DETAILED MODELLING FOR THE POSTCLOSURE SAFETY ASSESSMENT OF OPG'S DGR

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ABSTRACT

As part of the postclosure safety assessment undertaken for the proposed Deep Geologic Repository (DGR) for Low and Intermediate Level Waste (L&ILW) at the Bruce nuclear site, calculations were undertaken to evaluate the repository's potential postclosure impacts. Impacts were evaluated for a Normal Evolution Scenario, describing the expected long term evolution of the repository and site following closure, and for several Disruptive Scenarios, which consider events that could lead to possible penetration of barriers, abnormal degradation, and/or loss of containment.

The postclosure modelling was conducted using both detailed models with three-dimensional representation of the repository geometry, and with an overall (system) assessment-level model. The purpose of the detailed modelling described in this paper was to evaluate postclosure performance in terms of repository pressures, repository resaturation levels, mass flow rates of gas at various levels in the shaft, groundwater flow and radionuclide transport through the saturated geosphere and shaft seals, and capture rates of radionuclides by a hypothetical water supply well. The results of the detailed modelling were used to inform overall assessment-level (system) modelling that was performed using the compartmental modelling code AMBER and which is described in a companion paper.

Two separate detailed modelling studies were undertaken: 1) generation of gas in the repository, repository resaturation, and transport of gas through the geosphere and shaft sealing system was simulated using T2GGM, a modified version of the TOUGH2 gas transport code with coupled gas generation, and 2) transport of groundwater and radionuclides through the saturated geosphere and shaft seals was simulated with FRAC3DVS-OPG.

The gas generation model (GGM) incorporated within T2GGM was developed expressly for the L&ILW waste that will be present at the DGR. GGM calculates generation and consumption of oxygen, hydrogen, carbon dioxide, methane, hydrogen sulphide and nitrogen from degradation of the various organic and metallic waste streams.

Results from the Normal Evolution Scenario groundwater model show that radionuclide transport is diffusion dominated and very slow, with virtually no transport beyond the immediate vicinity of the repository. Results from gas modelling indicate that the repository will take hundreds of thousands of years to resaturate, and that there will be no gas flow within the shaft for the Reference Case and most Normal Evolution sensitivity cases. In the few cases where gas flow in the shaft does occur, it is restricted to lower portions of the shaft. No gas enters the shallow groundwater system. The gas modelling also indicates that in most cases, repository pressures will equilibrate near the expected steady-state in-situ pressure. In no cases do the gas pressures exceed the lithostatic pressure.

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 at the Bruce nuclear site in the Municipality of Kincardine, Ontario. An Environmental Impact Statement (EIS) [1] and a Preliminary Safety Report (PSR) [2] for the proposed repository were submitted to the Canadian Nuclear Safety Commission for the Joint Review Panel in April 2011.

Two of the supporting documents for the EIS and PSR are the detailed gas [3] and groundwater [4] modelling reports. These reports describe numeric modelling that was used to inform the assessment scale modelling described in the postclosure safety assessment reports [5,6]. The assessment modelling approach and results are further described in a companion paper [7] and will not be described further here.

This paper provides an overview of data sources (Section 2), the gas and groundwater modelling codes (Section 3), calculation cases (Section 4), discretization and property assignment (Section 5), the gas (Section 6) and groundwater (Section 7) modelling results, and the overall conclusions arising from the detailed modelling (Section 8).

2. DATA SOURCES AND REFERENCE CASE

Most of the data used in the modelling are specific to the DGR system and have been taken from the waste characterization, site characterization, and repository engineering programs. The overall DGR program has been structured such that the safety assessment has been produced in multiple iterations, with data freezes in synchronization with the inventory, design and geosciences programs.

Data was either obtained from published literature or referenceable documents, or was released for use within the DGR project using a data clearance process. In the latter case, approved data have been documented using a data clearance form that records the persons providing and approving the dataset, together with the purpose and nature of the dataset, its status/history, and any limitations/restrictions on its use/application.

Table 1 summarizes the reference values used for the key parameters. Further details on model parameters used in gas and groundwater modelling are provided in a Data report [8] or the associated modelling reports.

Site stratigraphy, environmental head and geosphere hydraulic conductivity profiles are presented in Figure 1. The figure also defines the bedrock groundwater zones that encompass the modelling domain.

Table 1. Reference values for key parameters

Parameter	Value(s)
Repository	
Repository depth	680 m
Average repository initial height	7 m
Panel footprint	2.4×10^5 m^2
Excavated volume	Excavated: 5.3×10^5 m^3; Void: 4.2×10^5 m^3.
Waste volume (as disposed)	Panel 1: 6.8×10^4 m^3 ; Panel 2, 1.3×10^5 m^3
Mass of organics	2.2×10^7 kg (waste, packages & engineering)
Mass of metals	6.6×10^7 kg (waste, packages & engineering)
Backfilling of rooms and tunnels	None except monolith in immediate vicinity of shafts
Monolith properties	K_h and K_v 1×10^{-10} m/s; porosity 0.1; effective diffusion coefficient 1.25×10^{-10} m^2/s (degraded from closure)
Repository HDZ	K_h 1×10^{-6} m/s, $K_v = K_h$; porosity 4 x rock mass
Repository EDZ	K_h 10^3 x rock mass, $K_v = K_h$; porosity 2 x rock mass
Rockfall	Rockfall affects all rooms and tunnels,10 m into ceiling immediately after closure
Anaerobic Corrosion rates	Carbon steel and galvanized steel: 1 μm/a (unsaturated), 2 μm/a (saturated), Passivated carbon steel, stainless steel and Ni-alloys: 0.1 μm/a Zr-alloys: 0.01 μm/a
Anaerobic Degradation rates	Cellulose: 5×10^{-4} /a, Ion exchange resins, plastics and rubber: 5×10^{-5} /a
Shaft	
Internal diameter (lower section)	Main: 9.15 m; Ventilation: 7.45 m; Combined: 11.8 m (concrete lining and HDZ removed)
Length (lower section)	483.5 m (top of monolith to top of bulkhead at top of intermediate groundwater zone)
Backfill and seals	Sequence of bentonite-sand, asphalt, LHHPC and engineered fill. LHHPC bulkheads (degraded from closure) keyed across the inner EDZ
Vertical and horizontal hydraulic conductivity	Bentonite-sand: 1×10^{-11} m/s; Asphalt: 1×10^{-12} m/s; LHHPC: 1×10^{-10} m/s; Engineered fill: 1×10^{-4} m/s
Diffusion and transport porosity	Bentonite-sand: 0.3; Asphalt: 0.02; LHHPC: 0.1; Engineered fill: 0.3
Effective diffusion coefficient	Bentonite-sand: 3×10^{-10} m^2/s; Asphalt: 1×10^{-13} m^2/s; LHHPC: 1.25×10^{-10} m^2/s; Engineered fill: 2.5×10^{-10} m^2/s
EDZ	Inner EDZ, 0.5 x shaft radius thick, K_v x 100 rock mass, $K_h = K_v$; porosity 2 x rock mass Outer EDZ, 0.5 x shaft radius thick, K_v x 10 rock mass, $K_h = K_v$; porosity = rock mass
Geosphere	
Host rock type	Low permeability argillaceous limestone (Cobourg Formation)
Temperature at repository depth	22 °C
Hydraulic heads	+165 m at top of the Cambrian sandstone Observed variable head profile with underpressures in the Ordovician (up to -290 m) 0 m at the top of the Lucas Formation (top of the shallow groundwater zone)
Deep groundwater zone:	
horizontal hydraulic conductivity	8×10^{-15} to 4×10^{-12} m/s for most formations; 1×10^{-9} in the Shadow Lake Formation and 3.0×10^{-6} in the Cambrian sandstone
vertical hydraulic conductivity	10% of horizontal hydraulic conductivity for most formations 0.1% in Coboconk and Gull River formations, isotropic in Cambrian
transport porosity	0.009 to 0.097
effective diffusion coefficient	2.2×10^{-13} to 2.4×10^{-11} m^2/s (some anisotropy)
horizontal hydraulic gradient	0
Intermediate groundwater zone:	
horizontal hydraulic conductivity	5×10^{-14} to 2×10^{-7} m/s
vertical hydraulic conductivity	10% of horizontal hydraulic conductivity for most formations; isotropic in Guelph Formation and Salina A1 Unit upper carbonate
transport porosity	0.007 to 0.2
effective diffusion coefficient	3×10^{-14} to 6.4×10^{-11} m^2/s (some anisotropy)
horizontal hydraulic gradient	0
Shallow groundwater zone:	
horizontal hydraulic conductivity	1×10^{-7} to 1×10^{-4} m/s
vertical hydraulic conductivity	10% of horizontal hydraulic conductivity for all formations
transport porosity	0.057 to 0.077
effective diffusion coefficient	6×10^{-12} to 2.6×10^{-11} m^2/s
horizontal hydraulic gradient	0.003
Abbreviations used in the table:	K_v: vertical hydraulic conductivity K_h: horizontal hydraulic conductivity LHHPC: Low Heat High Performance Cement

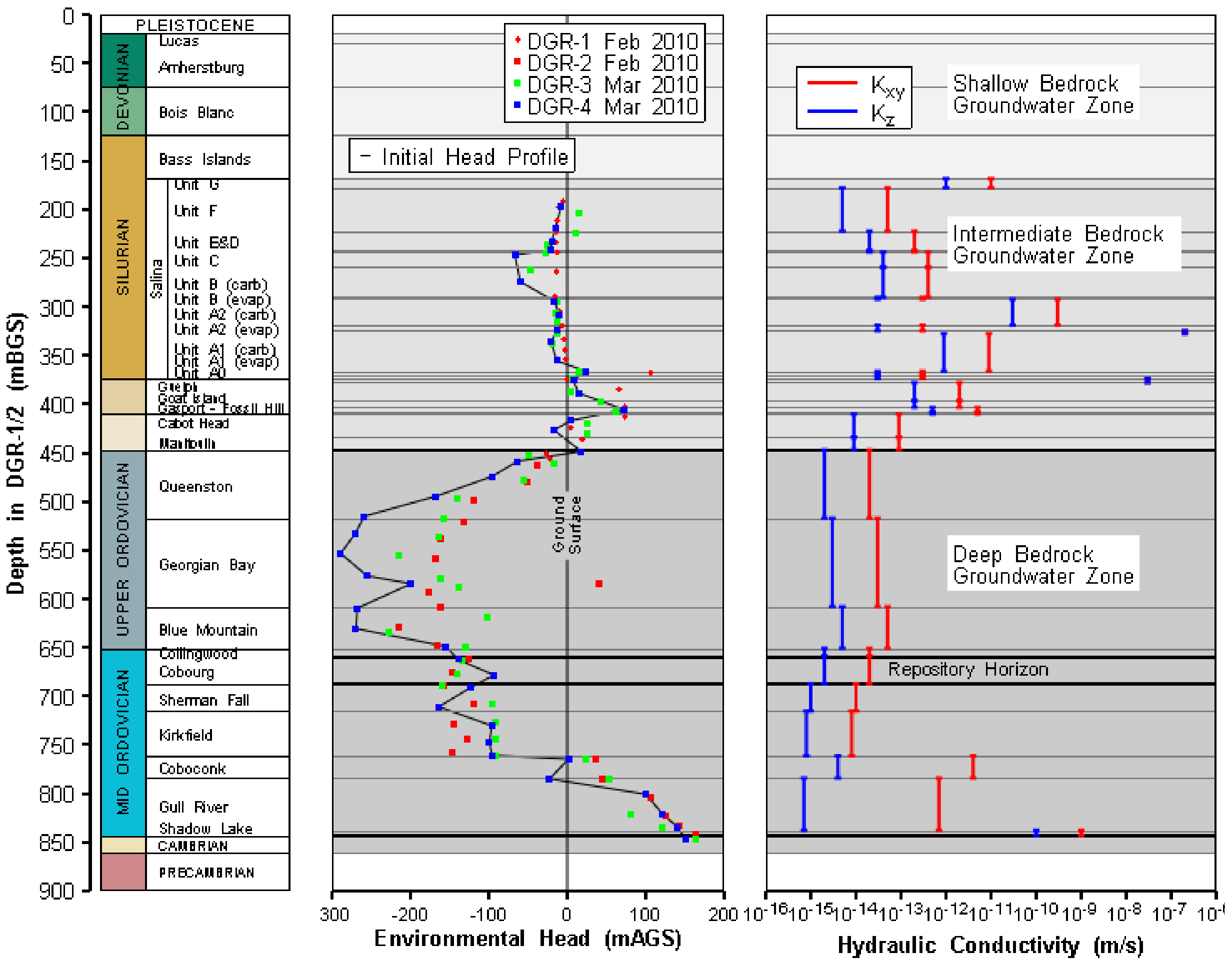

Figure 1. Site reference stratigraphy and geosphere hydraulic properties

Capillary pressure and relative permeability data are important parameters for gas modelling as they control the transport of gas within the geosphere and seal system. Within the T2GGM code, the parameters are represented as functions of liquid saturation using the modified van Genuchten equations [9] as presented in the iTOUGH2 reference manual [10]. The equations, referred to in this paper as the "van Genuchten curves" are characterized by three parameters: λ, m, and n. λ^{-1} is analogous to air-entry pressure, while m and n control the shape of the curves. Van Genuchten parameters for the seal system were derived from external sources and are described in [8]. For the geosphere, van Genuchten parameters were fitted to petrophysical analyses of DGR rock core samples as part of the site characterization program [11, 12]. For most of the calculation cases, a single set of parameters was used for the lower-permeability Silurian and Ordovician rocks (Figures 2 and 3). Sensitivity cases evaluated the impact of changes to the parameters. Within the excavation damaged zones (EDZ), the magnitude of the air entry pressure (λ^{-1}) was reduced to reflect increased permeability in these zones.

