Ra-226 in the soil/sediment compartment, Bq/m<sup>3</sup>;

$e_{Rn}$  is the Rn-222 emanation power;

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<sup>53</sup> Based on Equation 9 of Amiro (1992).

$\lambda_{Rn}$  is the decay constant of Rn-222, /a;

$D_{Rn}$  is the diffusivity of Rn-222 through bulk material, m<sup>2</sup>/a; and

$\theta_t$  is the total porosity of the soil compartment.

The diffusivity of Rn-222 through bulk soil is calculated with the following empirical relationship<sup>54</sup>:

$$D_{Rn} = 335 \theta_t e^{(-26.1 M)} \quad (D87)$$

where:

$M$  is the moisture content of soil (weight water/wet weight soil).

The air concentration of Rn-222 above water,  $C_{air[Rn,Water]}$ , is given by:

$$C_{air [Rn, Water]} = \chi_{RnWat} D_{wat} \quad (D88)$$

where:

$\chi_{RnWat}$  is the flux of Rn-222 released from the water compartment, Bq/m<sup>2</sup>/a.

The flux of Rn-222 released from surface water,  $\chi_{RnWat}$ , is given by:

$$\chi_{RnWat} = \lambda_{RnWat} C_V [Ra - 226] \quad (D89)$$

where:

$\lambda_{RnWat}$  is the aquatic transfer coefficient for radon (m/a).

The concentration in outdoor air over the farmland and shore region of the lake is simply the volumetric concentration in the associated atmosphere compartment,  $C_v$  (Bq/m<sup>3</sup>).

Air concentrations for HTO in the atmosphere compartments are given by:

$$C_{air [HTO]} = C_V [H - 3] P_{HT - HTO} \quad (D90)$$

Air concentrations for HT in the atmosphere compartments are given by:

$$C_{air [HT]} = C_V [H - 3] \left( 1 - P_{HT - HTO} \right) \quad (D91)$$

For the air above water compartments (which is represented in equilibrium with the associated water compartment), the concentration of HTO in the air is given by:

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<sup>54</sup> Based on Equation 10 of Amiro (1992).

$$C_{air [HTO]} = P_{WatAir [HTO]} C_{L[H-3]} \quad (D92)$$

The C-14 concentration in air within the plant canopy,  $C_{canopy}$ , Bq/m<sup>3</sup>, is used with  $P_{PlantAir}$  to provide a C-14 concentration in plants and is calculated according to:

$$C_{canopy} = \frac{f_{CO2} F_{Voln}}{u_{canopy} Z_C W_{Soil}} \quad (D93)$$

where:

$f_{CO2}$  is the fraction of annual input of C-14 leaving the soil surface as CO<sub>2</sub> per annum (unitless);

$F_{Voln}$  is the transfer flux of C-14 from the soil to the atmosphere (Bq/a);

$u_{canopy}$  is the windspeed within the plant canopy (m/a);

$Z_C$  is the height of the plant canopy (m); and

$W_{Soil}$  is the width of the soil compartment perpendicular to the direction of the air flow within the canopy (m).

For the calculation of air concentrations within the house, the floor area of the house is taken to be greater than the cross-sectional area of the shaft over which it is situated, therefore, the concentration in the air of a house situated above the main shaft,  $C_{Air[House]}$  (Bq/m<sup>3</sup>), is given by:

$$C_{Air[House]} = \frac{f_{GasHouse} F_{gas}}{\left( \lambda_{house} + \frac{f_{GasHouse} V_{GasFlux[Main]}}{A_{house} Z_{house}} \right) A_{house} Z_{house}} \quad (D94)$$

where:

$f_{GasHouse}$  is the fraction of the gas flux beneath the house that enters the air in the house, which is conservatively taken to be unity for this Postclosure SA;

$F_{gas}$  is the flux rate of gas from the shafts/EDZs to the floor area of the house (Bq/a);

$\lambda_{house}$  is the turnover rate of air in the house (/a);

$V_{GasFlux[Main]}$  is the volumetric gas flux from the main shaft (m<sup>3</sup>/a);

$A_{house}$  is the floor area of the house (m<sup>2</sup>); and

$Z_{house}$  is the height of the house (m).

The volumetric gas flux from the main shaft,  $V_{GasFlux[Main]}$ , m<sup>3</sup>/a, is given by:



$$V_{GasFlux[Main]} = \frac{A_{MainShaft}}{A_{BothShafts}} Q_{Gas} (1 - f_{Dissolved}) \frac{R_{Gas} T}{P_{Atm} m_{CH4}} \quad (D95)$$

where<sup>55</sup>:

$A_{MainShaft}$  is the cross-sectional area of the main shaft (m<sup>2</sup>);

$A_{BothShafts}$  is the combined cross-sectional areas of both shafts (m<sup>2</sup>);

$Q_{Gas}$  is the total flux of free gas to the Shallow Bedrock Groundwater Zone (kg/a); and

$f_{Dissolved}$  is the fraction of the free gas flux to the Shallow Bedrock Groundwater Zone that dissolves in the groundwater (unitless);

$R_{Gas}$  is the ideal gas constant (J/K/mol);

$T$  is the temperature (K);

$P_{Atm}$  is the atmospheric pressure (Pa); and

$m_{CH4}$  is the molar mass of CH<sub>4</sub> (g/mol).

### D.6.15.3 Concentrations in Plants

The concentration in crops,  $C_{Plant[Crop]}$  (Bq/kg fresh weight), for radionuclides other than H-3 and C-14 is provided by:

$$C_{Plant [Crop]} = P_{PlantIrrig} C_{Well} + P_{PlantSoil [Crop]} C_{T[Soil]} \quad (D96)$$

where:

$C_{Well}$  is the concentration in well water (Bq/m<sup>3</sup>).

The HTO concentration in crops,  $C_{PlantCrop[HTO]}$  (Bq/kg fresh weight), is provided by:

$$C_{Plant [Crop] [HTO]} = P_{PlantAir [HTO]} C_{air [HTO]} \quad (D97)$$

The OBT concentration in crops,  $C_{PlantCrop[OBT]}$  (Bq/kg fresh weight), is provided by:

$$C_{Plant [Crop] [OBT]} = P_{PlantAir [OBT]} C_{air [HTO]} \quad (D98)$$

The C-14 concentration in crops,  $C_{PlantCrop[C14]}$  (Bq/kg fresh weight), is provided by:

$$C_{Plant [Crop] [C14]} = P_{PlantAir [C14]} C_{canopy [C14]} \quad (D99)$$

<sup>55</sup> Note that AMBER will convert between molar mass to kg/mol.

The concentration in wild forage,  $C_{Plant[Wild]}$  (Bq/kg fresh weight), is calculated in a similar manner:

$$C_{Plant [Wild]} = P_{PlantSoil [Wild]} C_{TSed} \quad (D100)$$

#### D.6.15.4 Concentrations in Animal Produce

The concentration in honey,  $C_{honey}$  (Bq/kg fresh weight), is calculated using:

$$C_{honey} = P_{HonPlant} C_{Plant [Fruit and Berries]} \quad (D101)$$

The concentration in honey is related to that in fruit and berries, given that they will flower before they are harvested.

The concentration in farm animal produce,  $C_{Anm[Farm]}$  (Bq/kg fresh weight), is calculated by:

$$C_{Anm [Farm]} = P_{AnmInh} C_{air [Farm]} + P_{AnmSoil} C_{T[Soil]} + P_{AnmWat} C_{Well} + P_{AnmPlant} C_{Plant [Crop]} \quad (D102)$$

The concentration in wild animal produce,  $C_{Anm[Wild]}$  (Bq/kg fresh weight), is calculated by:

$$C_{Anm [Wild]} = P_{AnmInh} C_{air [Wetland]} + P_{AnmSoil} C_{sed [Wetland]} + P_{AnmWat} C_{L[WetlandWater]} + P_{AnmPlant} C_{Plant [Wild]} \quad (D103)$$

The concentration in aquatic animals,  $C_{Aq}$  (Bq/kg fresh weight), is provided by:

$$C_{Aq} = P_{AqWat} C_{V[Water]} \quad (D104)$$

Where  $C_{V[Water]}$  (Bq/m<sup>3</sup>) is the total volumetric concentration in the associated water compartment.

## D.7 EXPOSURE CALCULATIONS

### D.7.1 Dose Due to Ingestion of Plants, Honey, Animal Produce and Aquatic Animals

The internal dose from ingestion of plants,  $P_{IngPlant}$  (Sv/a per Bq/kg fresh weight plant), honey,  $P_{IngHoney}$  (Sv/a per Bq/kg fresh weight), animal produce,  $P_{IngAnm}$  (Sv/a per Bq/kg fresh weight animal), and aquatic animals,  $P_{IngAq}$  (Sv/a per Bq/kg fresh weight aquatic animal), is given by<sup>56</sup>:

<sup>56</sup> Based on Clause 6.15.4.1 of CSA (2008).

$$\begin{aligned}
 P_{IngPlant} &= P_{49} \\
 P_{IngHoney} &= P_{59} - Honey \\
 P_{IngAnm} &= P_{59} \\
 P_{IngAq} &= P_{69}
 \end{aligned}
 = g_f I_f DCF_f \quad (D105)$$

where:

$g_f$  is the fraction of plant or animal produce from contaminated source (unitless);

$I_f$  is the intake of plant or animal produce (kg fw/a); and

$DCF_f$  is dose coefficient for intake by ingestion (Sv/Bq).

### D.7.2 Dose due to External Irradiation from Air

The effective dose rate due to external irradiation from air,  $P_{ExtAir}$  (Sv/a per Bq/m<sup>3</sup>), is given by<sup>57</sup>:

$$P_{ExtAir} = P(e)_{19} = f_o [f_u + (1 - f_u) S_b] DCF_a \quad (D106)$$

where:

$f_o$  is the fraction of total time spent by the individual at the particular location (accounts for working and living at different locations);

$f_u$  is the time spent outdoors at a particular location as a fraction of total time spent at that location;

$S_b$  is the shielding factor for cloudshine or fraction of the outdoor cloudshine dose that is received indoors; and

$DCF_a$  is the effective dose coefficient for a semi-infinite cloud (Sv/a per Bq/m<sup>3</sup>).

### D.7.3 Dose Due to Inhalation

The internal dose from inhalation of air,  $P_{InhAir}$  (Sv/a per Bq/m<sup>3</sup>) is given by<sup>58</sup>:

$$P_{InhAir} = P(i)_{19} = I_h DCF_i OF_i \quad (D107)$$

where:

$I_h$  is the inhalation rate (m<sup>3</sup>/a);

$DCF_i$  is the dose coefficient for inhalation (Sv/Bq); and

<sup>57</sup> Based on Clause 6.2.1.2 of CSA (2008).

<sup>58</sup> Clause 6.13.1 of CSA (2008).

$OF_i$  is the occupancy factor, or fraction of time and individual is exposed to the inhalation hazard (unitless).

#### D.7.4 Dose from Rn-222

The dose rate from exposure to Rn-222,  $P_{Rn222}$  (Sv/a per Bq/m<sup>3</sup>), is calculated directly from the air concentration according to:

$$P_{Rn222} = DCF_{Rn222} OF_i \quad (D108)$$

where:

$DCF_{Rn222}$  is the dose coefficient for external irradiation and inhalation for Rn-222 (Sv/a per Bq/m<sup>3</sup>).

#### D.7.5 Dose from Water Immersion

The external dose from surface water immersion and taking a bath,  $P_{ImmSwim}$  and  $P_{ImmBath}$  (Sv/a per Bq/L), for all radionuclides except H-3 are provided below. The dose from swimming is given by<sup>59</sup>:

$$P_{ImmSwim} = P(e)_{29} = DCF_w OF_w \quad (D109)$$

where:

$DCF_w$  is the dose coefficient for immersion in an infinite, uniformly contaminated water medium (Sv/a per Bq/L) and

$OF_w$  is the fraction of the year spent swimming in the surface water body (unitless).

The dose from taking a bath for all radionuclides except H-3 is given by<sup>60</sup>:

$$P_{ImmBath} = P(e)_{29} = DCF_w D_c \rho OF_w' \quad (D110)$$

where:

$D_c$  is a correction factor to account for the finite size of a bathtub;

$\rho$  is the removal factor to account for processes such as sedimentation and removal of radionuclides by water treatment plants (unitless); and

$OF_w'$  is the fraction of the year spent taking baths (unitless).

The dose rate from immersion due to H-3 takes account of skin absorption,  $P_{ImmSwim[HTO]}$  and  $P_{ImmBath[HTO]}$  (Sv/a per Bq/L). The H-3 dose from swimming is given by<sup>61</sup>:

<sup>59</sup> Based on Clause 7.6.1.1 of CSA (2008).

<sup>60</sup> Based on Clause 7.6.1.1 of CSA (2008).

<sup>61</sup> Based on Clause 7.6.2.1 of CSA (2007).

$$P_{ImmSwim} [HTO] = P(e)_{29-HTO} = S_a D_s DCF_f OF_w \quad (D111)$$

where:

$S_a$  is the skin surface area (m<sup>2</sup>); and

$D_s$  is the diffusion rate for water-wetted skin (L/a/m<sup>2</sup> skin surface area).

Note that  $DCF_f$  is the dose coefficient for ingestion.

The H-3 dose from taking a bath is given by<sup>62</sup>:

$$P_{ImmBath} [HTO] = P(e)_{29-HTO} = S_a D_s DCF_f \rho OF_w \quad (D112)$$

### D.7.6 Dose due to External Irradiation from the Soil

The external dose due to irradiation from contaminated soil,  $P_{ExtSoil}$  (Sv/a per Bq/m<sup>3</sup>), is provided by<sup>63</sup>:

$$P_{ExtSoil} = P(e)_{39} = f_o f_r \left[ f_u + (1 - f_u) S_g \right] DCF_g \quad (D113)$$

where:

$f_o$  is the fraction of total time spent by the individual at the exposure location (unitless);

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

$f_u$  is the time spent outdoors at the exposure location as a fraction of total time spent at that location;

$S_g$  is the shielding factor for groundshine, or fraction of the outdoor groundshine dose received indoors due to shielding by buildings (unitless); and

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

### D.7.7 External Dose from Contaminated Shore and Riverbank

The external dose from contaminated shoreline and riverbank sediment,  $P_{ExtSed}$  (Sv/a per Bq/m<sup>3</sup>), is given by<sup>64</sup>:

$$P_{ExtSed} = P(e)_{89} = OF_s W_s DCF_s DF_s \quad (D114)$$

<sup>62</sup> Based on Clause 7.6.2.1 of CSA (2007).

<sup>63</sup> Based on Clause 6.14.1 of CSA (2008).

<sup>64</sup> Based on Clause 7.9.1 of CSA (2008).

where:

$OF_s$  is the shoreline occupancy factor, or fraction of time an individual spends over contaminated shoreline (unitless);

$W_s$  is the shore-width factor that describes the shoreline exposure geometry (unitless);

$DCF_s$  is the dose coefficient for sediment uniformly contaminated to a depth of 5 cm (Sv/a per Bq/m<sup>3</sup>); and

$DF_s$  is the dilution factor for shoreline deposits.

### D.7.8 Internal Dose from Drinking Water

The internal dose from drinking contaminated water,  $P_{IngWat}$  (Sv/a per Bq/L), is provided by<sup>65</sup>:

$$P_{IngWat} = P(i)_{29} = rf_w k''_w I_w DCF_f \quad (D115)$$

where:

$rf_w$  is the removal factor to account for processes such as sedimentation and removal of radionuclides by water treatment plants (unitless);

$k''_w$  is the fraction of drinking water intake from the contaminated source (unitless);

$I_w$  is the drinking water intake rate (L/a); and

$DCF_f$  is the dose coefficient for intake by ingestion (Sv/Bq).

### D.7.9 Dose due to Ingestion of Soil

The dose from incidental ingestion of soil,  $P_{IngSoil}$  (Sv/a per Bq/kg dry weight soil), is given by<sup>66</sup>:

$$P_{IngSoil} = P(i)_{3mass\ 9} = I_s EF_s DCF_f \quad (D116)$$

where:

$I_s$  is the incidental intake of soil (kg dry weight/d); and

$EF_s$  is the number of days per year in which incidental soil ingestion may occur.

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<sup>65</sup> Clause 7.5.1 of CSA (2008).

<sup>66</sup> Based on Clause 6.15.4.1 of CSA (2008).

### D.7.10 Dose due to Ingestion of Sediments

For sediments,  $P_{IngSed}$  (Sv/a per Bq/kg dry weight sediment), a dilution factor is included, which allows for non-equilibrium between suspended sediments and shoreline/riverbank deposits<sup>67</sup>:

$$P_{IngSed} = P(i)_{89} = I_s EF_s DCF_f DF_s \quad (D117)$$

where:

$I_s$  is the incidental intake of sediment (kg dry weight/d); and

$DF_s$  is the dilution factor for shoreline deposits.

## D.8 DOSE CALCULATIONS

The CSA (2008) dose expressions define the relevant source components in the parameter name, however, the differing approach adopted for the site-specific biosphere model means that a different naming convention has been used. Therefore, it is helpful to be explicit about the dose rate calculations, which are described below.

### D.8.1 External Irradiation from Soil

The dose rate due to external irradiation from the soil,  $E_{ExtSoil}$  (Sv/a) is given by:

$$E_{ExtSoil} = P_{ExtSoil} C_V [Soil] \quad (D118)$$

### D.8.2 External Irradiation from Sediments

The dose rate due to external irradiation from sediment,  $E_{ExtSed}$  (Sv/a) is given by:

$$E_{ExtSed} = P_{ExtSed} C_{Vsed} \quad (D119)$$

### D.8.3 Irradiation Due to Immersion in Water

The dose rate due to irradiation from water immersion,  $E_{ImmWat}$  (Sv/a) is given by:

$$E_{ImmWat} = P_{ImmSwim} C_V [Lake] + P_{ImmBath} C_{Well} \quad (D120)$$

### D.8.4 Irradiation Due to Immersion in Air

The dose rate due to external irradiation from air,  $E_{ExtAir}$  (Sv/a) is given by:

$$E_{ExtAir} = P_{ExtAir} C_{air} \quad (D121)$$

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<sup>67</sup> Clause 7.10.1 of CSA (2008).

**D.8.5 Internal Irradiation Due to Inhalation**

The internal irradiation dose due to inhalation of air,  $E_{InhAir}$  (Sv/a) is given by:

$$E_{InhAir} = P_{InhAir} C_{air} \quad (D122)$$

**D.8.6 Internal Irradiation Due to Ingestion of Plants**

The dose rate due to ingestion of crops,  $E_{IngPlant}$  (Sv/a) is given by:

$$E_{IngPlant} = P_{IngPlant} C_{Plant} \quad (D123)$$

**D.8.7 Internal Irradiation Due to Ingestion of Honey**

The dose rate due to ingestion of honey,  $E_{IngHoney}$  (Sv/a) is given by:

$$E_{IngHoney} = P_{IngHoney} C_{honey} \quad (D124)$$

**D.8.8 Internal Irradiation Due to the Ingestion of Animal Produce**

The dose rate due to ingestion of animal produce,  $E_{IngAnm}$  (Sv/a), is given by:

$$E_{IngAnm} = P_{IngAnm} C_{Anm} \quad (D125)$$

**D.8.9 Internal Irradiation Due to the Ingestion of Aquatic Animals**

The dose rate due to ingestion of aquatic animals,  $E_{IngAq}$  (Sv/a), is given by:

$$E_{IngAq} = P_{IngAq} C_{Aq} \quad (D126)$$

**D.8.10 Internal Irradiation Due to Incidental Ingestion of Soil**

The dose rate due to incidental ingestion of soil,  $E_{IngSoil}$  (Sv/a), is given by:

$$E_{IngSoil} = P_{IngSoil} C_{T[Soil]} \quad (D127)$$

**D.8.11 Internal Irradiation Due to Incidental Ingestion of Sediment**

The dose rate due to incidental ingestion of sediment,  $E_{IngSed}$  (Sv/a), is given by:

$$E_{IngSed} = P_{IngSed} C_{TSed} \quad (D128)$$



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## APPENDIX E: MATHEMATICAL MODEL FOR C-14 IN THE REPOSITORY

C-14 is a key radionuclide for the Human Intrusion Scenario and for the Severe Shaft Seal Failure Scenario (QUINTESSA and SENES 2011). C-14 is associated with a number of different waste types, in a number of physical and chemical forms. Once released from the wastes C-14 is expected to be present in a number of gaseous, aqueous and solid (precipitate) compounds in the repository. Due to the significance of this radionuclide, its behaviour requires specific consideration. This appendix describes the forms of C-14 in the wastes, release of C-14 from the wastes, and the behaviour of C-14 in the repository. The mathematical models used to represent the conceptual models, and their implementation in the assessment level (AMBER) model is described.

### E.1 FORM OF C-14 IN THE WASTES

C-14 is present as (OPG 2011):

- Carbonate ions on the exchange sites of resins (dominant source in DGR);
- Surface contamination on a range of waste types; and
- An activation product in the matrix of irradiated metals.

### E.2 BEHAVIOUR OF CARBON IN THE DGR

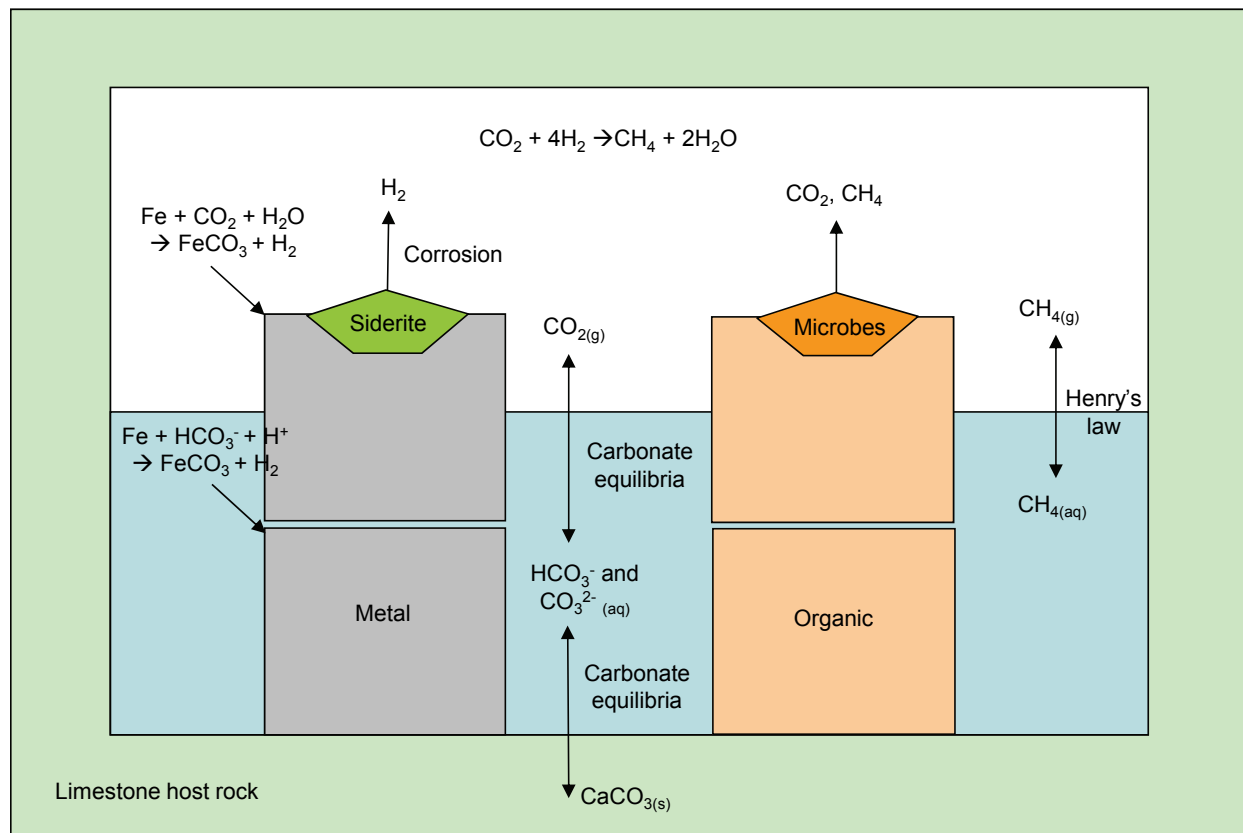
C-14 is not the only isotope of C present in the DGR. There are significant amounts of C-12 and C-13 associated with the wastes and the host rock/porewater. The release and partitioning of C-14 is controlled not only by its form in the wastes, but by chemical reactions driven by stable C-12 and C-13 ('bulk') in the DGR. The behaviour of C-14 therefore reflects the behaviour of bulk carbon: this is termed a specific activity model.

Figure E.1 describes the behaviour of carbon in the DGR. The limestone host rock is dominantly formed from  $\text{CaCO}_3$  (calcite). The host rock porewater is, therefore, saturated with carbonate/bicarbonate ions in equilibrium with the partial pressure of  $\text{CO}_2$ . Carbonate equilibria reactions control the amounts of carbon present as  $\text{CO}_2$  gas, aqueous carbonate/bicarbonate ions and solid calcite.

