DEEP GEOLOGIC

# REPOSITORY

FOR OPG's LOW & INTERMEDIATE LEVEL WASTE

# Postclosure Safety Assessment (V1): System and Its Evolution

**June 2009**

Prepared by:
R Little, A Bath, P Humphreys, F King, R Metcalfe,
J Penfold, D Savage, G Towler and R Walke

NWMO DGR-TR-2009-04

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

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*Preliminary*

# Postclosure Safety Assessment (V1): System and Its Evolution

NWMO DGR-TR-2009-04

June 2009

Recommended by: ______________________ June 27, 2009

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

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

This report describes the DGR system and its evolution under the range of possible scenarios that might affect the system in the future. The DGR system comprises the waste and its packaging, the engineered repository, its geological setting, and the surface environment.

A high-level description of each of these system components is provided below.

| | |
|---|---|
| Waste: | • The total as-disposed volume of L&ILW is about 196,000 $m^3$, in about 50,000 containers.<br>• The total amounts of organics, metals and concrete in the wastes and their packaging are approximately 22,000 tonnes, 54,000 tonnes, and 66,000 tonnes, respectively.<br>• The wastes are grouped into 11 LLW and 11 ILW categories, and are to be emplaced in a range of steel and concrete waste containers and overpacks.<br>• The total activity at 2062, the earliest potential closure date, is about 16,000 TBq. Key radionuclides in terms of total activity include H-3, C-14 and Ni-63 at short times, and Nb-94 and Zr-93 at long times. |
| Repository: | • The repository floor is to be 680 m below ground surface in competent and low permeability Ordovician argillaceous limestone (the Cobourg Formation).<br>• The repository will comprise two shafts, a ring tunnel and associated facilities, two access tunnels and 45 waste emplacement rooms in two panels. The South Panel will contain most of the LLW, whereas the East Panel will hold all the ILW and some LLW.<br>• The DGR will be connected to the surface via a Main Shaft (used for access) and a Ventilation Shaft.<br>• The repository rooms and tunnels will not be backfilled. At closure, the access tunnels will be sealed off from the shafts by the emplacement of concrete monoliths at the base of the shafts. The shafts will then be backfilled with a sequence of materials (bentonite/sand, asphalt, concrete and engineered fill).<br>• The total amounts of concrete and metals in the repository (excluding the waste packages, and the concrete and metals in the shafts other than the monoliths) will be about 65,000 and 3,000 tonnes, respectively. |

| | |
|---|---|
| Geological Setting: | • The proposed repository location is on the eastern edge of the Michigan Basin in a large block of unfractured rock which is tectonically stable. A c. 850 m thick sequence of sedimentary rocks overlies the granitic basement rocks. The sequence from the ground surface down to the granite comprises:<br>▪ c. 20 m of unconsolidated Quaternary sediments (clay, sand, silt, gravel)<br>▪ c. 105 m of Devonian dolostones (dolomitic limestones);<br>▪ c. 325 m of Silurian dolostones and shales;<br>▪ c. 400 m of Ordovician shales and argillaceous to shaley limestone; and<br>▪ c. 15 m of Cambrian sandstone.<br>• The DGR is to be located within a 725 m thick sequence of predominantly low conductivity Ordovician and Silurian rocks (<$10^{-10}$ m $s^{-1}$) through which transport of contaminants is expected to be diffusion dominated. Significant under-pressures exist in the Ordovician rocks.<br>• The low conductivity rocks are underlain by overpressured Cambrian sandstones and overlain by a 180 m sequence of relatively high conductivity Devonian rocks ($10^{-7}$ to $10^{-4}$ m $s^{-1}$) through which transport of contaminants is expected to be advection dominated.<br>• The porewater in the Silurian and Ordovician sediments is saline (with total dissolved solids of 100 to 350 g $L^{-1}$), mildly acidic (pH 5.1 to 7.0) and reducing. The porewaters in the Devonian sediments have total dissolved solids (ranging from 0.10 to 2.5 g $L^{-1}$), are mildly alkaline (pH 7.0 to 8.3) and are mainly oxidizing (Eh –50 to 340 mV). |
| Surface Environment: | • Climate: annual precipitation is c. 0.98 m $a^{-1}$ and annual average temperature is 8.9°C with average daily temperatures varying from -3.4°C to 20.1°C.<br>• Topography: the Bruce Site is about 190 m above sea level. The area is relatively flat, with a small bluff along the eastern edge of the site.<br>• Surface water bodies: The dominant surface water feature is Lake Huron with a total surface area of 59,600 $km^2$ and mean depth of 59 m. There are no major rivers in the vicinity of the Bruce Site, although there are several small streams that eventually discharge into Lake Huron.<br>• Soils: there is generally a shallow layer of topsoil, typically about 30 cm, overlying silt till with occasional regions of peat-like material.<br>• Land uses: on the Bruce Site land uses are presently restricted to those associated with the nuclear operations and support activities. The region around the Bruce Site is mainly used for agriculture (arable and livestock), recreation and some residential development.<br>• Flora and fauna: The site is vegetated with balsam fir, sugar maple and American beech. There is also a meadow and wetland area. There is a wide variety of wildlife in the area, such as perch, northern pike, lake whitefish, lake trout, green and wood frog, chipping sparrow, American robin, black-capped chickadee, groundhog, red and grey squirrel, snowshoe hare, wild turkey and white-tailed deer.<br>• Natural resources: No oil, gas, salt seams or minerals. Some extraction of sand and gravel from surface deposits in the region. Groundwater aquifer down to around 100 m is used for municipal and domestic water elsewhere in the region, but downstream from the Bruce site the water flows under and into Lake Huron. |

The significant uncertainties associated with the future evolution of the DGR system and potential exposure pathways that might occur are addressed at one level through the systematic identification and assessment of a sufficiently comprehensive range of system evolutions (scenarios). The purpose of scenario identification and development is not to predict the future; rather, it is to use scientifically informed expert judgement, field data on the past evolution of the site, and the results of supporting modelling to develop a range of future evolutions of the DGR against which the performance of the system can be assessed.

The set of scenarios to be assessed has been identified, justified and documented in a systematic, transparent, and traceable manner using a structured analysis of relevant features, events, and processes (FEPs). A scenario (the Normal Evolution Scenario) of the expected evolution of the DGR system and its degradation (loss of barrier functions) with time has been identified and qualitatively described by considering the FEPs external to the system that provide the system with both its boundary conditions and with factors that might cause change in the system.

Additional scenarios (Disruptive Scenarios) have also been identified and described that examine the impacts of unlikely disruptive events that would lead to possible penetration of barriers and abnormal degradation and loss of containment. These Disruptive Scenarios are unlikely or “what if” cases that test the robustness of the DGR.

The following set of scenarios is identified and described in this report.

**Normal Evolution Scenario**

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

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

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

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

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

Currently, the Earth is in a configuration where periodic ice ages occur, with nine major cycles in the past million years. Key factors contributing to these cycles – variations in solar insolation to the northern hemisphere and the arrangement of the continents – will not change appreciably over the next million years. Although global warming is likely to delay the onset of the next ice-sheet advance and to curtail its duration, it is likely that glacial/interglacial cycling will resume in the long term and therefore it is prudent to consider the potential effect on the DGR system.

The impacts of glacial/interglacial cycles in the Deep and Intermediate Bedrock Groundwater Zones are expected to be limited to changes in the stress regime resulting from ice-sheet loading and unloading which might result in rockfall in the repository (which might also result from seismic activity).

The surface environment will change significantly over these time frames. Initially there could be changes due to global warming, but regionally the area is expected to be in a temperate climate and ecosystem. As climatic conditions cool in the long term, ecosystems are expected to change from temperate to tundra. Agriculture and forestry becomes less viable, although small centres of human population may continue based on external supplies of food and energy, or by hunting, fishing and trapping, much as is observed in present-day tundra communities. As the climate grows progressively cooler and drier, arctic conditions are established with permanent human habitation in the vicinity of the site becoming increasingly less likely. The warming of the climate following ice-sheet retreat can result in re-establishment of tundra and potentially temperate ecosystems and the re-population of the site. Each glacial/interglacial cycle also causes biosphere change due to glacial and periglacial processes (e.g., the development of proglacial lakes, the erosion and deposition of surface deposits, and the formation of soils).

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

**Human Intrusion Scenario**

Given the depth of the DGR, the type of human activity that might directly impact the closed repository is a deep borehole, unintentionally drilled into the repository as part of a future geological exploration programme. Even then, the probability of occurrence is very unlikely because of the low economic resource potential of the rocks and the small footprint of the DGR. Nevertheless, the possibility of such inadvertent human intrusion cannot be ruled out over the long timescales of interest to the safety assessment. Such a borehole could provide an enhanced permeability pathway to the surface environment and potential for direct exposure to waste. The resulting scenario is referred to as the Human Intrusion Scenario.

This scenario considers the same evolution of the DGR system as for the Normal Evolution Scenario, with the only difference being the occurrence of human intrusion into the repository at some time after control of the site is no longer effective.

In this scenario, an exploration borehole is drilled down through the geosphere. Upon encountering the repository, the drilling crew would register a loss of drill fluid into the repository void if the repository pressure is less than the drill fluid pressure, or, if the repository pressure is greater than the drill fluid pressure, a surge of gas and/or slurry (water and some suspended waste) from the repository up the borehole. Current technology necessary to drill to 680 m depth would enable the drillers to ascertain the nature of the void that had been encountered and to limit any significant upflow from the repository (this is standard practice in sedimentary rocks where one may encounter natural gas).

In an exploration borehole, the investigators would most likely collect samples or conduct measurements at the repository level, which would readily identify if there were still significant residual radioactivity. In this case the investigators would likely choose to close and seal the borehole, once their measurements were complete rather than extend the borehole further down into the geosphere. Sealing the borehole would avoid any further release of residual radioactivity direct to the surface. Nevertheless, the Human Intrusion Scenario considers the case where the intrusion is inadvertent, is not recognised to have occurred and no restrictions are imposed, and the borehole and drill site are not sealed and closed to current standards.

In this “what if” case, contaminants can be released and humans and non-human biota exposed via three pathways: direct release to the surface of pressurised gas and slurry prior to sealing of the borehole; retrieval and examination of core samples contaminated with waste; and the long-term release of contaminated groundwater into permeable geosphere horizons via the exploration borehole, circumventing part of the natural geological barrier. These releases would result in the exposure of the drill crew, laboratory technicians (who examine the core), residents living near the site at the time of intrusion, and site residents who might occupy the site subsequent to the intrusion event.

**Severe Shaft Seal Failure Scenario**

The Normal Evolution Scenario takes account of the role of engineered barriers and assumes that their performance meets design specifications; it includes an expected degree of degradation of barriers with time. However, it is unlikely but possible that the materials may not perform as designed. For example, they might not be fabricated or installed appropriately (and not detected by DGR quality control procedures), or the long-term performance of the seal materials may deteriorate due to unexpected physical, chemical and/or biological processes. Either situation could result in an enhanced permeability pathway to the surface environment. The shaft seals are the most important engineered barriers, so a “what if” scenario is considered in which the materials have the properties of engineered fill (crushed rock), and is referred to as the Severe Shaft Seal Failure Scenario.

This scenario considers the same evolution of the DGR system and the same exposure pathways and groups as the Normal Evolution Scenario, the only difference being that the performance of the shaft seals and shaft excavation damaged zones (EDZs) is very poor (e.g., the shaft seals have the hydraulic characteristics of engineered fill/crushed rock. In particular it is assumed that the shaft seals and the shaft EDZs have physical and chemical properties of crushed rock from the time of closure of the repository. Like the other Disruptive Scenarios, the scenario is a bounding, “what if” scenario that is designed to investigate the robustness of the DGR system.

**Open Borehole Scenario**

The DGR site will have several deep boreholes around the repository, used for site characterization initially and for monitoring during and after operation. These boreholes will not intersect the repository itself, but will be some distance away. In all cases, the boreholes will be licensed through the Ontario Ministry of Natural Resources and they will be outside the repository footprint. Furthermore, they would normally be sealed at the end of their useful lifetime. Consequently they would have no effect on the repository performance. However, the Open Borehole Scenario considers the consequences of a deep borehole not being properly sealed. Such a situation would be expected to be very unlikely as good practice and quality control would prevent such a situation occurring. However, the situation is one of a limited number of potential events that could result in an enhanced permeability pathway to surface environment and therefore merits investigation.

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

**Extreme Earthquake Scenario**

The DGR site is located in a seismically stable region, so large earthquakes are very unlikely and the repository is designed to handle the expected level of earthquakes for the area. However the assessment timescales are sufficiently long that, after the repository has been closed, a very large earthquake could occur in the region, possibly related to future post-glacial rebound.

Such an earthquake could affect the repository if sufficiently large and close. In particular, it could cause rockfall within the repository, reduce the performance of the shaft seals, and/or reactivate a hypothetical closed fault in the vicinity of the DGR. Because the event could have a number of consequences resulting in enhanced permeability pathways to the surface environment, it is useful to assess it as a “what if” scenario, referred to as the Extreme Earthquake Scenario.

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

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

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# 1. INTRODUCTION

Ontario Power Generation (OPG) is proposing to build a Deep Geologic Repository (DGR) for Low and Intermediate Level Waste (L&ILW) near the existing Western Waste Management Facility (WWMF) at the Bruce site in the Municipality of Kincardine, Ontario (Figure 1-1). The Nuclear Waste Management Organization, on behalf of OPG, is currently preparing an Environmental Impact Statement (EIS) and Preliminary Safety Report (PSR) for the proposed repository.

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

The Version 1 work builds upon a scoping assessment conducted by Quintessa in 2002 and 2003 (Penfold et al. 2003) and has been refined to take account of the revised waste inventory and repository design, and the greater understanding of the site that is being developed as the project proceeds.

This report (System and its Evolution) is one of a suite of documents that presents the Version 1 SA studies (Figure 1-2), which also includes the Postclosure SA main report (Quintessa et al. 2009), the Normal Evolution Scenario Analysis report (Walke et al. 2009a), the Human Intrusion and Other Disruptive Scenarios Analysis report (Penfold and Little 2009), the Features, Events and Processes report (Garisto et al. 2009), the Data report (Walke et al. 2009b), the Groundwater Modelling report (Avis et al. 2009), and the Gas Modelling report (Calder et al. 2009).

## 1.1 PURPOSE AND SCOPE

This safety assessment has been carried out using an approach based on the ISAM safety assessment methodology developed within the International Atomic Energy Agency's (IAEA's) ISAM project (IAEA 2004) (Figure 1-3).

The approach comprises the following basic steps.

1. The context of the assessment is defined, documenting the high-level assumptions and constraints that reflect the purpose and focus of the assessment.
2. The current information on waste, repository, geosphere and biosphere systems that are relevant to postclosure safety are reported, along with identified areas of uncertainty.
3. A range of internally consistent potential future evolutions (scenarios) is systematically identified.
4. Conceptual and mathematical models and data are developed for these scenarios and a range of calculation cases, which explore key areas of uncertainty, are identified and implemented in software tools.
5. Following the running of the software tools and the generation of results, the results are analysed, interpreted and discussed to inform on the performance of the system, its overall robustness, and the nature and role of key uncertainties.
6. The key findings of the assessment are then identified and discussed, together with their implications for the future DGR programme.