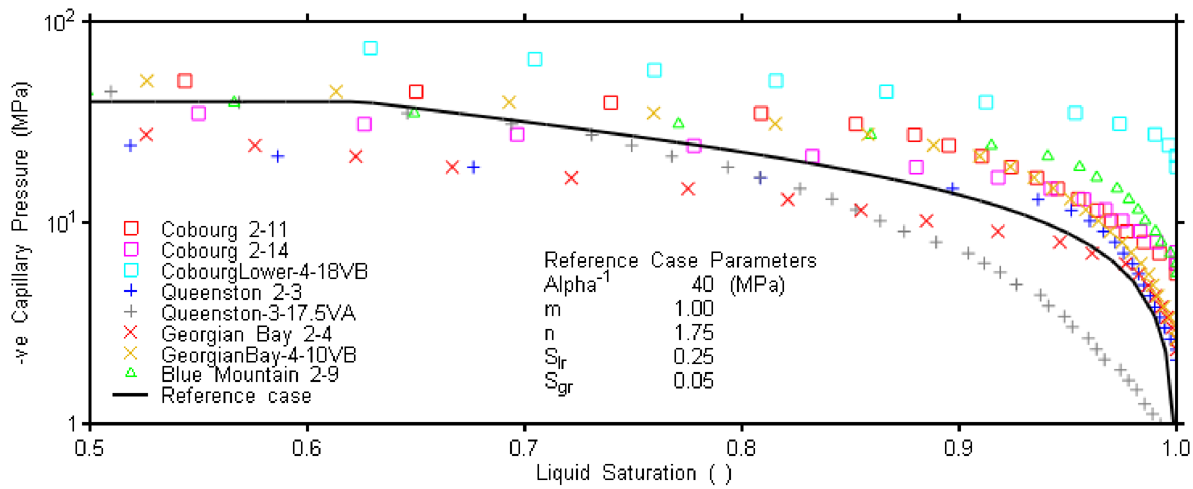

Figure 2. Low-permeability Silurian and Ordovician reference capillary pressure function

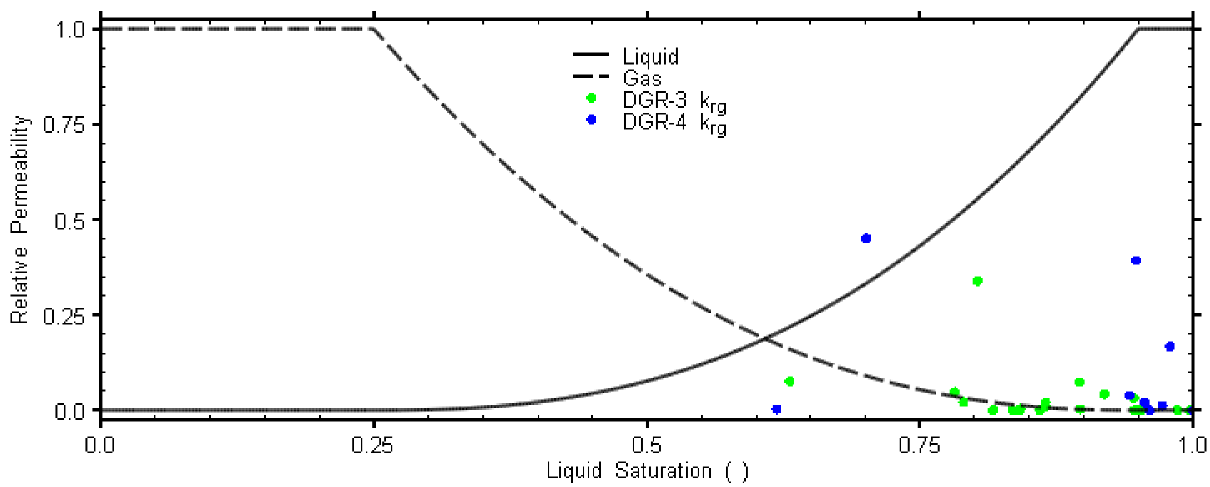

Figure 3. Low-permeability Silurian and Ordovician reference relative permeability function

3. DETAILED MODELLING CODES

3.1 Gas Generation & Transport Model – T2GGM

Gas generation within the repository is one of the key factors in the postclosure safety of the proposed facility. Gas is generated and consumed within the repository by various microbial and corrosion processes. The repository interacts with the geosphere through the flow of gas and water into and out of the repository. Following closure, the build-up of gas within the sealed repository affects the water resaturation time and could lead to the release of gaseous radionuclides through either the sealing system or the geosphere.

Since gas generation requires water under anaerobic conditions, a coupled model of gas generation and transport was developed and implemented in a code designated T2GGM [13]. The code comprises a component which models gas generation within the DGR due to corrosion and microbial degradation of the waste packages, and a component which models the two-phase transport of the gas through the repository and into the DGR shafts and geosphere (Figure 4) as well as water from the shafts and geosphere into the repository.

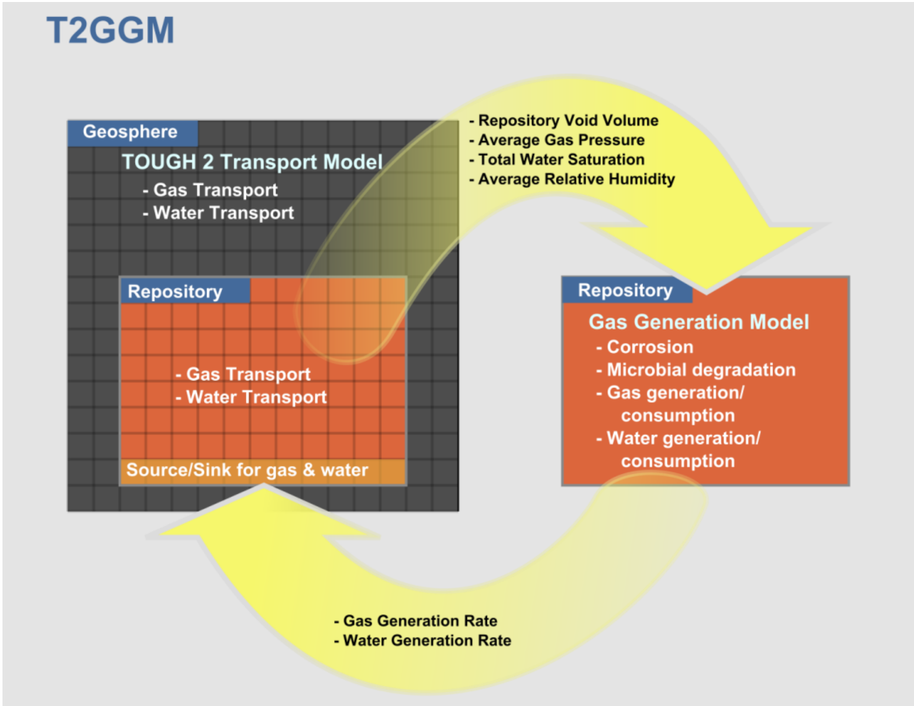

Figure 4. Coupling gas generation and transport in T2GGM

The Gas Generation Model (GGM) calculates the rates of generation/consumption of gas and water due to the various corrosion, degradation and microbial processes acting on the waste, and the composition of the gas within the repository. It ensures mass balance of water, carbon (C) and iron (Fe). Other elements are conservatively assumed not to be limiting and are not tracked for mass balance (e.g., N needed to support microbial reactions). GGM is integrated with the widely used two-phase flow code TOUGH2 [14]. TOUGH2 is used with the EOS3 equations of state (water and air) and has been modified to use gases other than air (CH_4, CO_2, H_2, air). Methane was used for most calculation cases presented in this paper.

3.2 Groundwater Flow and Transport Code – FRAC3DVS_OPG

The groundwater flow and transport modelling is used to provide estimates of groundwater flow rates in the shaft and geosphere, to estimate concentration and mass flow rates of radionuclides at various points in the intermediate and deep bedrock systems, and to estimate capture of radionuclides by a water supply well located in the shallow groundwater system.

All detailed groundwater modelling was performed using FRAC3DVS OPG (Version 1.3.0) [15]. FRAC3DVS-OPG is a successor code to FRAC3DVS [16], a three-dimensional numeric model describing subsurface flow and solute transport. It has been used extensively by NWMO for previous flow and transport simulations relating to deep geologic repositories.

4. CALCULATION CASES

Detailed modelling was performed for a number of parameter and conceptual model sensitivity cases, over a 1 Ma time frame starting at repository closure. All cases were derived from a

Reference Case characterization of the system that assumes a constant present day climate, with no change in boundary conditions during the 1 Ma assessment period. Cases encompassed both variations on the Normal Evolution (NE) scenario and several Disruptive Scenarios (DS). Figures 5 and 6 illustrate the naming, derivation, and purpose of each case for gas and groundwater modelling respectively.