The presence of metal and organic materials in the wastes perturbs the equilibria through the generation and consumption of carbon species as the wastes degrade, although the system will be strongly buffered by the limestone host rock. Key reactions are:

- Generation of  $\text{CO}_2$  and  $\text{CH}_4$  gases from microbial degradation of organic wastes;
- Generation of  $\text{H}_2$  gas from corrosion of metal wastes, which can be used by methanogenic bacteria to reduce  $\text{CO}_2$  to  $\text{CH}_4$ ; and
- $\text{CO}_2$  enhanced corrosion of metals, resulting in the consumption of  $\text{CO}_2$  and precipitation of  $\text{FeCO}_3$  (siderite).

$\text{CH}_4$  gas will also dissolve in water in the DGR in accordance with Henry's law (Section 3.6.3.1 of QUINTESSA and GEOFIRMA 2011).



**Figure E.1: Behaviour of Carbon in the DGR (Simplified)**

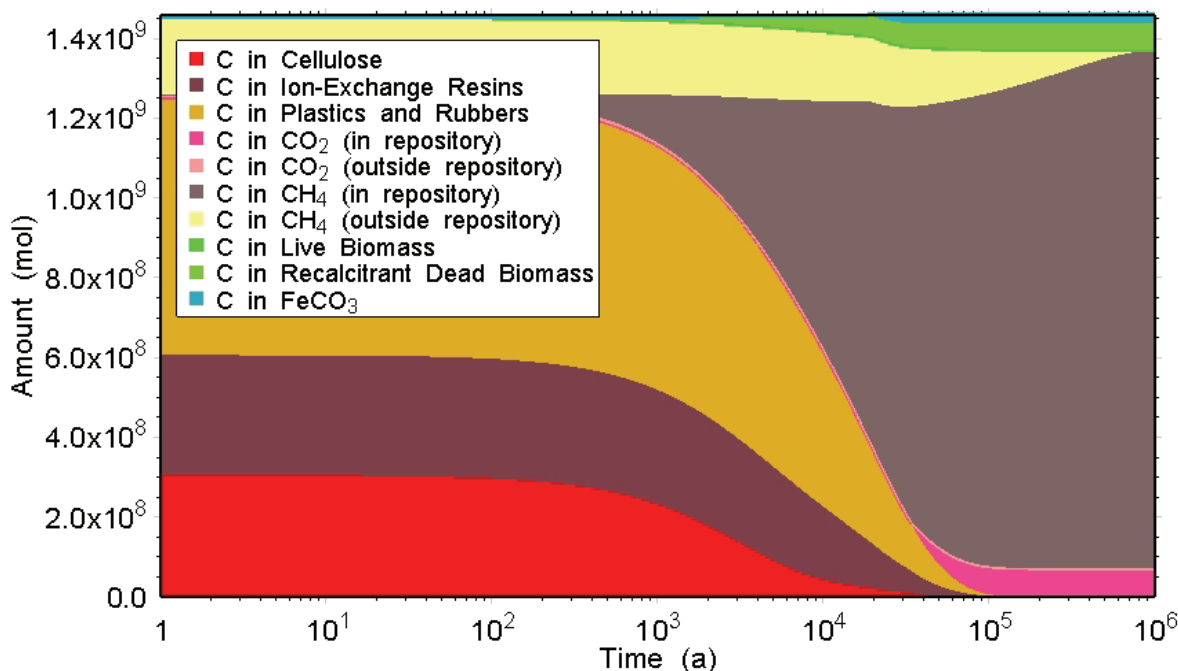
Generation of gases from the wastes, and the fate of bulk carbon are described by the T2GGM model (GEOFIRMA and QUINTESSA 2011). Figure E.2 shows the amounts of carbon in the DGR for the Reference Case (NE-RC). Carbon is initially present in organic wastes. As the wastes degrade the amount of organic biomass increases and carbon is released as CO<sub>2</sub> and CH<sub>4</sub> gas. Under highly reducing (methanogenic) conditions in the repository or surrounding rock, most of the CO<sub>2</sub> is reduced to CH<sub>4</sub> by H<sub>2</sub> generated from metal corrosion. Some carbon reacts with iron forming siderite, and some remains in recalcitrant biomass. At long times, it is expected that bulk carbon from the degrading organic wastes is dominantly in the form of CH<sub>4</sub> and CO<sub>2</sub> gas plus a small amount of siderite precipitate. These are the species that need to be represented in the safety assessment models.

### **E.3 BEHAVIOUR OF C-14 IN DGR AND IMPLEMENTATION IN THE ASSESSMENT LEVEL (AMBER) MODEL**

C-14 is present in three primary chemical forms in the wastes. A conceptual model of the release of C-14 has been developed for each chemical form and the associated waste types. The subsequent partitioning of C-14 is consistent with the behaviour of bulk carbon in the DGR.

For clarity, the implementation of the conceptual model in the assessment level (AMBER) model is described concurrently for each chemical form of C-14. The mathematical models used to parameterize the transfer rates in AMBER are described in the subsequent section.

26 Oct 2010  
NE-RC\_NWL\_3DSR2\_R2.GGM



Note: Figure 5.12 in GEOFIRMA and QUINTESSA (2011).

**Figure E.2: Amounts of Carbon in the DGR for the Reference Case**

### E.3.1 C-14 PRESENT IN ION EXCHANGE RESINS

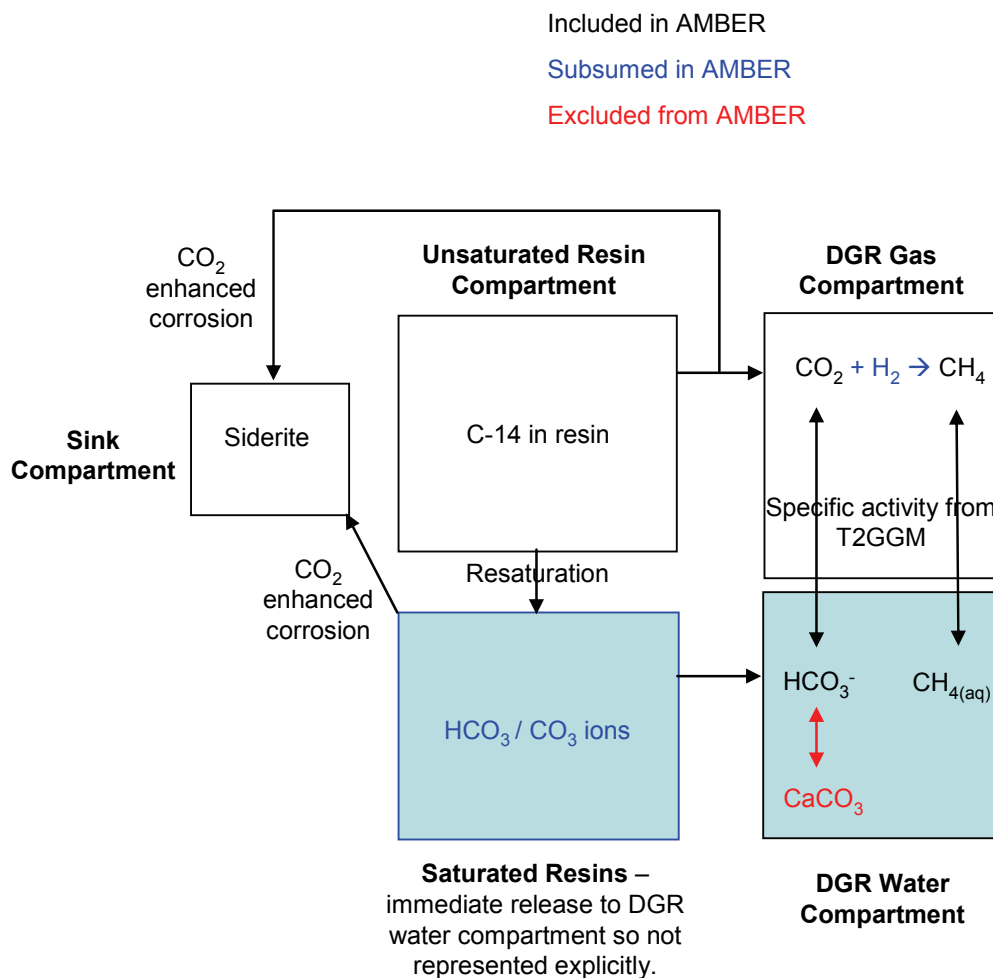
#### E.3.1.1 Conceptual Model

C-14 is present in carbonate and bicarbonate ions on the exchange sites of IX resins (Yim and Caron 2006). WWMF data indicates that C-14 is released as gas from IX resins in storage. The ability of the resins to hold the carbonate/bicarbonate on contact with water depends on the type of resin and the ions in the water. In particular, Cl<sup>-</sup> will displace HCO<sub>3</sub><sup>-</sup> from anion resins (Yim and Caron 2006), so on contact with the highly saline water from the Cobourg it is likely that the carbonate ions will be rapidly released.

Experiments (Habayeb 1985, Dayal and Reardon 1992) with OPG IX resins mixed with cement indicate that C-14 release from these resins is retarded. In the DGR, resins are not expected to be grouted, but many resins will be contained in concrete shields. So there is potential for retardation of C-14 released from the resins due to reaction with the cement. Conservatively this is ignored here and it is assumed that C-14 in resins is released immediately upon contact with water.

### E.3.1.2 AMBER Representation

Figure E.3 shows the implementation of the conceptual model in AMBER. Boxes represent AMBER compartments, and arrows represent transfers between compartments. Black text describes the dominant chemical species and processes represented in AMBER. Blue text describes secondary species and non-rate limiting intermediate processes that are not represented explicitly in AMBER, but are assumed to be subsumed within the AMBER representation. Red text describes processes and species excluded from the model.



**Figure E.3: AMBER Representation of the Release and Partitioning of C-14 in Resins**

C-14 is released as gas from the unsaturated wastes. The release rate is 0.0005/a, based on the measured C-14 release rate from OPG ILW IX resin wastes in storage at WWMF (Section 7.4.2.1 of OPG 2011), and consistent with general C-14 release rates from L&ILW measured in Asse (Bracke and Muller 2008).

C-14 is released from the resins as soon as they come into contact with water, due to resaturation of the DGR. Since no account is taken of the containers in the safety assessment, they are not represented explicitly in the AMBER model, and C-14 is released directly to water in the DGR.

Some of the C-14 released from the wastes can react with iron producing siderite. The fraction of C-14 that forms siderite is specified in AMBER based on the results of the T2GGM model (which includes siderite formation).

C-14 will partition between gas and water in the DGR. The key controlling reactions are carbonate equilibria, CO<sub>2</sub> reduction to CH<sub>4</sub>, and Henry's law for dissolution of CH<sub>4</sub> gas. These processes are not represented explicitly in AMBER. Instead C-14 is partitioned between water and gas based on the results of T2GGM. See Appendix E.4.3.

### **E.3.2 C-14 Present as Surface Contamination**

#### **E.3.2.1 Conceptual Model**

C-14 present as surface contamination will dissolve as soon as it comes into contact with water in the DGR. Data from L&ILW waste in storage at WWMF indicates that C-14 will also be released as gas.

#### **E.3.2.2 AMBER Representation**

The AMBER representation is identical to that described previously for resins. The (anaerobic) unsaturated gas release rate was assumed to be the same as for the resins. (Release rates for LLW in storage given in Section 7.4.2.1 of OPG (2011) are likely more relevant to aerobic conditions).

### **E.3.3 C-14 Present in the Matrix of Metals**

#### **E.3.3.1 Conceptual Model**

C-14 is an activation product, dominantly present as carbides in metals. As the metals corrode the carbides become 'available' and hydrolyze, ultimately forming CO<sub>2</sub> and CH<sub>4</sub>. C-14 is therefore released as radiolabelled CO<sub>2</sub> and CH<sub>4</sub>.

The CO<sub>2</sub> will react with ferrous metals forming siderite, and with water forming aqueous carbonate/bicarbonate ions. C-14 will partition between water and gas in the DGR based on the results of T2GGM. See Appendix E.4.3.

In the humid anaerobic conditions in the DGR, unsaturated and saturated metals corrode at the same rate. Therefore the release model does not need to consider the water level in the DGR.

#### **E.3.3.2 AMBER Representation**

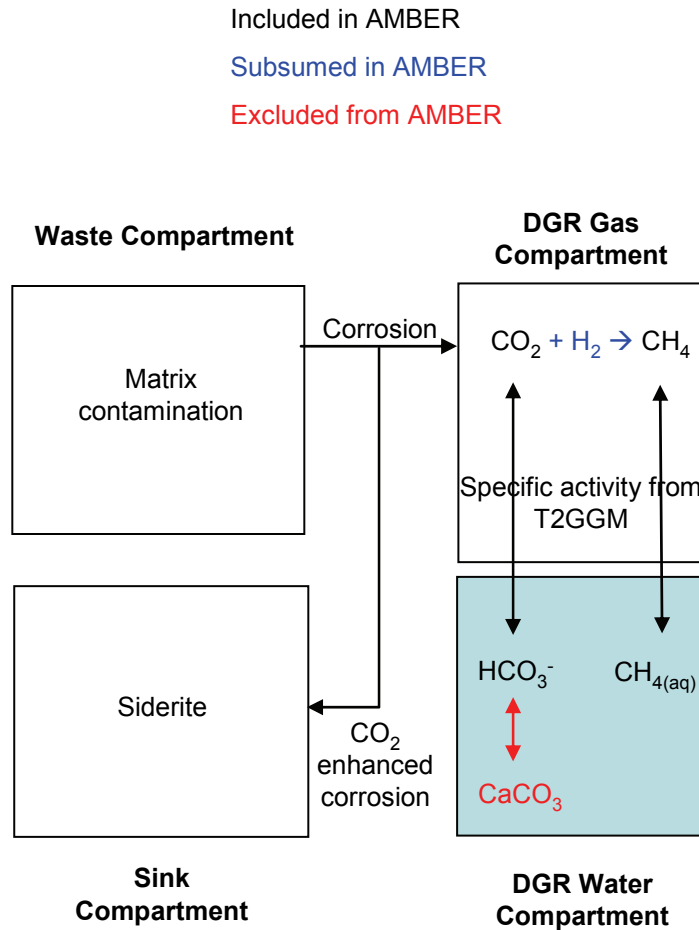
Figure E.4 shows the implementation of the conceptual model in AMBER. Boxes represent AMBER compartments, and arrows represent transfers between compartments. Black text describes the dominant chemical species and processes represented in AMBER. Blue text describes secondary species and rapid intermediate processes that are not represented explicitly in AMBER, but are assumed to be subsumed within the AMBER representation. Red text describes processes and species excluded from the model.

C-14 is released as radiolabelled CO<sub>2</sub> and CH<sub>4</sub> gases at the same rates from unsaturated and saturated metals. C-14 will partition between gas and water in the DGR. The key controlling reactions are carbonate equilibria, CO<sub>2</sub> reduction to CH<sub>4</sub>, and Henry's law for dissolution of CH<sub>4</sub> gas. These processes are not represented explicitly in AMBER. Instead C-14 is partitioned between water and gas based on the results of T2GGM.

Some of the C-14 released from the wastes can react with iron producing siderite. The fraction of C-14 that forms siderite is specified in AMBER based on the results of the T2GGM model (which includes siderite formation).

**E.4 MATHEMATICAL MODEL**

The mathematical model describes the transfer rates, which represent processes in the AMBER model.



**Figure E.4: AMBER Representation of the Release and Partitioning of C-14 Present in the Matrix of Metals**



#### E.4.1 Release of C-14 Present as Surface Contamination and on the Exchange Sites of Resins to Water in the DGR

C-14 is released as gas from the unsaturated resins. A release rate of  $5E-4$  /a is specified in AMBER based on the measured C-14 release rate from OPG ILW IX resin wastes in storage at the WWMF (Section E.3.1.2).

C-14 is released immediately on contact with water.

$$F_A = \frac{h_{water}}{h_{waste}} \quad h_{water} \leq h_{waste} \quad (E1)$$

$$F_A = 1 \quad h_{water} > h_{waste}$$

where:

$F_A$  is the fraction of the C-14 inventory available for release in water (unitless);

$h_{water}$  is the height of water in the emplacement room, m (time dependent); and

$h_{waste}$  is the height of the waste, m.

The rate of C-14 release is equal to the ratio of the rate of change of availability (i.e., the derivative of  $F_A$ ) divided by the quantity of unavailable waste remaining.

The derivative of  $F_A$  is:

$$\frac{\partial F_A}{\partial t} = \frac{\partial h_{water}}{\partial t} \cdot \frac{1}{h_{waste}} \quad (E2)$$

The C-14 transfer rate from the waste to water compartments,  $\lambda_{Avail}$  (/a) is:

$$\lambda_{Avail} = \frac{\frac{\partial h_{water}}{\partial t} \cdot \frac{1}{h_{waste}}}{1 - F_A} \quad (E3)$$

#### E.4.2 C-14 Present in the Matrix of Metals

C-14 is released congruently with corrosion of metal wastes.

$$F_A = \frac{C.t}{M} \quad C.t \leq M \quad (E4)$$

$$F_A = 1 \quad C.t > M$$

where:

$F_A$  is the fraction of the C-14 inventory available for release in water (unitless);

$C$  is the metal corrosion rate, m/a;

$M$  is the effective thickness of the metal, m; and

$t$  is the time, a.

The rate of C-14 release is equal to the ratio of the rate of change of availability (i.e., the derivative of  $F_A$ ) divided by the quantity of unavailable waste remaining.

The derivative of  $F_A$  is:

$$\frac{\partial F_A}{\partial t} = \frac{C}{M} \quad (\text{E5})$$

The C-14 transfer rate from the waste to water compartments,  $\lambda_{Avail}$ , /a is:

$$\lambda_{Avail} = \frac{C/M}{1-F_A} \quad (\text{E6})$$

### E.4.3 C-14 Specific Activity Model

In the AMBER model, C-14 is released from the waste compartments to the DGR gas, water and siderite compartments. The fraction of C-14 released that is transferred to the siderite compartment is derived from the T2GGM model.

C-14 is partitioned between the DGR water and gas compartments in proportion to the amounts of bulk carbon in water and gas, which are derived from T2GGM. The amount of bulk carbon in gas is calculated using the ideal gas law:

$$n_{cg} = (P_{CO_2} + P_{CH_4}) \cdot V_g / RT \quad (\text{E7})$$

where:

$n_{cg}$  is the number of moles of carbon in gas (mol);

$P_{CO_2}$  is the partial pressures of carbon dioxide gas from T2GGM (time-dependent) (Pa);

$P_{CH_4}$  is the partial pressures of methane gas from T2GGM (time-dependent) (Pa);

$V_g$  is the volume of gas in the DGR, which depends on the saturation and is calculated by T2GGM (time-dependent) ( $\text{m}^3$ );

$R$  is the gas constant (8.314 J/mol/K); and

$T$  is the temperature (K).

The amount of bulk carbon in water in the DGR is equal to,

$$n_{cw} = V_w [IC] \quad (\text{E8})$$

where:

$n_{cw}$  is the number of moles of carbon in water;

$V_w$  is the volume of water in the DGR, which depends on the saturation and is calculated by T2GGM (time-dependent) ( $m^3$ ); and

$[C]$  is the solubility limit for inorganic carbon ( $mol/m^3$ ).

The C-14 partition coefficient between gas and water varies with time and is equal to  $n_{cg}/n_{cw}$ .

The total amount of C-14 released from the wastes and still present in the repository is distributed so that the fraction  $n_{cg}/(n_{cg}+n_{cw})$  is in the gas, and the balance is in water.

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## APPENDIX F: MODELLING ADVECTION, DISPERSION AND DIFFUSION IN COMPARTMENT MODELS

### F.1 ADVECTION AND DISPERSION

Generally, advective transport of dissolved radionuclides occurs through a medium which interacts with the solute, through various processes collectively referred to as sorption. Although other approaches are possible, the usual approach is to treat the sorption processes as being fast and independent of the concentration. This leads to a fixed fraction of the radionuclides being in solution, with the ratio between the amount in solution and the total being called the retardation. The effect of this is simply to scale the transport rates, and so it is irrelevant to much of the discussion that follows. Of course, when absolute timescales are important, e.g., in determining the amount of decay that occurs, they must be accounted for.

For the purposes of the discussion here, advection in one-dimension is considered. This represents an average over a suitably chosen area. The chain of compartments that are considered is along the line of this flow, and their cross-sectional area is set to the averaging area.

The end-point for an advective part of the system is the outgoing flux (amount per unit time) at the outlet end. The input is taken to be the incoming water and solute mass flux.

The general continuum approach to advective transport in a porous medium is to use an advection-dispersion equation,

$$R \frac{\partial C}{\partial t} = -v \frac{\partial C}{\partial x} + D \frac{\partial^2 C}{\partial x^2}, \quad (\text{F1})$$

where  $C$  is the concentration,  $R$  is the retardation,  $v$  is the advective velocity and  $D$  is the dispersion coefficient. The advective velocity is the average velocity in the pores (equal to the Darcy velocity divided by the porosity) and the dispersion coefficient is often written as

$$D = \alpha v, \quad (\text{F2})$$

where  $\alpha$  is the dispersion length.

The dispersive term represents spreading due to the heterogeneities in the system. At the scale of individual pores in the porous medium, there is clearly heterogeneity, but heterogeneity generally exists on all scales. The dispersion length can be thought of as representing the characteristic length scale of this heterogeneity. For the Fickian approach to dispersion (i.e., using a diffusion-like term) to be fully correct the dispersion length should be a fixed property of the medium. Experimentally, the measured dispersion length is found to be strongly correlated with the length-scale of the experiment, and in practice is often taken to be a fraction of the total transport distance,  $L$ . The ratio defines the Peclet number,

$$Pe = \frac{L}{\alpha}. \quad (\text{F3})$$

The Peclet number is the ratio between the advective and dispersive components of the transport over the length scale of interest. Peclet numbers of 6 to 10 are typically used for natural porous media.

An important point to note for the later discussion is that the very act of defining a Peclet number is an admission that the Fickian representation of dispersion is not self-consistent. This advection-dispersion equation, with a fixed Peclet number is therefore a means of obtaining an approximate breakthrough curve at the end of the transport path. This reinforces the view that the test of a good numerical discretization scheme is how well it represents the breakthrough, but also emphasizes that the continuum equation should not be assumed to provide definitive results.

The compartment modelling approach to advection and dispersion can be motivated in two ways. It can be thought of either by considering the transport processes at the boundaries between compartments or by considering a direct discretization of the advection-dispersion equation. Indeed, the discretized equations that arise are identical to those obtained by using a finite-volume or finite-difference approach with central differences for the dispersion term and upwinding (i.e., backward differences relative to the flow direction) for the advective term.

In a finite-difference approach, upwinding is introduced to prevent oscillatory behaviour that arises in advective systems. Essentially, it adds just enough “numerical” dispersion to damp out the oscillations. In order to separate this numerical dispersion from the physical dispersion, consider a system with no dispersion. If the transport path is discretized into  $N$  equal length cells or compartments then the evolution equation for the concentration in one of these (not at either end) is

$$R \frac{\partial C_i}{\partial t} = - \frac{v}{\delta x} (C_i - C_{i-1}), \quad (F4)$$

where  $\delta x$  is the cell size ( $L/N$ ). Note that the transport time,  $T$  is given by  $\frac{LR}{v} = N \frac{\delta x R}{v}$ .

In the compartment approach, it is usual to consider the solute mass  $A$  in each compartment rather than the concentration. The corresponding equation is obtained by multiplying by the volume,  $V$ , and porosity,  $\theta$ ,

$$\frac{\partial A_i}{\partial t} = - \frac{Q}{V\theta R} (A_i - A_{i-1}), \quad (F5)$$

where  $Q$  is the total water flow rate between compartments.

This simple system can be solved analytically, to give the breakthrough at the end of the transport leg for a unit pulse input at the start. The solution is most easily obtained by using a Laplace transform. Denoting the flux after  $N$  cells as  $F_N(t)$  and its Laplace transform as  $\bar{F}_N(s)$ , with the transfer rate given by

$$\mu = \frac{Q}{V\theta R} = \frac{v}{R\delta x} = \frac{N}{T}, \quad (F6)$$

The Laplace transformed flux is

$$\bar{F}_N = \mu \bar{A}_N = \frac{\mu^N}{(\mu + s)^N}. \quad (F7)$$

The time-domain solution is

$$F_N = \mu A_N = \mu \frac{(\mu t)^{N-1} e^{-\mu t}}{(N-1)!}, \quad (\text{F8})$$

but it is easier to obtain moments of the breakthrough curve from the Laplace transform. The mean is given by

$$\langle t \rangle = \frac{N}{\mu} = T \quad (\text{F9})$$

and the standard deviation

$$\sigma_t = \sqrt{\langle t^2 \rangle - \langle t \rangle^2} = \sqrt{\frac{N}{\mu^2}} = \frac{T}{\sqrt{N}}. \quad (\text{F10})$$

So, the mean breakthrough time is exactly correct and the standard deviation is inversely proportional to the square root of the number of cells.