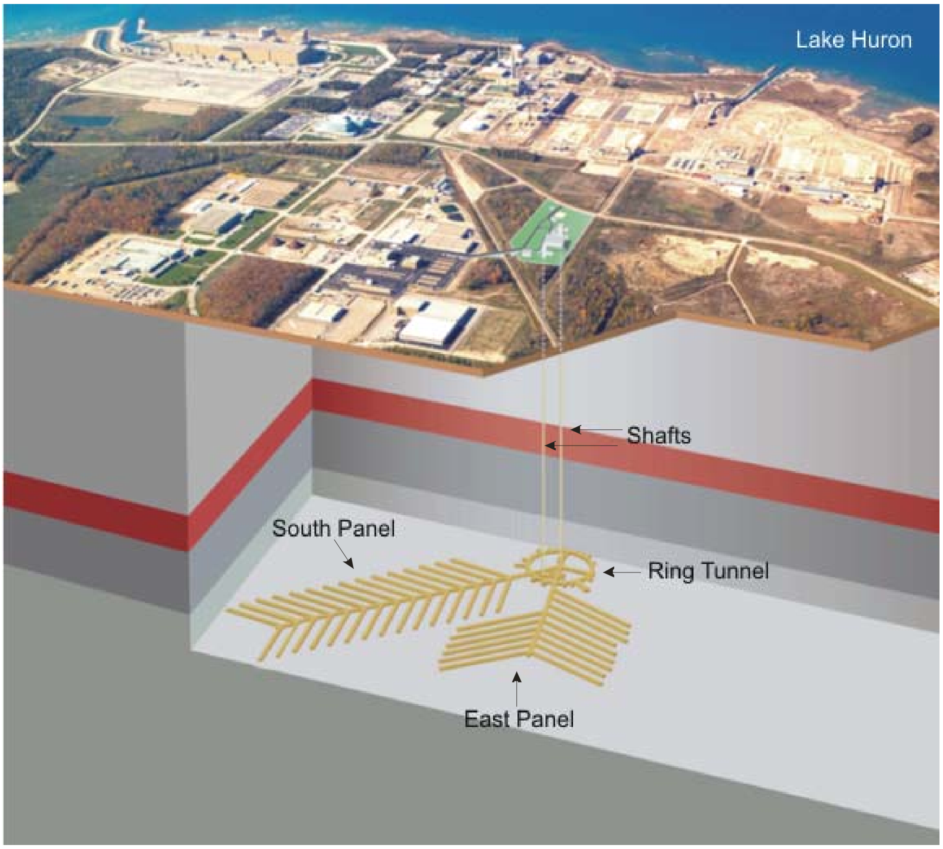



**Figure 1-1: The DGR Concept at the Bruce Site**

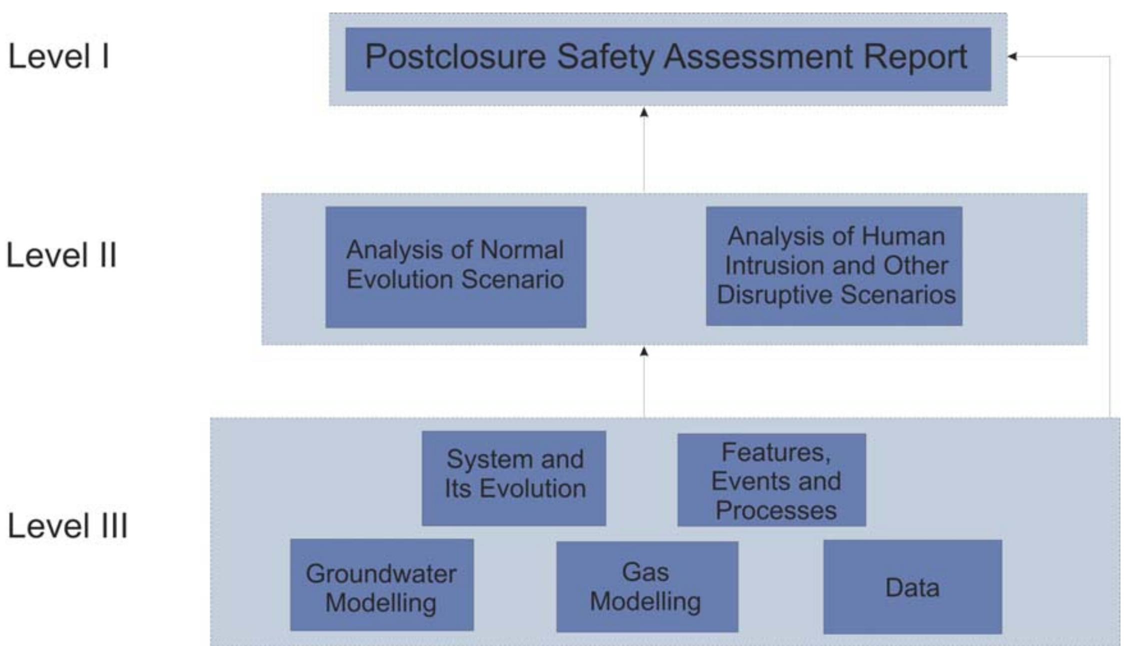



**Figure 1-2: Document Structure for the Version 1 Postclosure Safety Assessment**

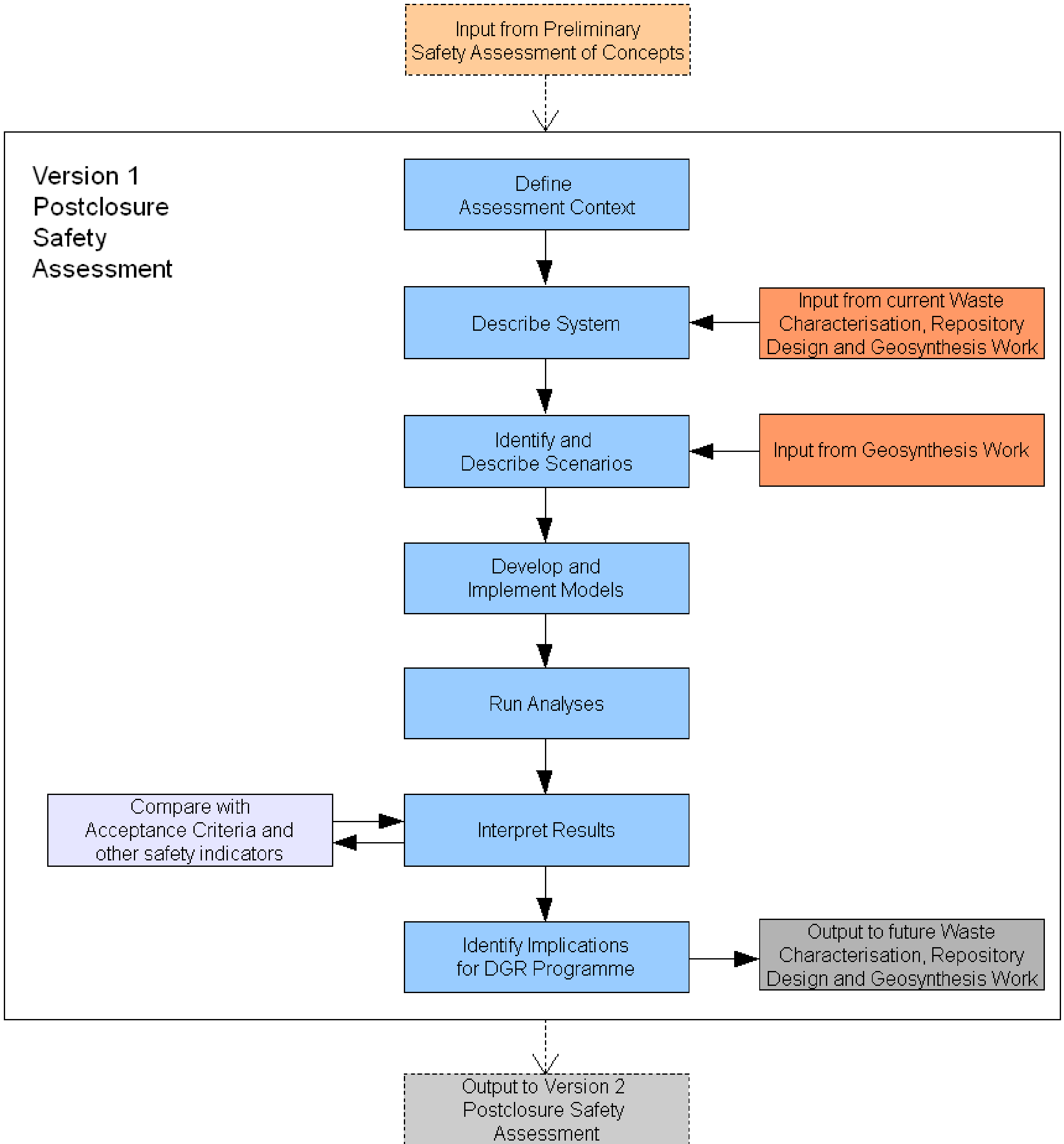



**Figure 1-3: Approach used for the Version 1 Postclosure Safety Assessment**

The purpose of this report is to describe Steps 2 and 3 of the safety assessment approach used in the Version 1 SA. It therefore describes the DGR system (Step 2) and its evolution under a range of possible scenarios that might affect it in the future (Step 3).

Scenarios are defined as “a postulated or assumed set of conditions or events. They are most commonly used in analysis or assessment to represent possible future conditions or events to be modelled, such as the possible future evolution of a repository and its surroundings” (CNSC 2006). The purpose of scenario identification and development is not to predict the future;

rather, it is to use scientifically informed expert judgement, field data on the past evolution of the site, and the results of supporting modelling to develop a sufficiently comprehensive range of possible future evolutions of the DGR against which the performance of the system can then be assessed. It is therefore the purpose of this report to describe the DGR system and its possible future evolution.

This report provides a primarily qualitative, rather than quantitative, description of the evolution of the DGR system. A more quantitative description of the system's evolution is provided in the conceptual model developed in the Normal Evolution Scenario Analysis report (Walke et al. 2009a) and the Human Intrusion and Other Disruptive Scenarios Analysis report (Penfold and Little 2009). The more quantitative description in these reports is informed by the results of detailed groundwater and gas modelling presented in Avis et al. (2009) and Calder et al. (2009), respectively.

## 1.2 REPORT OUTLINE

The key components of the DGR system are first described in Section 2. Based on the current (early 2009) understanding of the site and its processes, the key features, events and processes (FEPs) that are considered to affect the system's evolution over the timescales of interest (i.e., those over which geological events, repository evolution and health and environmental impacts are to be quantified or numerically bounded) are then identified. FEPs external to the DGR system and their likely impact on its evolution are identified in Section 3. The impact of these external FEPs and certain key internal FEPs on the evolution of the waste and repository (Section 4), the geosphere (Section 5), and the biosphere (Section 6) is then described. The resulting expected evolution of the entire system (the Normal Evolution Scenario) is presented in Section 7, whilst other less likely evolutions leading to possible abnormal degradation and loss of containment (Disruptive Scenarios) are identified and described in Section 8.

The expectation of how a repository is likely to evolve is derived from many features, events and processes. These features, events and processes can exhibit spatial and temporal variability in expression and there are interactions between them that affect their likelihood, mode and degree of expression. The characteristics and likelihood of occurrence of some FEPs can be estimated with less uncertainty than is the case for others. Therefore, where possible in this report, the degree of confidence or uncertainty that underlies any particular statement is documented by consistently using qualified estimates of the likelihood that the statement reflects a situation that will occur, as indicated by the scale in Figure 1-4.

The report has been written for a technical audience that is familiar with: the scope of the DGR project; the general characteristics of the Bruce site; and the process of assessing the long-term safety of a deep geologic repository.

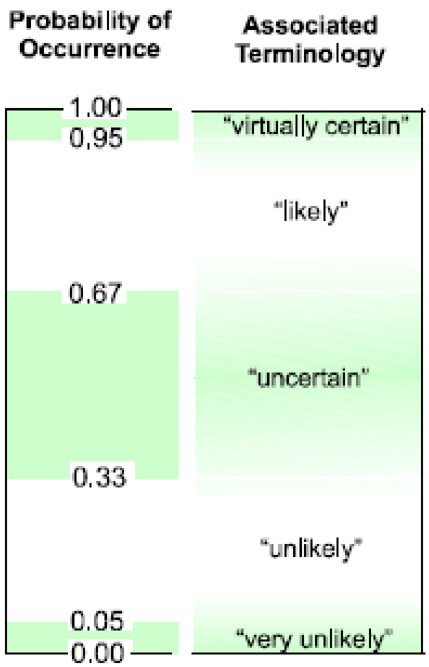



**Figure 1-4: Terminology Associated with Confidence that a Specified Event or Process will Occur (McMurry et al. 2003)**

# 2. DGR SYSTEM DESCRIPTION

The DGR system comprises the waste and its packaging, the engineered repository, the geological setting, and the surface environment. An overview of each of these components is presented in the following subsections which summarise the key features of the DGR system – further details are provided in the data report (Walke et al. 2009b). The primary data sources are:

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

## 2.1 WASTE

### 2.1.1 Categories and Characteristics

The DGR will accept operational and refurbishment L&ILW from OPG-owned nuclear power plants. No consideration is given to decommissioning wastes in this assessment since OPG is not seeking a licence to emplace decommissioning waste in the DGR. The DGR will not accept used nuclear fuel.

The L&ILW is categorised according to the characteristics of the waste (OPG 2008). These categories and the waste characteristics are summarised in Table 2-1 and Table 2-2.

Certain wastes will be conditioned prior to being sent to the DGR. The main waste conditioning practices undertaken by OPG are incineration (resulting in the generation of the bottom ash and baghouse ash) and compaction (resulting in the generation of compacted waste bales and boxes). In addition, the assessment assumes that steam generators from the planned refurbishment programmes will be filled with grout and cut into smaller sizes. In addition, some LLW has historically been conditioned by other methods, such as grouting with cement, immobilisation with bitumen, and the addition of polymeric absorbers. Cementitious grout has been or will be added to some ILW to provide mechanical support for waste retrieval and handling rather than as a waste conditioning agent. Since the proportion of wastes that has been/will be subject to such waste conditioning is small, such conditioning is not taken account in the assessment.

### 2.1.2 Packaging

The range of waste containers and overpacks that will be used by OPG for the storage and eventual disposal of L&ILW in the DGR is described in OPG (2008). It is recognised that, in practice, each waste category may use several types of waste containers and overpacks, and conversely each waste container/overpack may not be exclusive to a single waste category. However, Walke et al. (2009b) has identified the most common waste containers and overpacks for each waste category as “reference”, as summarised in Table 2-3.

**Table 2-1: Low Level Waste Categories**

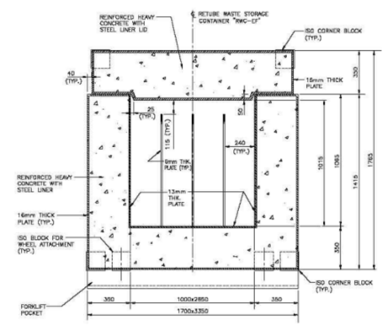
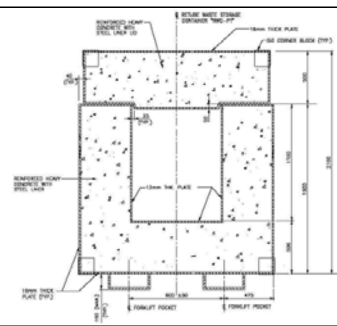
| Waste Category | Description |
|---|---|
| Bottom ash | Coarse (54 wt% > 9.5 mm) heterogeneous ash and clinker from waste incineration. |
| Baghouse ash | Fine (90 wt% < 0.8 mm) homogeneous ash from waste incineration, with low density. |
| Compacted wastes (bales) | Compacted waste. % by volume: paper 24%, plastic 37%, rubber 7%, cotton 4%, metal 15%, other organics 3%, other inorganics 10%. |
| Compacted wastes (boxes) | As compacted waste bales, but contained in a mild steel B25 compactor box. |
| Non-Processible (drums) | Metal, wood, concrete, glass, absorbent, etc. that cannot be processed. Generally, the bulk density is very low because of the low packing density of irregular objects. Waste contained in carbon steel drums. % by volume: metal 33%, absorbent 14%, paper 8%, plastic 5%, wood 7%, cotton 3%, rubber 2%, glass 2%, concrete 6%, other materials 19%. |
| Non-Processible (boxes) | As non-processible drummed waste, but contained in a sheet metal box. |
| Non-Processible (other) | Large and irregularly shaped objects such as heat exchangers, encapsulated tile holes, tile hole liners, miscellaneous large objects (e.g., fume hoods, glove boxes, processing equipment), reactor refurbishment large objects (e.g., pre-heaters, heat exchangers), and large objects retrieved from trenches. Most of these are metallic and would be emplaced "as is" in the DGR. OPG (2008) also provides specific data for feeder pipes, but these wastes are included in the non-processible (other) category for this Version 1 SA. |
| LLW Resins | Polystyrenedivinyl benzene copolymer ion exchange (IX) resin, approximately 0.5 mm in diameter, granulated active carbon and polymer beads. These arise from Bruce A/B auxiliary systems. |
| ALW Resins | Polystyrenedivinyl benzene copolymer IX resin, approximately 0.5 mm in diameter, arising from liquid effluent treatment plants. |
| ALW sludges | Sludge arising from liquid effluent treatment plant, contained in a box. Sludge contains a clay-based flocculant, comprised of a blend of clay minerals, polymers and pH adjusting agents. |
| Steam generators | Redundant steam generators from refurbishment. The steam generators consist of Inconel 600 tubes, carbon steel shell and shroud, and head and tubesheet. |

**Table 2-2: Intermediate Level Waste Categories**

| Waste Category | Description |
|---|---|
| CANDECON resins | Polystyrenedivinyl benzene copolymer IX resin, approximately 0.5 mm in diameter, containing EDTA and other chelating agents as well as corrosion inhibitor. |
| Moderator resins | Polystyrenedivinyl benzene resin beads, approximately 0.5 mm in diameter, from moderator system. Resins have sulfonic acid groups on the cation and quaternary ammonium groups on the anion. Generally the anion portion contains nitrate (37 g/l), carbonate and borate, whereas cation portions can contain up to 30 g/l of gadolinium. |
| PHT resins | Polystyrenedivinyl benzene resin beads, approximately 0.5 mm in diameter, from the Primary Heat Transport (PHT) system. Resins have sulfonic acid groups on the cation and quaternary ammonium groups on the anion. Generally the cation portion contains mostly iron and lithium, whereas the anion portion is mostly carbonate. |
| Misc. resins | Miscellaneous polystyrenedivinyl benzene resin beads. |
| Irradiated core components | The material is typically alloys such as Inconel-600 or stainless steel 304L and comprises items such as flux detectors and liquid zone control rods. |
| Filters and filter elements | Filters and filter elements from PHT and moderator streams. Filters are stainless steel and carbon steel permanent vessels containing resin impregnated pleated paper, honeycomb-wound viscose elements and epoxy impregnated fibreglass, and stainless steel disposable filters containing sintered stainless steel woven wire mesh. |
| IX columns | IX columns contain polystyrenedivinyl benzene resin from the Pickering PHT system. |
| Retube Waste (Pressure Tubes) | Zr-2.5%Nb alloy. |
| Retube Waste (End Fittings) | Stainless steel (SS-403). |
| Retube Waste (Calandria Tubes) | Zircaloy-2. |
| Retube Waste (Calandria Tube Inserts) | Stainless steel (SS-410). |

**Table 2-3: Reference Containers and Overpacks***

| Container name, wastes and overpack | Picture | Container name, wastes and overpack | Picture |
|---|---|---|---|
| Carbon steel ash bin (AIBN)<br>• Bottom ash<br>• Baghouse ash<br><br>Reference Overpack:<br>• LLW sheet metal overpack (BINOPK) |  | Mild steel bale rack (BRACK)<br>• Compacted waste (bales)<br><br>Reference Overpack:<br>• Not yet specified. Therefore the current SA does not take overpack into account |  |
| Mild steel compactor box (B25)<br>• Compacted waste (boxes)<br><br>Reference Overpack:<br>• None |  | Carbon steel drum bin (DBIN)<br>• Non-processible waste (drummed)<br><br>Reference Overpack:<br>• 10% overpacked in LLW sheet metal overpack (BINOPK) |  |
| Non-pro box (NBP47)<br>• Non-processible waste (boxes)<br><br>Reference Overpack:<br>• None |  | Low Level Resin Pallet Tank (RTK)<br>• ALW resins<br>• LLW resins<br><br>Reference Overpack:<br>• Not yet specified. Therefore the current SA does not take overpack into account |  |

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

### 2.1.3 Volumes

The final volume of L&ILW to be disposed in the DGR has been estimated by OPG according to several scenarios, capturing the influence on waste arisings of key decisions concerning the potential operating life of CANDU reactors at Bruce, Pickering and Darlington. The most recent estimates are presented by OPG (2008) and are adopted here.

The estimated volumes are presented in Table 2-4. The raw or net volume refers to the waste material itself, whereas the disposal volume is the volume occupied by the waste packages in the repository including an allowance for the waste containers and any overpacks.

**Table 2-4: Waste Volumes to be Disposed (OPG 2008)**

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

### 2.1.4 Contaminants and Other Materials

A large number of radioactive and non-radioactive species are present in L&ILW wastes, but most of these are present in small amounts and only a subset need to be considered in safety assessment calculations. Screening calculations have been conducted that included the full set of contaminants identified in the 2008 inventory (OPG 2008), and identified potentially important contaminants for consideration in the safety assessment (Walke et al. 2009b). Table 2-5 summarises the total amounts of radionuclides and chemical species in the LLW and ILW considered derived from data presented for each waste category in Walke et al. (2009b).

**Table 2-5: Amounts of Radionuclides, Elements and Chemical Species in Waste for which Safety Assessment Calculations are Undertaken**

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

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

Table 2-6 summarises the amount of organics, metals and concrete in the wastes and their containers and overpacks.