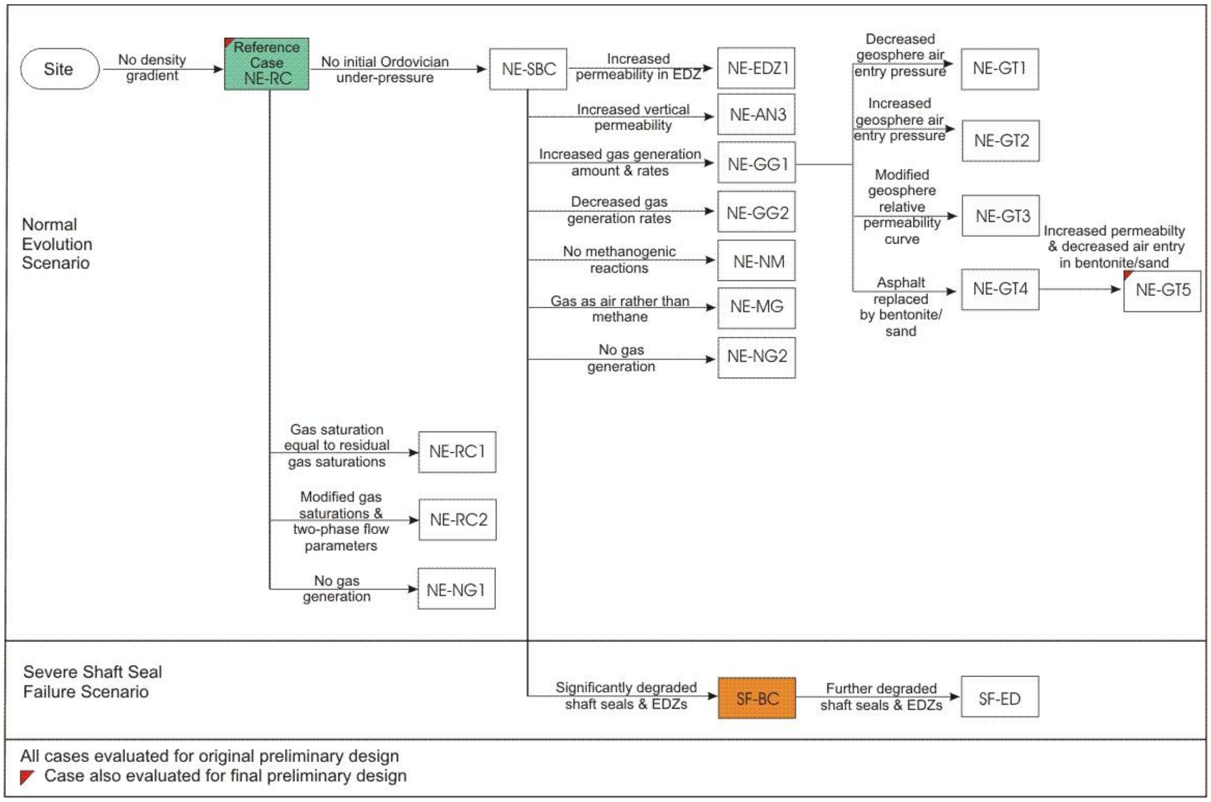

Figure 5. Calculation cases for detailed gas modelling

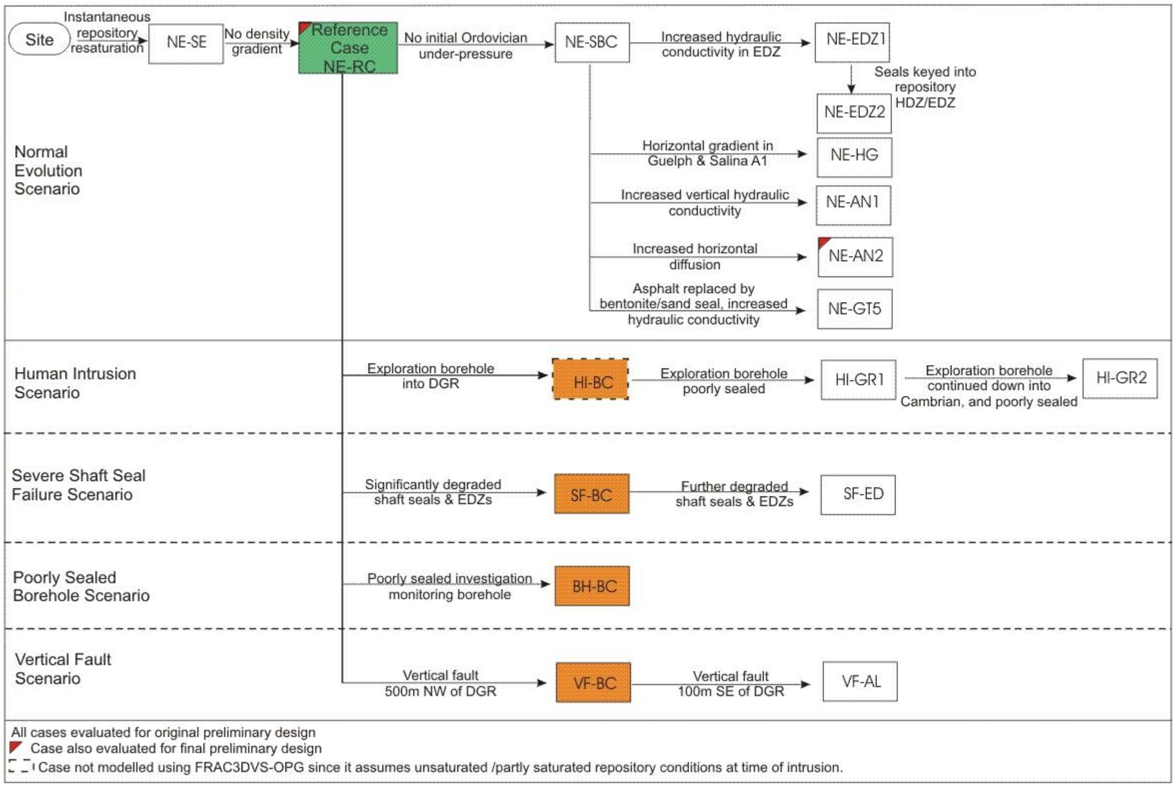

Figure 6. Calculation cases for detailed groundwater modelling

5. DISCRETIZATION AND PROPERTY ASSIGNMENT

5.1 Gas Modelling

In general, two-phase flow modelling is computationally demanding. Detailed modelling was performed using a number of model domains, with model scale and dimensionality optimized to reflect the performance requirements and numeric constraints associated with individual calculation cases.

The primary model was designated the three Dimensional Detailed (3DD) model. It included a representation of the repository panels, access tunnels and shaft system. The planned repository will have two shafts (main and ventilation) that are located in close proximity. For modelling purposes, these were combined to form a single shaft with the effective cross-sectional area equivalent to that of the two designed shafts. Access tunnel layout was also simplified and individual emplacement rooms in each panel combined. The resulting model grid consisted of 126,000 nodes and 390,000 connections. Figure 7 is an illustration of the 3DD model discretization.

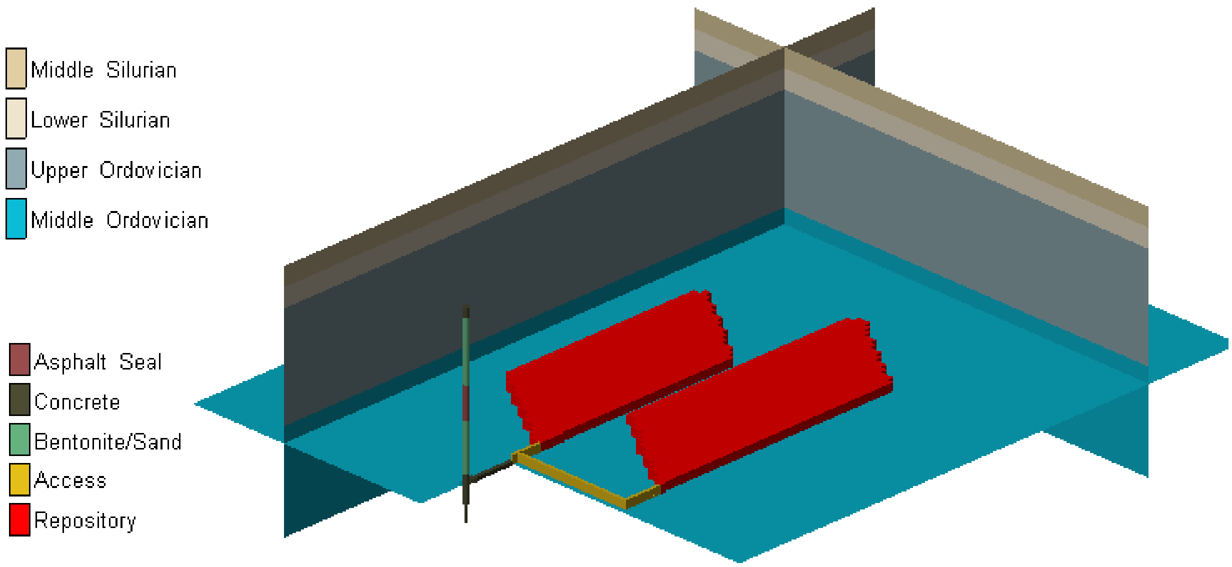

Figure 7. 3DD Gas Model Discretization

A simplified 3D model, called the Three-Dimensional Simplified Repository and Shaft (3DSRS) model was used for a number of cases. Consisting of 10,000 nodes and 29,000 connections, it represented a quarter-section model of the shaft and combined repository panels. The vertical domain of the 3D model was restricted to the formations from the Shadow Lake to the Guelph, inclusive. For those few calculation cases that indicated gas flow up the shaft, a two-dimensional model (2 Dimensional Radial Simplified, or 2DRS) was used to simulate shaft flows only. It extended from the Cobourg to the top of the Salina G formation and was used to calculate potential gas flow rates from the shaft into the Shallow Bedrock Groundwater Zone.

5.2 Groundwater Modelling

There are two groundwater models: 1) a three-dimensional model similar to the 3DD gas model; and, 2) a three-dimensional model of the shallow bedrock groundwater system.

The primary 3DD groundwater model is discretized at a higher level of detail than the 3DD gas model, and has increased vertical extents, including the entire intermediate and deep groundwater system (Figure 8).

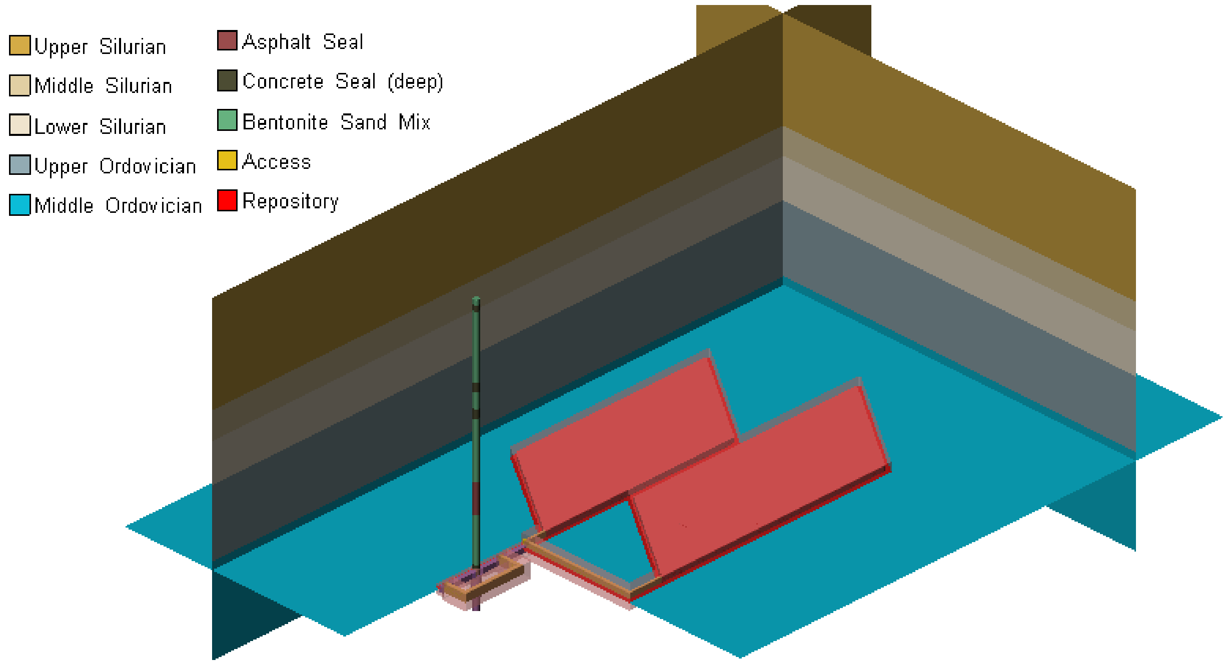

Figure 8. 3DD Groundwater Model Discretization

The shallow bedrock groundwater model (3 Dimensional Simple Upper or 3DSU) is limited to the Shallow Bedrock Groundwater Zone only and was used to calculate the capture fraction of a hypothetical water supply well. The water supply well was located down gradient of the shaft (the source location), and at a depth consistent with current regional well usage. Figure 9 is a schematic representation of the model.

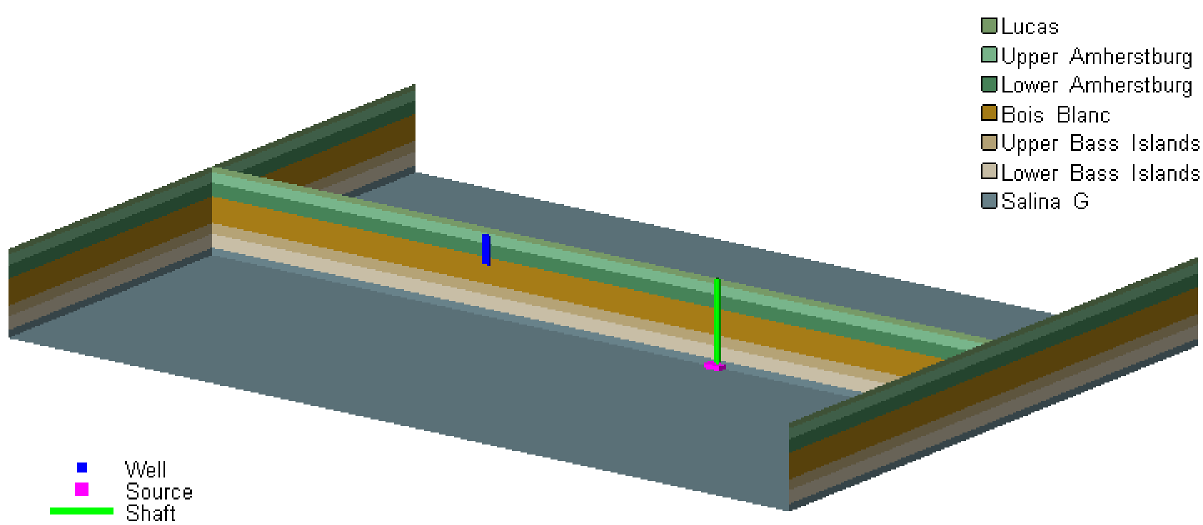

Figure 9. 3DSU Groundwater Model Discretization

6. GAS MODELLING RESULTS

This section presents results for selected normal evolution cases and for a single shaft failure case. Results are described in terms of repository pressures and saturations and flow rates of gas through the shaft seal systems in those cases where such flow occurs. Although both dissolved gas and free-phase gas flow rates are calculated by T2GGM, only the latter are presented in this paper. Concentrations of dissolved gas were extremely low in all cases.

6.1 Reference Case (NE-RC)

The NE-RC case assumes 10% gas saturations within an underpressured Ordovician geosphere, consistent with site characterization results. The initial head profile presented in Figure 1 was used to calculate the initial pressure distribution in the model. The operational phase of the facility was simulated as a 60 year period when shaft and repository pressures were set to atmospheric and gas saturations were set to 100%. At closure, the monolith (emplaced concrete seal within access tunnels and the bottom part of the shafts) and shaft seals are assumed to be placed instantaneously at specified gas saturations.

From this point forward, gas forming from degradation and corrosion reactions starts to pressurize the repository. The first few years involve sustained gas and water consumption due to aerobic degradation. There is a sharp peak in the rate of gas consumption (primarily hydrogen) and water production during the ferric iron and sulphate reduction stages due to hydrogen oxidation.

The longest sustained period of gas generation occurs during the methanogenic stage up to 4000 years. Gas generation here is primarily due to the production of hydrogen through the corrosion of the carbon and galvanized steels. Methane generation via the microbial metabolism of carbon dioxide and hydrogen and the exhaustion of the metallic wastes causes a decline in the amount of hydrogen present after this time. The NE-RC case parameters maximize microbial activity and gas generation by assuming that microbes are active if there are organics and water present, regardless of salinity or other factors, and that essentially complete degradation occurs.