This can be compared to the analytic solution of the advection-dispersion equation, with a downstream boundary condition at infinity. The Laplace-transformed breakthrough curve is given by

$$\bar{F}_{Disp} = e^{\frac{Pe}{2} \left[ 1 - \sqrt{1 + \frac{4Ts}{Pe}} \right]} \quad (\text{F11})$$

from which the mean and standard deviation can be obtained as

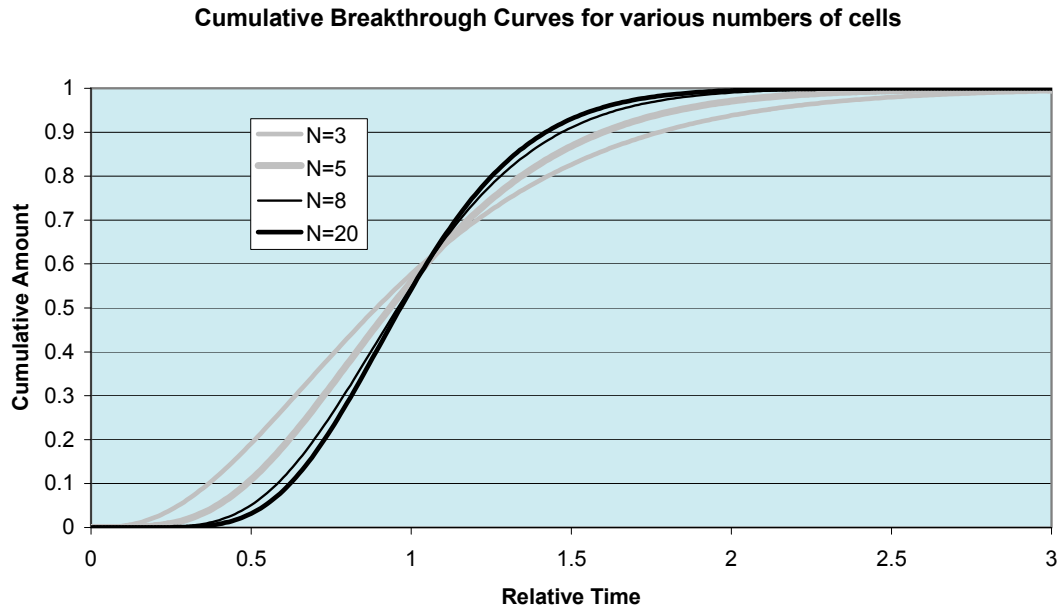
$$\langle t \rangle_{Disp} = T \quad (\text{F12})$$

and

$$\sigma_{t,Disp} = T \sqrt{\frac{2}{Pe}}. \quad (\text{F13})$$

Thus, in terms of the standard deviation of the breakthrough curve, a purely advective discretization of  $N$  cells is equivalent to a Peclet number,  $Pe = 2N$ .

Figure F.1 shows the breakthrough curves that are obtained for different numbers of cells or compartments. Given what was said about the correctness of the advection dispersion equation, comparing the breakthrough curves in more details is not warranted. Essentially, uncertainty in the basic conceptual model is larger than the numerical differences, and uncertainty in the data (especially in the Peclet number) is also significant.



**Figure F.1: Analytically Calculated Breakthrough Curves for Various Numbers of Cells or Compartments Showing the Effect of Numerical Dispersion**

If the required Peclet number is 10, then using five compartments will give the correct standard deviation. If more compartments are used, then dispersive transfers would need to be included to add in the extra dispersion. This could be achieved by using an adjusted dispersion length

$$\alpha_{adj} = \alpha - \frac{1}{2} \delta x \quad (F14)$$

Note that an interesting side effect of simply using advective transfers and allowing the dispersion to be solely “numerical” is that no material is transferred upstream, in contradiction to what the advective-dispersion equation says, but arguably more physically plausible.

## F.2 DIFFUSION

In diffusive parts of the system, the treatment of retardation is exactly as in the advective parts. Diffusive transport is one-dimensional in the direction of the concentration gradient.

For diffusive barriers, the end point of interest is the flux at the end, the same as for the advective case. The case of matrix diffusion is different and that is discussed later.

For a purely diffusive system the governing equation is the Fickian diffusion equation,

$$R \frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial x^2} \quad (F15)$$

where  $C$  is the concentration,  $R$  is the retardation and  $D$  is the diffusion coefficient. In this case, the conceptual basis for the equation is good.



In modelling a diffusive part of the system, the first consideration is whether it needs to be modelled in any level of detail. If the diffusion time is rapid, then it may not be necessary to discretize and in some cases it may not be necessary to represent the feature. The characteristic diffusion time,  $T$ , is simply given by

$$T = \frac{RL^2}{D}, \quad (\text{F16})$$

where  $L$  is the thickness of the diffusive barrier.

For times much longer than the diffusion time, a steady-state profile may be established and the flux is then independent of compartment structure. Thus, the relevance of the transient phase is a key issue.

As for the advection-dispersion case, the compartment discretization can be motivated either by considering the diffusion process at the boundaries between compartments or by considering a direct discretization of the diffusion equation. The discretized equations that arise are identical to those obtained by using a finite-volume or finite-difference approach with central differences for the diffusion.

If the diffusive barrier is discretized as  $N$  equal cells or compartments, then the equation for the concentration in one of these is

$$R \frac{\partial C_i}{\partial t} = -\frac{D}{\delta x^2} (C_i - C_{i-1}) - \frac{D}{\delta x^2} (C_i - C_{i+1}), \quad (\text{F17})$$

where  $\delta x$  is the cell size ( $L/N$ ). The diffusive transfer is split into two to reflect the two diffusive transfers in the compartment model.

In the compartment approach, it is usual to consider the amount in each compartment rather than the concentration. The corresponding equation is obtained by multiplying by the volume,  $V$ , and porosity,  $\theta$ ,

$$\frac{\partial A_i}{\partial t} = -\frac{\theta D \chi}{V \theta R} \frac{(A_i - A_{i-1})}{\delta x} - \frac{\theta D \chi}{V \theta R} \frac{(A_i - A_{i+1})}{\delta x}, \quad (\text{F18})$$

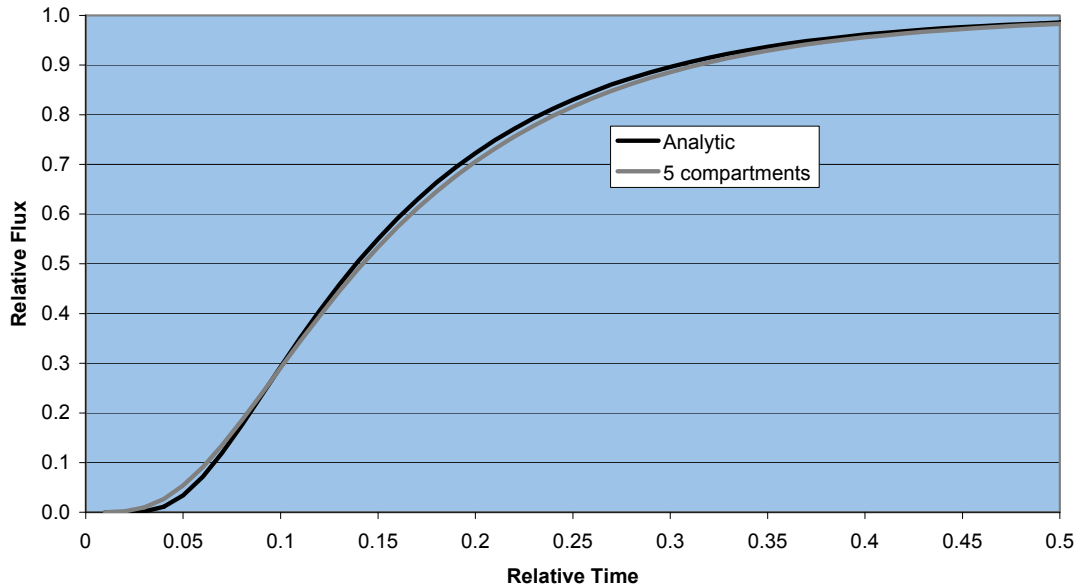
where  $\chi$  is the cross-sectional area. Note that for a radial system, these equations would need to be slightly reformulated to use the appropriate areas and volumes.

The diffusive barrier equation can be characterized by a single parameter, the characteristic time  $T$ . The time axis of the breakthrough curve scales with this.

Consider the case with a fixed unit concentration on one side of the barrier and zero concentration on the other. The flux leaving the barrier can be calculated as an infinite sum (see, for example, Carslaw and Jaeger, 1959). The result is

$$F(t) = \frac{\theta D}{L} \left\{ 1 + 2 \sum_{n=1}^{\infty} (-1)^n e^{-Dn^2 \pi^2 t^2 / RL^2} \right\}. \quad (\text{F19})$$

This can be compared to a result using five compartments in the barrier. Carslaw and Jaeger (1959) note that for a diffusion dominated system, the error resulting from discretization into compartments is equal to the inverse of the number of compartments squared.



**Figure F.2: Analytically Calculated Breakthrough Curve for the Diffusion Problem Compared to a Solution with Five Compartments in the Barrier**

As can be seen from Figure F.2 the breakthrough curve matches well. The results are plotted relative to the steady-state flux and with the time relative to the characteristic diffusion time,  $T$ .

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## APPENDIX G: AMBER CODE

### G.1 PROBLEM DESCRIPTION/IDENTIFICATION

The AMBER code allows users to implement their own mathematical models to represent contaminant transport within a compartment model approach. The compartment modelling approach represents features of interest as compartments of a user defined volume, within which the distribution of contaminants is unimportant (either because the features are well-mixed, or the average concentration within a feature is sufficient for the required transport and/or exposure modelling). These may be assigned a specific spatial location and orientation (e.g., an area of contaminated soil). Exchanges between compartments ('transfer processes') are generally described with first-order linear differential equations<sup>68</sup>. These can be used to represent a wide range of physically-based or empirical transport processes.

AMBER is not a specific model, but provides a controlled and user-friendly graphical framework for implementing and analysing specific models.

### G.2 SOFTWARE PLAN

Summary information for AMBER is given in Table G.1, including the following.

- Software name and version number.
- Software classification and relevant QA standards.
- Key roles and accountabilities, including identifying the Primary Holder.
- Key deliverables, tasks, schedules, and methods.
- Verification and validation activities (or a plan describing these activities).
- Configuration management and change control method, and which components will be controlled.

For application to the postclosure safety assessment of the OPG L&ILW DGR project, AMBER is classified as "Nuclear Grade" within the NWMO Technical Computing Software procedure.

This appendix provides a linkage between the status of AMBER as maintained under TickIT, and the expectations of NWMO PROC-EN-0002 (NWMO 2010).

### G.3 THEORY MANUAL

As noted in Appendix F.1, AMBER solves first-order linear differential equations to allow the calculation of time-dependent contaminant inventories in compartments. For the  $i^{\text{th}}$  compartment, the rate at which the compartment inventory changes with time is given by:

$$\frac{dN_i}{dt} = \left( \sum_{j \neq i} \lambda_{ji} N_j + \lambda_M M_i + S_i(t) \right) - \left( \sum_{j \neq i} \lambda_{ij} N_i + \lambda_N N_i \right) \quad (\text{G1})$$

where:

---

<sup>68</sup> AMBER does allow some non-linear processes, such as solubility, to be represented.

$i$  and  $j$  are indices denoting the  $i^{\text{th}}$  and  $j^{\text{th}}$  compartments;

$N$  and  $M$  are the amounts of contaminants  $N$  and  $M$  in a compartment ( $M$  is the precursor of  $N$  in a decay/degradation chain), mol;

$S(t)$  is a time dependent external source of contaminant  $N$ , mol/a;

$\lambda_M$  and  $\lambda_N$  are the decay constant for contaminants  $M$  and  $N$ , 1/a, respectively; and

$\lambda_{ji}$  and  $\lambda_{ij}$  are transfer coefficients representing the gain and loss of contaminant  $N$  from compartment  $i$  by transfer from and to compartment  $j$ , 1/a, respectively.

The solution of the matrix of first-order differential equations provides the time-dependent inventory of contaminant  $N$  in each compartment.

**Table G.1: Key Components of the Software Plan for the AMBER Code**

<b>Software Plan Component</b>	<b>Relevant Information for AMBER Code</b>
Software name and version number	AMBER 5.3
Software classification and relevant QA standards	The AMBER code is a commercial code maintained by Quintessa under the British Standards Institution's (BSI) guidelines for the application of ISO 9001:2008 to computer software (TickIT) (BSI 2007).
Key roles and accountabilities, including identifying the Primary Holder	Quintessa is responsible for the development, maintenance, documentation and supply of the AMBER code.
Key deliverables, tasks, schedules, and methods	A new version of AMBER is issued approximately every 12-15 months. The new version fixes any identified bugs with the previous version and incorporates improvements identified via user feedback. The software update procedure is conducted under a TickIT compliant system.
Verification and validation activities (or a plan describing these activities).	Each version of AMBER is verified through using it to solve a standard set of calculation problems. The associated models and their results are then documented in a verification test document. Code validation is not applicable since AMBER does not have a pre-defined model.
Configuration management and change control method, and which components will be controlled	Source code is controlled consistent with the requirements of procedure PR-5c of Quintessa's Quality Management System, which is TickIT compliant.

AMBER has two solvers for the first-order differential equations: the Laplace solver (Maul 1991) and the time-step solver (Robinson 2001). If the variable 't' (time) has been used in expressions that are used directly or indirectly to calculate source terms and/or transfers, the time-step solver will be automatically used by AMBER. If 't' has not been used (other than for observer parameters), the user will be given the option to choose either the Laplace solver or the time-step solver. For such cases, the Laplace solver will generally be faster and more accurate. It also handles differences in scale within a problem better (e.g., large amounts in one compartment and small amounts in another).

Following the calculation of the time-dependent inventory of contaminant  $N$  in each compartment, estimates of the associated compartment concentrations (from the compartment sizes) can be made and associated impacts calculated using user-defined equations. Further details concerning the input of user-defined equations into AMBER (including those for solubility limitation) and the associated syntax are provided in the AMBER Reference Guide (QUINTESSA 2009a).

#### **G.4 REQUIREMENTS SPECIFICATION**

AMBER pre-dates Quintessa's Software QA system and no requirements specification is available. The changes that are made on each release have been minor and significant changes to the core functionality of AMBER (the solver and expression handling) are avoided.

AMBER users are encouraged to send details of bugs and development ideas to the code's developers. A web-based "bug tracker", which is accessible to the AMBER development team from Quintessa, is used not only for reporting suspected bugs but also for logging development ideas. The changes required for a new release are selected from this list, with priorities assigned according to user demand.

#### **G.5 DESIGN DESCRIPTION**

AMBER pre-dates Quintessa's Software QA system and is therefore treated as a legacy code and no design description is available. The changes that are made on each release are minor and significant changes to the core functionality of AMBER (the solver and expression handling) are avoided. The AMBER "bug tracker" is used to keep a record indicating how bugs are fixed or how the development ideas are implemented. If the changes are significant an internal technical note is produced to describe the change.

#### **G.6 SOURCE CODE**

The source code for AMBER 5.3 is maintained by Quintessa and is not available to third parties.

#### **G.7 VERIFICATION REPORTS FOR THEORY, REQUIREMENTS, DESIGN AND CODE**

The verification of AMBER 5.3 is described in QUINTESSA (2009d). In addition, an extensive set of published reports on analyses undertaken using AMBER by multiple organizations over several years provides both additional verification and some validation of AMBER (see QUINTESSA 2009b).

#### **G.8 VALIDATION REPORT(S)**

Code validation is not applicable since AMBER does not have a pre-defined model.

## **G.9 COMPUTER PROGRAM ABSTRACT**

### **G.9.1 Purpose**

AMBER 5.3 is a commercially available software tool that allows users to build their own dynamic compartment models to represent the migration, degradation and fate of radioactive and non-radioactive contaminants in environmental systems. AMBER was originally developed for modelling contaminants from radioactive waste repositories and this remains its core area of application and development, although it has also been used to assess routine and accidental short-term contaminant releases.

### **G.9.2 Code History**

AMBER was developed in the early/mid 1990s by the Environmental Division of Intera Information Technologies (which later became QuantiSci and then Enviros Consulting). Version 3.0 was the first commercially available version. In 2000, Enviros Consulting signed an agreement with Quintessa to develop and maintain AMBER jointly. In 2009, Quintessa obtained the intellectual property rights to AMBER from Enviros Consulting. Peter Robinson has always been the lead developer and software engineer for the code.

AMBER has been applied to a wide range of problems concerned with the migration of contaminants through the environment. Examples include:

- The modelling, for a variety of organizations including CIEMAT, DSRL, ENEA, ENRESA, IAEA, JNES, KAERI, NECSA, NWMO and SSM, of the release of radionuclides from near-surface and deep radioactive waste disposal facilities and their subsequent migration through the geosphere and biosphere and associated impacts on humans; and
- The modelling of long-term and short-term releases of radionuclides, stable contaminants and organics to the surface environment and their subsequent impact on the environment and humans for a variety of organizations including the European Commission, EPRI, FSA, JAEA, JNC, KRMC and Nagra.

### **G.9.3 Operating Requirements**

The recommended system requirements needed to run AMBER are a PC with a Pentium II processor or equivalent with at least 128 MB of RAM installed, running under the Windows 2000, XP, Vista or Windows 7 operating system. AMBER will run on lower specification machines but its performance will be reduced, e.g. calculations will run more slowly. The Q2DGrapher charting package requires Microsoft .NET framework version 2.0 or higher to have been installed. At least 105 MB of hard disk space should be available.

AMBER licences are controlled via USB hardware security keys (dongles). AMBER can be installed on any number of PCs, but in order to run, a dongle must be connected to the PC and the associated drivers installed.

### **G.9.4 Components**

Running AMBER 5.3 requires the associated executable and associated support files (various .dll, .ocx and .irs files) that are automatically installed with the executable. Once an AMBER model has been generated and saved, an AMBER case file (.cse file) is created that contains the associated input information. The associated results are stored in an .adf file.

### **G.9.5 Capabilities**

AMBER gives the user the flexibility to define:

- Any number of compartments;
- Any number of contaminants and associated decays;
- Any number of transfers between compartments;
- Algebraic expressions to represent source terms and transfer processes operating between compartments;
- Algebraic expressions to represent the uptake of contaminants by humans and other output quantities of interest; and
- Deterministic, probabilistic and time varying parameter values.

Key features incorporated into AMBER include:

- Powerful, user-friendly graphical interface which gives AMBER the "look and feel" of a Windows application;
- Fast and accurate Laplace transform and numerical time-step solvers;
- Time varying source terms and transfer processes;
- Built in graphing of results;
- Monte Carlo and Latin Hypercube sampling; and
- Tailoring of results format.

### **G.9.6 Limitations**

AMBER uses a compartment model approach to represent the migration and fate of contaminants in the environment. This places two conditions on the mathematical representation of a disposal system.

The first condition is that the system has to be discretized into a series of compartments. Using the compartment modelling approach, a disposal system may be represented by discretizing it into compartments which can correspond to the key features identified in the conceptual model. It is assumed that either uniform mixing occurs over the timescales of interest, or the distribution of the contaminant within the compartment is not important so that a uniform concentration over the whole compartment can be used either for subsequent transport or for deriving end points of interest. Therefore, each compartment should be chosen to represent a system component for which one or other of these assumptions is reasonable.

The second condition is that processes resulting in the transfer of contaminants from one compartment (the donor compartment) to another (the receptor compartment) need to be expressed as transfer coefficients that represent the fraction of the activity in the donor compartment transferred from to the receptor compartment per unit time. The mathematical representation of the inter-compartmental transfer processes takes the form of a matrix of transfer coefficients that allow the compartment amounts to be represented as a set of first order linear differential equations.

### **G.9.7 Documentation**

A series of documents have been produced to describe AMBER, its uses and verification.

- QUINTESSA (2009a). AMBER 5.3 Reference Guide. QE-AMBER-1, Version 5.3. Quintessa Limited, Henley-on-Thames, United Kingdom.
- QUINTESSA (2009b). AMBER 5.3 Examples, Users and References. Quintessa QE-AMBER-M1, Version 5.3. Quintessa Limited, Henley-on-Thames, United Kingdom.
- QUINTESSA (2009c). AMBER 5.3 Getting Started. QE-AMBER-2, Version 5.3. Quintessa Limited, Henley-on-Thames, United Kingdom.
- QUINTESSA (2009d). AMBER 5.3 Verification Summary. QE-AMBER-3, Version 5.3. Quintessa Limited, Henley-on-Thames, United Kingdom.

## **G.10 USER MANUAL**

Information is provided in the AMBER 5.3 Reference Guide and Getting Started documents (QUINTESSA 2009a,c).

## **G.11 PROGRAMMER MANUAL**

AMBER pre-dates Quintessa's Software QA system and is therefore treated as a legacy code and no programmer manual is available. The changes that have been made on each release were minor and significant changes to the core functionality of AMBER (the solver and expression handling) have not been made. The information required to build the code itself is contained within the Microsoft Visual Studio® project file. AMBER is built on the XVT Graphical Application Framework (Providence Software 2007). This provides the basic communication between the GUI and data classes.

## **G.12 VERSION TRACKING RECORD**

Version control is managed through Microsoft Visual Source Safe®, which is fully integrated with the Visual Studio® development environment. This enables versions of the code to be recovered either by label (set for each release) or by date. It also allows the history of changes to any source file to be tracked and allows the listing of all components that went into an AMBER build.



**REFERENCES FOR APPENDIX G**

- BSI. 2007. The TickIT Guide. A Guide to Software Quality Management System Construction and Certification to ISO 9001:2000. British Standards Institution document Issue 5.5. London, United Kingdom.
- NWMO. 2010. Technical Computing Software. Nuclear Waste Management Organization Procedure NWMO-PROC-EN-0002 R001. Toronto, Canada.
- Providence Software. 2007. Guide to XVT Development Solution for C++: for XVT version 5.8 (see also [www.xvt.com](http://www.xvt.com)).
- QUINTESSA. 2009a. AMBER 5.3 Reference Guide. Quintessa Ltd. QE-AMBER-1, Version 5.3. Henley-on-Thames, United Kingdom.
- QUINTESSA. 2009b. AMBER 5.3 Examples, Users and References. Quintessa Ltd. QE-AMBER-M1, Version 5.3. Henley-on-Thames, United Kingdom.
- QUINTESSA. 2009c. AMBER 5.3 Getting Started. Quintessa Ltd. QE-AMBER-2, Version 5.3. Henley-on-Thames, United Kingdom.
- QUINTESSA. 2009d. AMBER 5.3 Verification Summary. Quintessa Ltd. QE-AMBER-3, Version 5.3. Henley-on-Thames, United Kingdom.
- Robinson, P.C. 2001. DYLAN Time-stepping Algorithms: The Approach Used in the DYLAN Solver. Quintessa Report QRS-DYLAN-1. Henley-on-Thames, United Kingdom.
- Robinson, P.C. and P.R. Maul. 1991. Some Experience with the Numerical Inversion of Laplace Transforms. *Mathematical Engineering in Industry* 3, 111-131.

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## APPENDIX H: MODEL IMPLEMENTATION

### H.1 OVERALL APPROACH

Since there is little interaction between the DGR near-field/geosphere and the DGR biosphere models, it is convenient to use separate AMBER case files for each. The results of the nearfield and geosphere model are imported directly into the biosphere model. The implementation of the nearfield and geosphere model is described in Section H.2, while the implementation of the biosphere model is described in Section H.3.

### H.2 NEARFIELD AND GEOSPHERE MODEL

#### H.2.1 Discretization

##### H.2.1.1 Repository Discretization

Most waste categories are represented with a single compartment, as discussed in Appendix E. The waste compartments release contaminants to gas and water in the panels, consistent with the release models and the distribution of each waste category between the two panels.

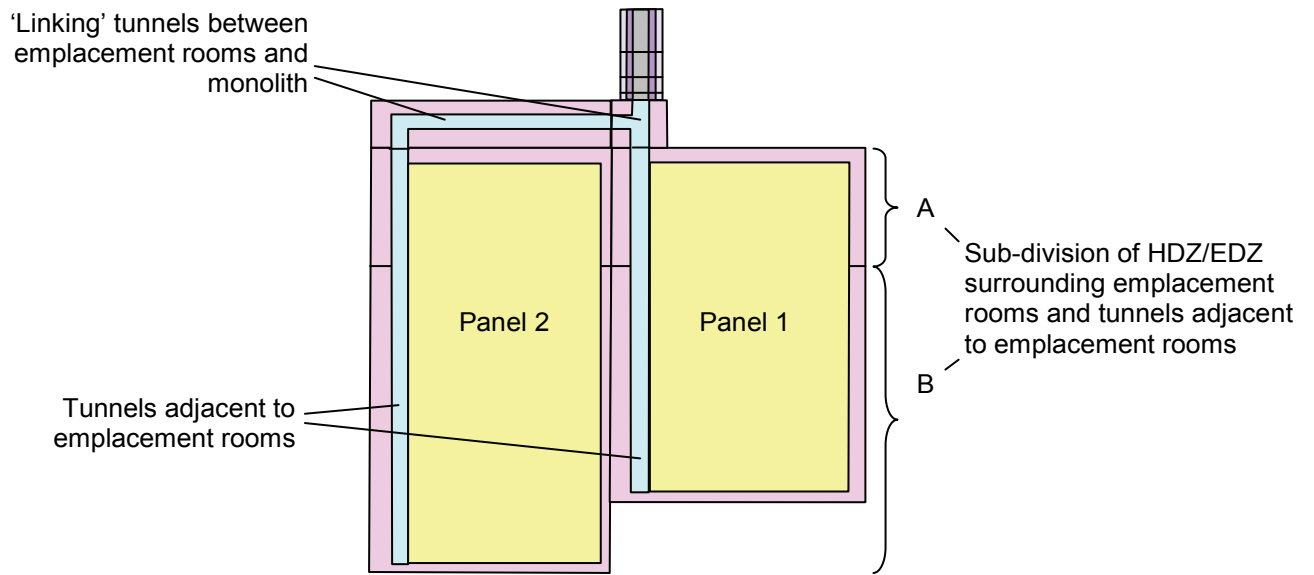
The discretization of the repository is illustrated in Figure H.1 and Figure H.2. This is based on the original preliminary design. The final preliminary design, described in the Preliminary Safety Report (Chapter 6 of OPG 2011), included a ventilation drift rather than return air ducting in the access tunnels, but is otherwise very similar. The changes are summarized in Section 4.4.1 of the current report. The AMBER model for both the original and final preliminary design is based on a single access tunnel connected to a single shaft, representing the shaft pathway from the waste rooms to the surface.