**Table 2-6: Amounts of Organics, Metals and Concrete in Wastes and their Containers and Overpacks**

| Material | | Amount (kg) | | | |
|---|---|---|---|---|---|
| | | LLW | | ILW | |
| | | Wastes | Containers and Overpacks | Wastes | Containers and Overpacks |
| Organics | Cellulose | 8.5E+06 | - | - | - |
| | Rubber and Plastics | 7.7E+06 | 2.1E+05 | - | - |
| | Resins | 1.5E+06 | - | 4.3E+06 | - |
| Metals | Carbon steel | 3.6E+06 | 2.9E+07 | 2.2E+06 | 2.7E+06 |
| | Stainless steel | 1.6E+06 | 2.8E+06 | 2.4E+06 | 1.0E+07 |
| | Zircaloy | - | - | 6.1E+05 | - |
| Concrete | | 9.2E+05 | 3.5E+06 | - | 6.2E+07 |

## 2.2 REPOSITORY

The reference repository design is described in Hatch (2008). Key points relevant to the safety assessment are described below.

The reference depth for the repository floor is 680 m below ground surface in competent and tight limestone (the Cobourg Formation).

The repository comprises two shafts, a ring tunnel and associated facilities, two access tunnels and 45 waste emplacement rooms (30 rooms[1] in the South Panel and 15 rooms in the East Panel) (Figure 2-1).

### 2.2.1 Construction and Physical Layout

2.2.1.1 Shafts

Access to the repository will be by shaft. A Main Shaft will be used to transfer waste packages from receipt facilities on the surface to the repository and to supply conditioned air to the repository. A Ventilation Shaft will be provided to allow routing of air away from underground operations. The Main and Ventilation Shafts will have 6.5 m and 4.5 m finished inside diameters, respectively.

The shafts will be excavated from the ground surface down to 710 m using the following techniques:

[1] 28 emplacement rooms are considered in Hatch (2008). However, the volumes of LLW specified in the 2008 inventory report (OPG 2008) require an additional two rooms to be added.

- backhoe and muck skips hoisted to the surface by a crane for 0 to 20 m below ground surface (bgs);
- standard drill and blast techniques to 411 m bgs; and
- mechanical excavation using a vertically-oriented road header for the remainder, in order to minimise the size of the excavation damaged zone (EDZ).

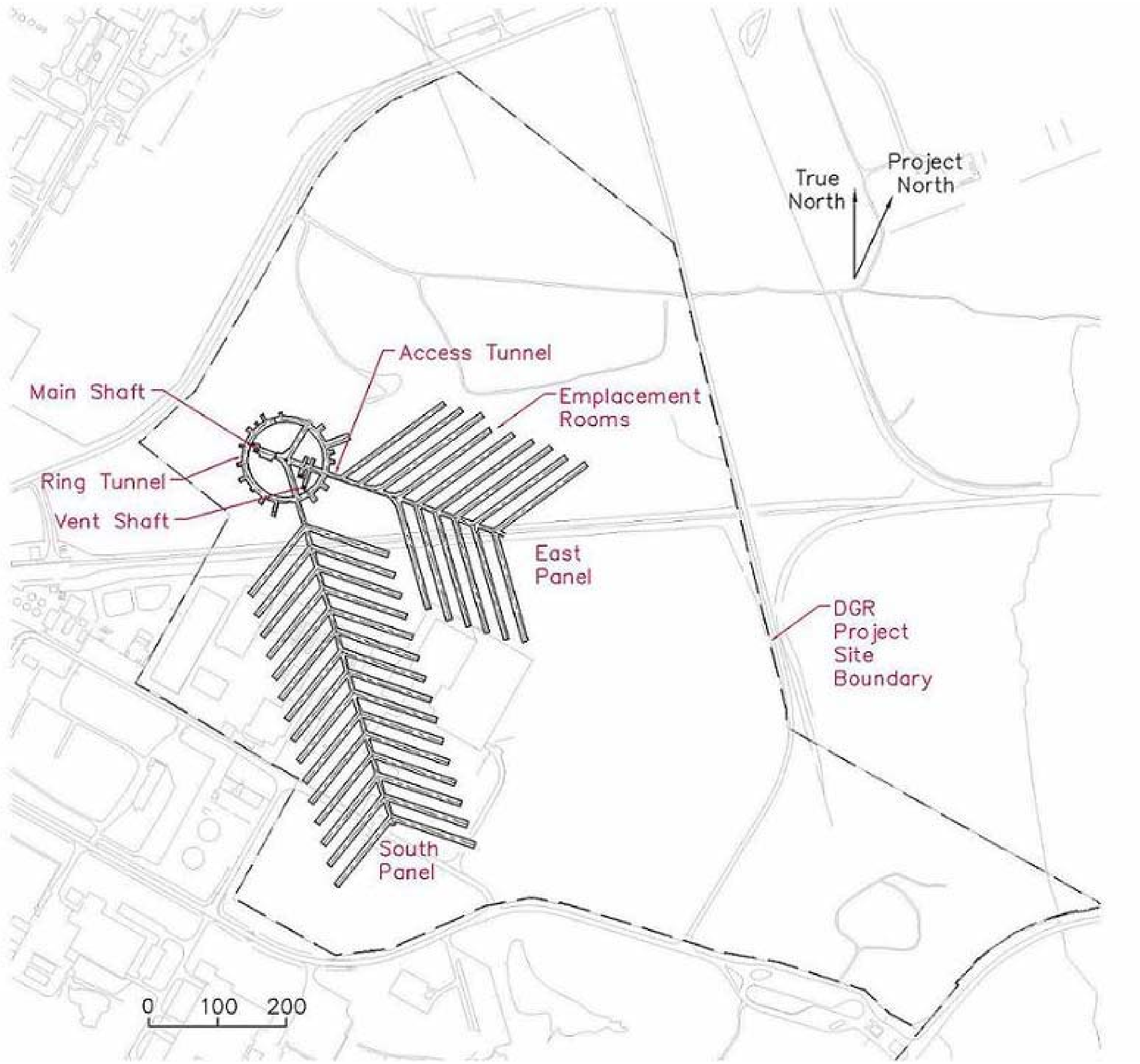



**Figure 2-1: General Layout of the Repository (Hatch 2008)**

The shafts will be concrete-lined to limit potential water inflow during construction and operation. It is anticipated that water inflow to the repository will be negligible during construction and operation and that any moisture will be carried by the ventilating air to the surface.

2.2.1.2 Ring Tunnel and Associated Facilities

The shafts will be located on a central ring tunnel from which the two access tunnels will radiate out to the emplacement rooms to the south and east, as shown in Figure 2-2. Underground support facilities (offices, workshops, refuge bays, maintenance areas, etc.) will be located on the ring.

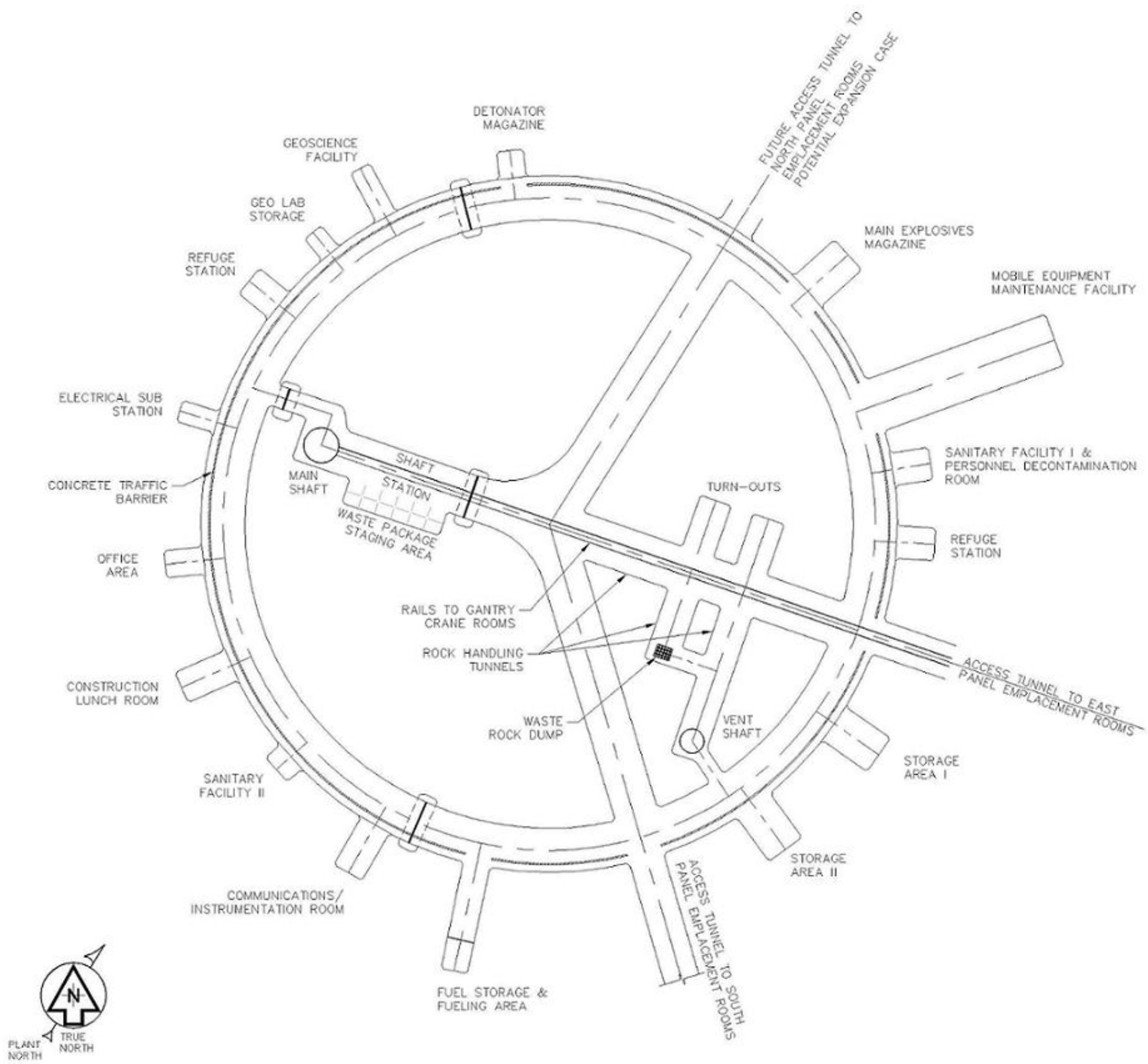



**Figure 2-2: Layout of the Ring Tunnel (Hatch 2008)**

The ring tunnel and its facilities (together with the access tunnels and emplacement rooms) will primarily be excavated using roadheaders. They will have concrete floors (typically 0.2 m thick), with shotcrete on the ceilings and extending half-way down the walls and rockbolts will be placed in the ceiling to provide roof support. Steel wire mesh, held in place by rock bolts, will be used in place of shotcrete in localised areas if rock conditions are favourable.

Waste packages destined for the South Panel of emplacement rooms will be moved using forklift trucks. Most of the waste packages destined for the East Panel will be similarly moved, but some will be of sufficient size and weight to require movement on rail cars towed by a forklift truck. A railway line will therefore run from the Main Shaft to the access tunnel for the East Panel. The concrete floor will be 0.6 m thick along the edges of this tunnel to accommodate embedded rails.

#### 2.2.1.3 Access Tunnels and Emplacement Rooms

Access to the emplacement rooms in the South Panel will be via a 6.5 m wide by 7 m high tunnel of length 488 m positioned on the southern side of the ring tunnel. There will be 30 emplacement rooms (see Figure 2-1). Each of the emplacement rooms will be 123.9 m in length, 8.6 m wide and 7 m high.

Access to the East Panel emplacement rooms will be via a 6.5 m wide by 7 m high tunnel of length 273 m positioned on the eastern side of the ring tunnel. A rail line will run the whole length of the access tunnel. There will be 15 emplacement rooms (see Figure 2-1). The emplacement rooms will be divided into six sizes (E-A, E-B…to E-F) with varying lengths (162.3 - 185.5 m), widths (7.4 - 8.6 m) and heights (5.7 - 7.2 m).

All access tunnels and emplacement rooms will be ventilated, with incoming flow through the bulk volume and return air flow ducted back to the exhaust Ventilation shaft.

### 2.2.2 Waste Emplacement

All LLW categories except steam generators and non-processible (other) categories will be placed in the South Panel. Since the LLW containers are generally rectangular and in standard modular sizes, emplacement will be easy to perform and emplacement rooms will be filled with waste and closed sequentially. Typical packing arrangements are shown in Figure 2-3. Overall packing efficiencies of 63% by volume are anticipated (Hatch 2008).

All ILW and large-size LLW will be placed in the East Panel. Six sizes of emplacement room are envisaged, with each type being used for the placement of particular types of waste package. The two E-A rooms will contain the shield plug containers and heat exchangers, whereas the single E-E room will accommodate the steam generators. These large items require in-room handling using a gantry crane, and rail lines to support it will run the whole length of the rooms concerned. The concrete floor will be 0.6 m thick along the edges of these rooms to accommodate embedded gantry crane rails. Forklift trucks will be used to emplace the other types of waste package.

Details of stacking layouts for the six sizes of emplacement room are given in Hatch (2008), and some are illustrated in Figure 2-4 and Figure 2-5. Overall packing efficiencies of 43% by volume are anticipated for placement of containers, although efficiencies range from 15% to 67% for individual rooms.

The total amount of concrete and steel associated with the emplacement rooms, and access and ring tunnels has been estimated to be 43,000 tonnes and 2,300 tonnes, respectively (Walke et al. 2009b).