Gas generation and water consumption rates then both continue to decline as the waste packages become fully degraded. Figure 10 shows predicted gas and water generation rates, while Figure 11 presents gas composition within the repository.

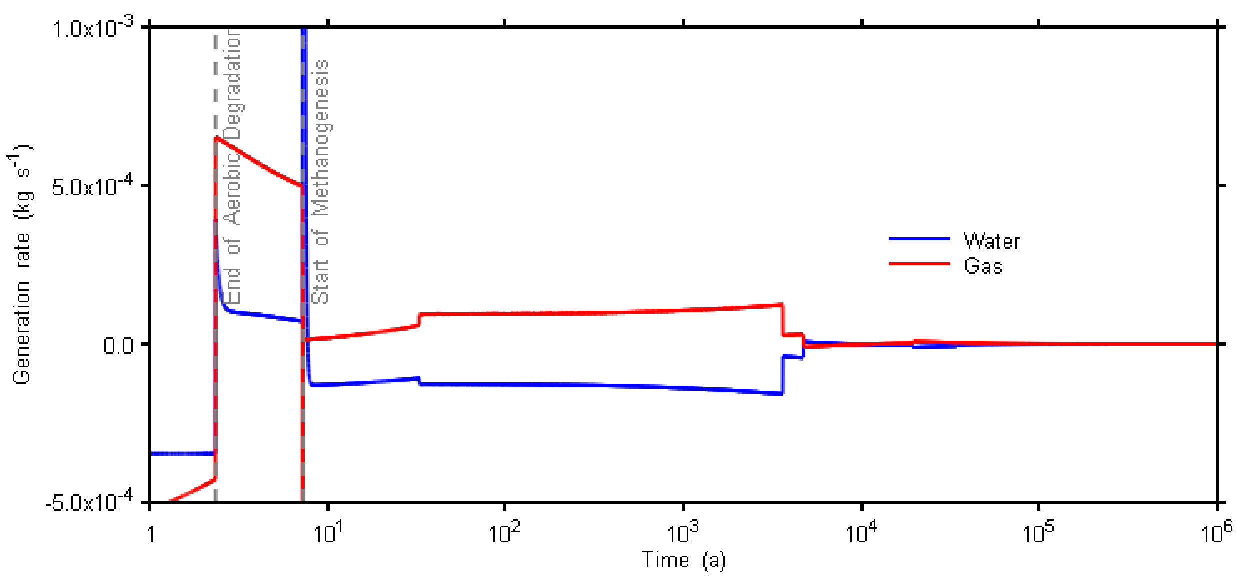

Figure 10. Reference case gas generation and water consumption rates in repository

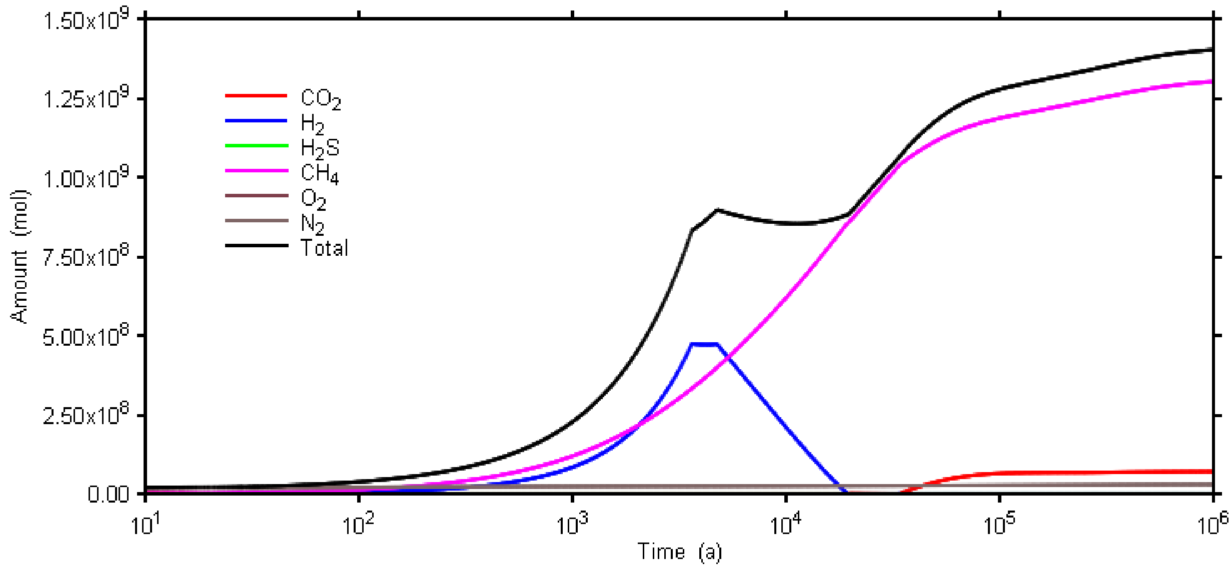

Figure 11. Amounts of Gas in the Vapour Phase within the Repository (Reference Case)

Pressures rise in the repository as gas is generated. The low permeability of the seal system prevents pressurized gas from traveling up the shaft. The reference case assumes that gas is present in the geosphere, albeit in small amounts due to the low gas saturations (10%) and low porosities of the rock mass. In addition to gas generated within the repository by degradation/corrosion, formation gas flows into the repository and contributes to the increase in pressure. Small amounts of formation liquid enter the repository during the period up to approximately 80 ka when pressure in the repository is lower than the liquid pressure in the surrounding geosphere. Subsequently, this water is expelled as pressures in the repository continue to increase. The evolution of repository pressure and saturation is shown in Figure 12. The repository saturation (the fraction of the repository volume that is filled with liquid) peaks at less than 0.01 or 1%. At the end of the 1 Ma simulation period, the repository is essentially dry.

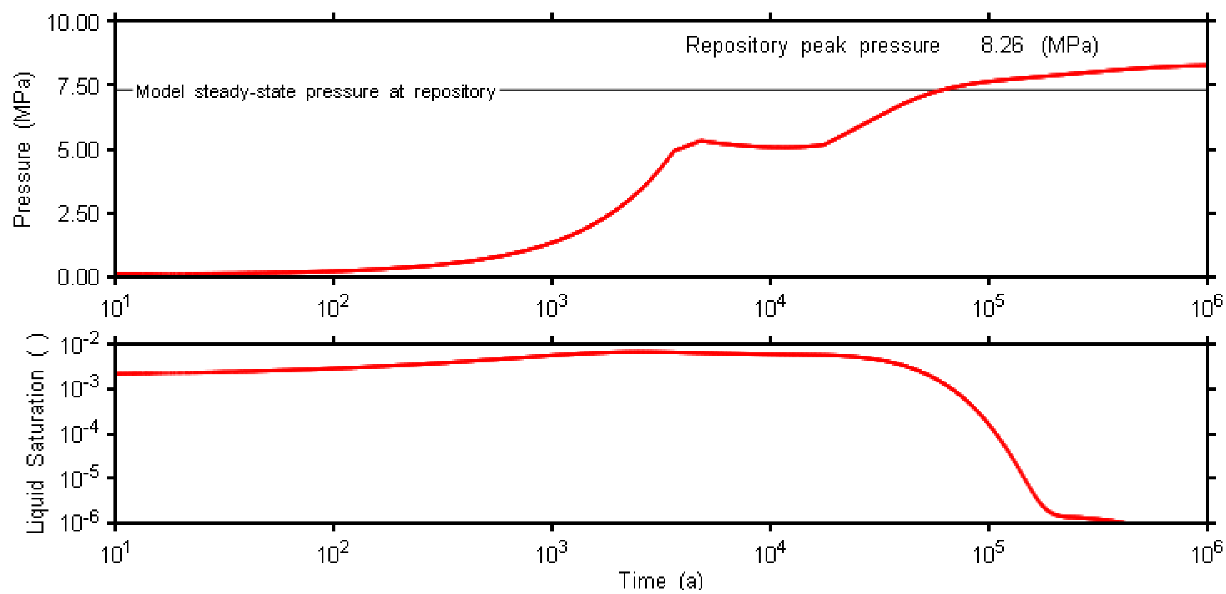

Figure 12. Evolution of Reference Case (NE-RC) repository pressure and liquid saturation

Within the surrounding geosphere, the repository has a limited impact, as shown in Figure 13. The pressure profile within the geosphere changes slightly as the initial underpressure is dissipated; however, by 1 Ma a significant underpressure is still present. Gas saturations are slightly reduced above and below the repository due to gas flow from the formation into the repository. Figure 13 also shows the steady-state pressure distribution which would be obtained if the underpressures dissipated entirely.

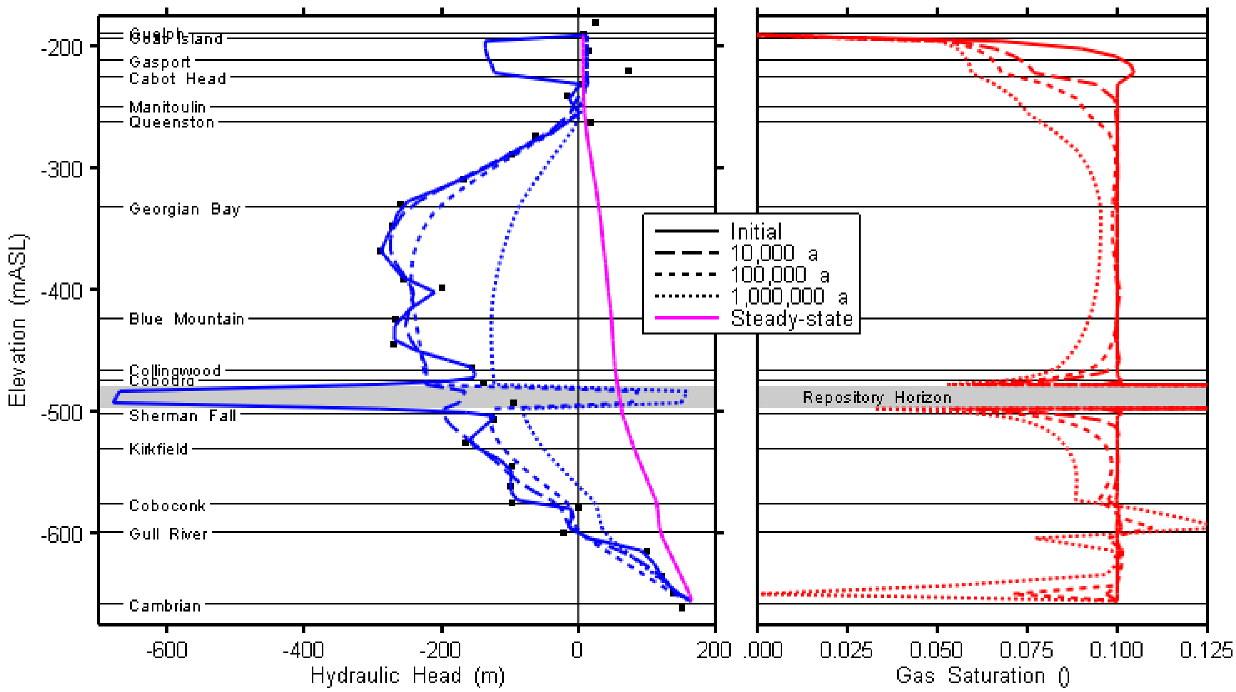

Figure 13. Evolution of Reference Case (NE-RC) geosphere liquid pressure (expressed as hydraulic head) and gas saturation profile

In summary, the NE-RC gas generation and transport model results show that:

- The oxygen, nitrates and sulphates initially present have virtually no impact on the long-term repository conditions.
- Microbial activity is an important factor in causing gas generation.
- Gas generation from the wastes is complete by 100 ka.
- The peak gas pressure is 8.3 MPa at 1 Ma. The continued rise of the peak pressure after 100 ka is due to the slow inflow of gas from the geosphere.
- Liquid saturations in the repository never exceed 1%. At the end of the simulation the repository is dry.

6.2 Simplified Base Case (NE-SBC)

The NE-SBC case assumed a liquid saturated geosphere with an initial pressure profile representative of steady-state groundwater conditions. In this case, the underpressures indicated in Figure 1 (as measured at the site) are assumed to have dissipated entirely. There is a vertical upwards hydraulic head gradient (see "steady-state" line on Figure 13) driven by the 165 mAGS head at the Cambrian formation. This is a conservative representation of the natural hydraulic pressures at the site that maximizes vertical transport.

The detailed model results show that gas generation progressed similarly to NE-RC. Consequently, pressure results are similar to the NE-RC, except that there is no formation gas flowing into the repository and pressures do not continue to rise after gas generation reactions are complete. Repository liquid saturations reach approximately 4% by the end of the simulation (Figure 14).