Given the small extent and importance of the HDZ surrounding the open access tunnels and emplacement rooms, it is combined with the more extensive EDZ around these locations. The HDZ/EDZ surrounding the emplacement rooms and adjacent access tunnels within each panel are subdivided into two sections (indicated with A and B in the figure). The mixed distribution of the wastes and the relatively free mixing of the repository water and gas mean that this subdivision is not required for the emplacement rooms and adjacent tunnels within each panel. The EDZ below the repository is expected to be several m thick, and is represented in the model as 6 m thick to align with the top of the Sherman Fall formation (see Figure H.2).

The HDZ surrounding the concrete monolith is an important pathway from the rooms to the shaft, so it is represented separately in AMBER. The gas and groundwater flow rates through this feature (kg/a) are input into AMBER from detailed gas and groundwater modelling.

The main and ventilation shafts are represented in the AMBER model with a single combined shaft, with the same total area for shaft and for EDZ. This combined shaft is located in the AMBER model at the distance from the ventilation shaft to the open access tunnels. The shaft and services area is not represented in the AMBER model, which focuses on the main contaminant transport pathway from the open access tunnels to the shafts. The shafts and ramp below the level of the repository are also not represented.

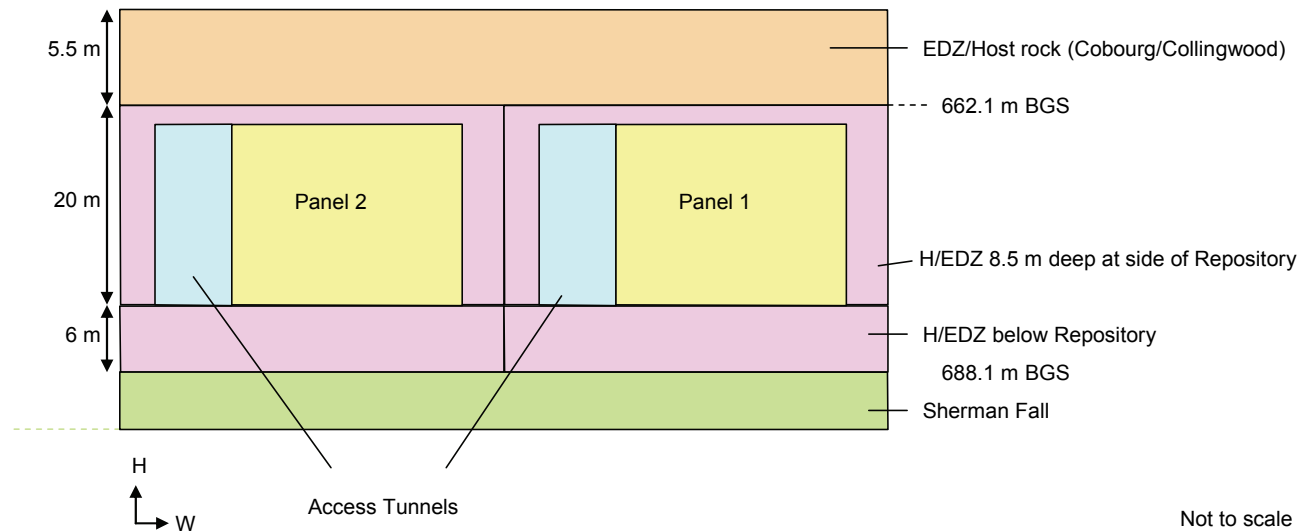
Figure H.3 and Figure H.4 provide cross-sections around the base of the shafts. This part of the model represents the main pathway for contaminants to migrate from the Panels to the shafts. The horizontal monolith and surrounding HDZ/EDZ are sub-divided with higher resolution towards the access tunnel side because of the large transport property change at this point.



- Key:**
- Emplacement rooms
  - Concrete monolith
  - Open access tunnels
  - Monolith HDZ
  - Repository HDZ/EDZ
  - Monolith EDZ

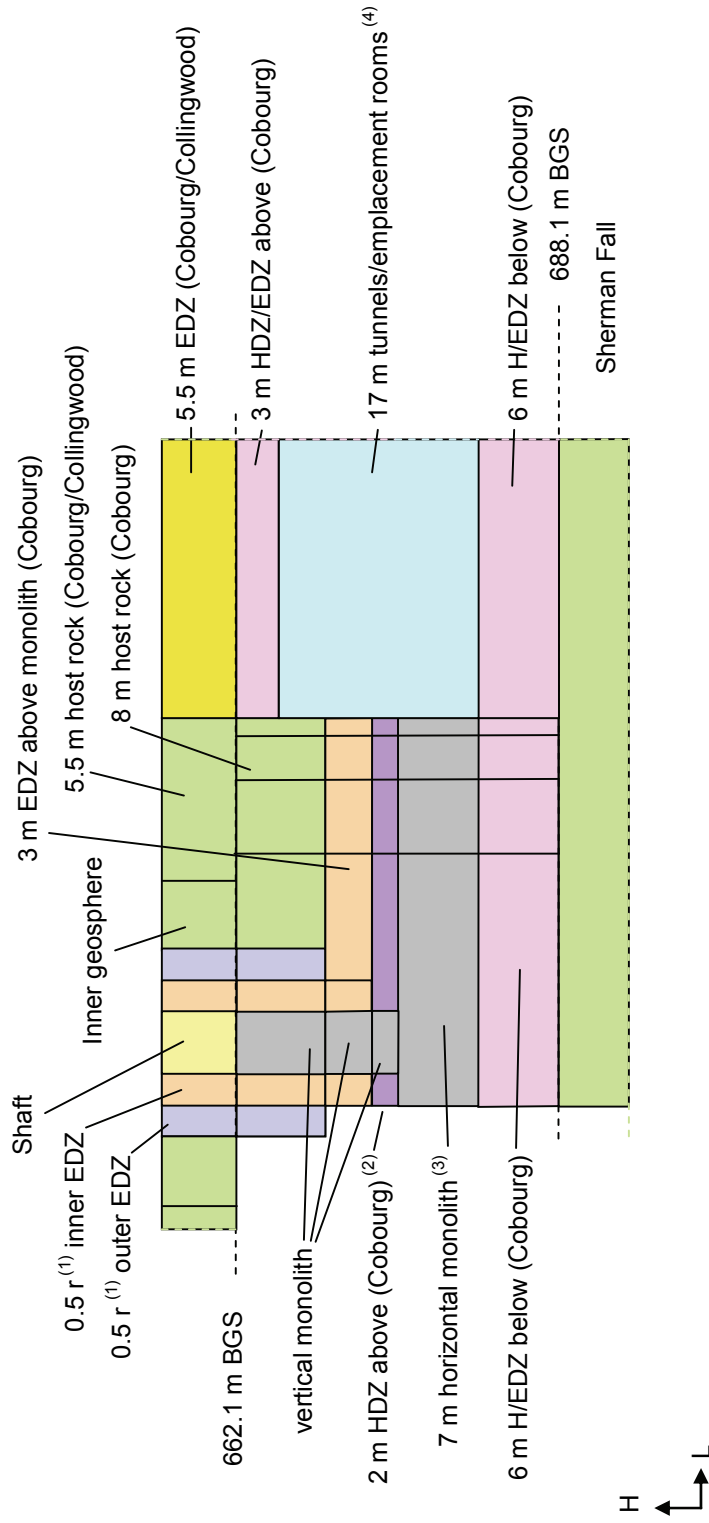
Not to scale

**Figure H.1: Plan View of the Repository Discretization**



Not to scale

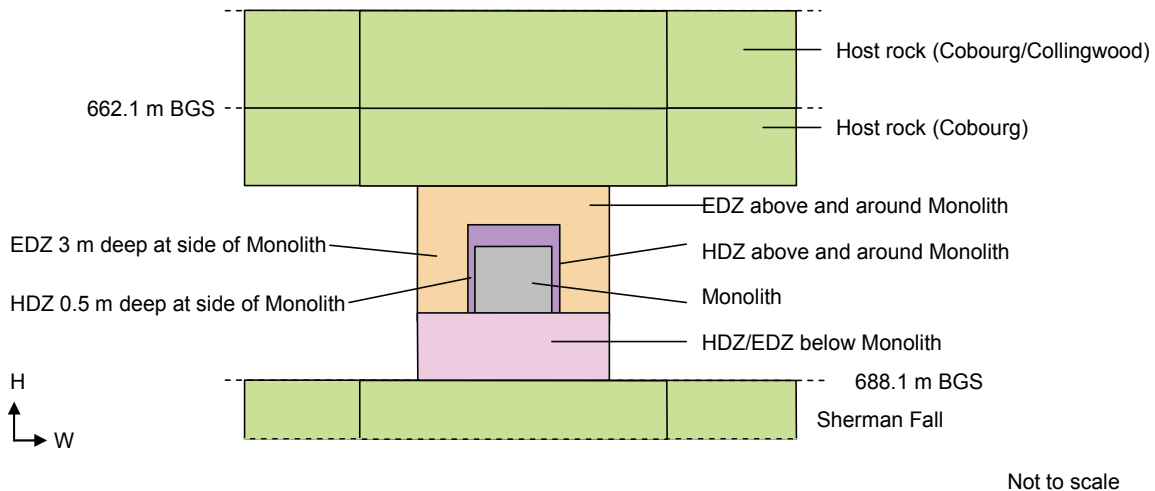
**Figure H.2: Cross-Section through the Emplacement Rooms**



Notes:

- 1 'r' is the shaft radius after removal of the 0.5 m HDZ.
- 2 Important groundwater pathway from tunnels to shaft.
- 3 Average height of repository from the Data report.
- 4 Based on nominal 7 m room height and 10-m rock fall.

**Figure H.3: Cross-Section of the Discretization around the Base of the Shaft**



**Figure H.4: Cross-Section around the Monolith**

### H.2.1.2 Geosphere and Shaft Discretization

The transport from the repository is expected to be primarily by diffusion, with some possibility of vertical advection through some components under some scenarios. Although diffusion occurs in three dimensions, the flat planar geometry of the DGR leads to the possibility of simplifying the assessment representation to a 1D system. Lateral diffusion from the repository is, therefore, conservatively not represented. The shafts represent the key potential contaminant transport pathway from the DGR to the Shallow Bedrock Groundwater System. The discretization in the geosphere above the DGR, therefore, focuses on representing lateral diffusion away from the shafts, while maintaining a representation of the rock above the repository footprint, as illustrated in Figure H.5.

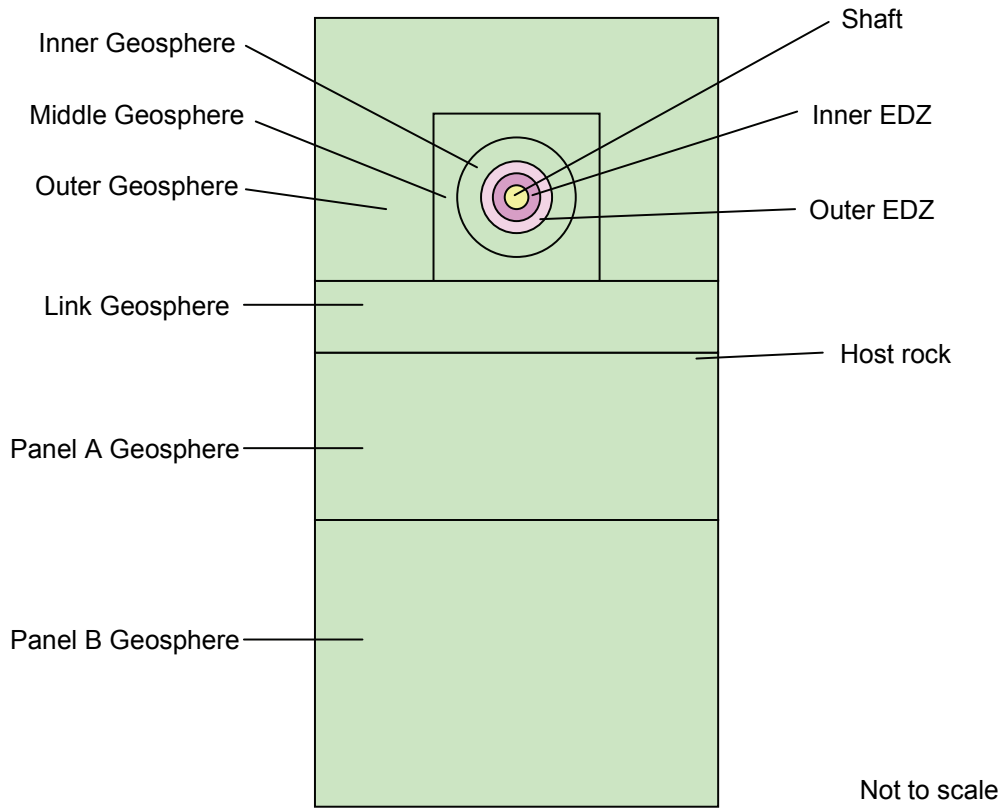
The vertical discretization of the geosphere and shafts is described in Table H.1. The discretization of the geosphere in the Deep Bedrock Groundwater Zone focuses on providing increasing compartment thicknesses away from the DGR for representing diffusion, up to a maximum layer thickness of about 60 m. Within the Intermediate Bedrock Groundwater Zone, the geosphere discretization focuses on formations with similar properties, while ensuring that the Guelph and Salina A1 upper carbonate formations are explicitly represented, due to the potential for horizontal groundwater flow within these formations. Only the Bass Island (upper and lower) and Bois Blanc formations are represented in the Shallow Bedrock Groundwater Zone, as any contaminant transport from the top of the shafts will focus on these formations and the groundwater well extends into the top of the Bois Blanc formation.

The vertical discretization of the shafts and their EDZs reflects that of the surrounding geosphere, with the exception of additional discretization within the Georgian Bay/Blue Mountain layer and within the asphalt seal to refine the representation of contaminant transport within these sections of the shafts.

**Table H.1: Vertical discretization of the Geosphere (Left) and Shaft (Right)**

Geosphere Discretization		
ID	Thickness (m)	Formations/Notes
S1	94.3	Bois Blanc, Bass Island
I12	9.3	Salina G
I11	12	Salina F (shale)
I10	32.4	Salina F (shale)
I9	37.3	Salina C, D & E (represented as limestone/dolostone)
I8	65.2	Salina B & Salina A2
I7	3	Salina A1 upper carbonate
I6	12.3	Salina A1 carbonate
I5	33.7	Salina A1 carbonate & evaporite, Salina A0
I4	4.1	Guelph
I3	12	Goat Island
I2	20.4	Goat Island, Gasport, Lions Head & Fossil Hill
I1	36.7	Cabot Head & Manitoulin (both shale)
D12	58.9	Queenston (shale)
D11	60.9	Queenston & Georgian Bay (shale)
D10	66.6	Georgian Bay & Blue Mountain (shale)
D9	22.5	Blue Mountain & Collingwood (represented as shale)
D8	5.5	Collingwood & Cobourg
D7	26	Repository Layer
D6	28	Sherman Fall
D5	45.9	Kirkfield
D4	23	Coboconk
D3	58.8	Gull River & Shadow Lake
D2	16.9	Cambrian
D1	Sink	Upper Precambrian

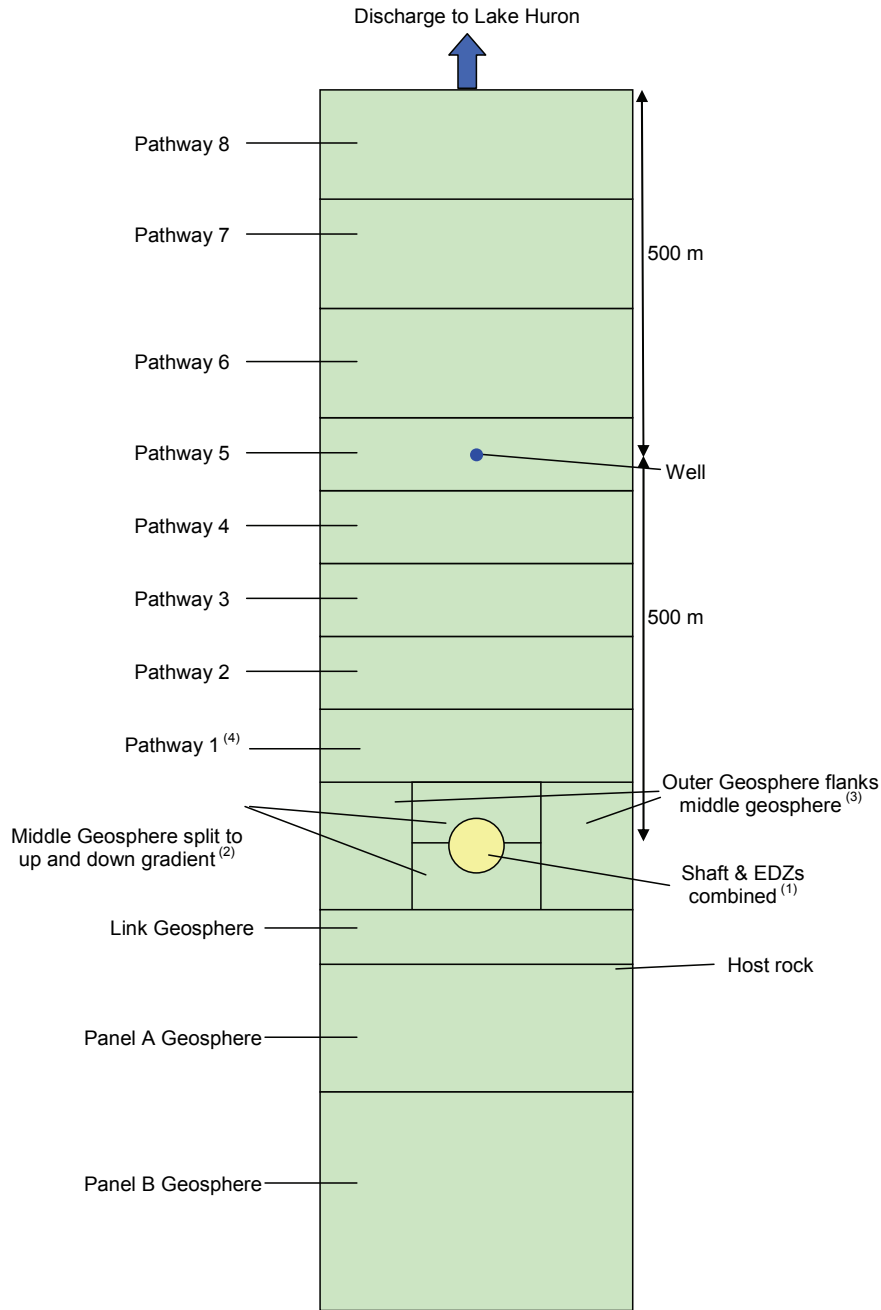
Discretization of Shaft and EDZs		
ID	Thickness (m)	Notes
S1_S6	94.3	
I12_S6	9.3	
I11_B3	12	Bulkhead 3
I10_S5	32.4	
I9_S5	37.3	
I8_S5	65.2	Ignore 2.7 m of B2 extending into Salina A2 evaporite
I7_B2	3	Bulkhead 2
I6_B2	12.3	Bulkhead 2
I5_S4	33.7	Ignore 1.9 m of B1 extending into Salina A0
I4_B1	4.1	Bulkhead 1
I3_B1	12	Bulkhead 1
I2_S3	20.4	
I1_S3	36.7	
D12_S3	58.9	
D11_S2c	40.9	Asphalt
D11_S2b	15	Asphalt
D11_S2a	5	Asphalt
D10_S1b	33.3	
D10_S1a	33.3	
D9_S1	22.5	
D8_S1	5.5	
V Mon	13	Ignore monolith below repository floor
H Mon	7	



**Figure H.5: Illustration of Discretization within Each Geosphere Layer in the Deep and Intermediate Bedrock Groundwater Zones above the DGR**

The horizontal discretization within the Shallow Bedrock Groundwater Zone is illustrated in Figure H.6. The shallow system is discretized to include five compartments between the shafts and the groundwater well (the key pathway to the terrestrial biosphere), to provide a suitable representation of contaminant transport with groundwater advection (see Appendix F).





Notes:

- 1 Horizontal hydraulic conductivity of engineered fill, inner and outer EDZs sufficiently similar to represent the shaft and EDZs as a single compartment
- 2 Advection dominates in the shallow system, so there is no need for the extra discretization of the inner geosphere; flow towards the lake, so middle geosphere split to up- and down-gradient
- 3 Outer geosphere flanking the shaft needs to be retained to capture an appropriate fraction of advection from up-gradient of the shaft
- 4 Pathway 1 is positioned above part of the outer geosphere in the layer below

**Figure H.6: Horizontal Discretization within the Shallow Bedrock Groundwater Zone**

### **H.2.1.3 Discretization of the Gas Pathway via the Shafts**

The detailed gas modelling focuses on the DGR and the shaft in the Deep and Intermediate Bedrock Groundwater Zones; the detailed modelling does not extend to the Shallow Bedrock Groundwater Zone (see Section 4.3 of GEOFIRMA and QUINTESSA 2011). Fluxes of free gas via the shafts as far as the Guelph formation are provided from the T2GGM modelling. The AMBER model includes compartments representing free gas in the shaft up to the Guelph and is discretized consistently with the surrounding geosphere; i.e., eight free-gas compartments in the shaft from geosphere level D8 to I3 (see Table H.1).

## **H.2.2 Nearfield and Geosphere Model Implementation**

### **H.2.2.1 Selecting the Calculation Case to Be Run**

A wide range of calculation cases and variant calculations are considered in the Postclosure SA. The cases are implemented in a single case file, such that only a single file need be maintained when changes are made. The case file includes a nameset option parameter (OPT\_CalculationCase) that is indexed over calculation cases. This enables the calculation that is to be run to be selected from a drop-down list. This parameter is used to define the model properties for the calculation being undertaken.

### **H.2.2.2 Model Hierarchy**

The model includes 316 compartments and 1177 transfers. The number of transfers is significantly greater than the number of compartments because diffusive transfers between compartments are represented with two transfers (a 'forward' transfer and a 'return' transfer) and because each compartment may interface with several surrounding compartments.

The compartments and transfers are organized via the AMBER model window using a hierarchy of submodels, as illustrated in Figure H.7 and Figure H.8.

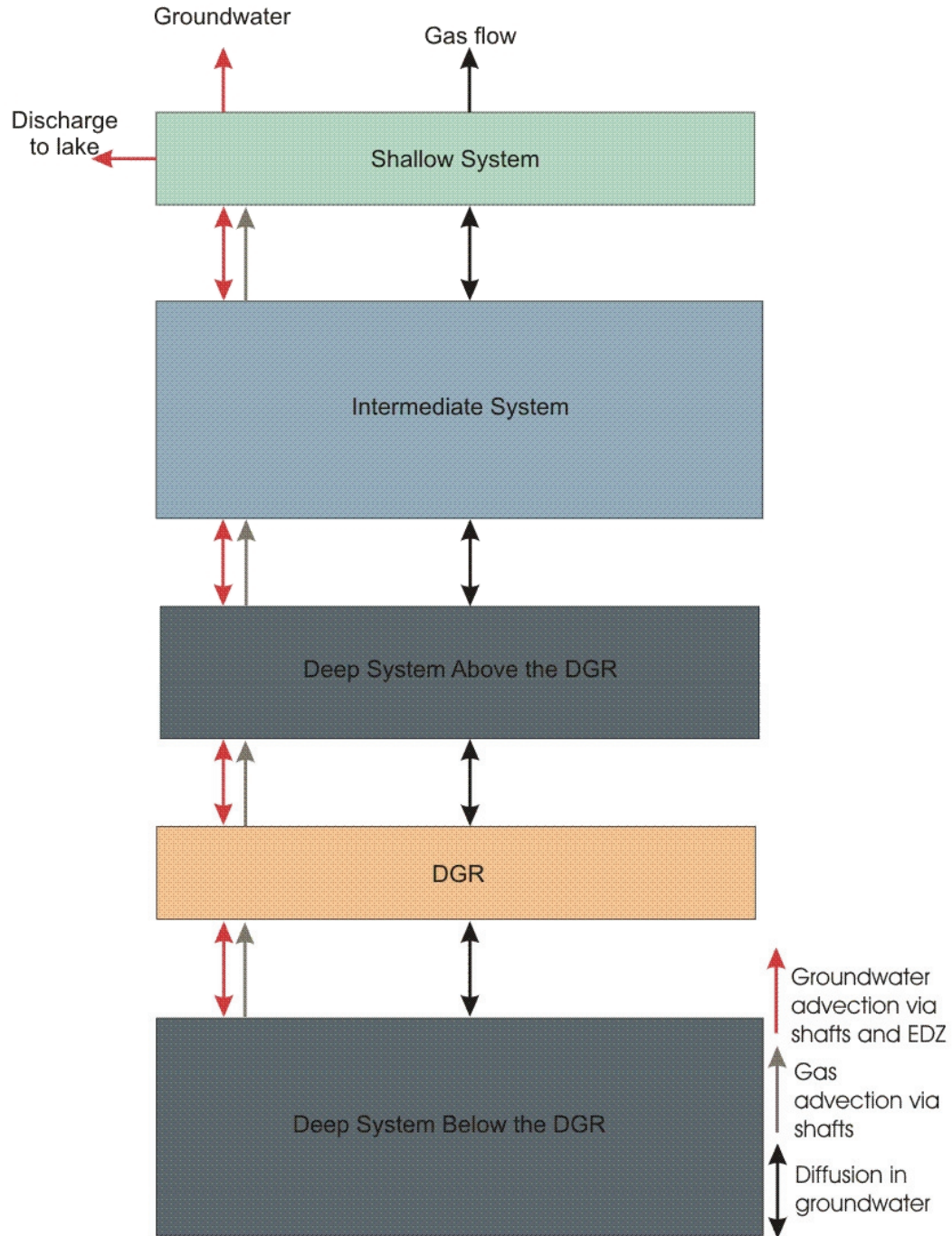
### **H.2.2.3 Importing Data**

The assessment model implemented in AMBER draws directly on detailed gas and groundwater flow calculations undertaken using T2GGM and FRAC3DVS-OPG. Outputs from the detailed models are formatted as AMBER import files, which are read directly by AMBER when the case file is loaded.