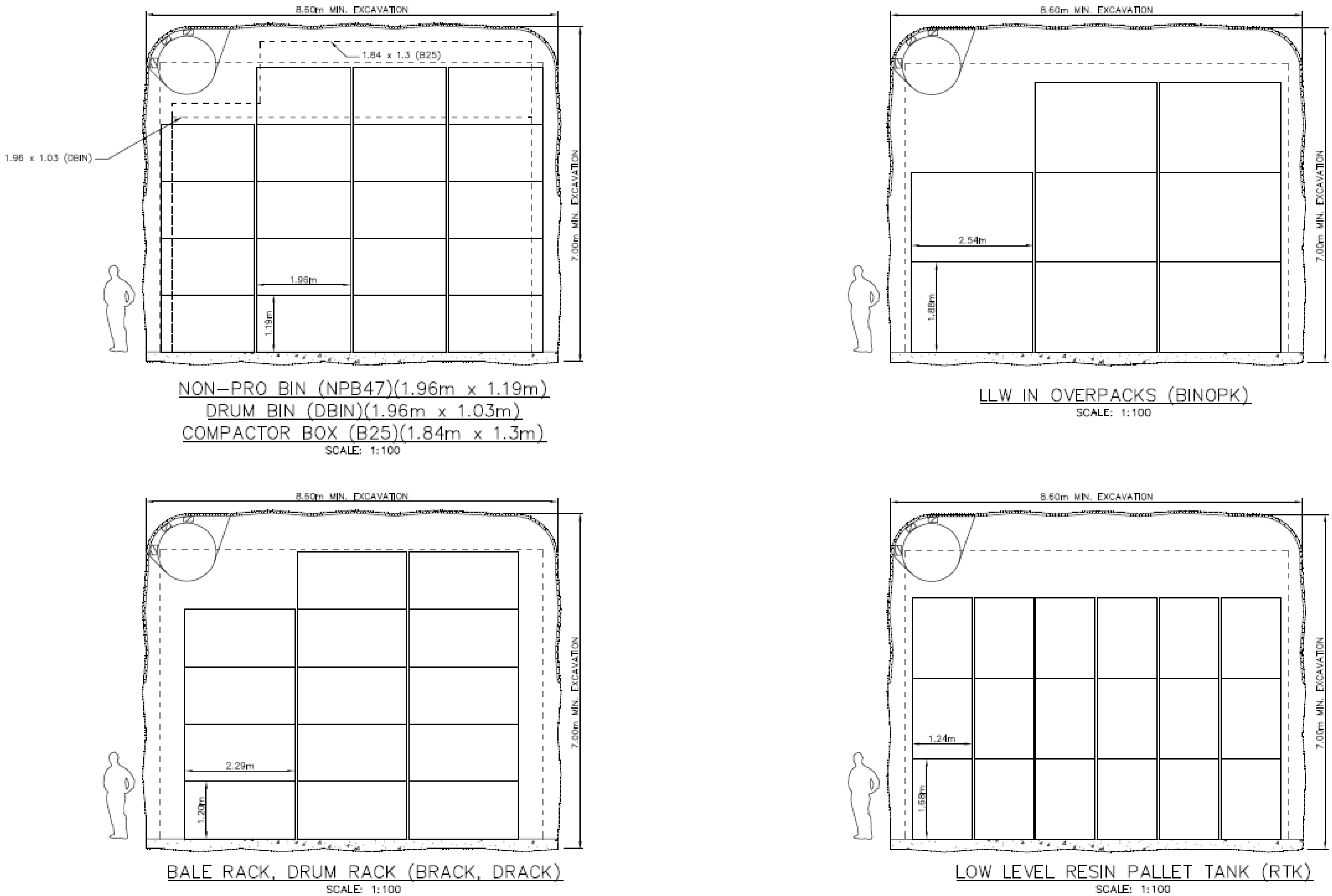



**Figure 2-3: Stacking Arrangements for Standard LLW Packages in the South Panel (Hatch 2008)**

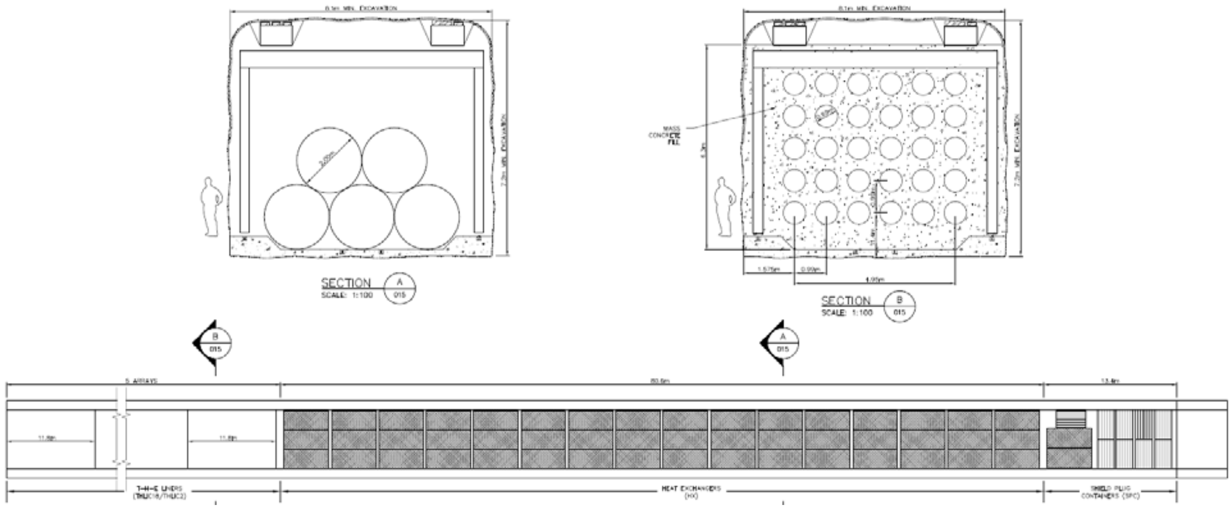



**Figure 2-4: Stacking Arrangements for E-A Emplacement Rooms in the East Panel (Hatch 2008)**

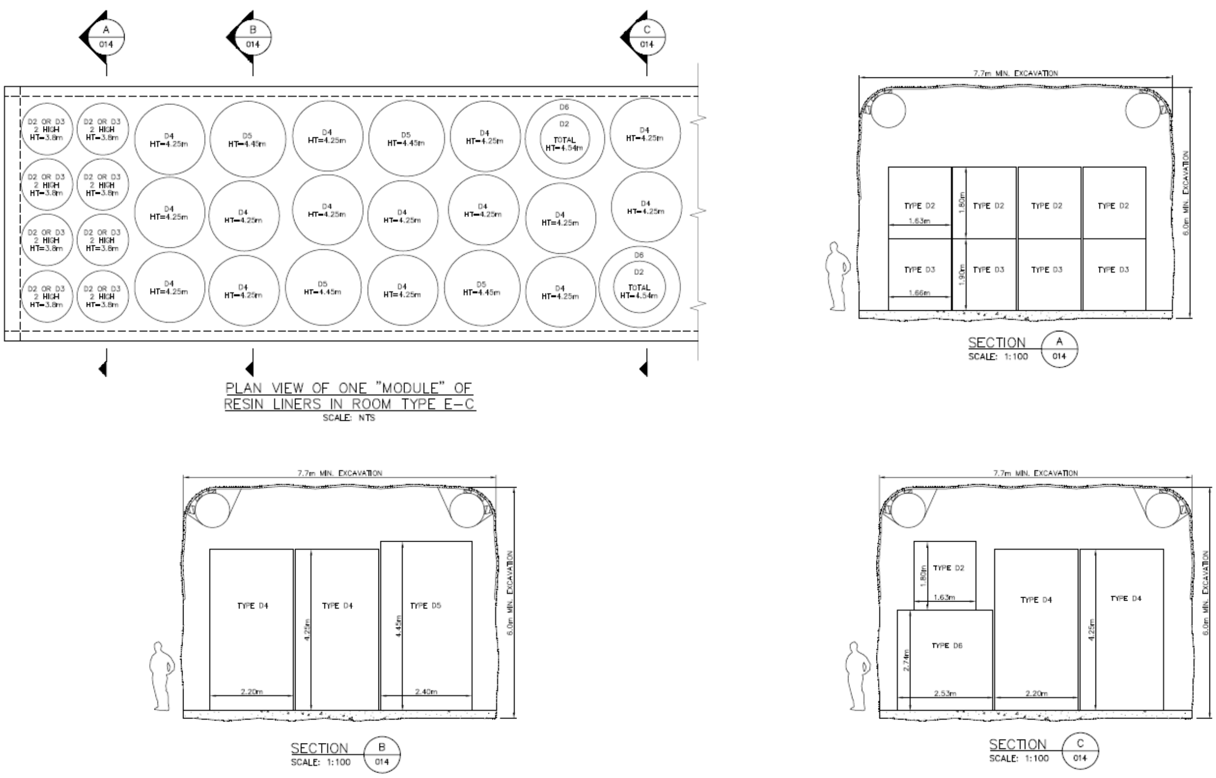



**Figure 2-5: Stacking Arrangements for E-C Emplacement Rooms in the East Panel (Hatch 2008)**

### 2.2.3 Closure

#### 2.2.3.1 Emplacement Rooms

Once an emplacement room has been filled with waste, closure panels will be constructed. These will be reinforced concrete walls designed to provide a secure, relatively air-tight seal to the room. A pressure- and fire-resistant door system will be installed to provide access to and security of the closed room. The rooms will remain ventilated during the operating lifetime of the repository: openings for ventilation (in and out) will be installed in the closure panels.

The emplacement rooms will not be backfilled, and the ventilation ducts will remain in the rooms on closure of the repository.

#### 2.2.3.2 Access Tunnels

The access tunnels will not be backfilled, and the ventilation ducts and rail lines will remain in the tunnels. In addition, all steelwork and furnishings will be removed from the Ventilation Shaft and emplaced in the access tunnels. All infrastructure connections (power, ventilation and water) to the panels will be disconnected and the access tunnels will be sealed, preventing further entry to the Panels. No details are given in Hatch (2008) as to the nature or location of any seals in the access tunnels, so it is assumed in this safety assessment that there are no seals present.

#### 2.2.3.3 Ring Tunnel and Associated Facilities

Any equipment that has been used within the ring tunnel will remain in the repository and all infrastructure connections (power, ventilation and water) to the panels will be disconnected. Any vehicle fuels and explosives will be removed to the surface.

#### 2.2.3.4 Shafts

Decommissioning of the shafts will consist of: the removal of shaft infrastructure; the removal of the concrete shaft liner from the base of the shaft sumps up to 183 m bgs; and the installation of a shaft seal comprised of a sequence of sealing materials. The Ventilation Shaft will be decommissioned and its seal installed before the same operation is carried out on the Main Shaft.

The shaft seal design assessed is illustrated in Figure 2-6 and described in the data report (Walke et al. 2009b) and comprises[2]:

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

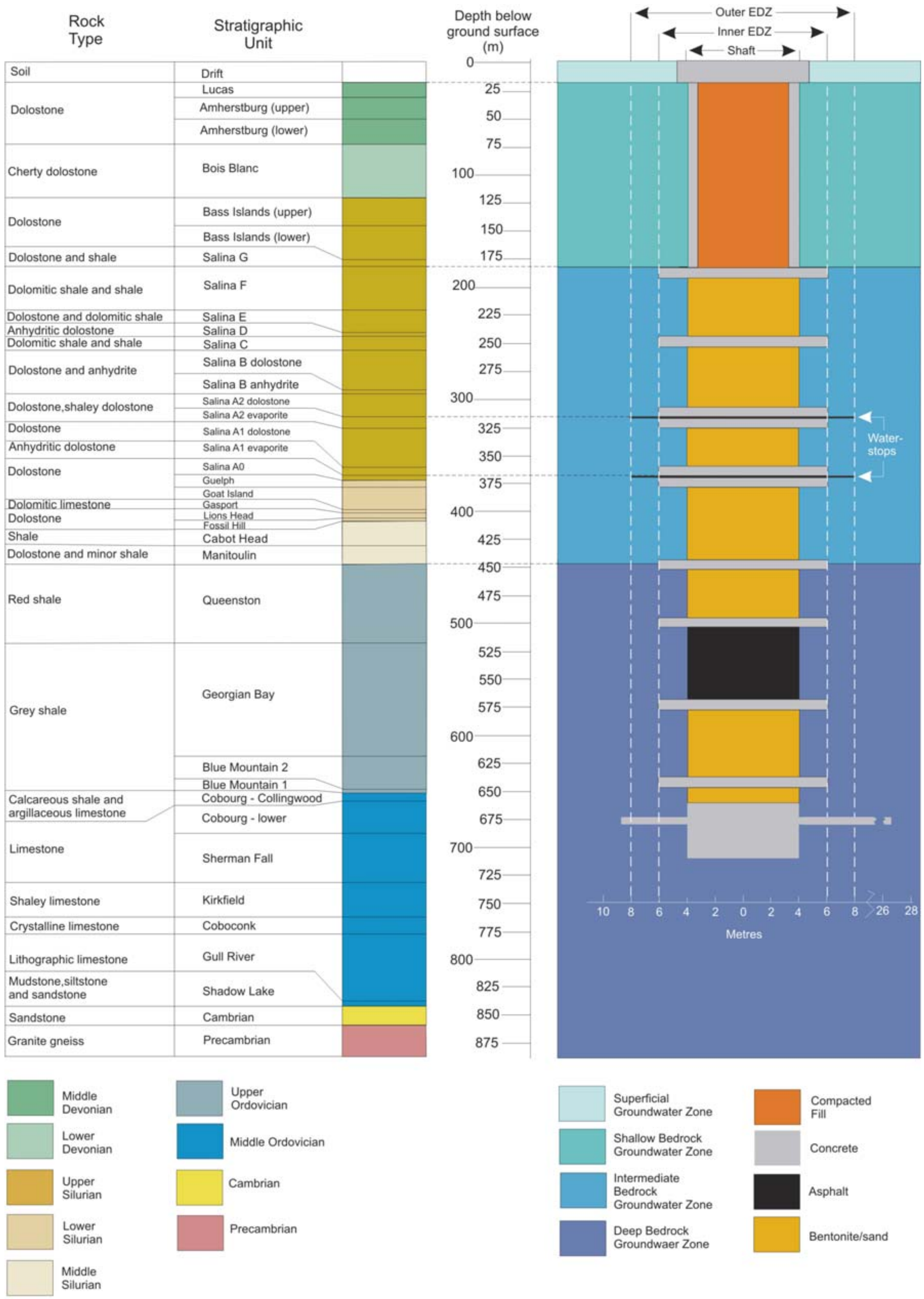



**Figure 2-6: Illustration showing Sequence of Shaft Sealing Materials**

- a **concrete monolith** that will be placed at the base of each shaft;
- a sequence of 11 **concrete bulkheads** in the shaft, all but one of which will be keyed into the rock surrounding the shaft to a radial distance equal to half the radius of the shaft[3]; and
- **backfill** between the concrete bulkheads, which with the exception of the asphalt waterstops (see below) will not be keyed into the surrounding rock. A 70:30 **bentonite/sand** mix will be used between the majority of bulkheads. It will be emplaced dry in the shaft and compacted. **Asphalt** will also be used in the lower shaft and at the top of the Salina A0 and Salina A2 evaporite zones. The two asphalt layers in the evaporite zones will act as waterstops and will be keyed into the rock surrounding the shaft to a radial distance equal to the radius of the shaft. The backfill in the upper shaft will be compacted **engineered fill** derived from crushed rock obtained during shaft excavation.

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

## 2.3 GEOLOGICAL SETTING

The nature of the geosphere of the Bruce site and wider region is described in detail by the 'Geosynthesis' reports: Damjanac (2008); Gartner Lee (2008a,b,c); Hobbs et al. (2008); and Sykes et al. (2008). This section provides a summary of the geological setting to provide context for the analysis of the geosphere system evolution that underpins the safety assessment. The reader is referred to the Geosynthesis reports for a more detailed description of the geological setting, geological history and geosphere processes. The geological history and analysis of geosphere processes described within the Geosynthesis reports form an important input into the analysis of the future evolution of the geosphere system.

An overarching conclusion that can be drawn from the Geosynthesis reports is the favourable nature of the geosphere at the Bruce for geological disposal: stable tectonic setting; simple predictable geology; large thickness of very impermeable rock; absence of transmissive features such as faults; geochemical and hydrogeological evidence for very low rates of groundwater flow and hydraulic isolation at depth; and suitable mechanical properties for the successful development of stable excavations and sealing of access shafts. Key evidence in support of this overarching conclusion is presented in this section.

### 2.3.1 Geology

The proposed repository location is on the eastern edge of the Michigan Basin (Figure 2-7). The Michigan Basin is a 'bulls-eye' basin, filled with over 4 km thickness of Palaeozoic sedimentary rocks that gently dip towards the centre of the basin. The basement comprises Precambrian granitic gneiss. The Palaeozoic sedimentary sequence comprises Cambrian sandstones overlain by Ordovician, Silurian and Devonian limestones, shales, dolostones and dolomitic

[3] The concrete bulkhead in the Shallow Bedrock Groundwater Zone will not be keyed into the rock (Hatch 2008).

limestones and evaporites. Figure 2-8 shows the bedrock geological map, for the region around the DGR site, and Figure 2-9 shows a cross-section through the Michigan basin. Data from the DGR-2 borehole at the DGR site are shown in Figure 2-9.

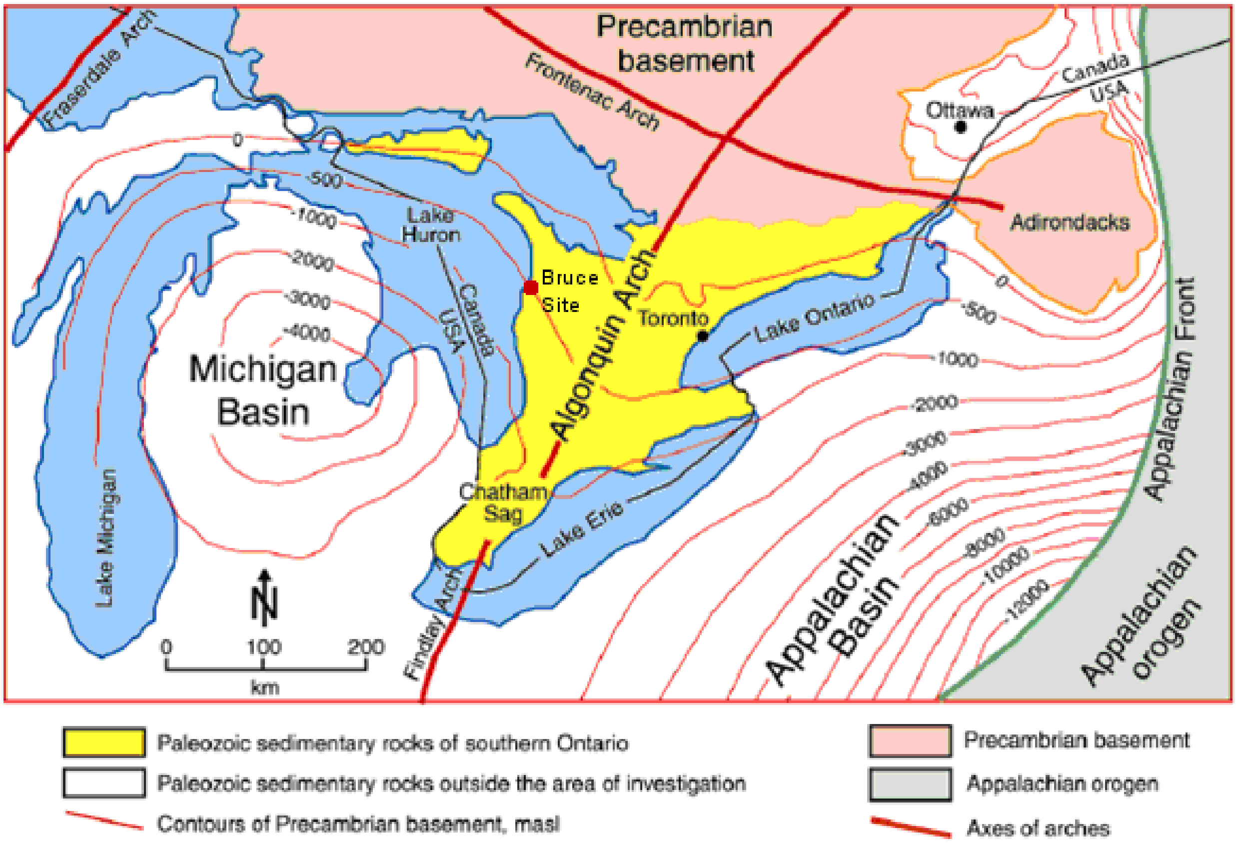



**Figure 2-7: Large-scale Tectonic Elements in Southern Ontario[4] (Gartner Lee 2008a)**

[4] Note masl = metres above sea level.

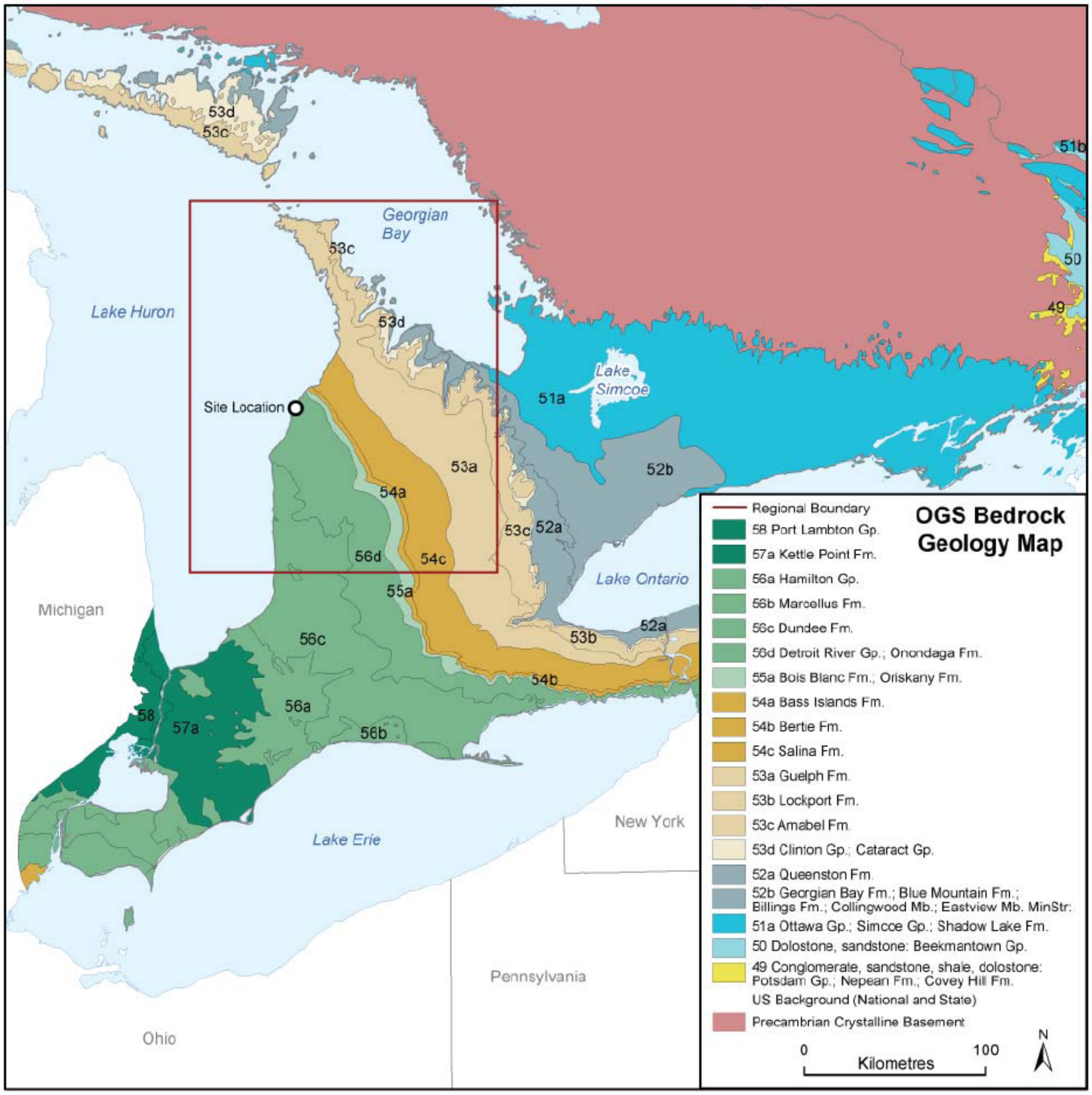



**Figure 2-8: Geologic Map of Southern Ontario (Gartner Lee 2008a) (Note that the boundary of the regional study area considered by Gartner Lee 2008a is marked)**