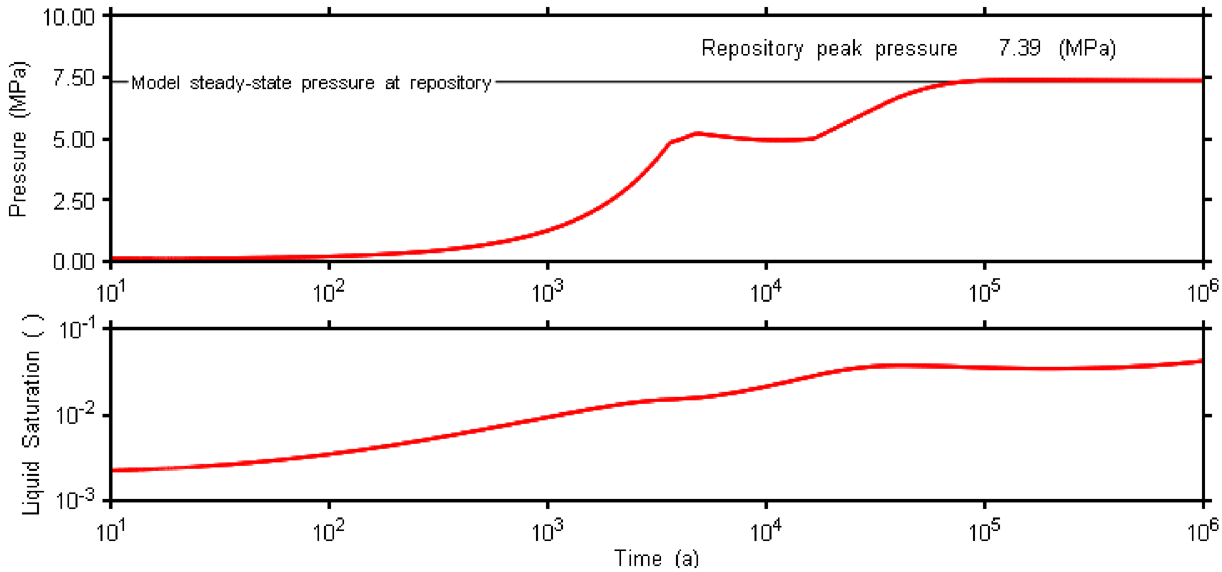

Figure 14. Evolution of NE-SBC repository pressure and liquid saturation

6.3 Increased Gas Generation Rates (NE-GG1)

In this case, the NE-SBC geosphere assumptions are used, while higher values are assumed for gas generation rates and initial waste package material amounts. The increased gas generation causes repository pressure to rise earlier, but it still equilibrates around the hydraulic pressure in the surrounding geosphere, as shown in Figure 15.

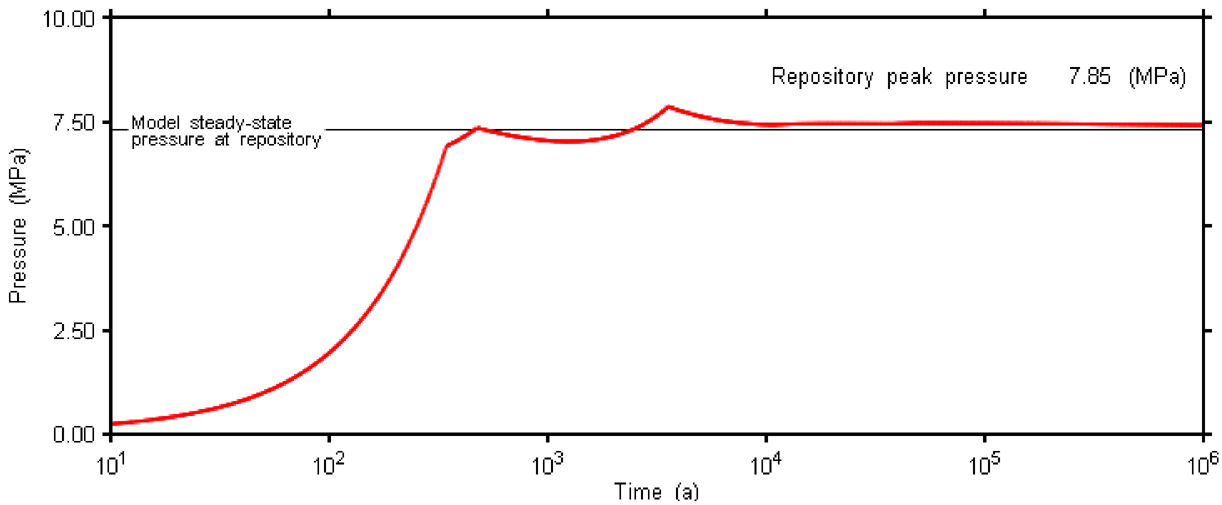

Figure 15. Evolution of NE-GG1 repository gas pressure

Gas transport in this case is still limited in extent and magnitude. There is virtually no transport of gas into the host rock surrounding the repository due to the extremely low-permeability of the host rock. Figure 16 illustrates areas with gas saturations in excess of 10^{-4} (i.e. 0.01%) at 10,000 a.

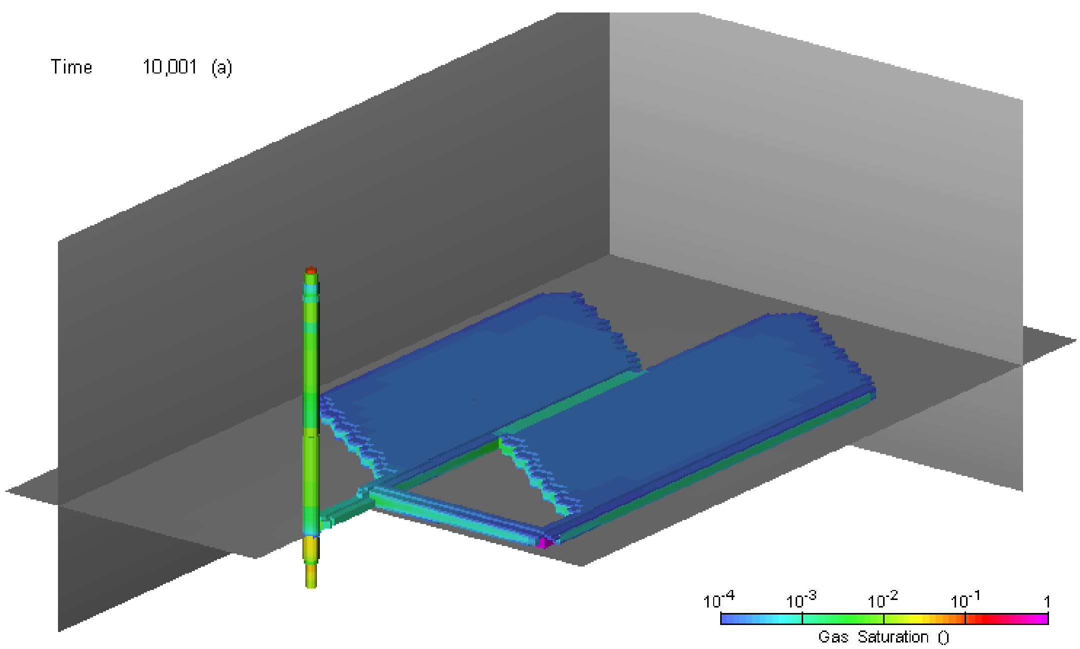

Figure 16. Evolution of NE-GG1 repository pressure and liquid saturation

Figure 16 shows that gas has reached the top of the 3DD model domain in the shaft at 10,000 a. The 2DRS model was used to determine shaft transport above the 3DD model domain. As shown in Figure 17, gas leaves the shaft at the Guelph formation, and does not travel further vertically. This is due to the difference in capillary pressure between the concrete seal in the shaft at that location and the relatively high-permeability Guelph formation. The gas pressure is higher in the concrete than in the Guelph and the gradient is thus outward into the formation.

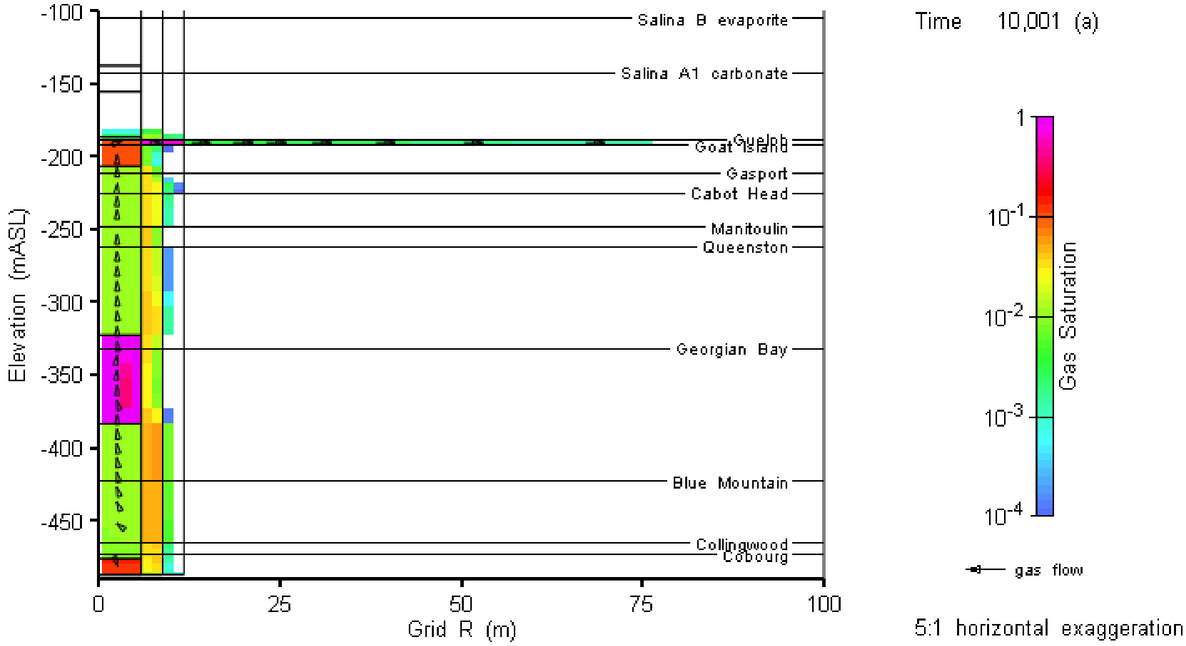

Figure 17. NE-GG1: gas flow in shaft at 10,000 a

This behavior is found in all Normal Evolution cases where pressures in the repository are sufficient to initiate gas flow up the shaft. Figure 18 presents the evolution of shaft gas flow at four different elevations. The effectiveness of the seal system is apparent in the reduction of gas flow rates at increasing elevations. As the gas rises in the shaft, a portion exits radially and dissolves in porewater in the EDZ and intact rock. This is the cause of the reduction in gas flow rates between the Collingwood and Georgian Bay formations, and the smaller reduction between the Georgian Bay and Gasport. The zero total flow at the Salina A2 is further evidence of the effectiveness of the Guelph (just above the Goat Island formation) in diverting gas from the shaft.

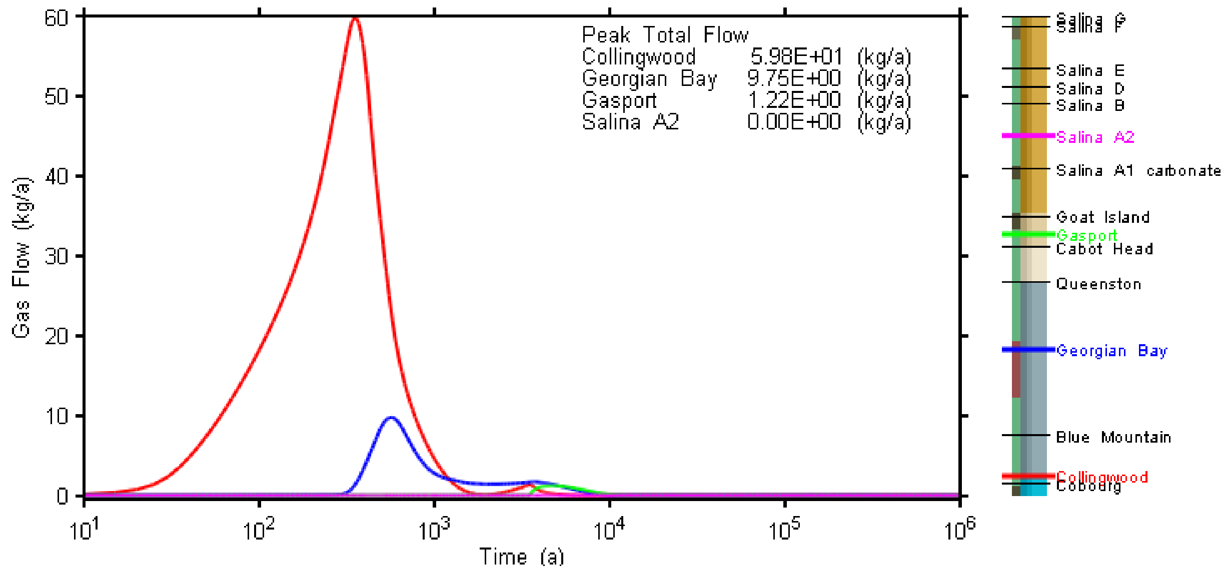

Figure 18. Evolution of NE-GG1 shaft gas flow

6.4 Shaft Failure – Base Case (SF-BC)

The Shaft Failure cases are disruptive event cases where the shaft seal material is degraded and does not perform as designed. For the SF-BC case, the seal material is assumed to have a uniform hydraulic conductivity of 10^{-9} m/s, which is a factor of 100-1000 higher than the reference value for the primary seals. The capillary pressure for the degraded material is set to zero at all liquid saturations. For all other parameters, the case uses NE-SBC assumptions. The higher permeability shaft leads to a relatively rapid ingress of water into the repository. As gas generation proceeds, the pressure in the repository exceeds that of the liquid saturated shaft, causing a rapid release of gas. Subsequent gas generation causes continual flow of gas up the shaft, which drops slowly as the gas generation rate within the repository decreases (Figure 19).