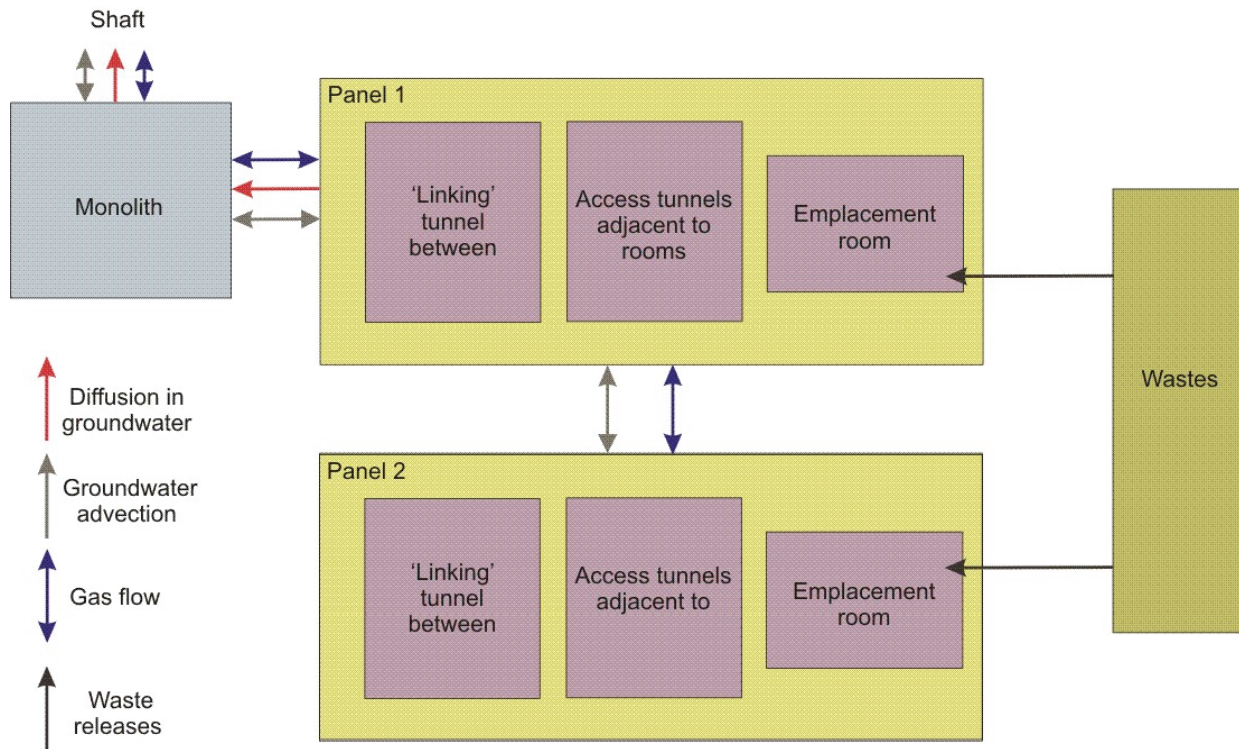
Table H.2 provides a list of the T2GGM and FRAC3DVS-OPG information that is imported into AMBER, together with the import file (.aaf) that contains the data for all of the associated calculation cases. Further details are included in Appendix J.

### **H.2.2.4 Parameterization**

The AMBER model includes about 250 parameters. The parameters have been grouped using a prefix codes at the beginning of the parameter name. The groups are listed in Table H.3, together with a brief description.



**Figure H.7: Illustration of the Top-Level AMBER Sub-Model Hierarchy for the Nearfield and Geosphere Model**



**Figure H.8: Illustration of the AMBER Sub-Model Hierarchy for the DGR within the Nearfield and Geosphere Model**

**Table H.2: Detailed Modelling Results Imported into the Nearfield and Geosphere Model**

FRAC3DVS-OPG		T2GGM	
Parameter	File	Parameter	File
<ul style="list-style-type: none"> <li>Volumetric groundwater flows (<math>m^3/a</math>) - over specific model interfaces</li> </ul>	FRAC_20Jan11.aaf	<ul style="list-style-type: none"> <li>Gas flows (<math>kg/a</math>) - over specific model interfaces</li> <li>Gas mass (<math>kg</math>) - Within specific model components</li> <li>Fractional repository saturation (-)</li> <li>Partial pressure of <math>CO_2</math> and <math>CH_4</math> (Pa)</li> </ul>	<ul style="list-style-type: none"> <li>T2_20Jan11.aaf</li> <li>T2_20Jan11.aaf</li> <li>GGM_20Jan11.aaf</li> <li>GGM_20Jan11.aaf</li> </ul>

**Table H.3: Parameter Nomenclature Used**

Prefix	Description
EXP_	Export parameter
GEN_	General model parameter
GEO_	Geosphere parameter
IMP_	Import parameter
Metric_	Observer parameter used for metric comparisons against FRAC3DVS-OPG
OBS_	Observers
OPT_	Nameset option parameters
REP_	Repository parameter
SWT_	'Flag' (switches) parameters that indicate when processes are turned on or off
TR_	Transfer rate expression
WST_	Waste parameter

### H.2.2.5 Waste Release Times

Instantaneous and congruent releases are considered for releasing contaminants from waste to groundwater in the DGR. These are reflected in parameters that define when the release can start (WST\_t\_start) and when the release model finished (WST\_t\_finish). All waste categories start to release contaminants from time zero. The end time of the release for waste categories that release contaminants via corrosion and that use a congruent model is determined by the thickness of the waste and the corrosion rate. Availability for waste categories that use an instant release model is implemented as occurring over a period of one year to avoid zero divides in the model.

### H.2.2.6 Partitioning between Gas and Water

For contaminants that can enter the gas phase in the DGR, the partitioning is expressed with a partition factor that relates the concentration in the gas phase to that in the water phase ( $P_{GasWater}$ ). Transfers from water to gas ( $\lambda_{WaterGas}$ , /a) are then implemented using the following expression:

$$\lambda_{WaterGas} = P_{GasWater} \frac{(1 - f_{Sat})}{f_{Sat}} \lambda_{Rapid} \quad (H1)$$

where

$f_{Sat}$  is the fractional repository saturation (unitless); and

$\lambda_{Rapid}$  is a transfer rate that is rapid in relation to other model processes (/a).

The transfer from gas to water is represented with:

$$\lambda_{WaterGas} = (1 - P_{GasWater}) \frac{f_{Sat}}{(1 - f_{Sat})} \lambda_{Rapid} \quad (H2)$$

### H.2.2.7 Exporting Data

Once the AMBER calculations are complete for the nearfield and geosphere model, the results for specific parameters are saved to an export file (NF\_GEO\_Rsults.aaf) and are imported to the biosphere model. Table H.4 provides a list of the parameters that are included in the export file.

**Table H.4: Export Parameters Generated by the Nearfield and Geosphere Model**

Data	AMBER Parameter
Radionuclide fluxes to the biosphere (Bq/a) - over potential interfaces to the biosphere	EXP_FluxesToBiosphere
Radionuclide concentration in groundwater within the Cambrian formation (Bq/m <sup>3</sup> )	EXP_C_L_Cambrian
Fraction of gas flux to the shallow system that dissolves in the flowing groundwater (-)	GEN_f_GasDissolve
Radionuclide concentration in waste categories (Bq/kg)	EXP_C_WasteStream
Average radionuclide concentration in waste within each panel (Bq/kg)	EXP_C_WastePanel
Radionuclide concentration in repository water (Bq/m <sup>3</sup> )	EXP_C_WaterPanel
Radionuclide concentration on suspended solids for human intrusion calculations (Bq/m <sup>3</sup> )	EXP_C_SuspSed
Radionuclide concentration in suspended siderite for human intrusion calculations (Bq/m <sup>3</sup> )	EXP_C_Siderite

## H.3 BIOSPHERE MODEL

### H.3.1 Biosphere Discretization

The current conceptual model for the groundwater pathway allows for any contaminants released from the repository to reach the biosphere from the Shallow Bedrock Groundwater Zone due to groundwater pumping from a well (about 500 m from the shafts) or due to groundwater discharge into Lake Huron (about 1000 m from the shafts). In addition, discharge can occur from the Guelph and Salina A1 upper carbonate formations into Lake Huron. The conceptual model also identifies eight key biosphere features, based on their potential to affect contaminant migration, accumulation and exposure of humans and non-human biota.

The key biosphere features can be divided into those through which contaminants can gradually migrate and accumulate, and those for which contaminant concentrations can be considered to be in local equilibrium with other biosphere media, over the timescales of interest to the

assessment. The former require representation with dynamic transfers between compartments, whereas the latter can be assessed by scaling to the dynamically modelled compartments.

The biosphere model equations are largely based on CSA (2008).

Features requiring dynamic modelling include the following.

- Agricultural soils might receive potentially contaminated irrigation water and form the substrate for crops.
- Surface water can become contaminated with water pumped from the well due to subsurface interflow from contaminated soils. Surface water may require further discretization to reflect differing water courses.
- Lake water receives potentially contaminated groundwater from the Shallow Bedrock Groundwater Zone close to the shore and potentially contaminated surface water. Contaminants reaching the lake would be mixed throughout the lake. Lake water requires further discretization to reflect Lake Huron dimensions and water flows.

Equilibrium features include the following.

- Well water is pumped from the Shallow Bedrock Groundwater Zone. It has the same concentration as the groundwater in the rock from which it is pumped.
- Atmospheric concentrations are associated with volatilization from contaminated soil. Concentrations in the air can be derived from the volatilization flux from the soil. Air within the home of the critical group has the same concentration as the surrounding air.
- Surface water bed sediment interacts with the surface water (e.g., by sedimentation and resuspension). Consistent with CSA (2008), surface water bed sediment is in local equilibrium with the water.
- Lake bed sediment interacts with lake water and can be considered to be in local equilibrium with lake water, consistent with CSA (2008).
- Biota are in equilibrium with the media around them (soil, water, air), as their growth is rapid compared with the timescales of interest in the assessment model.

The biosphere components that are in equilibrium with other biosphere media are indicated with dotted outlines in Figure 2.16 to Figure 2.18. The equilibrium assumptions are summarized in Table H.5.

Figure H.9 and Figure H.10 illustrate the discretization adopted for the dynamic components of the terrestrial and Lake Huron components of the biosphere, together with source terms and transfers.

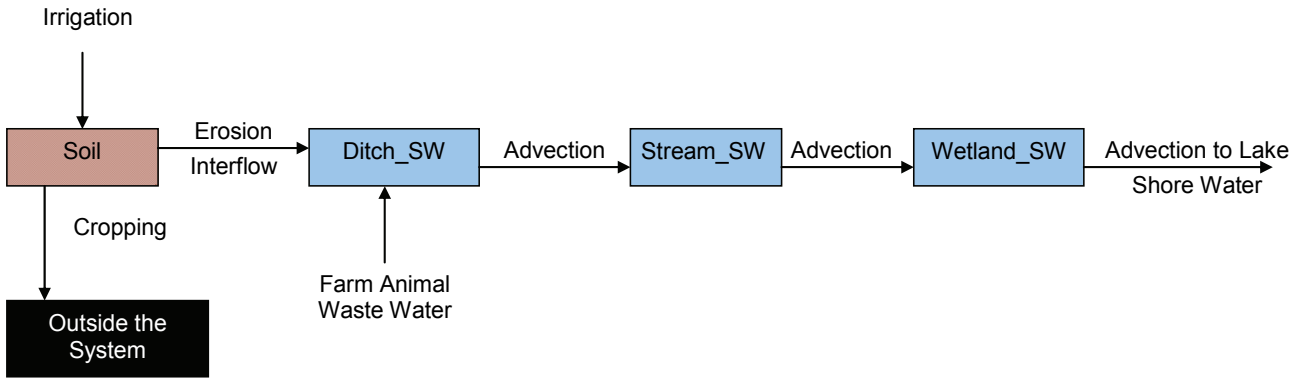
The only pathway for contamination of the terrestrial system by the groundwater pathway is pumping of potentially contaminated well water and its use for irrigation. Only the irrigated area of soil need be explicitly represented, within which the crops are grown in annual rotation such that a single soil compartment is suitable; therefore, no further horizontal discretization of the soil is required. Consistent with CSA (2008), the soil is modelled as a single layer due to the relatively well-mixed soil in the rooting zone of the crops and no vertical discretization of the soil is required. A simple, stylized representation is suitable for the context of long-term postclosure safety assessment; therefore, the irrigated land is taken to be in the vicinity of a small surface water drainage feature, which is analogous to the present-day railway ditch near the DGR site.

Semi-natural areas of the system can become contaminated via surface water from the irrigated farmland; therefore the pathway via the ditch to a natural stream and wetland (equivalent to the Baie du Doré) is included. The inclusion of these pathways in the calculations maximizes the number of potential exposure pathways for both humans and non-human biota.

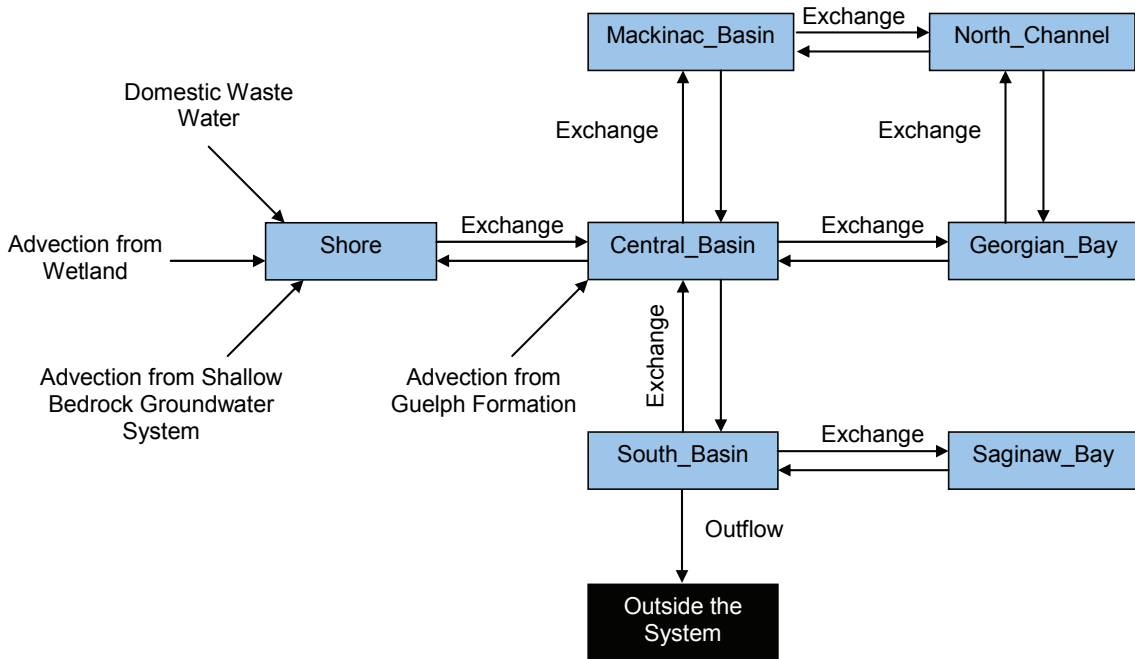
**Table H.5: Summary of Equilibrium Assumptions for the Biosphere Model for the Groundwater Pathway**

<b>Equilibrium Component</b>	<b>Parent Component</b>	<b>Pathway/Process</b>
Well water/irrigation water	Shallow Bed rock Groundwater Zone	Abstraction
Farm atmosphere	Irrigated soil	Volatilization
Stream atmosphere	Stream water	Volatilization
Lake atmosphere	Local lake water	Volatilization
Surface water bed sediment	Associated surface water compartment	Sedimentation/resuspension
Lake bed sediment	Associated lake water compartment	Sedimentation/resuspension
Cropped plants	Well water and Irrigated soil	Interception and Root uptake
Wild forage	Wetland sediment	Root uptake
Honey	Cropped plants	Transfer and production by bees
Farm animals	Well water	Ingestion
	Cropped plants	Ingestion
	Irrigated soil	Ingestion of adhered soil for farmed animals fed crops
	Farm atmosphere	Inhalation
Wild animals	Wetland water	Ingestion
	Wild forage	Ingestion
	Wetland sediment	Ingestion of soil adhered to forage Ingestion of soil from sources other than adhered to forage
	Wetland atmosphere	Inhalation
Surface water fish	Associated surface water compartment	Uptake
Lake fish	Associated surface water compartment	Uptake





**Figure H.9: Illustration of Discretization for the Dynamic Components of the Terrestrial System**



**Figure H.10: Illustration of the Discretization of the Dynamic Components of the Lake System together with Contaminant Flows**

Water consumed by animals is excreted to the nearby water course. Water used for domestic purposes is transferred to the lake shore.

While Lake Huron would likely not be present per se in the distant future, it is reasonably likely that a large lake would continue to exist in the area since the Great Lakes basin is a durable feature of the regional geology. It is convenient to model this large lake as Lake Huron, since that provides a clearer picture of the potential DGR impacts. Distribution of any contaminants in this lake requires it to be divided up into zones. The division of Lake Huron into zones for modelling is described in Section 6.1 of the Data report (QUINTESSA and GEOFIRMA 2011). An additional 'Shore' zone is defined within the Central Basin into which the Baie du Doré and flow from the Shallow Bedrock Groundwater Zone discharges. The 'Shore' zone is taken to extend 1 km along the shoreline adjacent to the DGR and 500 m from the shore with an average depth of 5 m.

While volatilization is explicitly represented in its contribution to atmospheric concentrations (see Table H.5), it is conservatively ignored as a transfer process.

### **H.3.2 Biosphere Model Implementation**

#### **H.3.2.1 Selecting the Calculation Case to Be Run**

The biosphere model imports contaminant fluxes and/or concentrations from the nearfield and geosphere model, as listed in Table H.4. The data is included in an AMBER export/import file that is generated by the associated nearfield and geosphere model (NF&GEO\_Results.aaf). In order to run a biosphere calculation for a specific case the following steps are needed.

- Ensure that the nearfield and geosphere export file (NF&GEO\_Results.aaf) generated for the specific case is stored in the same directory as the biosphere case file that is to be run.
- Select the calculation case to be run from the drop-down list via the nameset option parameter OPT\_CalculationCase.

A convenient way of managing the calculation cases is to store the nearfield and geosphere case, the biosphere case and the associated import files in a directory specific to each case.

Some calculation cases represent variants representing different biosphere and/or exposure considerations. These cases do not require a dedicated nearfield and geosphere calculation. Table H.6 provides a list of the biosphere calculation cases, together with the associated nearfield and geosphere calculation case.

In addition to the calculation cases listed in Table H.6, further variant calculations can be undertaken, as listed below.

- Surface erosion, with the fluxes from the top of the Deep Bedrock Groundwater Zone being captured by the well (NE-ER (Deep) biosphere option, based on the NE-RC nearfield and geosphere results).
- Use of groundwater from the Cambrian formation rather than the shallow system (NE-Cambrian biosphere option, based on the NE-RC nearfield and geosphere results).

**Table H.6: AMBER Nearfield and Geosphere Modelling Results Imported into the Biosphere Model**

<b>AMBER Biosphere Calculation Case</b>	<b>Associated AMBER Nearfield and Geosphere Calculation</b>
1. NE-RC: Reference Case (Transient)	NE-RC
2. NE-PD-RC: Final preliminary design	NE-PD-RC
3. NE-RC-WL: Water-limited reference case	NE-RC-WL
4. NE-SBC: Simplified Base Case (Steady-State)	NE-SBC
5. NE-SBC-WL: Water-limited simplified base case	NE-SBC-WL
6. NE-RS: Instant resaturation	NE-RS
7. NE-RT1: Instant release, no sorption, transient	NE-RT1
8. NE-RT2: Instant release, no sorption, steady-state	NE-RT2
9. NE-EDZ1: Enhanced shaft EDZ conductivity	NE-EDZ1
10. NE-BF: Backfilled repository	NE-BF
11. NE-HG: Horizontal gradient	NE-HG
12. NE-GT5: Increased gas generation, reduced shaft seal performance	NE-GT5
13. NE-PD-GT5: Increased gas generation, reduced shaft seal performance with the final preliminary design	NE-PD-GT5
14. NE-GG1: Increased gas generation	NE-GG1
15. NE-GG2: Reduced degradation rates	NE-GG2
16. NE-NM: No methanogenic gas reactions	NE-NM
17. NE-IV: Increased inventory	NE-IV
18. NE-CC: Tundra biosphere	NE-RC
19. NE-ER (Intermediate): Surface erosion	NE-RC

Note that no biosphere calculations were needed for the probabilistic case (NE-PC-A).

### H.3.2.2 Importing Data

In addition to the results generated by the nearfield and geosphere model (contained within the NF&GEO\_Results.aaf file), the biosphere model also imports data from the detailed gas modelling (see Table H.7).

**Table H.7: Detailed Modelling Results Imported into the Biosphere Model**

<b>T2GGM</b>	
<b>Parameter</b>	<b>File</b>
1) Gas flows (kg/a) - over specific model interfaces	T2_20Jan11.aaf
2) Fraction of the repository gas comprising CH <sub>4</sub> and CO <sub>2</sub> (-)	GGM_20Jan11.aaf

#### H.4 Models for Non-radioactive Contaminants

Iterations of the nearfield and geosphere (AMBER\_V2\_NF&GEOv1.cse) and the biosphere models (AMBER\_V2\_BIOv1.cse) have been developed that model non-radioactive contaminants. The system and the relevant contaminant transport processes are the same as for radiological species. Therefore, the models for radiological contaminants have been adapted to represent non-radioactive contaminants by undertaking the following steps.

- Changing the base units for the cases from Bq to kg.
- Replacing the list of radionuclide contaminants with the list of non-radioactive contaminants.
- Removing the radioactive decays.
- Removing reference to radionuclide-specific information in expressions.
- Including waste inventories for non-radioactive contaminants.

The non-radioactive version of the nearfield/geosphere and biosphere models (AMBER\_V2\_NF&GEOv1\_NR.cse and AMBER\_V2\_BIOv1\_NR.cse, respectively) are then capable of solving contaminant release and transport and are able of providing calculated concentrations in environmental media, which can be compared against environmental quality standards.

#### H.5 FEP Audit of AMBER Model

The assessment model implemented in AMBER has been checked against the list of FEPs included in the conceptual model (Appendix C). 134 out of the 136 screened-in FEPs are explicitly or implicitly represented in the AMBER model documented in Appendices D, E, F and H. For example:

- Packaging collapse (2.1.06.01) is explicitly represented through collapsed waste stacks;
- Mechanical processes and conditions in the geosphere (2.2.05) are explicitly taken into account through the consideration of rockfall; and
- Mineralization (2.1.08.06) FEPs are implicitly represented through adopting degraded properties for concrete.

Two FEPs included in the conceptual model are, however, excluded from the AMBER model. These are listed below, together with the associated justification for their exclusion from the AMBER model.

- The shaft lining (2.1.05.01) is not explicitly represented in the Shallow Bedrock Groundwater Zone. Concrete is represented with degraded properties in the model, such that the

degraded concrete lining in the shallow system will not have a significant effect on contaminant transport and there is not sufficient justification to explicitly include it in the model.

- The overburden (2.3.03.02) is not explicitly represented in the model. Contaminants in shallow groundwater are discharged directly to the biosphere via the well and via direct release to the lake. Any free gas from the top of the shallow system is transferred directly to the biosphere. Contaminants infiltrating through the soil are conservatively maintained within the biosphere by being directed to the local water course. Therefore, no contamination reaches the overburden, so it is excluded from the model.

#### **REFERENCES FOR APPENDIX H**

- 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 R000. Toronto, Canada.
- OPG. 2011. OPG's Deep Geologic Repository for Low and Intermediate Level Waste: Preliminary Safety Report. Ontario Power Generation Report 00216-SR-01320-00001 R00. 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 R000. Toronto, Canada.