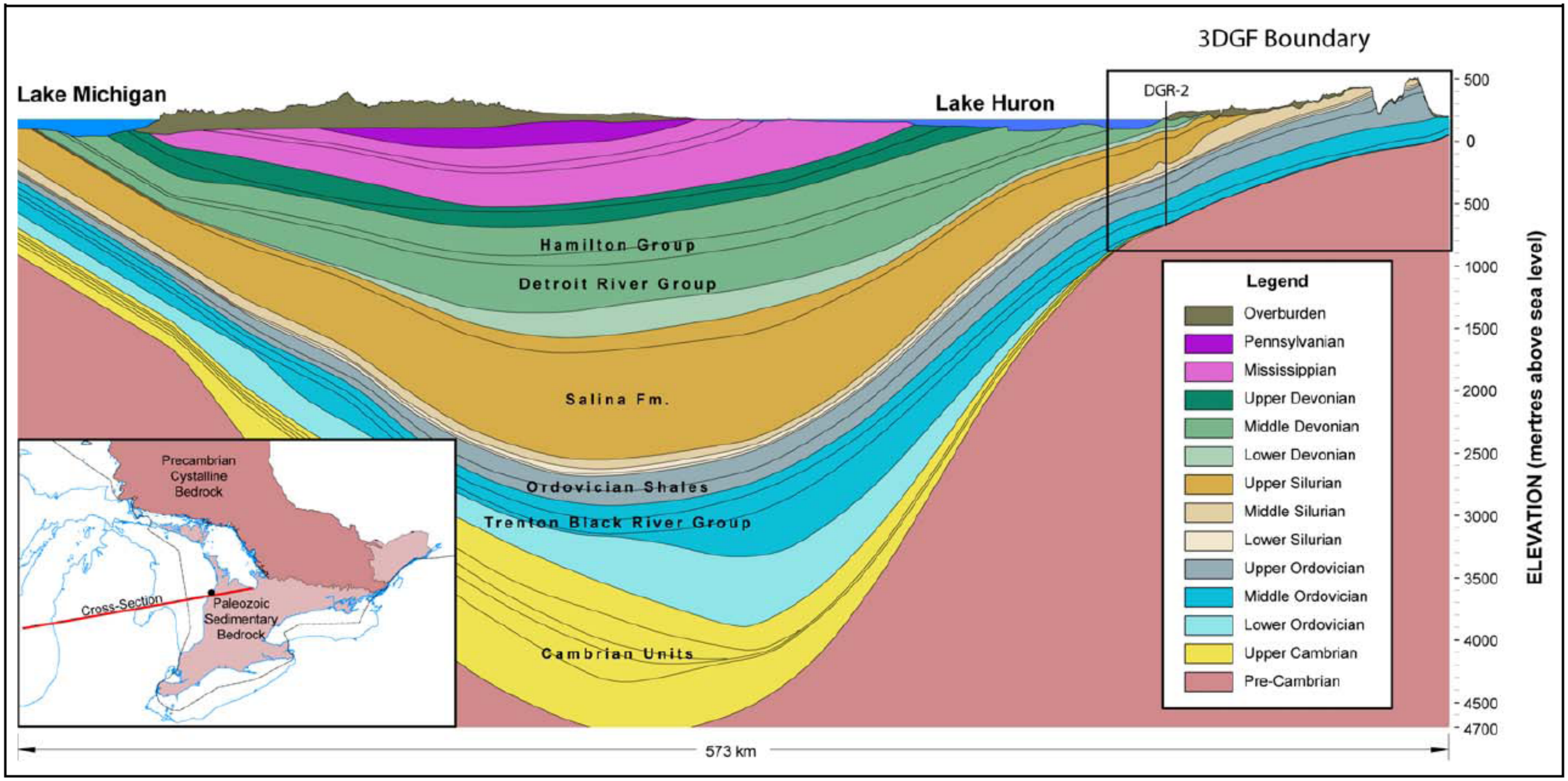



**Figure 2-9: Cross-section across the Michigan Basin (Gartner Lee 2008a) (The DGR-2 borehole at the Bruce site and the boundary of the 3D Geological Framework model of Gartner Lee 2008a are marked)**

The rocks forming the eastern side of the basin have been folded along a southwest to northeast axis, forming the Algonquin Arch (Figure 2-7). The arch existed as a basement high during deposition of Cambrian sediments and persisted throughout most of the Palaeozoic Era. The arch acted as a major structural control on depositional patterns, rising and falling with respect to the Michigan and Appalachian basins in response to vertical epeirogenic movements and horizontal tectonic forces (Gartner Lee 2008a). This structural control resulted in thinning, pinchouts, and erosional truncation of stratigraphic units as they approach and pass over the arch. Where the Algonquin Arch meets the northerly trending Findlay Arch there is a structural depression known as the Chatham sag. To the northeast the Frontenac Arch forms the pinchout margin of the sedimentary section of Southwestern Ontario.

The DGR site is located within the Bruce Megablock, a structural domain identified within the sedimentary sequence overlying the Precambrian basement. The Bruce Megablock is bounded to the west by the Grenville Front Tectonic Zone (GFTZ), the Niagara Megablock to the south, and the Georgian Bay Linear Zone to the east (Figure 2-10). The GFTZ has been tectonically stable for the last 1000 Ma, and therefore has not affected the deposition or structure of the overlying younger Palaeozoic rocks (Gartner Lee 2008a).

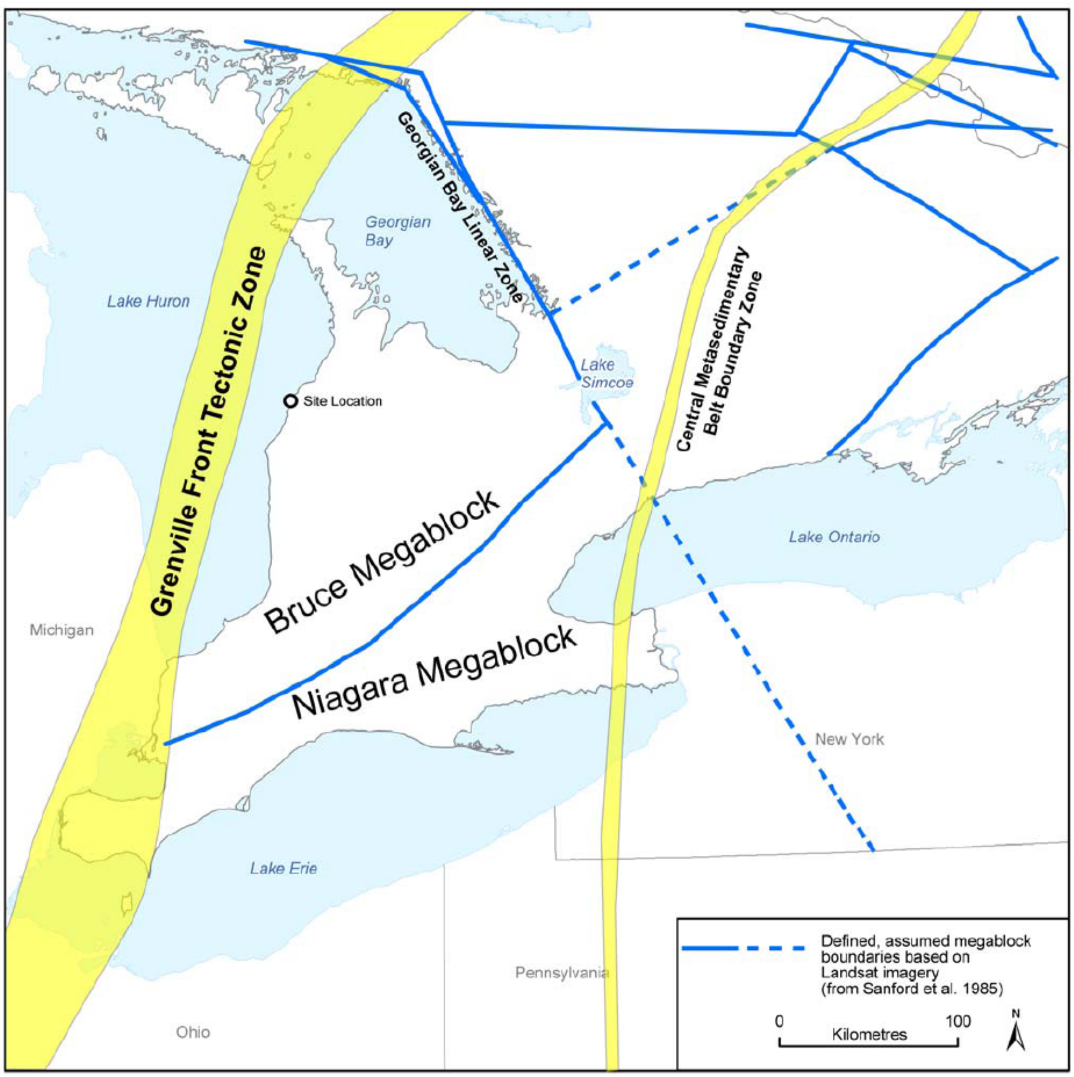



**Figure 2-10: Major structural boundaries of Southern Ontario (Gartner Lee 2008a)**

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

### 2.3.2 Stratigraphy

The Palaeozoic bedrock sequence overlying Precambrian granitic basement has been measured to be over 800 m thick in the DGR site investigation boreholes (Gartner Lee 2008a). It comprises (from top to bottom) (Figure 2-11):

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

Unconsolidated ('overburden') sediments overlie this bedrock sequence. These sediments are comprised of a comparatively complex sequence of Quaternary surface sands and gravels from former beach deposits (associated with Lake Huron) overlying clayey-silt to sandy silt till of glacial origin with interbedded lenses and layers of sand of variable thickness and lateral extent. The total thickness of this overburden varies from less than 1 m along the shore of Lake Huron to a maximum of about 20 m above the DGR site.

### 2.3.3 Hydrogeology

#### 2.3.3.1 Regional

A hydrogeological conceptual model has been developed by Sykes et al. (2008) for Southwestern Ontario. The conceptual model formed the basis for regional-scale groundwater modelling within a portion of Southwestern Ontario centred on the DGR site. Three groundwater domains are identified in this model: a shallow zone characterised by Devonian-aged formations which have a higher permeability and contain groundwaters with a relatively low Total Dissolved Solids (TDS) content; an intermediate zone which consists of Silurian formations, including low permeability shales and evaporite units in which the TDS content increases with depth; and a deep groundwater zone within the Ordovician shales and limestones, Cambrian sandstones (where present), and the Precambrian basement with a high TDS content. (Note that the Cambrian sandstones are discontinuous and pinch-out against the Precambrian basement). The superficial aquifer system represented by unconfined, semi-confined and confined aquifers present in the Quaternary glacial drift sediments can also be considered to be part of the shallow flow system in the regional model (Sykes et al. 2008).

In general, modern recharge infiltrates topographic highs, such as glacial moraines and the spine of the Algonquin Arch, and migrates through glacial drift and shallow bedrock aquifers, to ultimately discharge into topographic lows, such as streams and lakes. Modern groundwater flow in the Great Lakes region is primarily restricted to the shallow unconfined glacial drift aquifers (McIntosh and Walter 2006; Hobbs et al. 2008).

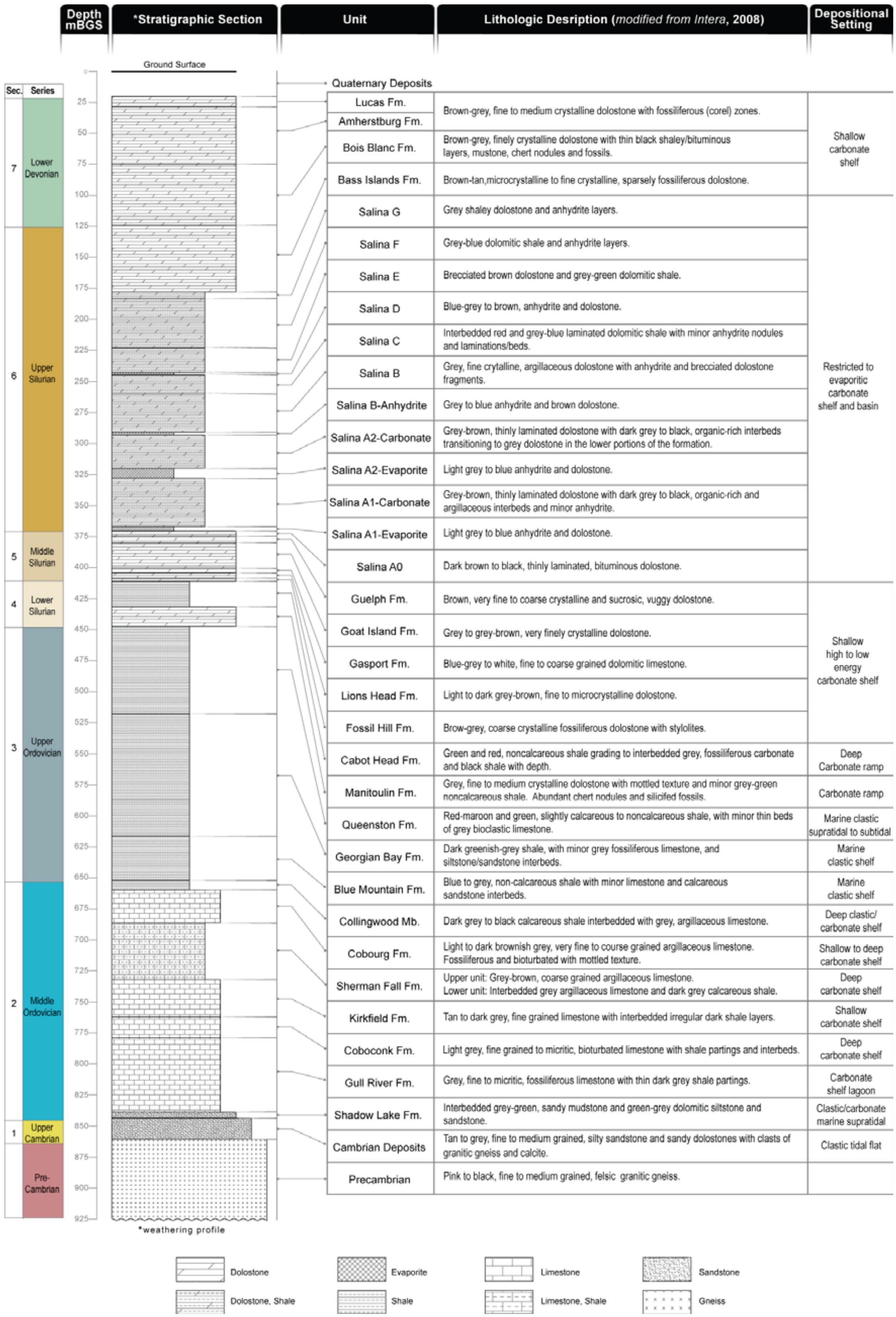



**Figure 2-11: Geological Stratigraphy at the DGR Site (Gartner Lee 2008c)**

The direction of groundwater flow in the shallow Devonian bedrock and glacial aquifers is gravity-driven and topographically controlled (Sykes et al. 2008). However, the low topographic gradients and high salinity of underlying basin formation waters prevent deep circulation of meteoric waters. In the intermediate and deep groundwater zones, the only potential location for groundwater recharge or discharge is along the bands along which these formations outcrop. Fresh water infiltrating into these zones is likely to have a major component of flow parallel to the strike of the formations because i) the density of the shallow waters in the bedrock are substantially higher than that of fresh water and they are therefore not easily displaced; ii) the absence of discharge areas in the basin, and therefore very low hydraulic gradients (Sykes et al. 2008; Mazurek 2004); and iii) the hydraulic conductivity rapidly decreases at the base of the shallow system.

#### 2.3.3.2 Local

At the local or site-scale, the same groundwater zones are considered as in the regional model, except that the surficial groundwater zone is explicitly considered.

- **The Surficial Deposits (Overburden) Groundwater Zone** – the overburden sediments in which fresh water enters the groundwater system from precipitation through the recharge zone and flows vertically downwards into the underlying Shallow Bedrock Groundwater Zone. Layers of sand and gravel constitute local aquifers whereas the till layers comprise aquitards.
- **The Shallow Bedrock Groundwater Zone** – the Devonian and Upper Silurian dolostone sequence of the Lucas, Amherstburg, Bois Blanc and Bass Islands Formations and the top of the Salina Formation (Salina G). The direction of groundwater flow is westward to a point of nearshore discharge in Lake Huron.
- **The Intermediate Bedrock Groundwater Zone** – includes the dolostone and shale sequence of the Salina, Guelph, Goat Island, Gasport, Lions Head, Fossil Hill, Cabot Head and Manitoulin Formations. The formations are dominantly of low permeability, movement of pore water is very slow and mass transport is considered to be diffusion dominated. However the Guelph, Salina A0 and Salina A2 evaporite are relatively more permeable. Total dissolved solids (TDS) increases with depth through the zone.
- **The Deep Bedrock Groundwater Zone** – is associated with the low permeability Ordovician shales and limestones and the underlying Cambrian sandstones and Precambrian granitic gneiss. Within the sediments, movement of pore water is very slow and mass transport is considered to be diffusion dominated. The repository is located in the Deep Bedrock Groundwater Zone at a depth of 680 m within the Cobourg Formation (argillaceous limestone).

Groundwater flow within the surficial deposits and bedrock of the area around the DGR site is directed generally northwestward toward Lake Huron, generally subparallel to the well-established surface drainage pattern shown in Figure 2-12. The groundwater levels in the bedrock beneath the Western Waste Management Facility (WWMF) on the Bruce Site occur between about 8 m to 10 m below ground surface. The bedrock water levels (i.e., those in the Shallow Bedrock Groundwater Zone) rise to levels above the bedrock indicating artesian conditions with respect to the bedrock surface.