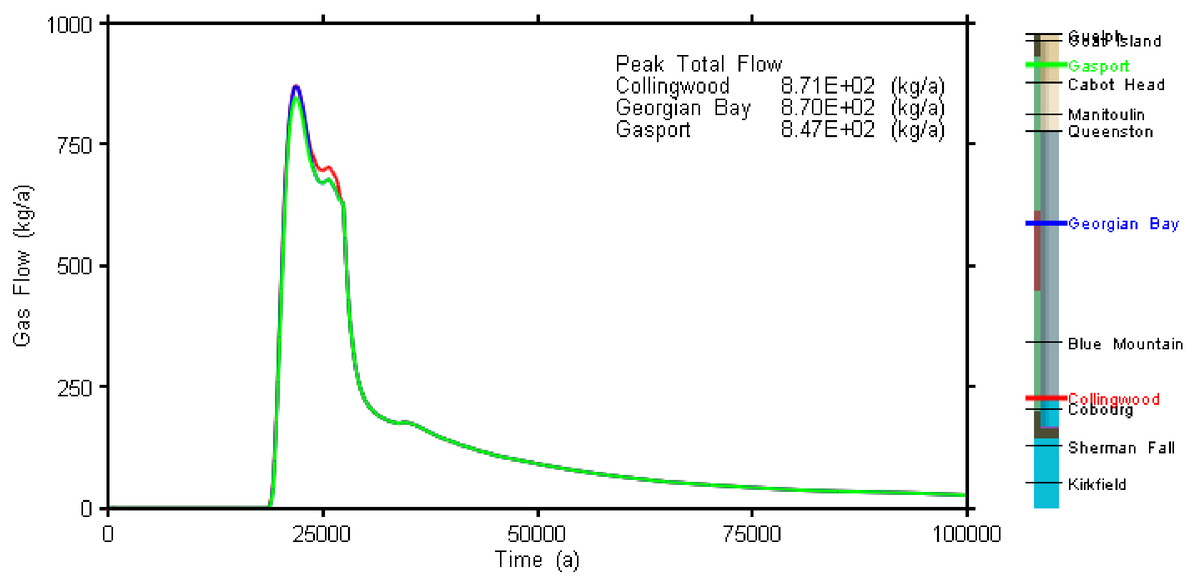

Figure 19. Evolution of SF-BC Shaft gas flow

In this case, the Guelph formation does not act as a gas sink, as the capillary pressure in the degraded shaft material is below that of the formation. All gas traveling up the shaft exits into the shallow bedrock groundwater system.

6.5 Case Comparison

Figures 20 and 21 present the repository pressure and saturation evolution for all calculation cases. It can be seen that repository pressures never exceed 10 MPa and are thus well below the estimated lithostatic pressure at the repository horizon (17 MPa). Repository saturations do not exceed 15% except for cases with no gas generation (NE-NG1 and NE-NG2) and the disruptive event shaft failure cases (SF-BC and SF-ED).

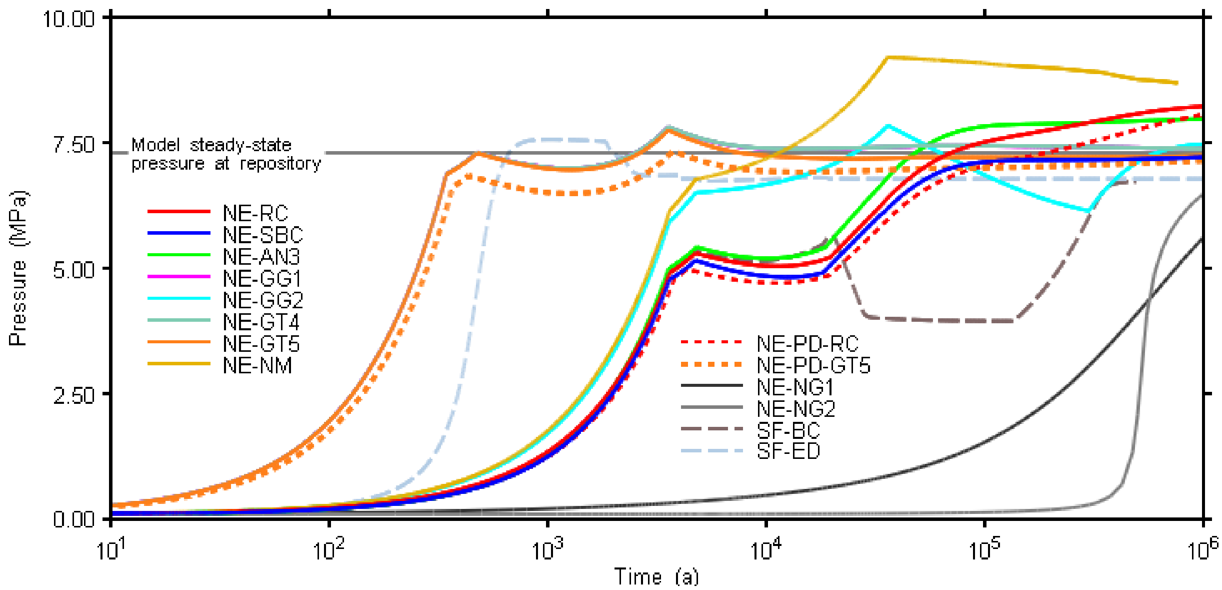

Figure 20. All Cases: Evolution of repository pressure

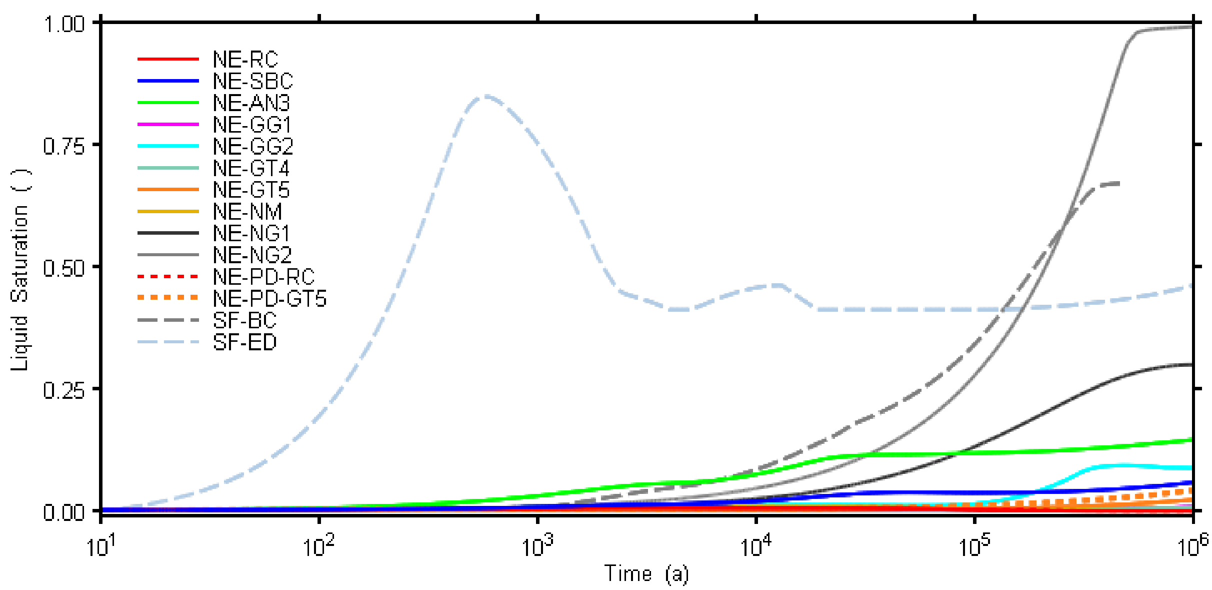

Figure 21. All Cases: Evolution of repository saturation

There are five normal evolution cases where pressures in the repository are sufficient to initiate flow up the shaft. These are high gas generation rate cases (NE-GG1 case or variants NE-GT4, NE-GT5, NE-PD-GT5), or high gas pressure case (NE-NM). As described previously, all shaft gas flow for normal evolution cases exits the shaft at the Guelph formation, with no free gas reaching the Shallow Bedrock Groundwater Zone. However, some gas may subsequently diffuse into the shallow groundwater via groundwater pathway in these cases, and providing a pathway for some C14 to reach shallow groundwater. Only the shaft seal failure cases have the potential for free gas to directly reach the shallow groundwater.

7. GROUNDWATER MODELLING RESULTS

As shown in the previous detailed gas modelling results, the repository remains largely unsaturated, while the surrounding rock mass and shaft seal is largely saturated. However, the detailed groundwater flow modelling was performed assuming that the repository was instantly saturated on closure.

Furthermore, it was assumed that all the radionuclides within the waste was instantly dissolved into the water saturated repository. For the detailed modelling of radionuclide transport, a single long-lived radionuclide (^{36}Chlorine) was used as a representative species. Inventory was allocated spatially into the two repository panels. This led to a slightly higher initial concentration in the North panel (Panel 1). Detailed results are presented for the normal evolution reference case (NE-RC) and for the human intrusion scenario case where an exploration borehole intersects the repository and the pressurized Cambrian formation below (HI-GR2). As can be seen in the case comparison presented subsequently, there is little variation among the NE calculation cases.

7.1 Reference Case (NE-RC)

The NE-RC case assumes a transient flow response starting with the hydraulic head profile described in Figure 1. The resulting head and advective velocity distribution at 100 ka is shown on a vertical slice through the repository and shaft in Figures 22 and 23. The velocity vectors in Figure 23 are shown only in those areas where the magnitude of the velocity is greater than 10^{-5} m/a, or expressed in other terms, greater than 10m of advective transport during the 1 Ma performance period.