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## **APPENDIX I: DGR AMBER MODELS**

### **I.1 PROBLEM DESCRIPTION**

Two DGR-specific models (AMBER\_V2\_NF&GEOv1 (for the repository, shafts and geosphere) and AMBER\_V2\_BIOv1 (for the biosphere) have been implemented in the AMBER 5.3 code to undertake radiological impact calculations for the following scenarios identified in the System and Its Evolution report (QUINTESSA 2011):

- Normal Evolution;
- Human Intrusion;
- Severe Shaft Seal Failure;
- Poorly Sealed Borehole; and
- Vertical Fault.

In addition, a variant of each of these models has been developed in which the radionuclides are replaced with non-radioactive contaminants (AMBER\_V2\_NF&GEO\_NRv1 and AMBER\_V2\_BIO\_NRv1)

The specification of the problem to be solved by the models is given in the associated scenario analysis reports, namely:

- Chapter 2 of the current report for the Normal Evolution Scenario; and
- Chapter 2 of the Human Intrusion and Other Disruptive Events analysis report (QUINTESSA and SENES 2011) for the Human Intrusion, Severe Shaft Seal Failure, Poorly Sealed Borehole and Vertical Fault Scenarios.

Each of the sections discusses the conceptual models for the scenario considered, identifying key features, events and processes to be modelled.

### **I.2 SOFTWARE PLAN**

Relevant information for the software plan for the DGR AMBER models is given in Table I.1.

### **I.3 THEORY**

The mathematical models solved by the DGR AMBER models and the associated constraints are described in Appendix D and E of this report for the Normal Evolution Scenario and Appendix D of QUINTESSA and SENES (2011) for the Disruptive Scenarios.

### **I.4 REQUIREMENTS SPECIFICATION**

The requirements for the DGR AMBER models (e.g., calculation of doses) are determined by the mathematical models documented in Appendix D and E of this report for the Normal Evolution Scenario and Appendix D of QUINTESSA and SENES (2011) for the Disruptive Scenarios.

### **I.5 DESIGN DESCRIPTION**

The implementation of the mathematical models in the DGR AMBER models is described in Appendix H of this report for the Normal Evolution Scenario, and Sections 2.4.2, 3.4.2, 4.4.2, and 5.4.2 of QUINTESSA and SENES (2011) for the Disruptive Scenarios.

**Table I.1: Key Components of the Software Plan for the AMBER Models**

Software Plan Component	Relevant Information for AMBER Models
Software name and version number	<p>AMBER_V2_NF&amp;GEOv1            AMBER_V2_BIOv1            AMBER_V2_NF&amp;GEO_NRv1            AMBER_V2_BIO_NRv1</p>
Software classification and relevant QA standards	<p>The general AMBER platform is maintained under Quintessa's Quality Management System (QUINTESSA 2010a), which is ISO 9001:2008 compliant.</p> <p>The above AMBER applications are classified as "Nuclear Grade" since they are intended to be used to provide postclosure safety analysis calculations in support of the DGR license application.</p> <p>This document therefore provides a linkage between the status of the AMBER models, and the expectations of NWMO PROC-EN-0002.</p>
Key roles and accountabilities, including identifying the Primary Holder	<p>Russell Walke (Quintessa) has been responsible for coordinating the development, maintenance and documentation of the AMBER models.</p>
Key deliverables, tasks, schedules, and methods	<p>These AMBER applications have been developed under a contract between NWMO and Quintessa Ltd. Results are described in the series of reports identified in Chapter 1 of this report.</p>
Verification and validation activities	<p>Verification of the model has been achieved by checking and recording the appropriate implementation of the mathematical model and data given in Appendices D and E of this report, and Sections 2.4.1, 3.4.1, 4.4.1 and 5.4.1, and Appendix D of QUINTESSA and SENES (2011), consistent with the requirements of the Project Quality Plan (QUINTESSA 2010c).</p> <p>Full validation of long-term safety assessment models is not possible due to the long timescales considered. However, confidence in the results obtained by the AMBER models is provided as summarized in this appendix.</p>
Configuration management and change control method	<p>Template file and control file and resulting case and result files are controlled. These have been controlled consistent with the requirements of project quality plan (QUINTESSA 2010c) and in particular Quintessa QMS Operation Procedure PR-5a (Production of Deliverables) (QUINTESSA 2010a).</p>



## **I.6 SOURCE CODE**

The commented template, control and case files used for the assessment have been provided to NWMO. Their format is determined by the requirements of the AMBER 5.3 code.

## **I.7 VERIFICATION FOR THEORY, REQUIREMENTS, DESIGN AND CODE**

The documents that describe the theory, requirements and design for the DGR AMBER models, together with the implementation of the model and data in AMBER, have been subject to peer review and verification, consistent with the requirements of the Project Quality Plan (QUINTESSA 2010c).

## **I.8 VALIDATION**

Complete validation of long-term safety assessment models is not possible due to the long timescales considered. Furthermore, these models are specific to the DGR at the Bruce nuclear site. However, confidence has been built in the results obtained by the DGR AMBER models through the following approaches:

- (1) The models are simplified and generally conservative representations of the potential impacts over a 1 Ma time frame. The equations are simple and generally consistent with those used for similar purposes by other radioactive waste management programs. The equations have been peer reviewed as part of their development.
- (2) The biosphere model is based on the CSA (2008) recommended biosphere model.
- (3) The model results have been compared with those obtained using the FRAC3DVS-OPG and T2GGM codes over the development of the postclosure safety case (see Section 7.3.3 of QUINTESSA et al. 2011). These codes have been used, tested and compared in three major internal iterations.
- (4) The model results have been checked for mass balance.
- (5) The AMBER framework has been used to construct for the development and application of similar postclosure assessment models for other facilities, as documented in the references in QUINTESSA (2009a).

## **I.9 COMPUTER PROGRAM ABSTRACT**

### **I.9.1 Purpose**

The DGR AMBER models have been developed by Quintessa using the AMBER 5.3 code to allow the calculation of the impacts of the disposal of L&ILW to the proposed DGR for four scenarios:

- Normal Evolution;
- Human Intrusion;
- Severe Shaft Seal Failure;
- Poorly Sealed Borehole; and
- Vertical Fault.

### **I.9.2 Model History**

The current DGR AMBER models were developed in 2010 by Quintessa staff for use in the Preliminary postclosure safety assessment.

### **I.9.3 Operating Requirements**

The recommended system requirements needed to run the DGR AMBER models are a PC with a Pentium processor or equivalent with at least 64 MB of RAM installed, running under the Windows 2000, XP, Vista or Windows 7 operating system. The models will run on lower specification machines but its performance will be reduced, e.g., calculations will run more slowly. At least 10 MB of hard disk space should be available.

The models have typically been run on dual 1.68 GHz processor PCs running Windows XP (Service Pack 3) with 3 GB of RAM.

### **I.9.4 Components**

In order to run, the DGR AMBER models require the AMBER 5.3 executable and associated support files (various .dll, .ocx and .irs files) to be installed on the PC. A USB hardware security key (dongle) also needs to be inserted into one of the PC's USB ports and the associated driver installed.

Template files (AMBER\_V2\_NF&GEOv1.tpl and AMBER\_V2\_NF&GEO\_NRv1.tpl) and an associated control file (BatchRun.ctl) have been developed to allow the model to run in batch mode. This enables calculation cases identified in Chapter 3 of this report to be run using the same template file.

Once the repository and geosphere models have been run for each case and saved to individual directories to generate associated output file (NF&GEO\_Results.aaf), the associated biosphere calculations can be undertaken by running the AMBER\_V2\_BIOv1.cse and AMBER\_V2\_BIO\_NRv1.cse case files via AMBER.

### **I.9.5 Capabilities**

The AMBER\_V2NF&GEOv1 and AMBER\_V2NF&GEOv1\_NR models represent the repository and geosphere for radioactive and non-radioactive contaminants, respectively. They model the release of contaminants from the wastes in the repository and their subsequent migration through the geosphere.

The AMBER\_V2\_BIOv1 and AMBER\_V2\_BIOv1\_NR models represent the biosphere for radioactive and non-radioactive contaminants, respectively. They represent the migration of contaminants through the biosphere and can be used to calculate the impacts for the four scenarios assessed.

All models can be used to calculate other endpoints of interested (e.g., contaminant fluxes and concentrations through/in various media).

### **I.9.6 Limitations**

The models have been implemented in AMBER recognizing the limitations underlying the AMBER 5.3 code (see Appendix F.9.6). The models are assessment-level models that have

been designed to represent the key processes, migration pathways and exposure pathways of relevance to the DGR. More detailed calculations of groundwater and gas flow and transport are undertaken by the FRAC3DVS-OPG (GEOFIRMA 2011) and T2GGM codes (GEOFIRMA and QUINTESSA 2011), respectively.

### **I.9.7 Documentation**

The DGR AMBER models, their use and their verification are described in the current report.

### **I.10 User Manual**

The features, capabilities and options for the models are described in Appendix H of this report for the Normal Evolution Scenario, and Sections 2.4.2, 3.4.2, 4.4.2, and 5.4.2 of QUINTESSA and SENES (2011) for the Disruptive Scenarios. Template files for the repository and geosphere models (AMBER\_V2\_NF&GEOv1.tpl and AMBER\_V2\_NF&GEO\_NRv1.tpl) and an associated control file (BatchRun.ctl) have been developed to allow the model to run in batch mode. Result files (.adf) and output files (.aaf) are generated for each calculation case. Once the repository and geosphere output files have been generated for a specific case, the biosphere calculations can be undertaken by running the AMBER\_V2\_BIOv1.cse and AMBER\_V2\_BIO\_NRv1.cse case files via AMBER. Details relating to the installation of the AMBER executable and the running of AMBER input files are provided in the AMBER 5.3 Reference Guide and Getting Started documents (QUINTESSA 2009b, c).

### **I.11 Programmer Manual**

Information concerning the use of AMBER is provided in the AMBER 5.3 Reference Guide (QUINTESSA 2009b). Specific information on the DGR AMBER models is provided in Appendix H of this report for the Normal Evolution Scenario, and Sections 2.4.2, 3.4.2, 4.4.2, and 5.4.2 of QUINTESSA and SENES (2011) for the Disruptive Scenarios.

### **I.12 Version Tracking Record**

The finalized versions of the AMBER models used for the current safety assessment are AMBER\_V2\_NF&GEOv1, AMBER\_V2\_BIOv1, AMBER\_V2\_NF&GEO\_NRv1 and AMBER\_V2\_BIO\_NRv1. All results reported in the associated safety assessment documentation have been generated from these versions of the models.

The full components of this version are the AMBER\_V2\_NF&GEOv1.cse, AMBER\_V2\_BIOv1.cse, AMBER\_V2\_NF&GEO\_NRv1.cse and AMBER\_V2\_BIO\_NRv1.cse files, and the documents as referenced in this appendix.

The AMBER case files are text based ASCII format files. The development of the case files has been undertaken iteratively up to the production of the final files. The full history of the file development is stored electronically and changes between each stage can be identified by comparing file differences.

**REFERENCES FOR APPENDIX I**

- GEOFIRMA. 2011. Postclosure Safety Assessment: Groundwater Modelling. Geofirma Engineering Ltd. report for the Nuclear Waste Management Organization NWMO DGR-TR-2011-30 R000. 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 R000. Toronto, Canada.
- QUINTESSA. 2009a. AMBER 5.3 Examples, Users and References. Quintessa Ltd. Memorandum QE-AMBER-M1, Version 5.3. Henley-on-Thames, United Kingdom.
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- QUINTESSA. 2010c. Postclosure Safety Assessment Services for OPG's Proposed Deep Geologic Repository: Project Quality Plan. Quintessa Ltd. Document QRS-1335B-PQP v3.0. Henley-on-Thames, United Kingdom.
- QUINTESSA. 2011. Postclosure Safety Assessment: System and Its Evolution. Quintessa Ltd. report for the Nuclear Waste Management Organization NWMO DGR-TR-2011-28 R000. Toronto, Canada.
- QUINTESSA and SENES. 2011. Postclosure Safety Assessment: Analysis of Human Intrusion and Other Disruptive Scenarios. Quintessa Ltd. and SENES Consultants Ltd. report for the Nuclear Waste Management Organization NWMO DGR-TR-2011-27 R000. Toronto, Canada.
- QUINTESSA, SENES and GEOFIRMA. 2011. 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 R000. Toronto, Canada.

## **APPENDIX J: AMBER DATA**

### **J.1 INTRODUCTION**

The appendix presents data used in the AMBER models, where they are not directly available in the Data report (QUINTESSA and GEOFIRMA 2011) and includes:

- Compartment dimensions (Section J.2);
- Properties for modelled geosphere layers (Section J.3);
- Importing data from detailed codes (Section J.4);
- Stack heights for the wastes (Section J.5); and
- Other model parameters (Section J.6).

### **J.2 DIMENSIONS**

#### **J.2.1 DGR Compartments and Surrounding HDZ/EDZ**

The dimensions for the compartments representing the waste panels, access tunnels and their surrounding HDZ/EDZs are presented in Table J.1. Dimensions for the compartments representing the horizontal section of the concrete monolith and its surrounding HDZ/EDZs are presented in Table J.2. Dimensions for the compartments representing the vertical section of the concrete monolith (i.e., that extending into the shafts) and its surrounding EDZs are presented in Table J.3.

#### **J.2.2 Shallow Bedrock Groundwater Zone**

The model for the Shallow Bedrock Groundwater Zone extends from the repository footprint to a point of groundwater discharge into the shore region of the lake. The distance from the shaft to the groundwater well is taken to be 500 m and the distance from the shaft to the point of discharge to the shore is taken to be 1000 m (see Section 2).

The dimensions for the compartments representing the Shallow Bedrock Groundwater Zone are given in Table J.4. The shaft in the shallow system is represented with a single compartment with the radius of the outer EDZ.

### **J.3 COMPARTMENT PROPERTIES**

Some of the compartments in the AMBER model represent a combination of geosphere layers and/or damaged zone characteristics. The properties of these compartments are determined from those given in the Data report. Weighted arithmetic averages are used for all properties, apart from the vertical effective diffusion coefficients for which weighted harmonic average values are used. The properties are given in Table J.5 for intact host rock.

Properties for rock compartments in and around the DGR are given in Table J.6.

**Table J.1: Dimensions for Compartments Representing Waste Panels, Access Tunnels and Associated HDZ/EDZs**

Compartments	Length (m)	Width (m)	Height (m)	Volume (m <sup>3</sup> )
<b>Panels</b>				
Panel 1	108.9	250	17	L·W·H*
Access tunnel adjacent to Panel 1	446.6	5.4	17	L·W·H <sup>+</sup>
H/EDZ below panel 1 (A)	198.5	231.8	6	L·W·H
H/EDZ above/around panel 1 (A)	198.5	231.8	20	752305
H/EDZ below panel 1 (B)	397	231.8	6	L·W·H
H/EDZ above/around panel 1 (B)	397	231.8	20	1504610.1
Panel 2	140.4	250	17	L·W·H*
Access tunnel adjacent to Panel 2	542.1	5.9	17	L·W·H <sup>+</sup>
H/EDZ below panel 2 (A)	198.5	232.3	6	L·W·H
H/EDZ above/around panel 2 (A)	198.5	232.3	20	732119.3
H/EDZ below panel 2 (B)	481.3	232.3	6	L·W·H
H/EDZ above/around panel 2 (B)	481.3	232.3	20	1775158.9
<b>Access tunnels between panels and monolith</b>				
Tunnel from panel 1	89.9	5.4	17	L·W·H <sup>+</sup>
H/EDZ below tunnel from panel 1	89.9	22.4	6	L·W·H
H/EDZ above/around tunnel from panel 1	89.9	22.4	20	32022.4
Tunnel from panel 2	5.9	244.4	17	L·W·H <sup>+</sup>
H/EDZ below tunnel from panel 2	22.9	244.4	6	L·W·H
H/EDZ above/around tunnel from panel 2	22.9	244.4	20	87421.9

Notes: L·W·H indicates that the volume is calculated in the model by multiplying length by width by height;

\* includes the volume of waste and fallen rock; <sup>+</sup> includes the volume of fallen rock.

**Table J.2: Dimensions for Compartments Representing the Horizontal Section of the Concrete Monolith and Associated HDZ/EDZs**

<b>Horizontal Monolith</b>	<b>Length (m)</b>	<b>Width (m)</b>	<b>Height (m)</b>	<b>Area</b>	<b>Volume (m<sup>3</sup>)</b>
Horizontal monolith 1	2.2	11.8	7	L·W	L·W·H
Horizontal monolith 2	6.6	11.8	7	L·W	L·W·H
Horizontal monolith 3	19.8	11.8	7	L·W	L·W·H
Horizontal monolith 4	57.7	11.8	7	L·W	L·W·H
H/EDZ below horizontal monolith 1	2.2	18.8	6	L·W	L·W·H
H/EDZ below horizontal monolith 2	6.6	18.8	6	L·W	L·W·H
H/EDZ below horizontal monolith 3	19.8	18.8	6	L·W	L·W·H
H/EDZ below horizontal monolith 4	57.7	18.8	6	L·W	L·W·H
HDZ above/around horizontal monolith 1	2.2	12.8	9	L·W	71.7
HDZ above/around horizontal monolith 2	6.6	12.8	9	L·W	215.1
HDZ above/around horizontal monolith 3	19.8	12.8	9	L·W	645.5
HDZ above/around horizontal monolith 4	57.7	12.8	9	629.3	1662.4
EDZ above/around horizontal monolith 1	2.2	18.8	12	L·W	242.9
EDZ above/around horizontal monolith 2	6.6	18.8	12	L·W	728.7
EDZ above/around horizontal monolith 3	19.8	18.8	12	L·W	2185.9
EDZ above/around horizontal monolith 4	57.7	18.8	12	838.7	5850.5
Cobourg above horizontal monolith 1	2.2	18.8	8	L·W	L·W·H
Cobourg above horizontal monolith 2	6.6	18.8	8	L·W	L·W·H
Cobourg above horizontal monolith 3	19.8	18.8	8	L·W	L·W·H
Cobourg above horizontal monolith 4	40	18.8	8	655.9	5247.2

Notes: L·W·H indicates that the volume is calculated in the model by multiplying length by width by height.

**Table J.3: Dimensions for Compartments Representing the Vertical Section of the Concrete Monolith and Associated EDZs**

Vertical Monolith	Height (m)	Full Radius (m)	Thickness (m)	Area (m <sup>2</sup> )	Volume (m <sup>3</sup> )
Vertical monolith adjacent to HDZ	2	5.9	n/a	109.3	A·H
Vertical monolith adjacent to repository EDZ	3	5.9	n/a	109.3	A·H
Inner EDZ adjacent to repository EDZ	3	8.85	2.95	136.8	A·H
Vertical monolith adjacent to Cobourg	8	5.9	n/a	109.3	A·H
Inner EDZ adjacent to Cobourg	8	8.85	2.95	136.8	A·H
Outer EDZ adjacent to Cobourg	8	11.8	2.95	191.4	A·H

Notes: A·H indicates that the volume is calculated in the model by multiplying area by height.

**Table J.4: Dimensions for Compartments Representing the Shallow Bedrock Groundwater Zone**

Compartment	Length (m)	Width (m)	Area (m <sup>2</sup> )
Panel B	481.3	464.1	L·W
Panel A	198.5	464.1	L·W
Link	61.8	464.1	L·W
Middle Geosphere Up-gradient	74.5	149	10881.8
Middle Geosphere Down-gradient	74.5	149	10881.8
Outer Geosphere	149	315.1	L·W
Pathway 1	149	464.1	L·W
Pathway 2	79	464.1	L·W
Pathway 3	79	464.1	L·W
Pathway 4	79	464.1	L·W
Pathway 5	79	464.1	L·W
Pathway 6	150	464.1	L·W
Pathway 7	150	464.1	L·W
Pathway 8	160.5	464.1	L·W

Notes: L·W indicates area calculated by multiplying length by width.



**Table J.5: Properties for Compartments Representing the Host Rock**

Model Layer	Porosity (-)	Grain Density (kg/m <sup>3</sup> )	Dry Bulk Density (kg/m <sup>3</sup> )	Horizontal Effective Diffusion Coefficient (m <sup>2</sup> /s)		Vertical Effective Diffusion Coefficient (m <sup>2</sup> /s)	
				without Anion Exclusion	for Anions	without Anion Exclusion	for Anions
S1	0.067	2700	2520	1.9E-11	9.4E-12	2.1E-11	1.0E-11
I12	0.172	2700	2240	1.7E-12	8.6E-13	8.6E-13	4.3E-13
I11	0.128	2760	2410	1.6E-11	8.2E-12	8.2E-12	4.1E-12
I10	0.128	2760	2410	1.6E-11	8.2E-12	8.2E-12	4.1E-12
I9	0.16	2800	2350	2.9E-11	1.5E-11	1.2E-11	6.2E-12
I8	0.15	2850	2420	2.5E-11	1.2E-11	1.0E-12	5.2E-13
I7	0.07	2720	2530	9.8E-12	4.9E-12	9.8E-12	4.9E-12
I6	0.019	2720	2670	7.2E-13	3.6E-13	3.6E-13	1.8E-13
I5	0.019	2750	2700	5.9E-13	2.9E-13	1.7E-13	8.5E-14
I4	0.057	2810	2650	6.4E-12	3.2E-12	6.4E-12	3.2E-12
I3	0.02	2730	2680	6.0E-13	3.0E-13	3.0E-13	1.5E-13
I2	0.024	2730	2660	1.3E-11	6.5E-12	4.4E-13	2.2E-13
I1	0.085	2780	2540	8.3E-12	4.1E-12	5.6E-13	2.8E-13
D12	0.073	2770	2570	4.0E-12	2.0E-12	2.0E-12	1.0E-12
D11	0.071	2760	2560	3.0E-12	1.5E-12	1.5E-12	7.2E-13
D10	0.074	2760	2560	3.0E-12	1.5E-12	1.5E-12	7.3E-13
D9	0.063	2740	2570	2.9E-12	1.5E-12	1.4E-12	7.1E-13
D8	0.013	2700	2660	1.7E-12	8.7E-13	8.5E-13	4.2E-13
D7	0.015	2710	2670	1.5E-12	7.4E-13	7.4E-13	3.7E-13
D6	0.016	2720	2680	8.8E-13	4.4E-13	4.4E-13	2.2E-13

Model Layer	Porosity (-)	Grain Density (kg/m <sup>3</sup> )	Dry Bulk Density (kg/m <sup>3</sup> )	Horizontal Effective Diffusion Coefficient (m <sup>2</sup> /s)		Vertical Effective Diffusion Coefficient (m <sup>2</sup> /s)	
				without Anion Exclusion	for Anions	without Anion Exclusion	for Anions
D5	0.021	2700	2640	1.7E-12	8.4E-13	8.4E-13	4.2E-13
D4	0.009	2690	2670	1.1E-12	5.4E-13	5.4E-13	2.7E-13
D3	0.029	2730	2650	3.1E-12	1.6E-12	5.7E-13	2.8E-13
D2	0.071	2660	2470	1.5E-11	7.7E-12	1.5E-11	7.7E-12
D1	0.038	2590	2490	6.0E-13	3.0E-13	6.0E-13	3.0E-13

Table J.6: Properties for Rock Compartments around the DGR

Media	Porosity (-)	Grain Density (kg/m <sup>3</sup> )	Bulk Density (kg/m <sup>3</sup> )	Horizontal Effective Diffusion Coefficient (m <sup>2</sup> /s)		Vertical Effective Diffusion Coefficient (m <sup>2</sup> /s)	
				without Anion Exclusion	for Anions	without Anion Exclusion	for Anions
Collingwood	0.012	2690	2660	2.0E-12	9.8E-13	9.8E-13	4.9E-13
Cobourg	0.015	2710	2670	1.5E-12	7.4E-13	7.4E-13	3.7E-13
Repository HDZ (Cobourg)	0.06	2710	2550	5.9E-12	3.0E-12	5.9E-12	3.0E-12
Repository EDZ (Collingwood)	0.024	2690	2630	3.9E-12	2.0E-12	3.9E-12	2.0E-12
Repository EDZ (Cobourg)	0.03	2710	2630	3.0E-12	1.5E-12	3.0E-12	1.5E-12
H/EDZ below panels & open tunnels	0.033	2710	2620	3.2E-12	1.6E-12	3.2E-12	1.6E-12
H/EDZ below monolith	0.04	2710	2600	3.9E-12	2.0E-12	3.9E-12	2.0E-12
H/EDZ above panels & open tunnels	0.035	2710	2620	3.5E-12	1.7E-12	3.5E-12	1.7E-12
EDZ above panels & open tunnels	0.013	2700	2660	3.5E-12	1.7E-12	3.5E-12	1.7E-12

### J.3.1 Shaft and Repository Footprint

The area represented in the model in the Deep and Intermediate Bedrock Groundwater Zones reflects the repository footprint. The height of each model layer is given in Table H.1. The areas adopted for the radial components of the model (the shaft compartments, inner EDZ, outer EDZ and inner geosphere) are given in Table J.7. The dimensions for the compartments representing the rest of the model footprint in the deep and intermediate systems are given in Table J.8.