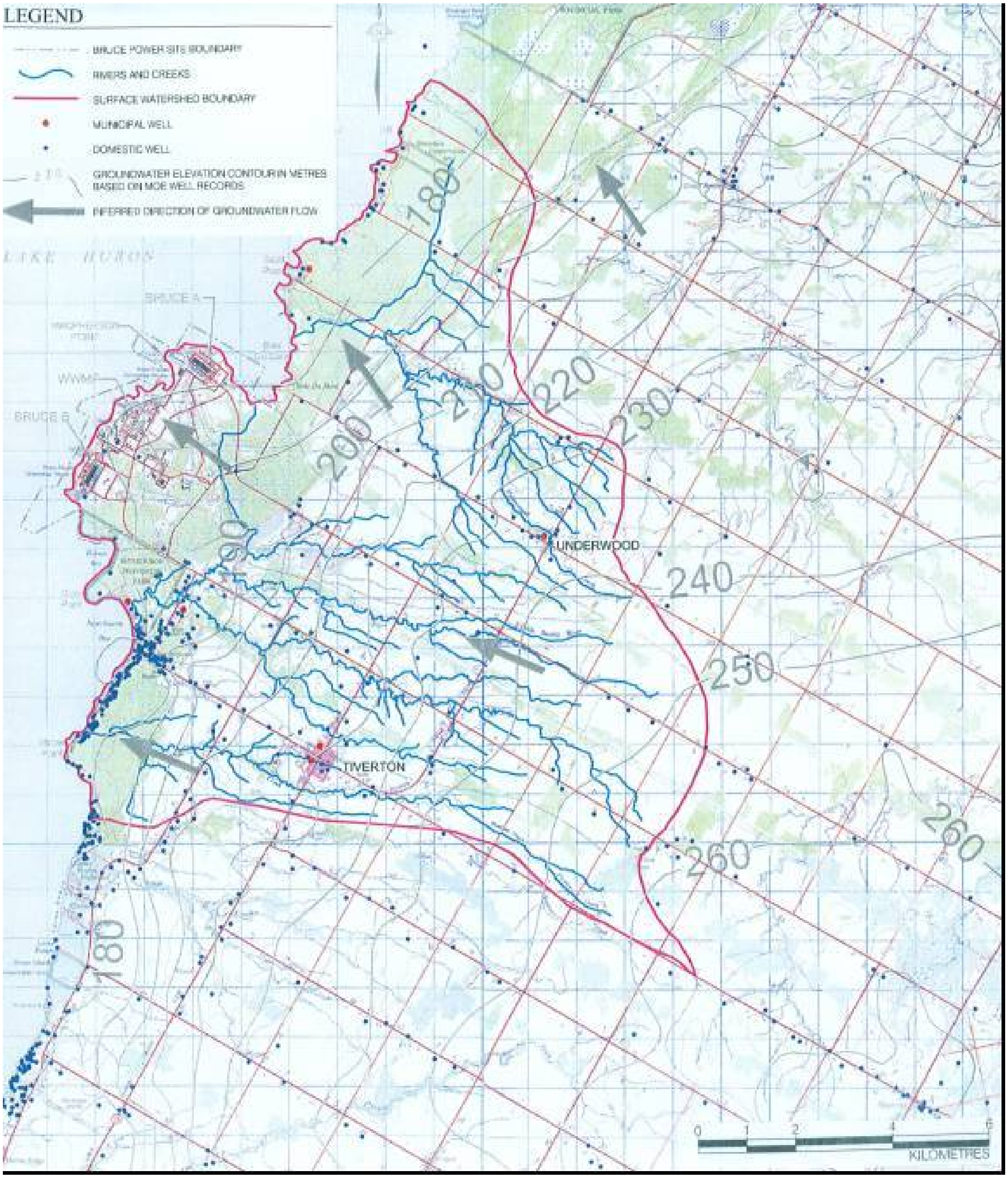



**Figure 2-12: Groundwater Levels (mASL) and Direction of Shallow Groundwater Flow in the Regional Study Area (OPG 2005)**

Figure 2-13 shows the hydraulic conductivity profile measured at the DGR site based on data from the on DGR-1 and DGR-2 site investigation boreholes (DGR 2009). The majority of the formations within the Intermediate and Deep Bedrock Groundwater Zones have very low hydraulic conductivities. These very low hydraulic conductivities are reflected in the trapping of hydrocarbons by equivalent formations elsewhere in the Michigan Basin: with the major regional hydrocarbon producing horizon being the “Niagaran Play” in Southwestern Ontario. Only trace hydrocarbons are present at the DGR site, with the equivalent formations to the Niagaran Play being the Salina A0 Formation through to the Fossil Hill Formation.

Further site investigations, including in particular boreholes DGR-3 and DGR-4, have indicated that the host rock conductivities are likely to be even lower. A revised geosynthesis report based on this and other new information was not available when the V1 safety assessment was in preparation. Consequently a base case geosphere has been conservatively defined based on the DGR-1 and DGR-2 hydraulic conductivities, while an alternative updated geosphere case has been defined using lower conductivities derived from initial measurements from the DGR-3 and DGR-4 boreholes.

Geochemical evidence (Hobbs et al. 2008) indicates that glacial or younger recharge is most often identified in shallow (<130 m) environments. Some of the lower permeability till deposits contain waters of glacial age that were trapped when the sediments were deposited. Salinity and hence the groundwater age increases with depth in the Shallow Bedrock Groundwater Zone. (Salinity continues to increase from the base of the Shallow Bedrock Groundwater Zone, through the Intermediate Bedrock Groundwater Zone, to the top of the Deep Bedrock Groundwater Zone).

Based on geochemical evidence presented in Hobbs et al. (2008), the porewaters in the deep and intermediate zones are considered to be very old, confirming the stability of these zones, consistent with their very low hydraulic conductivities. From this evidence, Hobbs et al. (2008) infer the brines in the deep and intermediate zones to be 250 million years old (see below), and hydrocarbons have remained trapped for more than 200 million years. However, the majority of these data are from producing oil and gas wells across the wider region, and therefore are subject to a degree of sampling bias towards geological traps. Groundwater age data are not available for the DGR site at the time of writing this report, but similar conclusions are expected.

Given the very low hydraulic conductivities of the intermediate and deep zones, the trapping of hydrocarbons (including gas) within these zones, the history of ice-sheet loading and unloading of the ground, and the erosion history, it is reasonable to expect that heads in the Deep and Intermediate Bedrock Groundwater Zones will not be in equilibrium with the present-day surface environment. This expectation is confirmed by groundwater head data from two site investigation boreholes drilled at the DGR site (DGR-1 and DGR-2 in Figure 2-11), which show a complex pattern of excess and deficient heads (Figure 2-14).

The specific cause(s) of the head profile are currently being investigated. Transient palaeoclimate simulations undertaken by Sykes et al. (2008) considered glacial loading and unloading, and injection of meltwaters during the Laurentide glacial eposide (~120 ka to 10 ka Before Present (BP)) based on the NN9930 model of Peltier (2008). It was found that glacial meltwaters did not penetrate below the top of the Salina F unit, which is consistent with the geochemical evidence (Hobbs et al. 2008). The model results indicated that this recent glacial unloading is unlikely to be responsible for the Ordovician under-pressures.

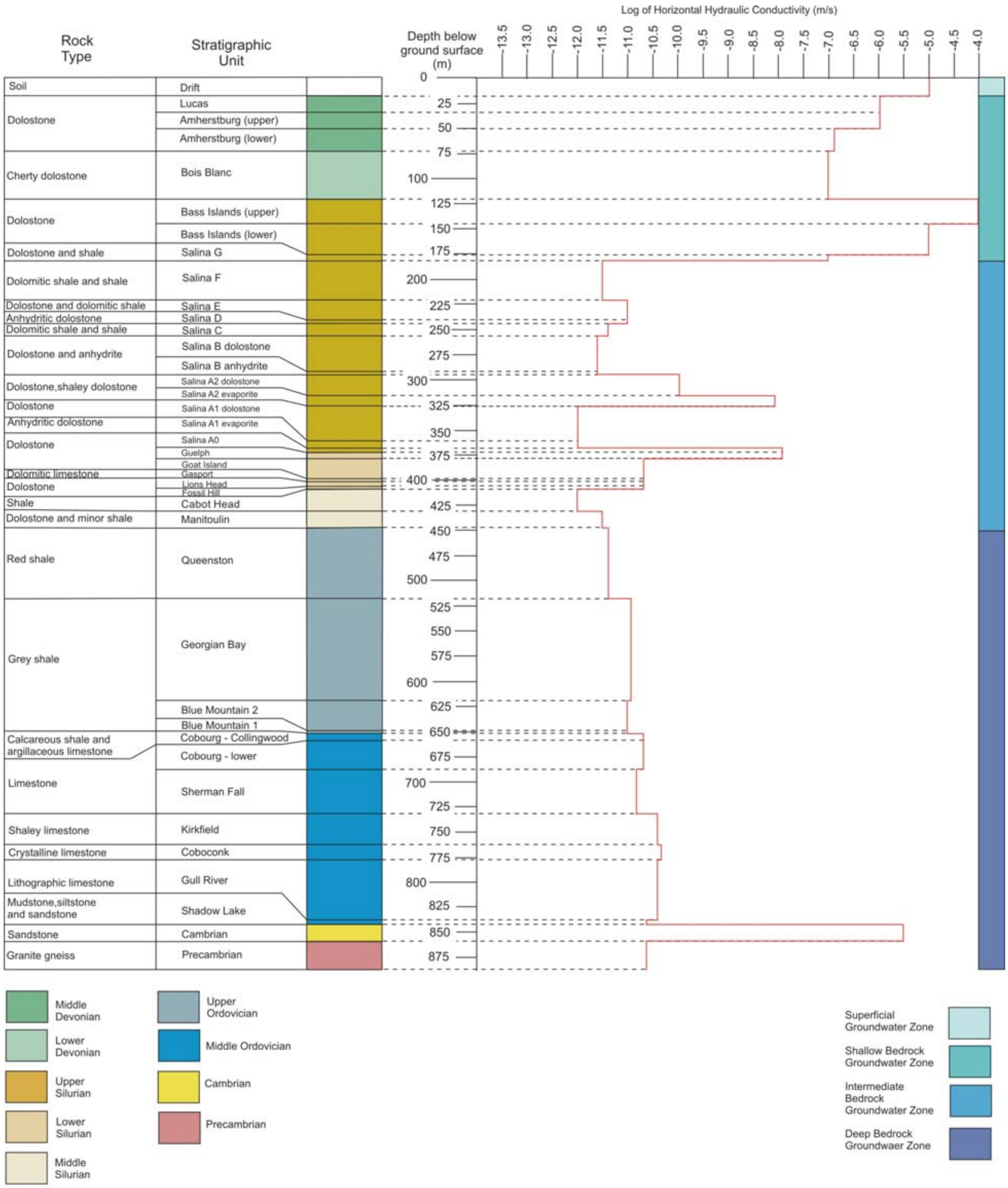



**Figure 2-13: Hydraulic Conductivity Profile Based on Data from DGR-1 and DGR-2 Site Investigation Boreholes**

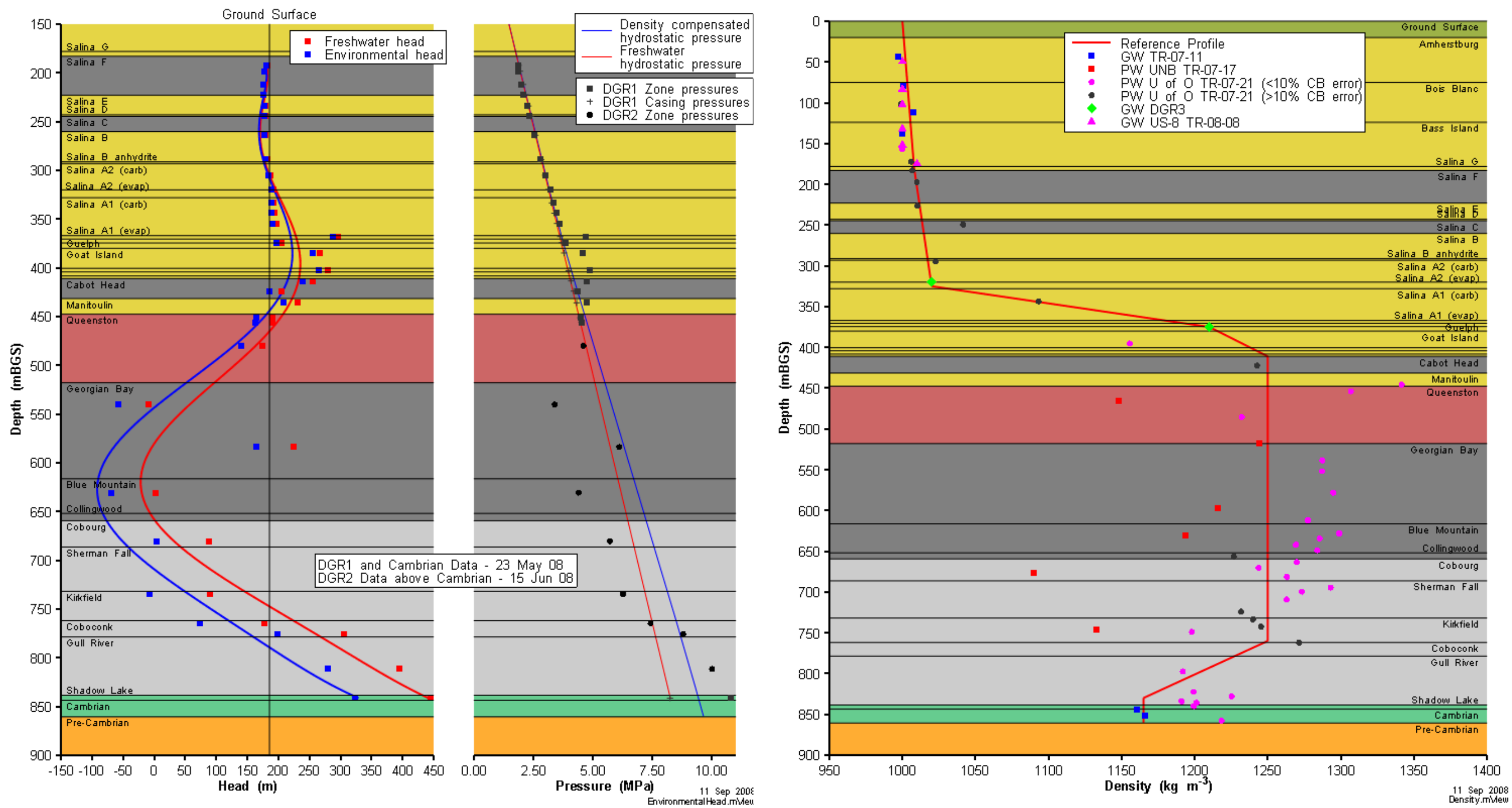



**Figure 2-14. Groundwater Vertical Head and Density (Salinity) Profiles Based on Data from DGR-1 and DGR-2 Site Investigation Boreholes**

Geochemical evidence indicates that the brines in the Michigan basin are formed by evaporation of sea water and are therefore connate waters (Hobbs et al. 2008). There is evidence for cross-formation flow associated with ancient events such as dolomitisation of Ordovician and Silurian formations. Although the timing of these cross-formational flow events is not known, the requirement for sufficient driving forces for movement of these fluids suggests that these events occurred in association with tectonic or orogenic events: the most recent being the Alleghenian Orogeny which ended approximately 250 Ma BP (Gartner Lee 2008a).

The geochemical evidence, combined with the groundwater flow modelling results suggests that one possible explanation for the Ordovician under-pressures may be sediment erosion since the Mississippian (359 to 318 Ma BP) (Gartner Lee, 2008a). However, it should be noted that >90% of the geochemical data are from oil and gas wells and hence geological traps. Data are not available for the DGR boreholes at the time of writing this report. Alternatively, the low pore fluid pressures may indicate the presence of a trapped non-wetting gas phase (Sykes et al. 2008). The latest site investigation data, subsequent to Sykes et al. (2008), currently indicates that the gas saturation in the Ordovician is low.

Although there are high vertical head gradients in the intermediate and deep zones, the hydraulic conductivities in these zones are so low that advective flows are negligible (and hence disequilibrium conditions have developed) and transport will be diffusion dominated. The only natural exceptions to this are within the Cambrian, Guelph, Salina A0 and Salina A2 evaporite formations. These formations are of much higher hydraulic conductivity and advective flow might occur within them.

The Cambrian formation is located below the repository and is associated with a high excess head. It is not expected that there is any flow within this formation, or from this formation to the biosphere. This is because the Cambrian formation pinches out against the Pre-Cambrian basin and is overlaing by the low permeability Ordovician and younger rocks. The cause of this excess head is unknown, but possibilities include:

- pressurisation by gas at depth within the Michigan Basin, with the head unable to dissipate because the Cambrian pinches out against low permeability formations;
- ancient glaciation and ice loading, with the heads yet to equilibrate with the present-day surface conditions;
- trapping of water millions of years ago that has been pressurised by the later stages (e.g., Silurian) of sediment deposition in the Michigan Basin; and
- basin centred variable density groundwater heads.

The future long-term evolution of these over-pressures towards equilibrium conditions is uncertain.

The Guelph, Salina A0 and Salina A2 evaporite formations are located above the repository. Even though they are of relatively high hydraulic conductivity, there is unlikely to be any significant flow in these formations at the DGR site because they lie between overlying low permeability Salina C, D, E and F formations and the underlying, low permeability Goat Island, Gasport, Lions Head, Fossil Hill, Cabot Head and Manitoulin formations. Topographically driven strike-parallel flow, resulting in discharge to Lake Huron where the Guelph, Salina A0 and Salina A2 evaporite formations sub-crops to the northwest of the DGR, might occur (Figure 2-15 and Sykes et al. 2008). Due to subdued topography the gradients will be low and the pathlengths are long (tens of km) resulting in very long travel times. However, it is also possible that these formations might discharge to the base of Lake Huron if any open fractures / faults provide preferential pathways.