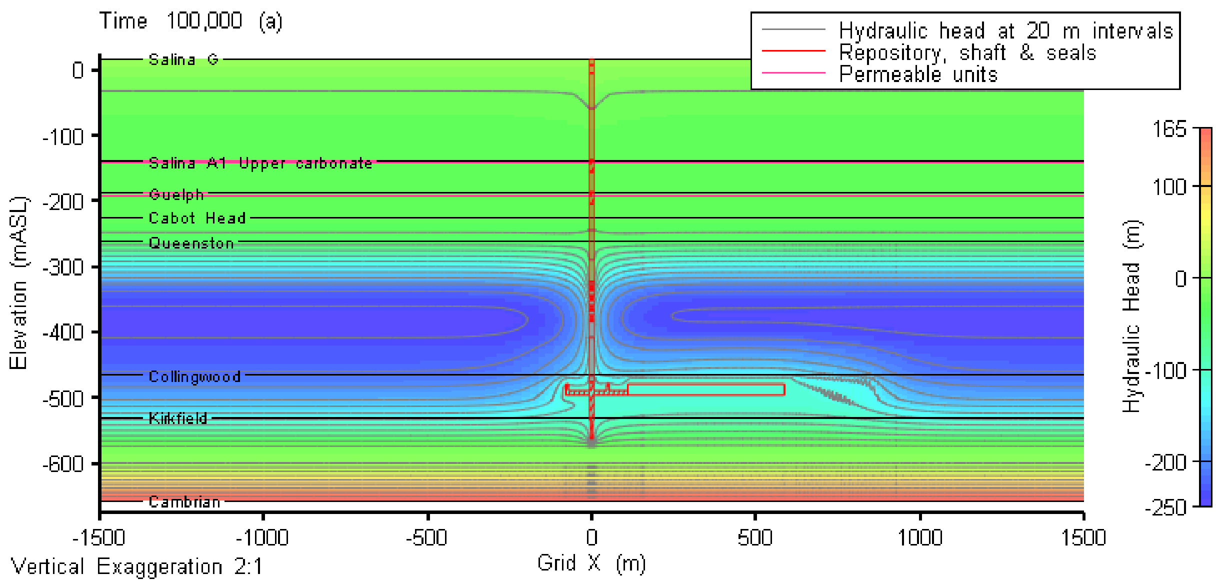

Figure 22. NE-RC: Head distribution at 100 ka

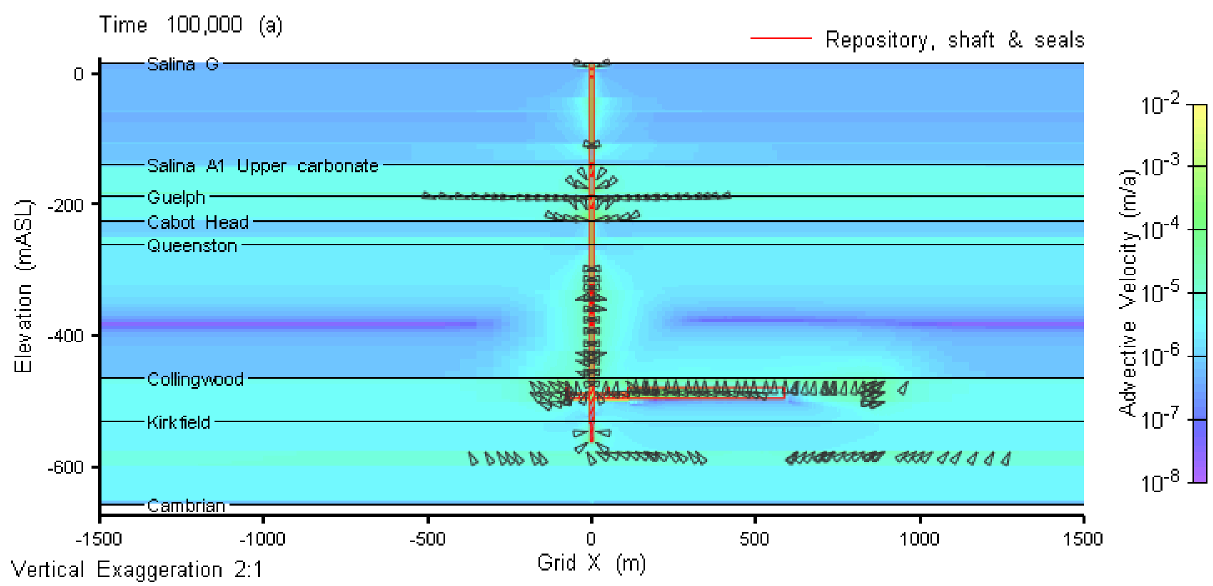

Figure 23. NE-RC: Advective velocity distribution at 100 ka

By 1 Ma the under pressure has further dissipated (Figure 24). Velocities induced by the underpressure gradient have also declined, as shown in Figure 25.

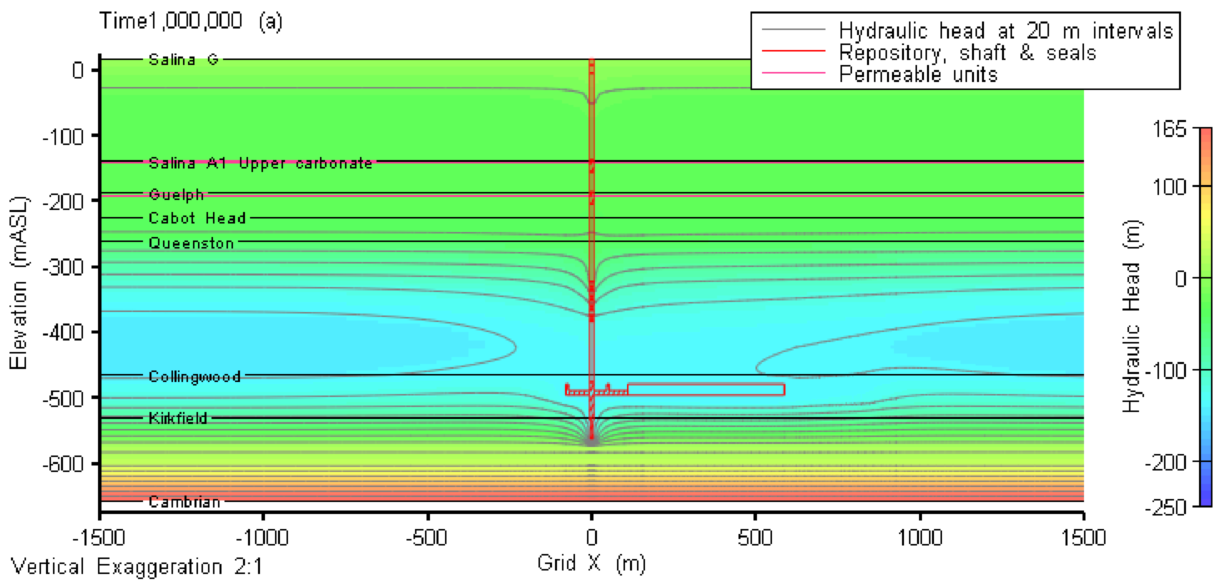

Figure 24. NE-RC: Head distribution at 1 Ma

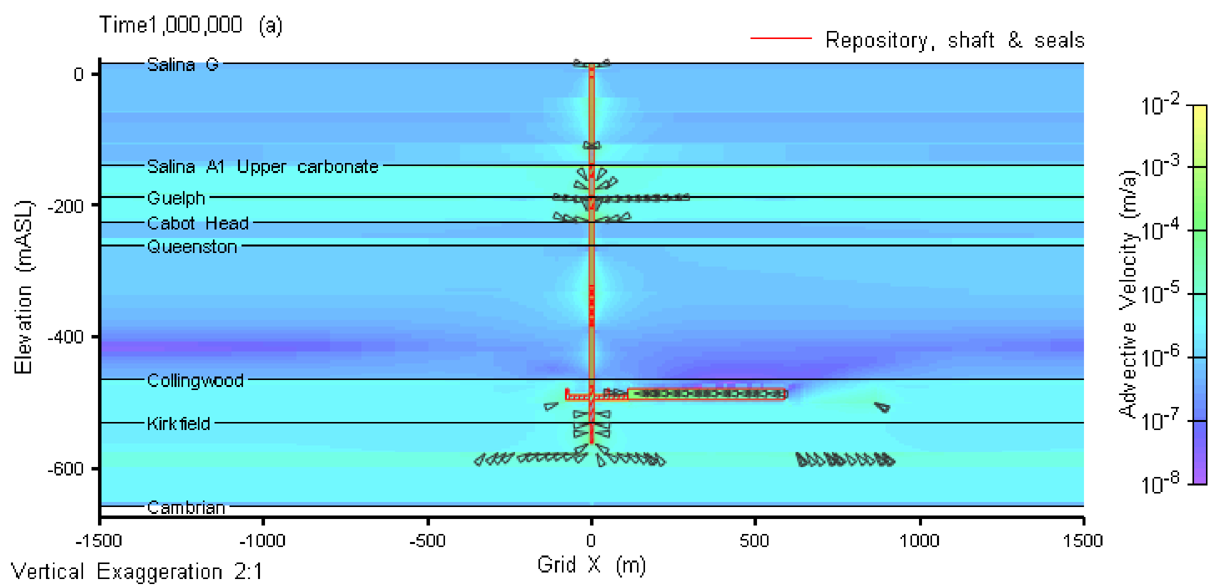

Figure 25. NE-RC: Advective velocity distribution at 1 Ma

Vertical profiles of Cl-36 concentrations are shown in Figure 26.

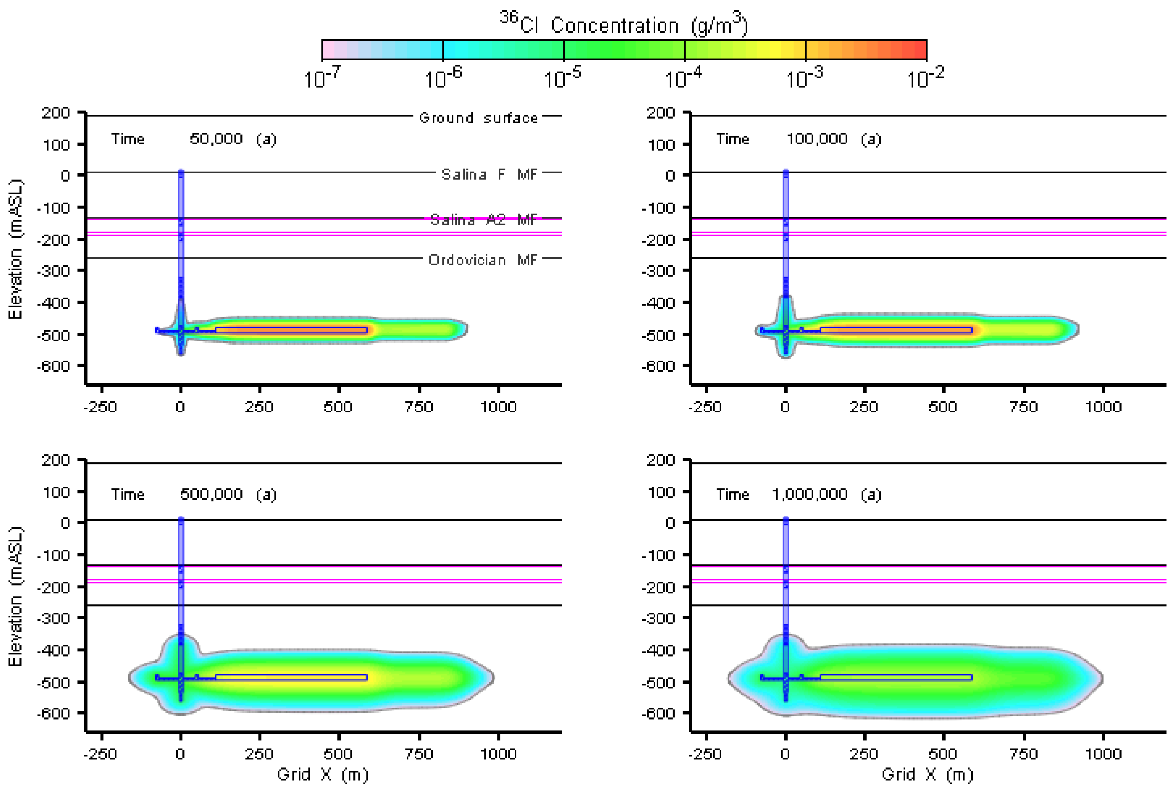

Figure 26. NE-RC: Cl-36 concentration at 50 ka, 100 ka, 500 ka, and 1 Ma

The very limited extent of the plume development is an indication that transport is diffusion dominated with exceedingly low concentrations of radionuclides outside the immediate vicinity of the repository. A three-dimensional presentation of the transport results at 1 Ma is given in Figure 27. Again, the limited extent of the plume is apparent.

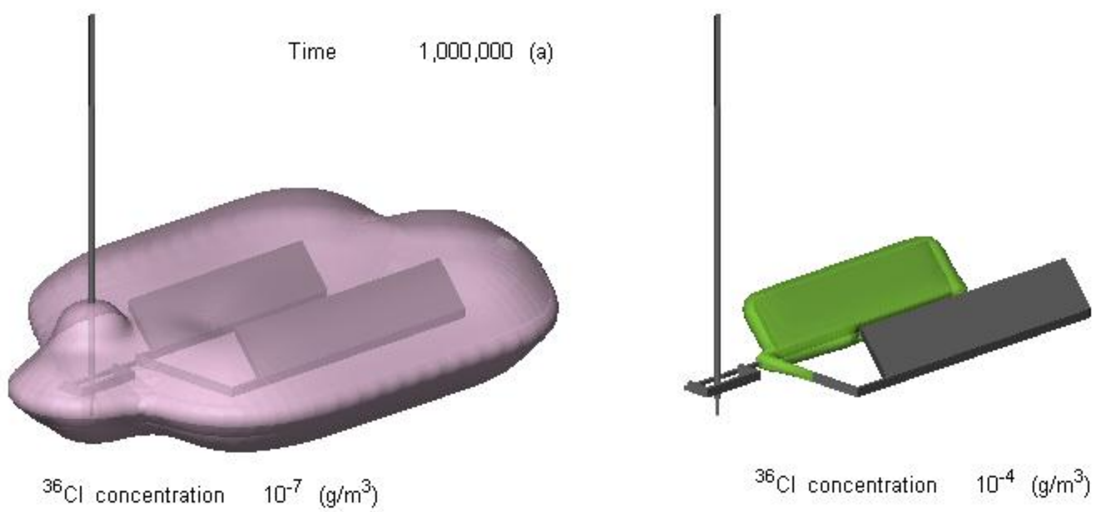

Figure 27. NE-RC: Cl-36 concentration isovolumes at 1 Ma

The 3DSU model was used only to develop capture ratios for the well. A constant unit mass flow rate (1 g/a) was applied to the source location at the point where the repository shaft reaches the more permeable shallow bedrock groundwater zone. Figure 28 is a cross-section showing simulated steady-state concentrations.