**Table J.7: Dimensions for Compartments Representing the Radial Components of the Model outside the Repository Layer**

Geosphere	Full radius (m)	Thickness (m)	Area (m <sup>2</sup> )
Shaft core	5.9	n/a	109.3
Shaft inner EDZ	8.85	2.95	136.8
Shaft outer EDZ	11.8	2.95	191.4
Inner geosphere	26.6	14.8	1785.4

**Table J.8: Dimensions for Compartments Representing the Radial Components of the Model outside the Repository Layer**

Geosphere	Length (m)	Width (m)	Area (m <sup>2</sup> )
Middle geosphere	149	149	19978.1
Outer geosphere	298	464.1	118323.7
Link geosphere	61.8	464.1	L·W
Panel A geosphere	198.5	464.1	L·W
Panel B geosphere	481.3	464.1	L·W

#### J.4 IMPORTING DATA FROM DETAILED CODES

Key potential pathways for contaminant migration from the DGR to the shallow system for the Normal Evolution Scenario include groundwater and gas flow via the shafts. The AMBER model draws directly on the results of detailed gas and groundwater modelling undertaken using T2GGM and FRAC3DVS-OPG:

- T2GGM represents gas generation, repository resaturation, groundwater and gas flow with a variety of different model discretisations (see Chapter 4 of GEOFIRMA and QUINTESSA 2011);
- FRAC3DVS-OPG represents groundwater flow within a model that encompasses the DGR, Deep and Intermediate Bedrock Groundwater Zones (see Chapter 4 of GEOFIRMA 2011).

Flow rates of free gas from the DGR to the shafts and upwards within the shafts are drawn from T2GGM, as described in Section J.4.3. Repository saturation, gas composition and partial pressures are also drawn from T2GGM, as described in Section J.4.4.

Groundwater flow rates via the monolith and shafts and their associated damaged zones in the AMBER model are drawn from FRAC3DVS-OPG<sup>69</sup> rather than T2GGM as explained below.

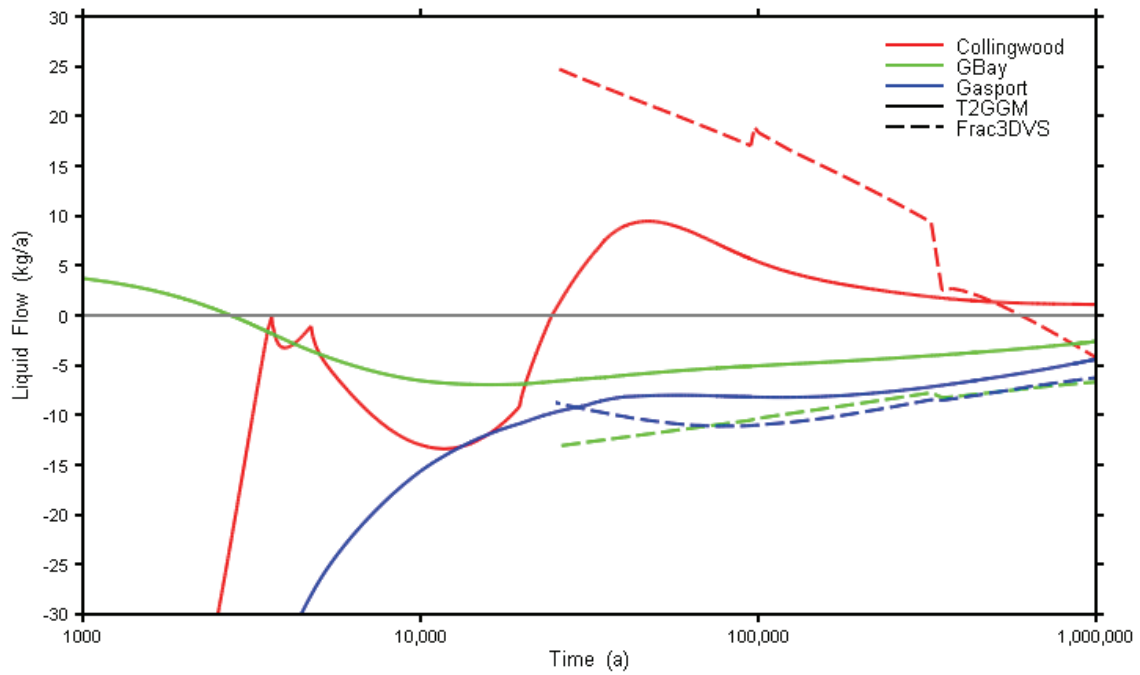
- The T2GGM models that encompass both the repository and the shafts do not extend to the Shallow Bedrock Groundwater Zone. However, the AMBER model needs a consistent set of groundwater flow rates that extend from the DGR to the shallow system. This full set of groundwater flows is available from FRAC3DVS-OPG models.
- FRAC3DVS-OPG and T2GGM calculate consistent groundwater head distributions (see Section 5.13.2 of GEOFIRMA and QUINTESSA, 2011) and the calculated groundwater flow rates in the shaft are broadly similar as a result. Calculated groundwater flow rates in the shaft are compared in Figures J.1 to J.3; the comparison shows that the calculated flow rates are generally within a factor of two or three for the central NE-RC and NE-SBC cases once T2GGM indicates that groundwater flow upwards within the shaft has commenced<sup>70</sup>, and that the FRAC3DVS-OPG results are generally conservative in comparison to T2GGM.
- The shaft groundwater flows are initially set to zero before flow upwards has commenced, even though T2GGM results may indicate downwards flow. Note in Figure J.1 that the downward flow continues at long times in the upper formations in the NE-RC case due to the Ordovician underpressure.

The use of groundwater flow rates calculated by FRAC3DVS-OPG is described in Section J.4.1.

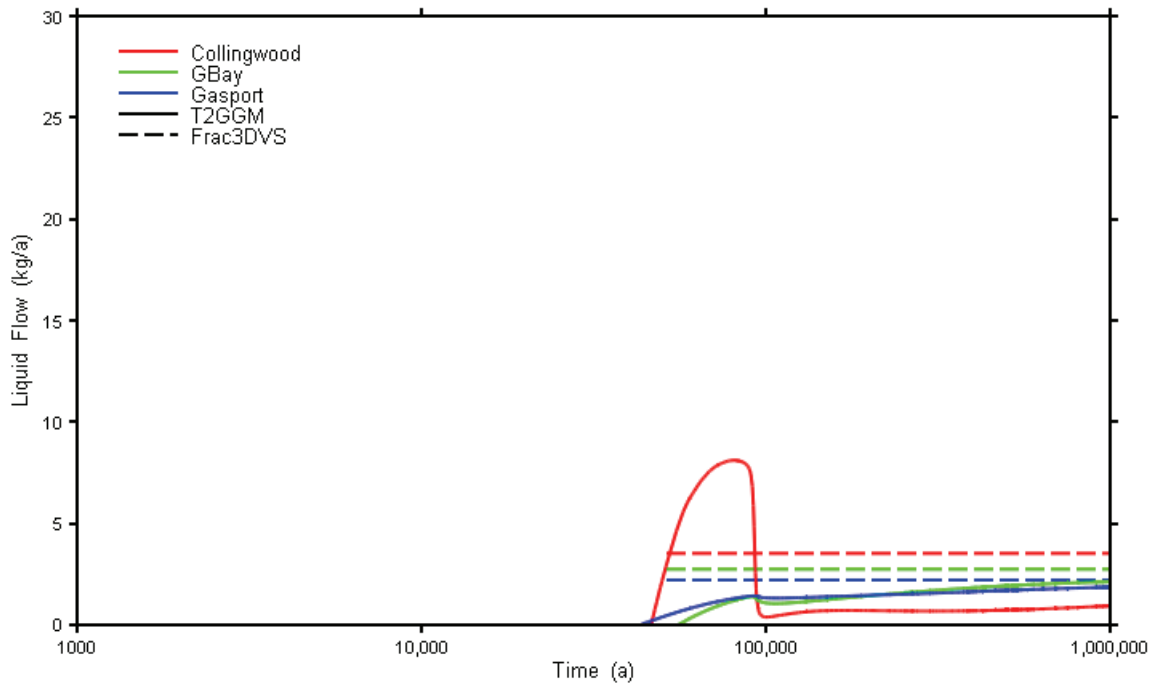
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<sup>69</sup> Note that transport in the rock mass in the Deep and Intermediate Bedrock Groundwater Zones is treated as diffusion only in the AMBER model.

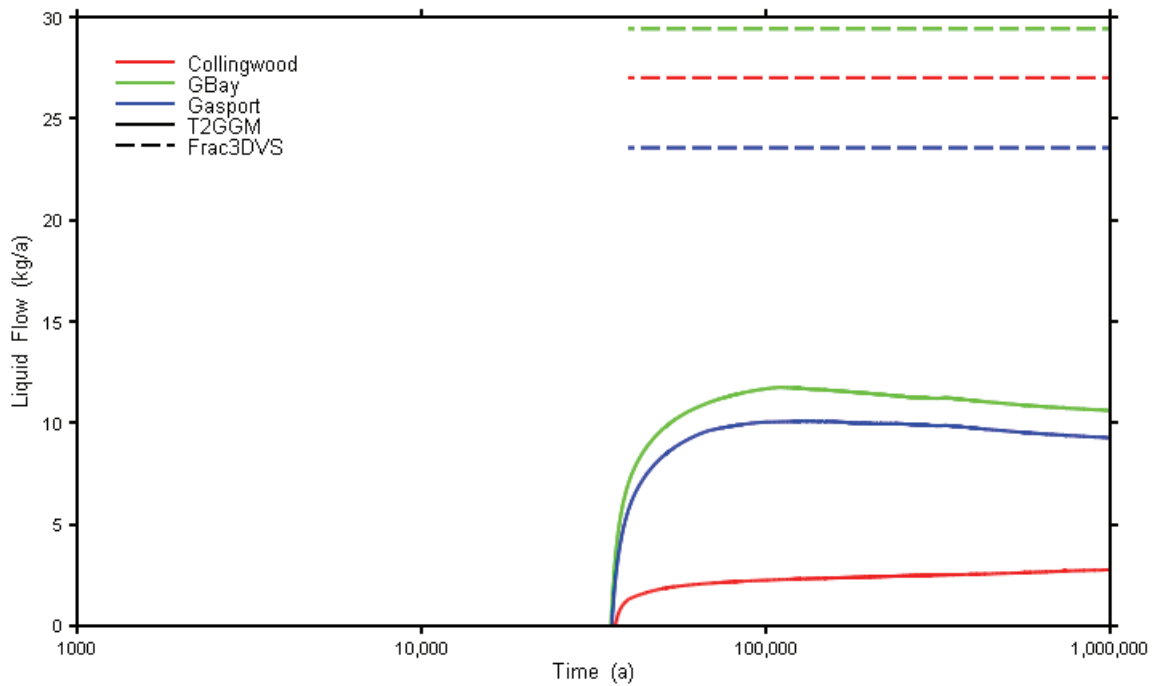
<sup>70</sup> The FRAC3DVS-OPG model represents a fully resaturated repository from the start of the calculations. FRAC3DVS-OPG groundwater flows are only used after T2GGM results showed that flow upward in shaft had commenced.



**Figure J.1: Total Groundwater Flow Rates Upwards (positive) and Downwards (negative) via the Shaft and its EDZs for the Reference Case (NE-RC NWL) Calculated by FRAC3DVS-OPG and T2GGM**



**Figure J.2: Total Groundwater Flow Rates Upwards via the Shaft and its EDZs for the Simplified Base Case (NE-SBC NWL) Calculated by FRAC3DVS-OPG and T2GGM**



**Figure J.3: Total Groundwater Flow Rates Upwards via the Shaft and Its EDZs for the NE-GT5 NWL Case Calculated by FRAC3DVS-OPG and T2GGM**

**J.4.1 Groundwater Flows from FRAC3DVS-OPG**

Volumetric groundwater flows ( $m^3/a$ ), generated by FRAC3DVS-OPG for each of the detailed groundwater calculation cases (both transient and steady-state), are stored in a series of Microsoft Excel spreadsheets. The spreadsheets are used as the basis for generating AMBER import files (.aaf).

Total volumetric horizontal groundwater flows towards the shaft across each of the specified zones around the monolith are provided, with the zones corresponding to the discretization in the AMBER model (see Figure J.4). Total volumetric groundwater flows vertically up the shaft and its EDZs are also provided, at a series of planes up the shaft (see Figure J.5), distinguishing between flow within the shaft inner EDZ and outer EDZ.

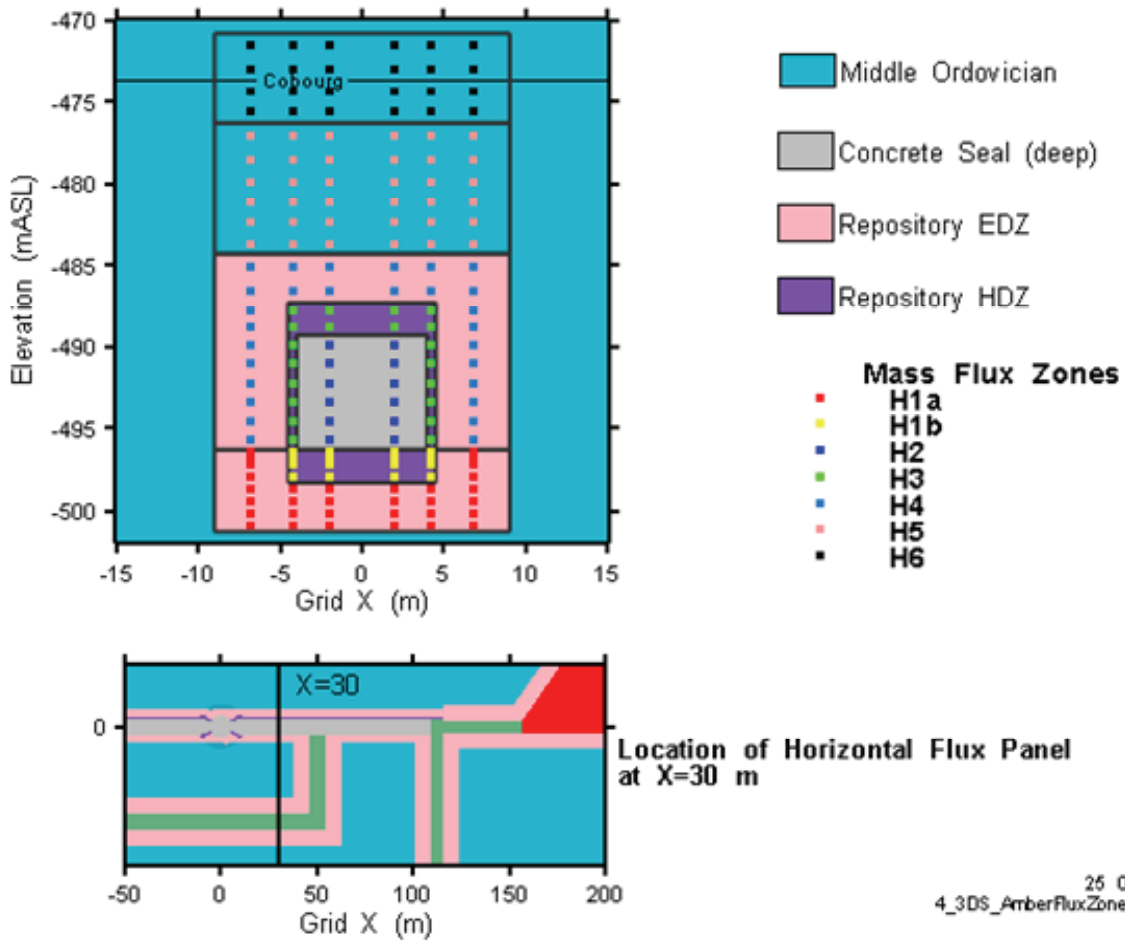


Figure J.4: Interfaces over which Horizontal Groundwater Flows are Provided from Detailed FRAC3DVS-OPG Calculations

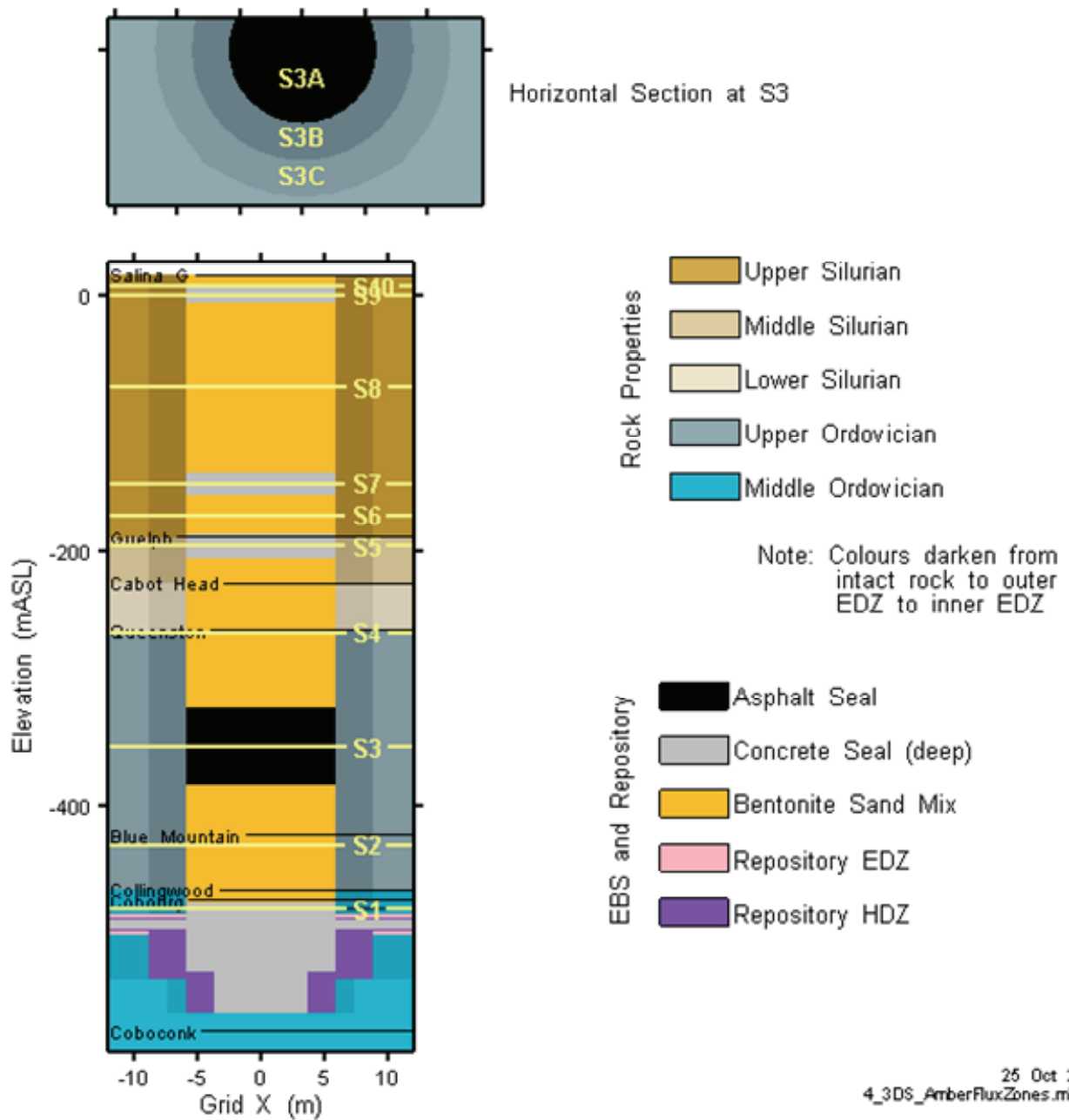


Figure J.5: Interfaces over which Vertical Groundwater Flows are Provided from Detailed FRAC3DVS-OPG Calculations



The FRAC3DVS-OPG calculation cases and the associated AMBER cases are given in Table J.9. FRAC3DVS-OPG calculations for transient cases are run to 1 million years, whereas the AMBER model runs to 10 million years. The groundwater flow rates at 1 million years are therefore used as the basis for defining the flow rates to the end of the calculation period for the transient cases (NE-RC-A and NE-PD-RC-A).

**Table J.9: FRAC3DVS-OPG Calculation Cases (3DS) for which Volumetric Groundwater Flows are Used in the AMBER Models**

<b>FRAC3DVS-OPG Calculation Case</b>	<b>AMBER Cases that use the Associated Groundwater Flows</b>
NE-RC (Transient)	NE-RC, NE-RC-WL, NE-RS, NE-RT1, NE-IV
NE-PD-RC (Transient)	NE-PD-RC
NE-SBC (Steady-State)	NE-SBC, NE-SBC-WL, NE-RT2, NE-BF, NE-GG1, NE-GG2, NE-NM
NE-EDZ1 (Steady-State)	NE-EDZ1
NE-HG (Steady-State)	NE-HG
NE-GT5 (Steady-State)	NE-GT5
NE-PD-GT5 (Steady-State)	NE-PD-GT5

The volumetric groundwater flows are stored in the FRAC\_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.

In addition to the volumetric groundwater flows, an average horizontal Darcy velocity of 1.3 m/a is provided from FRAC3DVS-OPG for the Bois Blanc and Bass Island formations, based on the 3DSU case, which is used for groundwater flow in the shallow system for all of the AMBER cases. Darcy velocities of 2.53E-3 m/a and 4.85E-2 m/a are provided by FRAC3DVS-OPG for the Guelph and Salina A1 upper carbonate formations for the NE-HG case.

#### **J.4.2 Initiation of Groundwater Flows, Based on T2GGM**

The times of initial groundwater flow away from the DGR, based on the T2GGM results, are shown in Table J.10, together with the AMBER cases for which the times are used. Prior to these times, no groundwater flow is modelled from the DGR or within the shaft in the Deep Bedrock Groundwater Zone. Note that for instant resaturation cases (NE-RS, NE-RT1 and NE-RT2) the time of initial groundwater flow away from the DGR is set to zero.

**Table J.10: Time of Initial Groundwater Flows**

<b>T2GGM Case</b>	<b>Time of Initial Groundwater Flow Away from the DGR (a)</b>	<b>Associated AMBER Cases</b>
NE-RC (NWL)	25,000	NE-RC, NE-IV
NE-PD-RC (NWL)	28,000	NE-PD-RC
NE-RC (WL)	55,000	NE-RC-WL
NE-SBC (NWL)	50,000	NE-SBC, NE-HG
NE-SBC (WL)	70,000	NE-SBC-WL
NE-GT5 (NWL)	40,000	NE-GT5
NE-PD-GT5 (NWL)	40,000	NE-PD-GT5
NE-EDZ1 (NWL)	50,000	NE-EDZ1
NE-GG1 (NWL)	125,000	NE-GG1
NE-GG2 (NWL)	400,000	NE-GG2
NE-NM (NWL)	22,000	NE-NM
NE-BF (NWL)	1,700	NE-BF

Notes: WL indicates water-limited case; NWL indicates non-water-limited case.

### **J.4.3 Free Gas Mass and Free Gas Flows from T2GGM**

Free gas masses (kg) and free gas flow rates (kg/a), generated by T2GGM for each of the detailed gas calculation cases, are stored in a series of Microsoft Excel spreadsheets. The spreadsheets are used as the basis for generating AMBER import files (.aaf). Note that any gaseous contaminants that dissolve in repository water and subsequently migrate in dissolved form from the DGR into the geosphere and/or shaft, are represented in the AMBER model as dissolved contaminants which are transported along with other dissolved contaminants within the groundwater.

Free gas masses are provided for the repository and for a series of regions in the shaft, which reflect the discretization of the shaft in the AMBER model. Free gas flow rates from the shaft regions are also provided. The shaft regions are illustrated in Figure J.6.