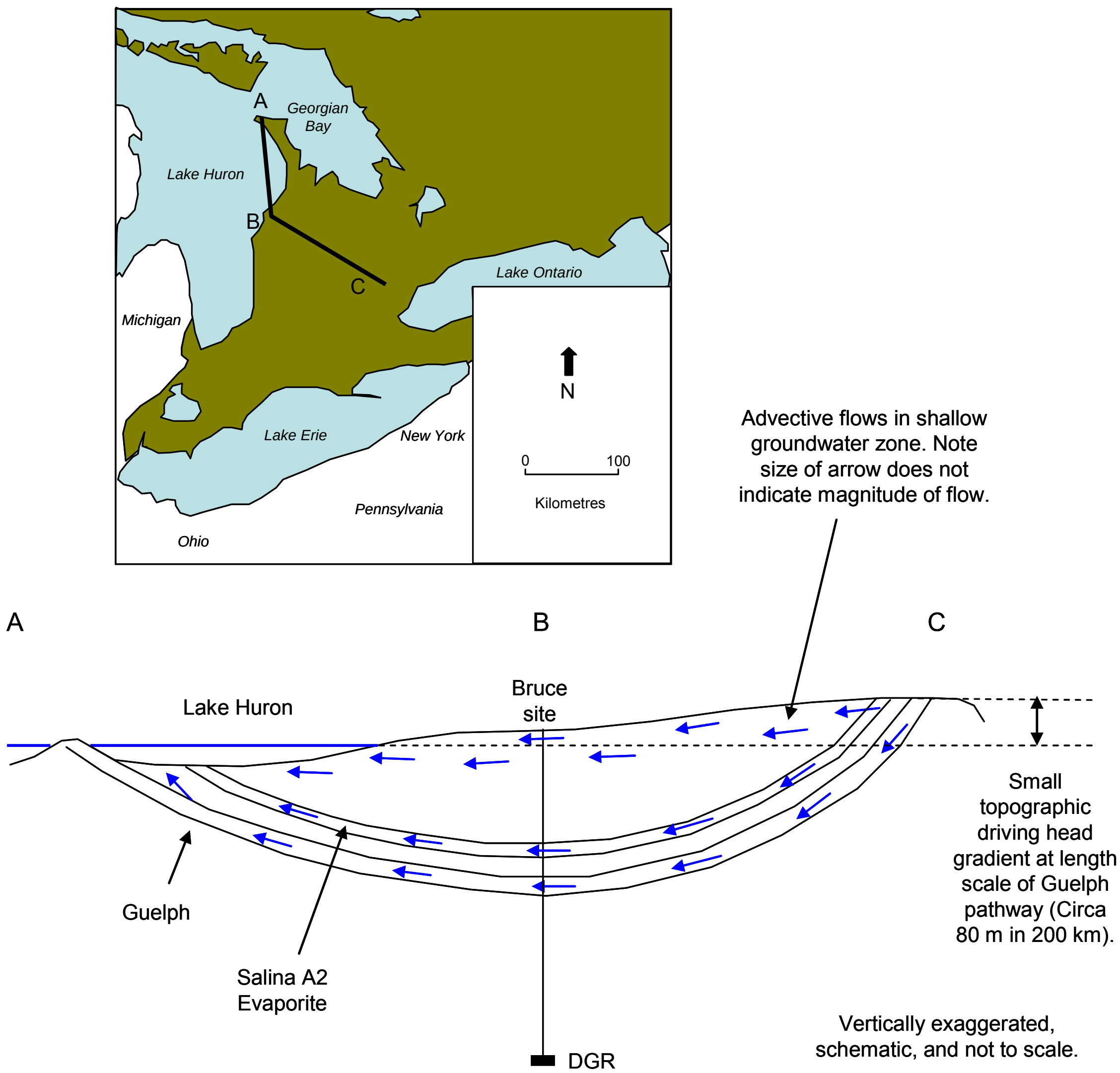



**Figure 2-15: Hypothetical Guelph Groundwater Flow Pathway**

#### 2.3.3.3 Excavation Damaged Zone

During construction of the DGR, an EDZ will develop around the emplacement rooms, the access tunnels and the shafts, in response to mechanical disturbance and stress relief. The thickness of the EDZ is estimated to be 7 m around the emplacement rooms and tunnels, and 4 m around the areas at the bases of the shafts that will be backfilled with concrete monoliths (Damjanac 2008). In the shafts, it is estimated to be equal to the radius of the shafts (Walke et al. 2009a).

The shaft EDZ will have a radially varying hydraulic conductivity, and has been further described in terms of an inner and outer EDZ each of thickness equal to half the radius of the shafts. The effective hydraulic conductivities of the inner and outer EDZs are taken to be 100 and 10 times that of the undamaged rock, respectively (see Data report, Walke et al. 2009b).

It is also expected that the EDZ will have increased porosities over the surrounding rock mass. Previous studies in Canadian Shield granite and in Opalinus Clay (Nagra 2002a) have suggested an increase of about a factor of two averaged over the inner EDZ volume.

The present-day hydraulic head data shows the repository horizon to be under-pressured (Figure 2-14). This will tend to result in groundwater flow towards the repository within the shafts / EDZ. However, this situation is likely to change within the assessment timeframe due, for example, to the generation of gas from corrosion of materials in the repository.

### 2.3.4 Geochemistry

At the time of developing this report there was limited site-specific information available on the geochemistry at the DGR site. Given the lack of site data, a set of geochemical parameter values was estimated as listed in Table 2-7. These estimates were based on deep formation waters from the Michigan Basin at localities other than the Bruce site, and by expert judgement based on knowledge of:

- groundwater compositions commonly found in shallow groundwater aquifers ('Surficial Groundwater Zone' and 'Shallow Bedrock Groundwater Zone' groundwaters);
- commonly observed controls on salinity gradients ('Intermediate Bedrock Groundwater Zone' porewaters);
- mineral-water equilibria that are often observed to buffer porewater compositions (e.g., buffering of HS- by pyrite; buffering of total concentration of dissolved inorganic carbonate species (TIC) by calcite); and
- mineral-water interactions suggested by the porewater investigations of Waber et al. (2007).

The parameters pH, $pCO_2$ and TIC are inter-related in groundwaters that are in equilibrium with carbonate minerals such as calcite, dolomite and ankerite. This equilibrium condition is expected to be met in the Intermediate and Deep Bedrock Groundwater Zones of the Bruce site because these minerals are common in the Ordovician shales and are the principal components of the Ordovician limestones. Furthermore, the activity coefficient for dissolved carbonate can be assumed to lie between values appropriate for seawater and Canadian Shield brines. When these conditions are specified and the Henry's Law constant for $CO_2$ dissolution in seawater is used, the anticipated pH range of 5 to 7 corresponds to a calculated $pCO_2$ between 0.1 kPa and 50 kPa. Preliminary groundwater measurements at the site have indicated a maximum $pCO_2$ value of 5.6 kPa.

The Eh conditions can also be bounded by making calculations that assume mineralogical buffering. Pyrite is present in the Ordovician shales and limestones beneath the Bruce site and thus allows an estimate of the redox potential for these rocks based purely on the sulphate-sulphide redox couple. This potential may not be in redox equilibrium with all other redox couples, but the S(VI)-S(II-) redox potential is likely to provide a lower limit of Eh values. These assumptions lead to a maximum (most oxidising) Eh of -0.017 V at pH = 5 and a minimum (most reducing) Eh of -0.15 V at pH = 7. Hematite ($Fe_2O_3$) is quite obviously responsible for the red colour of the Queenston shale, and alternative limiting Eh values can be calculated by specifying redox equilibrium between hematite and siderite ($FeCO_3$). Thus at pH = 5 and the maximum $pCO_2$ estimated above, Eh = -0.03 V. Therefore a suitable limiting range of Eh values is from -0.15 to 0.0 V, between pH = 5 and pH = 7.

**Table 2-7: Summary of Estimated Ranges of Key Geochemical Parameters**

| Determinand | Units | Surficial Groundwater Zone | | Shallow Bedrock Groundwater Zone | | Intermediate Bedrock Groundwater Zone[a] | | Deep Bedrock Groundwater Zone[a] | |
|---|---|---|---|---|---|---|---|---|---|
| | | Min | Max | Min | Max | Min | Max | Min | Max |
| pH | pH | 7 | 8.3 | 7.2 | 7.7 | 6.3 | 6.7 | 5.1 | 7.0 |
| Eh | mV | 100 | 300 | -50 | 340 | Reducing[c] | Reducing[c] | Reducing[c] | Reducing[c] |
| $O_2$(aq) | mg $L^{-1}$ | 0 | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 |
| Na | mg $L^{-1}$ | 30 | 130 | 10 | 130 | 33800 | 100000 | 16900 | 100000 |
| K | mg $L^{-1}$ | 0.5 | 5 | 0.5 | 10 | 240 | 3030 | 120 | 3030 |
| Ca | mg $L^{-1}$ | 10 | 100 | 20 | 300 | 16400 | 65000 | 8200 | 65000 |
| Mg | mg $L^{-1}$ | 10 | 60 | 10 | 150 | 20 | 7770 | 10 | 7770 |
| Cl | mg $L^{-1}$ | 1 | 15 | 1 | 100 | 20000[b] | 250000[b] | 100000[b] | 260000[b] |
| TIC | mg $L^{-1}$ | pH and calcite eq | pH and calcite eq | pH and calcite eq | pH and calcite eq | pH and calcite eq | pH and calcite eq | pH and calcite eq | pH and calcite eq |
| $SO_4$ | mg $L^{-1}$ | 100 | 300 Ca and gypsum eq | 70 | 1500 Ca and gypsum eq | 330 | c. 1250[d] Ca and gypsum eq | 165 | 1140 |
| $PO_4$ | mg $L^{-1}$ | <0.1 | 0.3 | <0.1 | 1.0 | No data | No data | No data | No data |
| HS- | mg $L^{-1}$ | 0 | 0 | 0 | pH, pyrite, siderite | pH, pyrite, siderite | pH, pyrite, siderite | pH, pyrite, siderite | pH, pyrite, siderite |
| TOC | mg $L^{-1}$ | 2 | 4 | 4 | 100 | No data | No data | 0 | 10 |
| TDS | mg $L^{-1}$ | 100 | 1000 | 1000 | 2500 | 100000 | 310000[b] | 150000[b] | 350000[b] |

**Notes:**

a. Only porewaters actually occur in this zone; the term ‘Groundwater Zone’ is used for consistency with Walke et al. (2009b).

b. Updated values based on Geoscience review of data from Phase 1 Site Characterisation Activities; other ions have not been adjusted to ensure that ‘minimum’ and ‘maximum’ groundwater compositions are charge-balanced.

c. Based on mineralogical indicators (e.g. presence of reduced phases such as pyrite, marcasite and sphalerite), reducing conditions prevail in the Intermediate and Deep Bedrock Groundwater Zones.

d. The water is highly saline and therefore this value was calculated using PHREEQC Version 2.15 and a PHREEQC-formatted version of the "Pitzer" thermodynamic datebase "data0.ypf.R2", which was produced by Sandia National Laboratories for the Yucca Mountain repository programme (USDOE 2007). The value is given only approximately owing to the inherent uncertainty in calculating mineral - solution equilibria in highly saline solutions.

The compilation of the above values is consistent with the regional data described by Hobbs et al. (2008), although there are some differences in the ranges of formation water compositions. These relatively insignificant differences are attributed to Hobbs et al. (2008) evaluating a larger number of samples, and more widely distributed samples.

Mineralogical information has recently become available from analyses of some deep rock samples from borehole DGR-2 (DGR 2008). The associated data are presented in Table 2-8 and Table 2-9. From these tables it is apparent that inorganic carbon (which will be predominantly in the form of carbonate minerals) is a significant constituent of the proposed host rocks (the Cobourg Formation) and surrounding lithologies. These carbonate minerals could act as an important pH buffer. However, it is also apparent that silicates, and most notably sheet silicates, are also present in these rocks. Potentially these minerals could sorb radionuclides. Another significant observation is that pyrite occurs in the host rocks and the surrounding rock formations. Although the abundances of this mineral are small (<<1%), the fact that it is present at all is good evidence that in-situ conditions are reducing.

### 2.3.5 Seismicity

Southwestern Ontario and the Bruce region lie within the tectonically stable interior of the North American continent; the stable interior region of North America is characterised by low rates of seismicity. Most recorded events have a magnitude less than **M** 5. Magnitude in this report is presented on the moment magnitude scale, **M**,[5] which is similar to the Richter magnitude, but a more direct indication of earthquake fault size. In general, earthquakes in stable interior regions such as the Bruce region occur at depths of 5 to 20 km in the Precambrian basement. Figure 2-16 shows all known earthquakes in the region up to 2007 (Gartner Lee 2008b) from the Geological Survey of Canada's National Earthquake Database. It shows that the Bruce region experiences sparse seismic activity, with no apparent concentrations of activity that might delineate regional active faults or other seismogenic features.

Given the lack of specific features along which seismicity is concentrated, the earthquake hazard may be attributed to the low-level seismicity that appears to occur at random (Gartner Lee, 2008b). This type of seismicity occurs in all regions of the world, at rates that vary according to the tectonic setting. In stable continental interior regions such as the Bruce site, the rates are very low for large events. Global studies cited by Gartner Lee (2008b) suggest that rare intra-plate earthquakes can have magnitudes as large as **M** 7, but occur extremely infrequently; for example, the overall rate of occurrence of events of **M** > 6 (large enough to cause significant fault rupture) in stable cratons around the world is 0.004 $a^{-1}$ per $10^6$ $km^2$.

A recent study of seismicity rates in the Canadian craton by Atkinson and Martens (2007) reports a Canadian craton rate of **M** ≥ 6 events of <0.001 $a^{-1}$ per $10^6$ $km^2$ with a variability (standard deviation) of about a factor of three. This density of seismicity (where density is the rate of activity per unit area) is applicable to the Bruce region. Thus an event of **M** ≥ 6 would be expected somewhere within a 20 km radius of the Bruce Site approximately once in 800,000 years (with an uncertainty of a factor of three on this return period).

[5] The moment magnitude scale was calibrated such that moment magnitude equals Richter magnitude in most cases (Hanks and Kanamori 1979).

**Table 2-8: Whole-rock Mineralogy Sampled in Borehole DGR-2 during Phase I Site Characterisation Activities**

| Depth (mbgs) | Formation | S (wt %) | $C_{org\text{-}}$ wt % | $C_{inorg.}$ wt % | Calcite wt % | Dolomite & Ankerite wt % | Siderite wt % | Quartz wt % | Albite wt % | K-feldspar wt % | Pyrite wt % | Sheet-Silicates wt % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 473.19 | Queenston | <0.1 | <0.1 | 4.9 | 8 | 31 | <2 | 10 | <2 | <2 | 0.2 | 40 |
| 491.83 | Queenston | 0.6 | 0.2 | 8.3 | 57 | 11 | <2 | 4 | <2 | <2 | 1.1 | 27 |
| 523.08 | Georgian Bay | 0.3 | <0.1 | 6.6 | 31 | 23 | <2 | 17 | <2 | 6 | 0.6 | 23 |
| 609.39 | Georgian Bay | 1 | 0.1 | 2.5 | 19 | 2 | <2 | 16 | <2 | 2 | 1.9 | 59 |
| 674.73 | Cobourg | 0.2 | 0.3 | 9.3 | 65 | 12 | <2 | 6 | <2 | 3 | 0.3 | 14 |
| 738.00 | Kirkfield | 0.3 | 0.1 | 9.7 | 77 | 3 | <2 | 3 | <2 | <2 | 0.5 | 16 |
| 770.60 | Cocobonk | 0.1 | 0.5 | 11.2 | 82 | 10 | <2 | <2 | <2 | <2 | 0.2 | 7 |
| 796.54 | Gull River | 0.3 | 0.4 | 10.6 | 82 | 5 | <2 | <2 | <2 | <2 | 0.5 | 10 |
| 813.70 | Gull River | 0.2 | 0.3 | 11.2 | 51 | 40 | <2 | 2 | <2 | <2 | 0.4 | 7 |
| 830.05 | Gull River | 0.6 | 0.2 | 9.6 | 64 | 16 | <2 | 3 | <2 | 2 | 1.1 | 15 |
| 840.06 | Shadow Lake | 0.3 | 0.6 | 9.9 | <1 | 79 | <2 | 2 | <2 | 2 | 0.5 | 17 |
| 846.31 | Cambrian | 0.5 | 0.3 | 6.3 | 1 | 49 | <2 | 22 | <2 | 16 | 0.9 | 11 |
| 852.39 | Cambrian | <0.1 | <0.1 | 0.1 | <1 | <2 | <2 | 84 | <2 | 10 | 0.2 | 6 |
| 855.89 | Cambrian | <0.1 | 0.1 | 0.1 | <1 | <2 | <2 | 65 | <2 | 30 | 0.2 | 5 |
| 861.90 | Precambrian | <0.1 | 0.2 | 1.1 | 4 | 5 | <2 | 24 | 4 | 40 | 0.2 | 23 |

[1)] Except in samples DGR2-1, where anhydrite-gypsum veins are recognized, no sulfate minerals were found in the other samples by optical microscopy and X-ray diffraction. Similarly, no solid chlorides were recognised.

**Table 2-9: Clay Mineral Content of Whole-rock for Formations Sampled in Borehole DGR-2 during Phase I Site Characterisation Activities**

| Depth (mBGS) | Formation | Measured on Separated Clay Fraction <2µm [1] | | | | | |
|---|---|---|---|---|---|---|---|
| | | Illite (wt.%) | Illite/ Smectite (wt.%) | Smectite (wt.%) | Chlorite (wt.%) | Chlorite/ Smectite (wt.%) | Kaolinite (wt.%) |
| 473.19 | Queenston | 39 | <1 | <1 | 10 | <1 | <1 |
| 491.83 | Queenston | 20 | <1 | <1 | 9 | <1 | <1 |
| 523.08 | Georgian Bay | 16 | <1 | <1 | 8 | <1 | <1 |
| 609.39 | Georgian Bay | 40 | <1 | <1 | 19 | <1 | <1 |
| 674.73 | Cobourg | 12 | <1 | <1 | 2 | <1 | <1 |
| 796.54 | Gull River | 9 | <1 | <1 | 1 | <1 | <1 |
| 840.06 | Shadow Lake | 15 | <1 | <1 | 2 | <1 | <1 |
| 852.30 | Cambrian | 3 | <1 | <1 | 2 | <1 | 2 |

[1] normalised to the difference of the sheet silicate to 100 wt%.