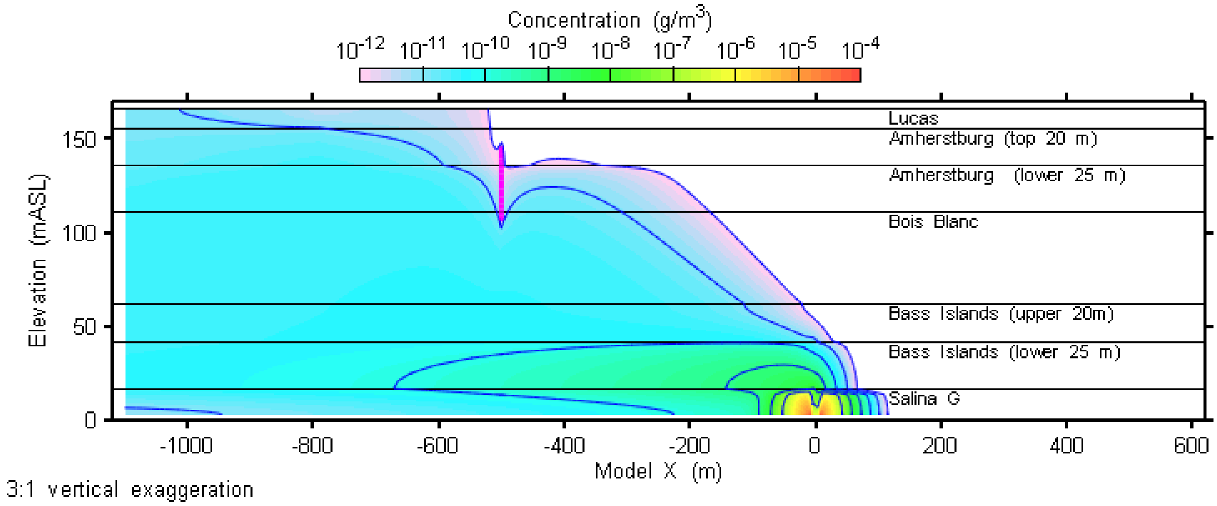

Figure 28. 3DSU NE-RC: Concentration distribution for a steady source at X=0 m. Well location is shown by vertical pink line at X=-500 m.

The water well captures a small portion of the plume, about 1%. The remainder of the mass exits the model into the lake compartment.

7.2 Inadvertent Human Intrusion Case (HI-GR1 and HI-GR2)

The human intrusion cases are based on a modified NE-RC case where an exploration borehole is inadvertently drilled from surface into the repository and then abandoned (HI-GR1), and through the repository into the Cambrian formation and then abandoned (HI-GR2).

In the HI-GR1 case, there is little to no flow from repository up through the abandoned borehole due to the small borehole size, low rock permeabilities and rock mass underpressure.

In the HI-GR2 case, pressurized formation fluid from the Cambrian is transmitted into the repository and then up to surface. Concentrations of Cl-36 at various times on a vertical slice through the borehole are presented in Figure 29. These results indicate that a pulse of Cl-36 is transported from the repository up the exploration borehole, where it is expelled outwards into the moderately permeable Silurian formations. Concentrations within these formations subsequently decrease over the remaining majority of the 1 Ma performance period.

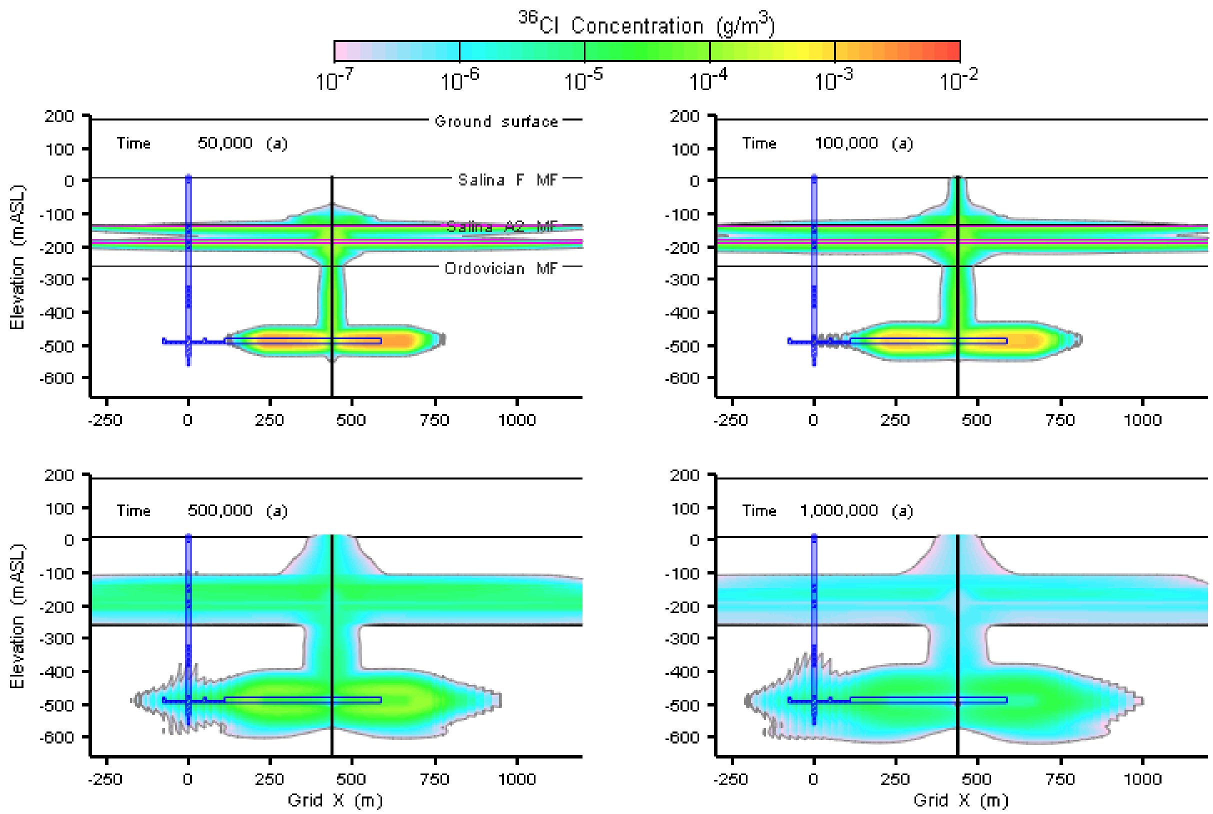

Figure 29. HI-GR2: Cl-36 concentration at 50 ka, 100 ka, 500 ka, and 1 Ma

7.3 Case Comparison

Case results of the detailed groundwater modelling are compared based on mass flow rates of Cl-36 into the Shallow Bedrock Groundwater Zone or horizontally through the permeable Silurian formations. As a point of reference, the very small rate of Cl-36 deposition due to natural atmospheric generation and deposition over the repository footprint is also shown on the comparison figures as natural background.

Figure 30 compares results for all normal evolution cases. It is noteworthy that for the NE-RC case, which is the reference case and is considered the most likely case, the mass flow rate to the Shallow Bedrock Groundwater Zone is below the plot cut off limit of 10^{-13} g/a. It is also noteworthy that the same is true of the NE-HG case, which is the only Normal Evolution case incorporating horizontal flow in the moderately permeable Silurian formations. The green dashed line for this case indicates the mass flow intercepted by the groundwater flowing in the moderately permeable Silurian formations, and the effectiveness of this interception as a mechanism for eliminating the transport of radionuclides from the repository towards the shallow bedrock.

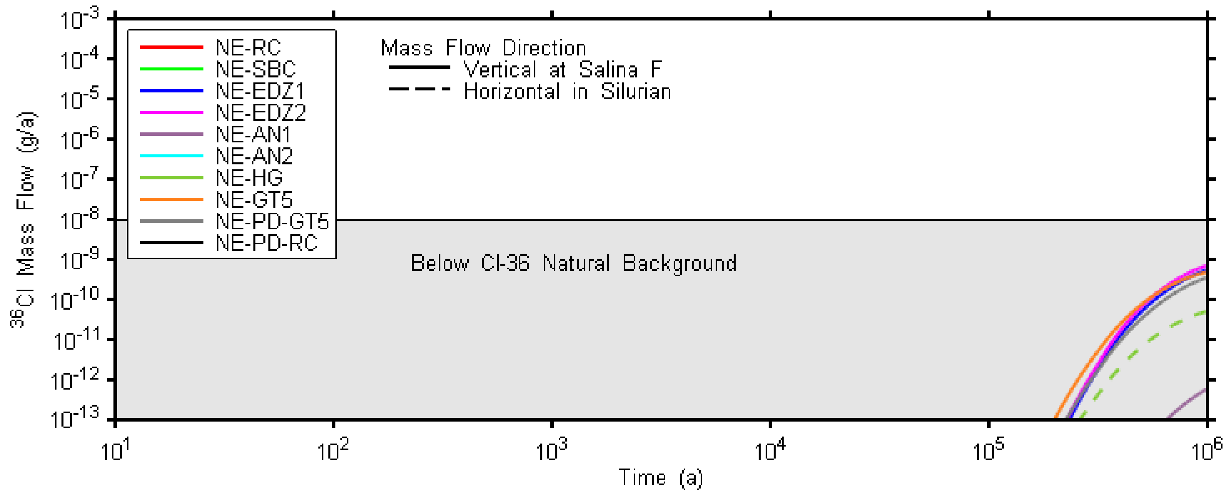

Figure 30. All NE Cases: Cl-36 mass flow rate

Of the Normal Evolution cases, the three cases with increased permeability of the shaft sealing materials (NE-EDZ1, NE-EDZ2, and NE-GT5) result in the greatest mass flows into the Shallow Bedrock Groundwater Zone, which are still very small.

Figure 31 compares peak mass flow rates for all disruptive scenario cases. The results indicate that the mass flow into the Shallow Bedrock Groundwater Zone peaks at approximately 10^{-4} g/a in the HI-GR2 case, and would be less than the natural cosmogenic background Cl-36 deposition rate in all other cases. The figure clearly indicates that radionuclide transport in groundwater will be effectively zero for nearly all cases, including the cases assuming a vertical fault near the repository (VF). Only inadvertent drilling through the repository and into the Cambrian (HI-GR2) would result in perceptible concentrations being released into the Shallow Bedrock Groundwater Zone.

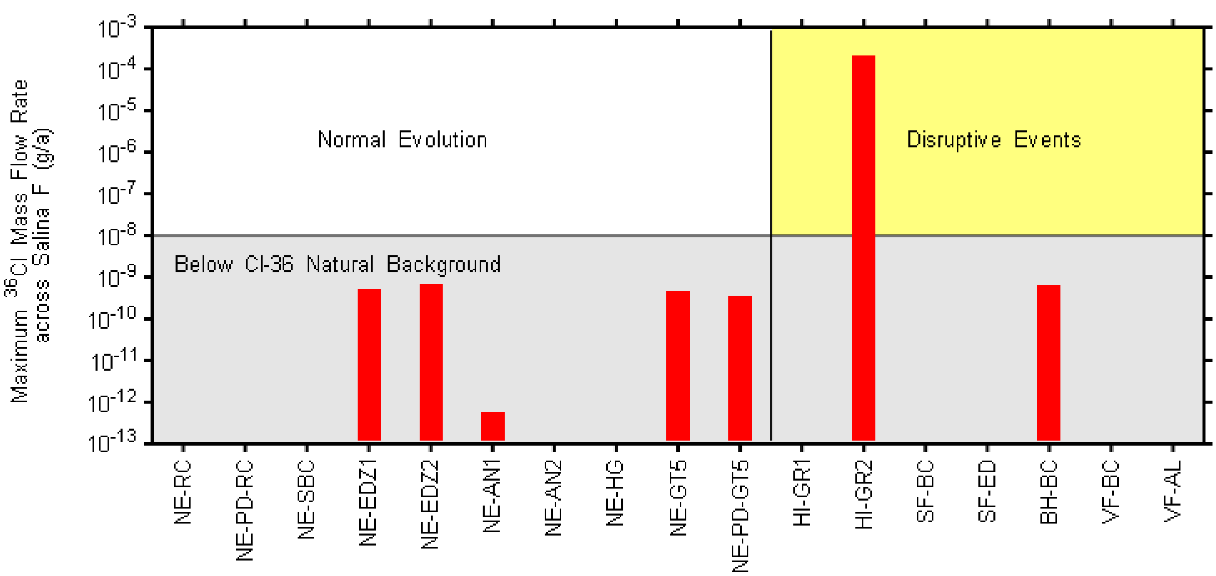

Figure 31. Peak Cl-36 Vertical Mass Flow across the Salina F for all Cases

8. CONCLUSIONS

The long-term performance of the proposed L&ILW repository at the Bruce nuclear site has been assessed with the use of detailed numeric models of gas transport and of groundwater flow and transport of radionuclides. Reference and variant cases were undertaken for the Normal Evolution Scenario, and for Disruptive Scenarios.

Two-phase flow modelling results indicate that the site geosphere acts as an effective barrier to gas flow. The shaft seals are also an effective barrier, and, in conjunction with the higher permeability Guelph Formation, prevent the transport of any free gas to the Shallow Bedrock Groundwater Zone. Gas reaches the shallow groundwater in small amounts under some higher gas generation rate cases as dissolved in groundwater. Only under disruptive scenarios does gas reach the shallow groundwater, and then only if extreme assumptions are made about the properties of the degraded shaft materials that characterize the scenarios.

The results of the groundwater flow and transport modelling indicate that in all Normal Evolution Scenario cases contaminant mass transport from the repository via groundwater would be diffusion dominated and that releases to the Shallow Bedrock Groundwater Zone are effectively zero. The only case with appreciable groundwater releases was the very unlikely case of Inadvertent Human Intrusion, where an exploration borehole is drilled from ground surface through the repository and into the pressurized Cambrian.

As noted in the introduction, the potential impact of these scenarios was addressed through assessment modelling [7].

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