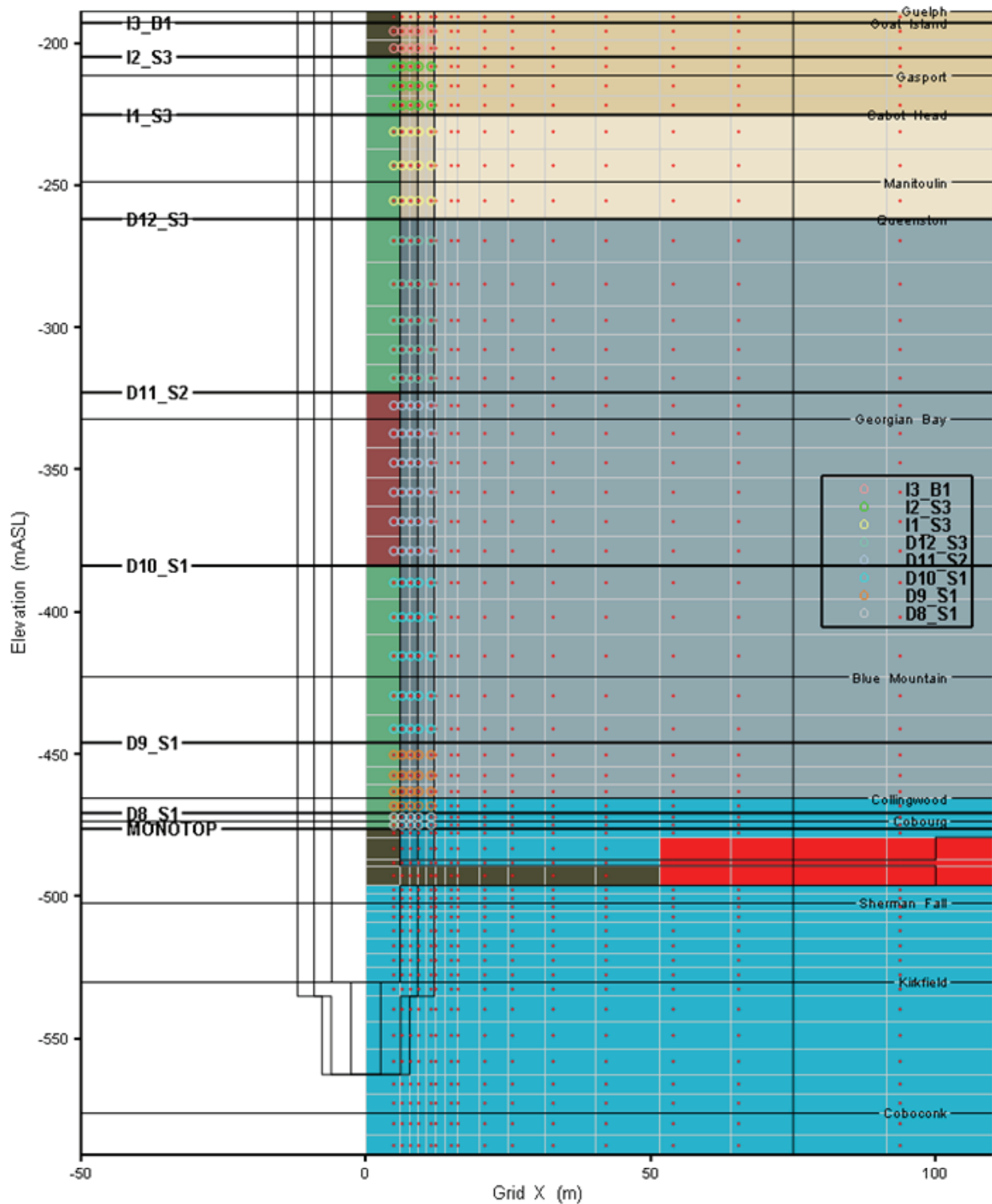


Figure J.6: Interfaces over which Total Free Gas Flows and Regions from which Total Free Gas Masses are Provided from Detailed T2GGM Calculations

While free gas flow in the shafts is apparent for the NE-GG1, NE-GT5, NE-NM and NE-BF cases<sup>71</sup>, the T2GGM modelling shows that this does not reach the Shallow Bedrock Groundwater Zone, as it is taken up by the more permeable formations in the Intermediate Bedrock Groundwater Zone. The AMBER models represent free gas flow via the shafts to the level of the Guelph formation for these cases, whereupon any contaminants in the gas enter the groundwater within the shaft. It is emphasised that this is a conservative representation, as the detailed gas modelling demonstrates that the free gas in the shaft is captured within the higher permeability Guelph formation. This conservatism is adopted due to uncertainty in the fraction of contaminants carried in free gas that might subsequently dissolve and migrate towards the Shallow Bedrock Groundwater Zone.

The AMBER models also include the option of undertaking additional 'what-if' calculations, whereby the free gas that reaches the level of the Guelph formation is permitted to travel directly to the Shallow Bedrock Groundwater Zone as free gas. Free gas flows to the shallow system can be 'switched-on' in the nearfield and geosphere and biosphere cases via the SWT\_ShaftGas parameter.

The free gas masses and free gas flow rates are stored in the T2\_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.

#### **J.4.4 Saturations, Partial Pressures, Gas Fractions and Siderite Fractions from T2GGM**

##### **J.4.4.1 AMBER Import Files based on T2GGM Outputs**

Repository water saturation, partial pressures and gas compositions are stored in output files generated by GGM for each T2GGM calculation. The data from GGM is copied into Microsoft Excel worksheets and converted into a format suitable for import into AMBER. Table J.10 provides the list of T2GGM cases and the associated AMBER models for which the data is used.

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 pressures; the data is presented in Table J.11 and Table J.12, respectively. The T2GGM outputs are extrapolated for cases that are not run to 10 million years, which is the duration of the AMBER calculations.

The saturations, partial 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.

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<sup>71</sup> The free gas flows reported in Table 8.2 of the Gas report (GEOFIRMA and QUINTESSA 2011) for the NE-RC-T2 case are formation gas and primarily represent gas moving into the shaft from Upper Ordovician formations and thence upwards; therefore, AMBER calculations for free gas flow from the repository to the shallow or surface systems are not relevant for this case.

**Table J.11: Fractional Repository Water Saturation Based on T2GGM (-)**

Time (a)	Calculation Case													
	NE-RC	NE-PD-RC	NE-RC-WL	NE-SBC	NE-SBC-WL	NE-EDZ1	NE-GG1	NE-GG2	NE-NM	NE-GT5	NE-PD-GT5	NE-BF		
0.1	1.81E-03	1.73E-03	1.80E-03	1.79E-03	1.77E-03	1.79E-03	1.20E-03	1.20E-03	1.79E-03	1.79E-03	1.79E-03	4.58E-03		
0.5	1.83E-03	1.74E-03	1.79E-03	1.79E-03	1.76E-03	1.79E-03	1.20E-03	1.20E-03	1.79E-03	1.79E-03	1.79E-03	4.59E-03		
10	1.96E-03	1.87E-03	1.90E-03	1.92E-03	1.89E-03	1.92E-03	1.35E-03	1.35E-03	1.92E-03	1.92E-03	1.91E-03	5.00E-03		
50	2.42E-03	2.30E-03	1.97E-03	2.42E-03	2.00E-03	2.43E-03	1.78E-03	1.88E-03	2.42E-03	2.33E-03	2.30E-03	6.66E-03		
100	2.79E-03	2.64E-03	1.87E-03	2.94E-03	2.06E-03	2.94E-03	2.10E-03	2.42E-03	2.94E-03	2.64E-03	2.61E-03	8.28E-03		
200	3.26E-03	3.08E-03	1.45E-03	3.80E-03	2.02E-03	3.80E-03	2.31E-03	3.30E-03	3.77E-03	2.84E-03	2.86E-03	1.08E-02		
500	4.22E-03	3.99E-03	1.18E-04	5.77E-03	1.39E-03	5.77E-03	2.33E-03	5.28E-03	5.64E-03	2.86E-03	2.89E-03	1.58E-02		
750	4.82E-03	4.57E-03	1.17E-04	7.08E-03	6.18E-04	7.08E-03	2.32E-03	6.53E-03	6.84E-03	2.85E-03	2.89E-03	1.81E-02		
1000	5.29E-03	5.04E-03	1.16E-04	8.19E-03	1.26E-04	8.19E-03	2.32E-03	7.55E-03	7.81E-03	2.85E-03	2.91E-03	1.93E-02		
1019	5.33E-03	5.07E-03	1.16E-04	8.27E-03	1.26E-04	8.27E-03	2.32E-03	7.63E-03	7.89E-03	2.85E-03	2.91E-03	1.94E-02		
1400	5.85E-03	5.60E-03	1.14E-04	9.68E-03	1.23E-04	9.68E-03	2.31E-03	8.86E-03	9.05E-03	2.85E-03	2.95E-03	1.97E-02		
1800	6.21E-03	5.99E-03	1.13E-04	1.09E-02	1.20E-04	1.09E-02	2.31E-03	9.82E-03	9.96E-03	2.84E-03	3.04E-03	1.94E-02		
2400	6.43E-03	6.29E-03	1.12E-04	1.22E-02	1.18E-04	1.22E-02	2.31E-03	1.07E-02	1.08E-02	2.84E-03	3.17E-03	1.86E-02		
3070	6.46E-03	6.35E-03	1.11E-04	1.32E-02	1.16E-04	1.32E-02	2.30E-03	1.12E-02	1.12E-02	2.83E-03	3.19E-03	1.73E-02		
4000	6.42E-03	6.32E-03	1.10E-04	1.38E-02	1.14E-04	1.38E-02	2.29E-03	1.13E-02	1.12E-02	2.82E-03	3.18E-03	1.49E-02		
5000	6.36E-03	6.28E-03	1.09E-04	1.45E-02	1.13E-04	1.46E-02	2.29E-03	1.12E-02	1.11E-02	2.81E-03	3.18E-03	1.25E-02		
10000	6.21E-03	6.20E-03	1.06E-04	1.96E-02	1.08E-04	2.23E-02	2.30E-03	1.16E-02	1.09E-02	2.80E-03	3.62E-03	5.69E-03		
18700	6.09E-03	6.20E-03	1.04E-04	2.85E-02	1.22E-03	3.51E-02	2.38E-03	1.19E-02	1.04E-02	2.97E-03	4.66E-03	1.67E-03		
25000	5.95E-03	6.14E-03	1.04E-04	3.31E-02	8.86E-03	4.10E-02	2.48E-03	1.18E-02	9.97E-03	3.14E-03	5.32E-03	5.84E-04		
46800	4.97E-03	5.43E-03	1.02E-04	3.77E-02	6.50E-03	4.66E-02	2.79E-03	1.08E-02	8.00E-03	3.69E-03	7.25E-03	4.56E-05		
50000	4.80E-03	5.30E-03	1.02E-04	3.77E-02	6.27E-03	4.65E-02	2.83E-03	1.07E-02	7.74E-03	3.76E-03	7.48E-03	2.59E-05		
75000	3.55E-03	4.26E-03	1.01E-04	3.70E-02	3.99E-03	4.45E-02	3.20E-03	1.08E-02	6.11E-03	4.36E-03	9.26E-03	4.66E-06		
100000	2.55E-03	3.34E-03	1.00E-04	3.65E-02	3.28E-03	4.19E-02	3.61E-03	1.38E-02	4.88E-03	4.97E-03	1.09E-02	4.07E-06		

Time (a)	Calculation Case													
	NE-RC	NE-PD-RC	NE-RC-WL	NE-SBC	NE-SBC-WL	NE-EDZ1	NE-GG1	NE-GG2	NE-NM	NE-GT5	NE-PD-GT5	NE-BF		
150000	1.26E-03	1.98E-03	1.01E-04	3.71E-02	2.96E-03	3.90E-02	4.44E-03	2.53E-02	3.40E-03	6.17E-03	1.37E-02	4.05E-06		
225000	4.13E-04	8.42E-04	9.99E-05	3.87E-02	3.92E-03	4.02E-02	5.66E-03	4.80E-02	2.32E-03	7.91E-03	1.74E-02	4.05E-06		
325000	8.23E-05	2.37E-04	1.99E-05	4.13E-02	6.21E-03	4.21E-02	7.22E-03	7.90E-02	1.43E-03	1.01E-02	2.16E-02	4.01E-06		
400000	2.55E-05	8.80E-05	4.28E-06	4.33E-02	8.12E-03	4.36E-02	8.34E-03	8.72E-02	7.81E-04	1.17E-02	2.44E-02	3.82E-06		
500000	7.79E-06	2.49E-05	4.36E-06	4.60E-02	1.07E-02	4.55E-02	9.80E-03	8.82E-02	3.44E-04	1.38E-02	2.78E-02	3.39E-06		
683000	4.14E-06	5.64E-06	4.34E-06	5.07E-02	1.55E-02	4.91E-02	1.23E-02	8.34E-02	1.79E-04	1.73E-02	3.35E-02	2.97E-06		
1000000	3.31E-06	3.82E-06	4.05E-06	5.83E-02	2.34E-02	5.49E-02	1.65E-02	7.37E-02	1.53E-04*	2.30E-02	4.22E-02	2.68E-06		
1500000	2.23E-06	2.98E-06	3.57E-06	6.88E-02	3.44E-02	6.41E-02*	2.23E-02	6.62E-02	1.53E-04*	3.18E-02*	5.56E-02*	2.67E-06*		
2000000	1.35E-06	2.25E-06	3.21E-06	7.77E-02	4.38E-02	7.33E-02*	2.76E-02	6.48E-02	1.53E-04*	4.06E-02*	6.91E-02*	2.67E-06*		
3000000	5.31E-08	1.12E-06	2.55E-06	9.14E-02	5.86E-02	9.17E-02*	3.71E-02	6.88E-02	1.53E-04*	5.83E-02*	9.60E-02*	2.67E-06*		
5000000	3.96E-09	7.45E-10*	8.80E-07	1.13E-01	8.08E-02	1.28E-01*	5.31E-02	8.11E-02	1.53E-04*	9.36E-02*	1.50E-01*	2.67E-06*		
10000000	3.96E-09	7.45E-10*	4.46E-10*	1.50E-01	1.18E-01	2.20E-01*	8.38E-02	1.07E-01	1.53E-04*	1.82E-01*	2.84E-01*	2.67E-06*		

Notes: Values are rounded to three significant figures for this report. \* indicates values extrapolated from T2GGM results.

**Table J.12: Partial Pressure of Combined CH<sub>4</sub> and CO<sub>2</sub> Based on T2GGM (Pa)**

Time (a)	Calculation Case													
	NE-RC	NE-PD-RC	NE-RC-WL	NE-SBC	NE-SBC-WL	NE-EDZ1	NE-GG1	NE-GG2	NE-NM	NE-GT5	NE-PD-GT5	NE-BF		
0	3.16E+01	3.16E+01	3.16E+01	3.16E+01	3.16E+01	3.16E+01	3.16E+01	3.16E+01	3.16E+01	3.16E+01	3.16E+01	3.16E+01		
0.1	2.10E+02	1.98E+02	2.10E+02	2.09E+02	2.09E+02	2.09E+02	1.25E+03	5.62E+01	2.08E+02	1.24E+03	1.17E+03	6.25E+02		
0.5	9.22E+02	8.61E+02	9.22E+02	9.18E+02	9.17E+02	9.19E+02	5.80E+03	1.55E+02	9.19E+02	5.81E+03	5.54E+03	2.99E+03		
10	1.48E+04	1.44E+04	1.81E+04	1.45E+04	1.75E+04	1.45E+04	7.04E+04	2.22E+03	1.19E+04	7.01E+04	6.52E+04	3.53E+04		
50	3.98E+04	3.69E+04	5.62E+04	3.78E+04	5.42E+04	3.79E+04	3.39E+05	4.20E+03	7.34E+02	3.39E+05	3.17E+05	1.24E+05		
100	7.94E+04	7.37E+04	1.12E+05	7.40E+04	1.05E+05	7.41E+04	6.44E+05	7.85E+03	2.02E-01	6.44E+05	6.01E+05	2.44E+05		
200	1.57E+05	1.46E+05	2.23E+05	1.45E+05	2.08E+05	1.45E+05	1.17E+06	1.51E+04	2.01E-01	1.17E+06	1.09E+06	4.79E+05		
500	3.76E+05	3.50E+05	5.01E+05	3.50E+05	4.97E+05	3.50E+05	2.29E+06	3.69E+04	2.00E-01	2.29E+06	2.13E+06	1.16E+06		
750	5.47E+05	5.09E+05	5.91E+05	5.12E+05	7.25E+05	5.12E+05	2.95E+06	5.50E+04	2.00E-01	2.94E+06	2.75E+06	1.69E+06		
1000	7.07E+05	6.58E+05	6.73E+05	6.65E+05	8.89E+05	6.66E+05	3.46E+06	7.30E+04	2.00E-01	3.45E+06	3.22E+06	2.19E+06		
1019	7.18E+05	6.69E+05	6.79E+05	6.77E+05	8.97E+05	6.77E+05	3.50E+06	7.44E+04	2.00E-01	3.49E+06	3.26E+06	2.23E+06		
1400	9.44E+05	8.80E+05	7.89E+05	8.95E+05	1.04E+06	8.96E+05	4.12E+06	1.02E+05	2.00E-01	4.10E+06	3.83E+06	2.94E+06		
1800	1.16E+06	1.08E+06	8.89E+05	1.11E+06	1.16E+06	1.11E+06	4.63E+06	1.30E+05	2.00E-01	4.61E+06	4.31E+06	3.62E+06		
2400	1.46E+06	1.36E+06	1.02E+06	1.40E+06	1.32E+06	1.40E+06	5.22E+06	1.72E+05	2.00E-01	5.20E+06	4.86E+06	4.53E+06		
3070	1.75E+06	1.63E+06	1.14E+06	1.69E+06	1.45E+06	1.69E+06	5.71E+06	2.19E+05	1.99E-01	5.67E+06	5.30E+06	5.39E+06		
4000	2.11E+06	1.96E+06	1.27E+06	2.04E+06	1.61E+06	2.05E+06	6.15E+06	2.82E+05	1.99E-01	6.11E+06	5.72E+06	6.43E+06		
5000	2.44E+06	2.28E+06	1.39E+06	2.38E+06	1.74E+06	2.39E+06	6.45E+06	3.50E+05	1.99E-01	6.40E+06	5.99E+06	7.46E+06		
10000	3.66E+06	3.41E+06	1.78E+06	3.58E+06	2.14E+06	3.60E+06	6.88E+06	6.66E+05	1.99E-01	6.77E+06	6.36E+06	1.10E+07		
18700	4.97E+06	4.64E+06	2.10E+06	4.86E+06	2.95E+06	4.93E+06	6.91E+06	1.15E+06	1.99E-01	6.77E+06	6.39E+06	1.42E+07		
25000	5.53E+06	5.16E+06	2.23E+06	5.42E+06	4.24E+06	5.50E+06	6.92E+06	1.44E+06	1.99E-01	6.75E+06	6.39E+06	1.51E+07		
46800	6.69E+06	6.25E+06	2.46E+06	6.51E+06	6.03E+06	6.61E+06	6.92E+06	2.27E+06	1.98E-01	6.74E+06	6.40E+06	1.54E+07		
50000	6.78E+06	6.34E+06	2.48E+06	6.59E+06	6.19E+06	6.70E+06	6.92E+06	2.37E+06	1.98E-01	6.74E+06	6.40E+06	1.52E+07		
75000	7.20E+06	6.73E+06	2.60E+06	6.92E+06	6.81E+06	7.02E+06	6.92E+06	3.03E+06	1.96E-01	6.74E+06	6.41E+06	1.41E+07		

Time (a)	Calculation Case												
	NE-RC	NE-PD-RC	NE-RC-WL	NE-SBC	NE-SBC-WL	NE-EDZ1	NE-GG1	NE-GG2	NE-NM	NE-GT5	NE-PD-GT5	NE-BF	
100000	7.36E+06	6.89E+06	2.68E+06	7.01E+06	6.98E+06	7.10E+06	6.92E+06	3.56E+06	1.95E-01	6.74E+06	6.42E+06	1.25E+07	
150000	7.50E+06	7.05E+06	2.80E+06	7.04E+06	7.04E+06	7.10E+06	6.91E+06	4.41E+06	1.94E-01	6.74E+06	6.43E+06	1.08E+07	
225000	7.64E+06	7.21E+06	2.94E+06	7.05E+06	7.04E+06	7.10E+06	6.91E+06	5.38E+06	1.92E-01	6.75E+06	6.45E+06	9.73E+06	
325000	7.77E+06	7.38E+06	3.10E+06	7.05E+06	7.04E+06	7.10E+06	6.90E+06	6.27E+06	1.91E-01	6.75E+06	6.47E+06	9.10E+06	
400000	7.84E+06	7.48E+06	3.20E+06	7.06E+06	7.05E+06	7.10E+06	6.89E+06	6.70E+06	1.89E-01	6.75E+06	6.48E+06	8.85E+06	
500000	7.91E+06	7.59E+06	3.33E+06	7.07E+06	7.06E+06	7.11E+06	6.89E+06	7.02E+06	1.88E-01	6.76E+06	6.50E+06	8.65E+06	
683000	7.99E+06	7.74E+06	3.53E+06	7.08E+06	7.07E+06	7.11E+06	6.88E+06	7.27E+06	1.86E-01	6.76E+06	6.52E+06	8.46E+06	
1000000	8.05E+06	7.89E+06	3.80E+06	7.11E+06	7.10E+06	7.12E+06	6.87E+06	7.37E+06	1.86E-01*	6.77E+06	6.55E+06	8.33E+06	
1500000	8.09E+06	8.00E+06	4.13E+06	7.14E+06	7.13E+06	7.12E+06*	6.87E+06*	7.37E+06*	1.86E-01*	6.77E+06*	6.55E+06*	8.33E+06*	
2000000	8.13E+06	8.07E+06	4.36E+06	7.17E+06	7.16E+06	7.12E+06*	6.87E+06*	7.37E+06*	1.86E-01*	6.77E+06*	6.55E+06*	8.33E+06*	
3000000	8.27E+06	8.24E+06	4.65E+06	7.21E+06	7.21E+06	7.12E+06*	6.87E+06*	7.37E+06*	1.86E-01*	6.77E+06*	6.55E+06*	8.33E+06*	
5000000	8.53E+06	8.52E+06	4.88E+06	7.25E+06	7.25E+06	7.12E+06*	6.87E+06*	7.37E+06*	1.86E-01*	6.77E+06*	6.55E+06*	8.33E+06*	
10000000	8.65E+06	8.65E+06	4.96E+06	7.28E+06	7.29E+06	7.12E+06*	6.87E+06*	7.37E+06*	1.86E-01*	6.77E+06*	6.55E+06*	8.33E+06*	

Note that the values are rounded to three significant figures for this report. \* indicates values extrapolated from T2GGM results.



For cases that are taken to be fully resaturated at closure, 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 water 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 NE-GG1, NE-GT5, NE-PD-GT5, NE-NM and NE-BF cases).

#### J.4.4.2 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 J.13.

**Table J.13: Final Fraction of Carbon in Siderite, Based on T2GGM**

<b>T2GGM Case</b>	<b>Siderite Fraction</b>	<b>Associated AMBER Cases</b>
NE-RC (NWL)	0.0138	NE-RC, NE-IV
NE-PD-RC (NWL)	0.0312	NE-PD-RC
NE-RC (WL)	0.0122	NE-RC-WL
NE-SBC (NWL)	0.0188	NE-SBC, NE-HG
NE-SBC (WL)	0.0422	NE-SBC-WL
NE-GT5 (NWL)	0.0098	NE-GT5
NE-PD-GT5 (NWL)	0.0093	NE-PD-GT5
NE-EDZ1 (NWL)	0.0183	NE-EDZ1
NE-GG1 (NWL)	0.0098	NE-GG1
NE-GG2 (NWL)	0.0015	NE-GG2
NE-NM (NWL)	0.0021	NE-NM
NE-BF (NWL)	0.0243	NE-BF

Note that these are rounded to four decimal places.

## J.5 WASTE STACK HEIGHTS

The majority of wastes will be disposed in carbon steel containers such as drums and boxes that are not anticipated to last for more than tens to a few hundred years post-closure. As the containers corrode, their contents will be available for release to water. Also, a stack of packages is anticipated to collapse as the containers corrode, and therefore wastes may be transferred from above the water level in the DGR to below the water level.

Table J.14 gives the impact of container collapse on the waste stack height. The degree of collapse is calculated assuming that the wastes also spread sideways, sufficient to fill the available space in the emplacement rooms and ignoring any rockfall. For these calculations a waste bulking factor of 1 is assumed. More complex behaviour comprising an initial volume increase followed by longer-term settlement and degradation is considered to be a secondary effect. Instant collapse on repository closure is assumed in the AMBER model. Waste packages are represented by their collapsed stack height. This maximizes their potential release to groundwater.

**Table J.14: Heights of the Collapsed Waste Stacks**

Waste Categories	Stack Height (Packages)	Stack Height (m)	Collapsed Height (m)	Collapsed Relative to Initial (%)	
LLW					
Bottom ash	4	5.6	5.16	92.1	
Baghouse ash	4	5.6	5.16	92.1	
Compacted wastes (bales)	5	6	4.79	79.9	
Compacted wastes (boxes)	4	5.2	4.45	85.6	
Non-processible (drums)	5	5.15	4.69	91.2	
Non-processible (boxes)	5	5.95	5.42	91.2	
Non-processible (other)	Small number of packages, assume as non-processible boxes				
LLW and ALW resins	3	5.04	4.36	86.5	
ALW sludges	5	5.15	4.69	91.2	
Steam generators	1	4.5	3.77	83.7	
ILW					
CANDECON, Moderator, PHT and Misc. Resins	1	4.25	3.34	78.5	
Filters and elements, Irradiated core components, IX columns	Concrete T-H-E arrays	5	6.5	Do not collapse	
	ILW shield containers	3	5.1	3.78	74.1
Retube Wastes (Pressure Tubes, Calandria Tubes and Calandria Tube Inserts)	2	4.5	3.38	75.0	
Retube Wastes (End Fittings)	2	3.84	3.48	90.5	

Notes: The degree of collapse is calculated assuming that the wastes spread sideways, sufficient to fill the available space in the emplacement rooms.

Some of the ILW wastes have very robust packaging, including thick concrete overpacks. These containers may remain structurally stable for tens of thousands of years, until either the concrete chemically degrades, or the containers are damaged by roof collapse. However, instantaneous collapse is conservatively assumed in the AMBER model.

For the final preliminary design, ILW filters and elements, irradiated core components, and IX columns are assumed to be placed in concrete containers called 'ILW shield containers', which are similar to those used for ILW resins. In the original preliminary design, the wastes are emplaced horizontally in large concrete arrays. The concrete arrays are not expected to collapse and water will not contact the waste until the water level has reached the level of the lowest T-H-E liners in the arrays, taken to be 0.7 m.

#### **J.6 OTHER MODEL PARAMETERS**

For rapid transfers, a rate of 5 /a is used, which is rapid relative to other model processes (e.g., repository resaturation).

#### **REFERENCES FOR APPENDIX J**

- 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 R000. 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 R000. Toronto, Canada.