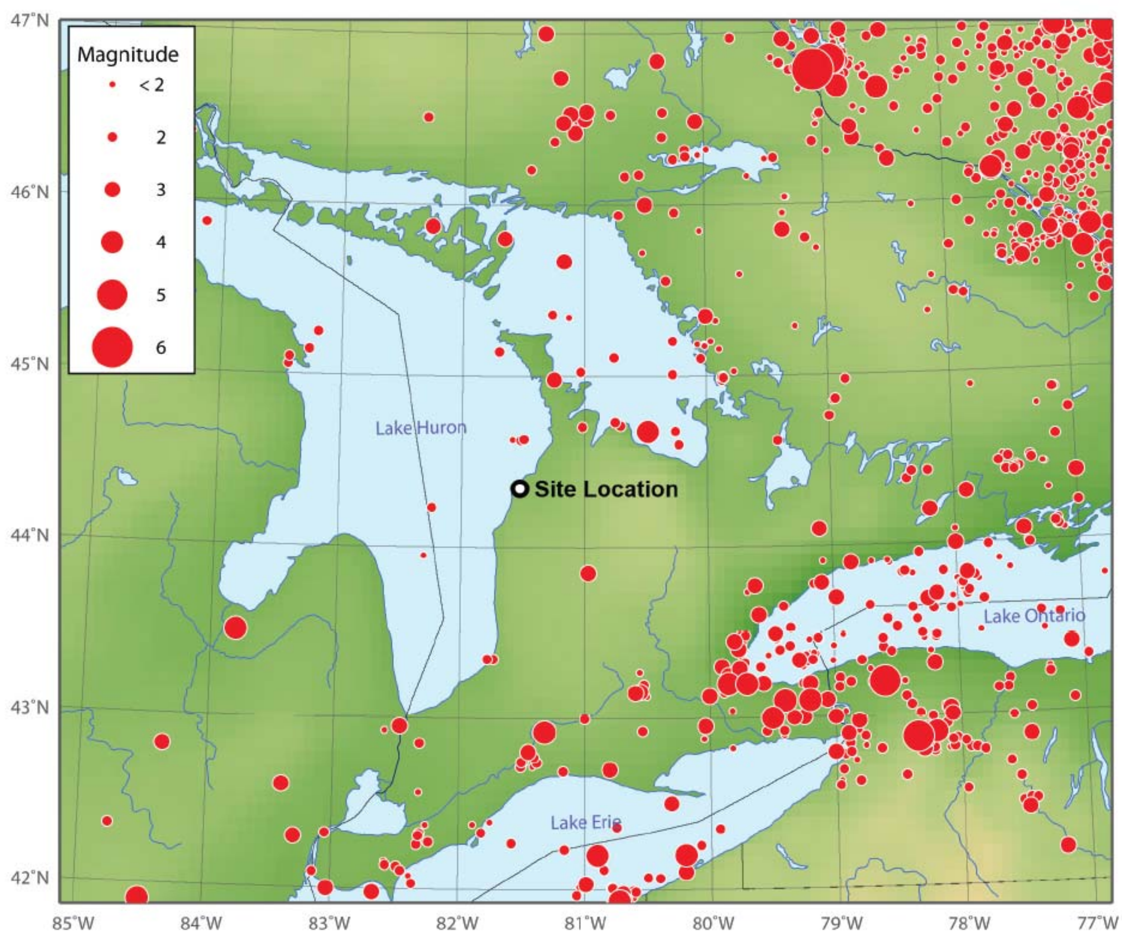



**Figure 2-16: Seismicity in the Region around the Bruce Site (Hayek et al. 2008)**

These findings provide a sense of the seismic recurrence rate of the Bruce region. With no seismic events of **M** > 5 recorded in the past 180 years, the likelihood of a large event in the Bruce region is very low, exhibiting a seismicity rate comparable to that of a cratonic region. However, the rate could potentially be affected if there was a future episode of glaciation, as such events lead to in-situ stress changes that may temporarily increase seismicity rates (Adams 1989).

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

### 2.3.6 Stress Regime

The compilation of regional in-situ stress data reveals a state of high compressive stress in Palaeozoic bedrock formations of the Michigan Basin. At the depth of the DGR, within the Deep Bedrock Groundwater Zone, the stress ratio, $\sigma_H/\sigma_v$, (where $\sigma_H$ is the maximum horizontal stress, and $\sigma_V$ is the maximum vertical stress) is estimated to be about 1.7 to 2.5 and the ratio $\sigma_H/\sigma_h$ (where $\sigma_h$ is the initial horizontal stress) is approximately 1.5 to 2.1 (Gartner Lee 2008c). Based on these stress ratios and an overburden stress of 17 MPa, the maximum and minimum horizontal stress magnitudes at the proposed repository depth would be approximately 36 MPa and 20 MPa, respectively. The horizontal stress magnitudes would be smaller in the Intermediate and Shallow Bedrock Groundwater Zones. The orientation of the maximum horizontal stress, $\sigma_H$, is estimated to be in the ENE direction (Gartner Lee 2008b). However, there is a lack of site-specific information.

## 2.4 SURFACE ENVIRONMENT

Maps showing the Bruce Site are provided in Figure 2-17 at the regional and local scales and in Figure 2-18 at the site scale.

The Bruce Site lies on the eastern shore of Lake Huron on the Douglas Point promontory. The topography around the Bruce Site is relatively low-lying, varying between 176 m above sea level (mASL) (level of Lake Huron) up to approximately 195 mASL (associated with the Nipissing Bluff). Elevations increase to approximately 230 mASL further inland to the east, associated with another bluff line, the Algonquin Bluff. Each of these bluffs represents remnants of post-glacial shorelines developed during the Holocene.

The biosphere can be defined as the surface environment, including inhabitants, in the vicinity of the proposed DGR site. The study areas suggested in the Guidelines for the Preparation of the Impact Statement for the DGR (CEAA and CNSC 2009) are as follows.

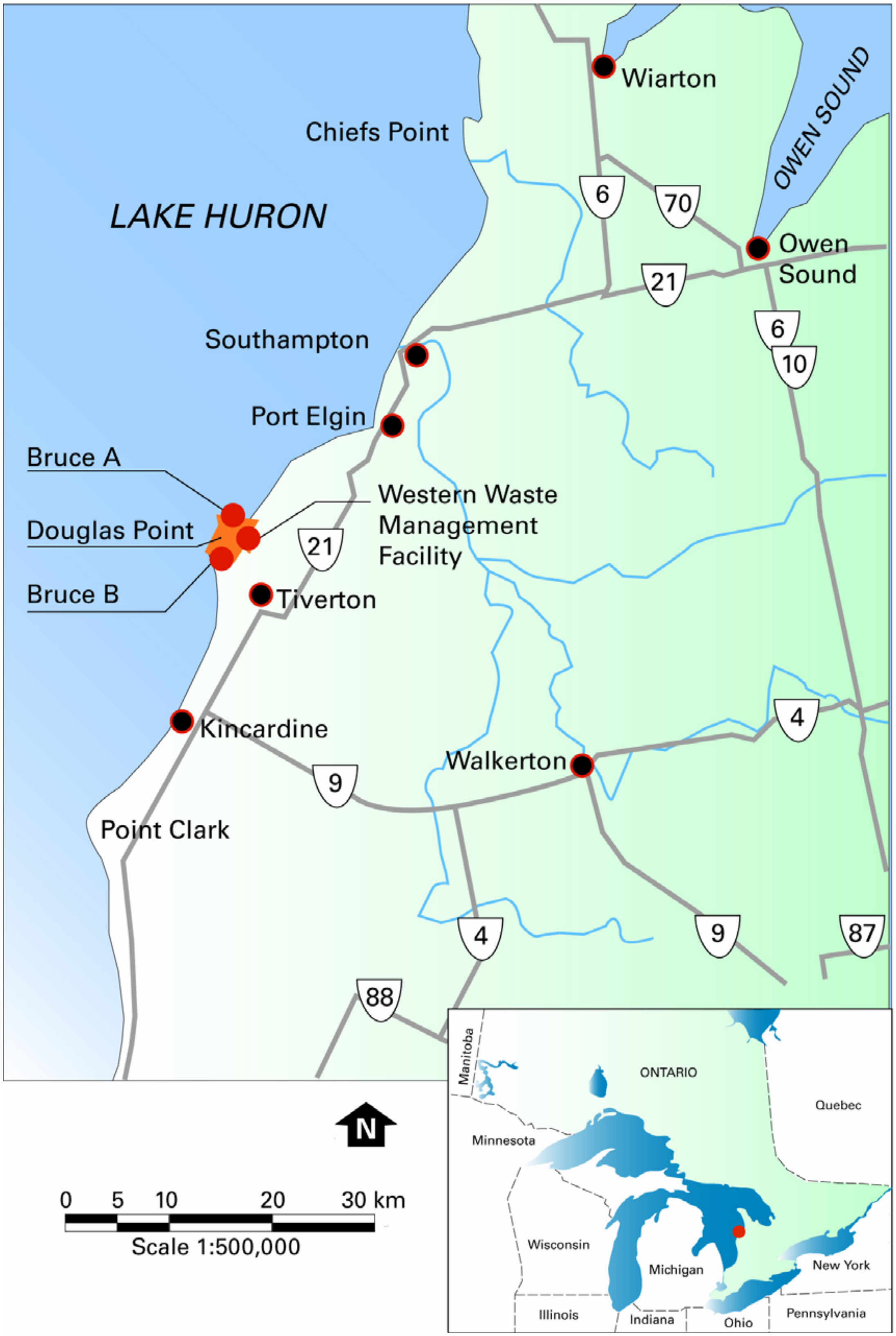



**Figure 2-17: Location of the Bruce Site**

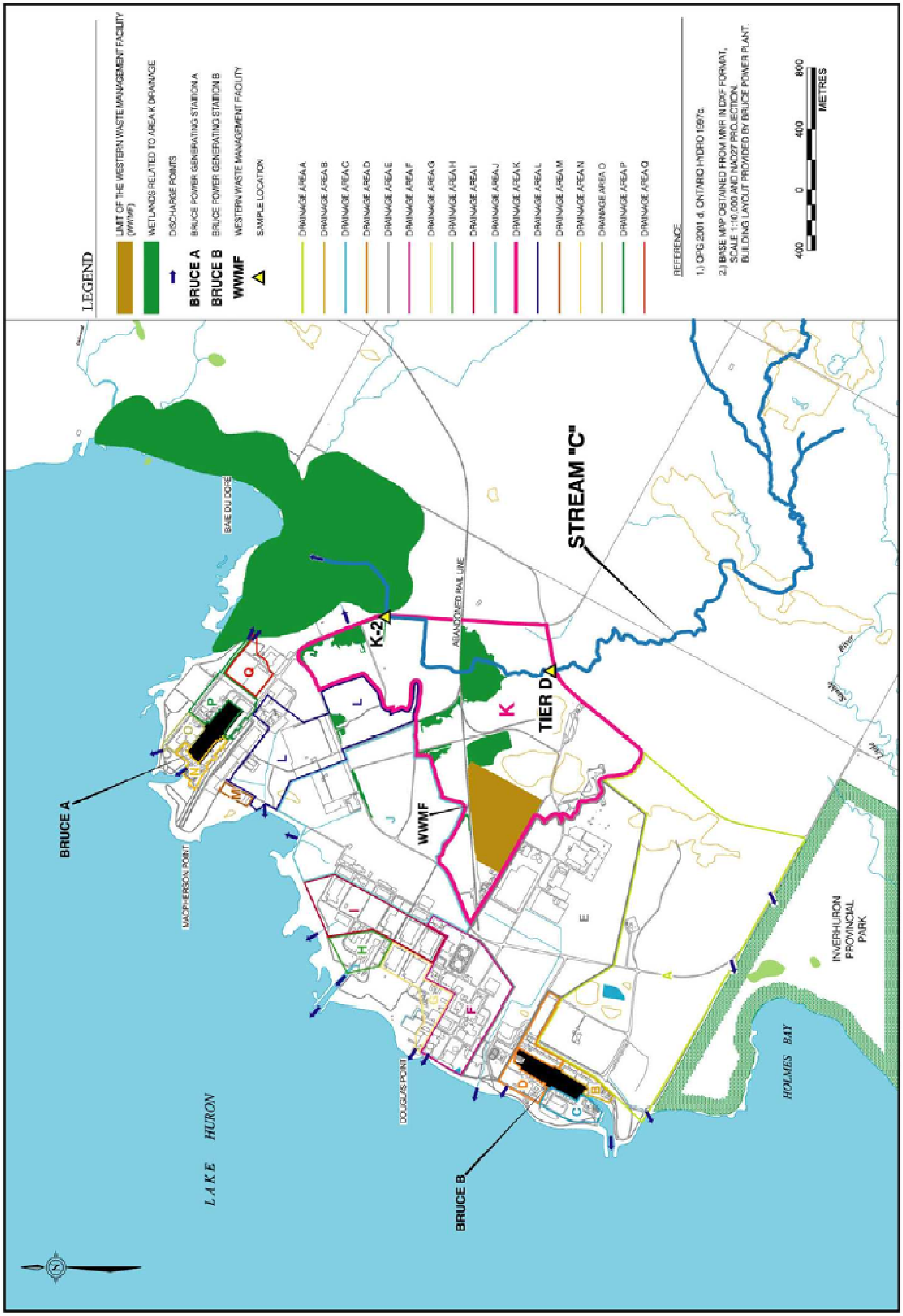



**Figure 2-18: Map of the Bruce Site and Surrounding Area**

- Site Study Area - includes the facilities, buildings and infrastructure at the Bruce Nuclear Site, including the existing licensed exclusion zone for the site on land and within Lake Huron, and particularly the property where the DGR is proposed.
- Local Study Area - the area existing outside the site study area boundary, where there is a reasonable potential for direct effects on the environment from any phase of the project, either through normal activities, or from possible accidents or malfunctions. The Local Study Area includes all of the Bruce Nuclear Site and the lands within the Municipality of Kincardine closest to it, as well as the area of Lake Huron adjacent to the facility. The boundaries may change as appropriate following an assessment of the spatial extent of potential impacts.
- Regional Study Area - the area within which there is the potential for cumulative biophysical and socio-economic effects. This area includes lands, communities and portions of Lake Huron around the Bruce Nuclear Site that may be relevant to the assessment of any wider-spread direct and indirect effects of the project.

The DGR EIS documentation will provide a detailed description of the biosphere with respect to the above study areas. Until this information is available, data from a recent EA at the site, the Western Waste Management Facility (WWMF) Refurbishment Waste Storage (RWS) project EA (OPG 2005), is used to provide a general description.

### 2.4.1 Atmosphere

The region has four distinct seasons with warm summers and mild winters. Because of lake effects, uncomfortably hot and humid conditions and long dry or wet spells are rare.

The annual mean temperature is 8.9 °C in the vicinity of the Bruce site. The mean daily temperatures fall below freezing from December through March. The coldest months are January and February, with a mean temperature of approximately -7 °C. The extreme lowest temperature recorded is -37 °C. During June to August, mean daily temperatures range from approximately 15 °C to 19 °C. The extreme high temperature recorded in the Regional Study Area is 36.1 °C.

In the Regional Study Area, there is a relatively even distribution of meteoric precipitation between winter and summer seasons (combining rain, snow, drizzle and freezing rain), typically totalling between 800 mm and 1,000 mm annually. Slightly more than 20 percent of this meteoric precipitation falls as snow. In winter, the region experiences a variety of storms with heavy snowfall and strong winds.

Severe weather events in the region generally include thunderstorms and lightning, ice storms, windstorms, extreme heavy meteoric precipitation and fog. In Southern Ontario, thunderstorms normally occur for 20 to 25 days a year. Freezing rain occurs, typically between 25 and 50 hours per year and is usually accompanied or followed by meteoric precipitation such as snow, wet snow, ice pellets, rain and fog.

The average wind speeds in the Regional Study Area are between 14 and 15 km/h (about 4 m/s), but winds are generally stronger in the winter season. In the Local Study Area, the most frequent winds have speeds in a range of 10 to 20 km $h^{-1}$ (2 to 6 m $s^{-1}$). The average wind speed in the Local Study Area (overall mean for three years of data) is 12.2 km $h^{-1}$ (3.4 m $s^{-1}$). The prevailing winds are from the south and southwest. The 1998 to 2000 wind rose for the Bruce site (at 10 m) is shown in Figure 2-19.

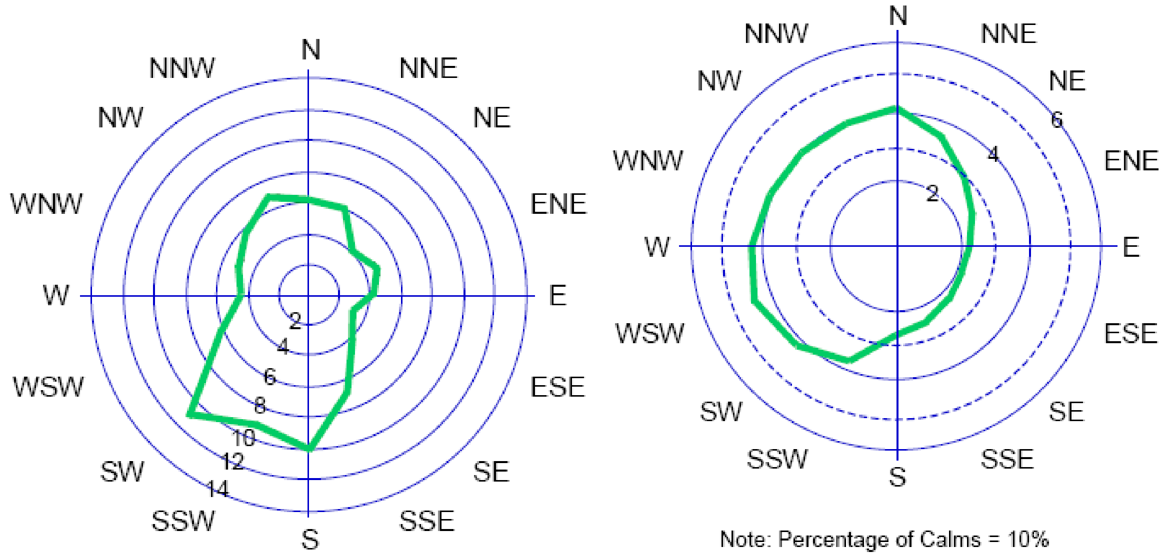



**Figure 2-19: Wind Direction % (Left) and Mean Wind Speed m $s^{-1}$ (Right) for the Bruce Site (OPG 2005)**

Air quality in the Regional Study Area is typical of the general air quality in Southwestern Ontario. Air quality effects are dominated by the following substances, which combine to produce smog or acid rain: carbon monoxide (CO); nitrogen oxides (NOx); volatile organic compounds (VOCs); sulphur dioxide ($SO_2$) and suspended particulate matter.

Small amounts of radiological emissions and non-radiological air pollutants are emitted to the atmosphere from operations at the Bruce site. Recent environmental assessment studies (e.g., Bruce Power 2005) note average airborne tritium concentrations of up to 0.3 Bq $m^{-3}$ for the region around the Bruce Site and up to 2 Bq $m^{-3}$ locally to the site. Average gross beta deposition rates for radioactive particulates of up to 21 Bq $m^{-2}$ per month are noted local to the Bruce Site, and atmospheric C-14 concentrations of up to about 0.05 Bq $m^{-3}$ dry air are recorded at the Bruce site boundary. These values are representative of the operational site, i.e., primarily due to the operating reactors and the low-level-waste incinerator.

### 2.4.2 Surface Water Bodies

The Bruce site is located adjacent to the Lake Huron shoreline, within the Stream “C” watershed, as illustrated in Figure 2-20. Stream “C” originates at the headwaters of the Little Sauble River and Underwood Creek. It ultimately discharges to Baie du Doré on Lake Huron just north of the Bruce site; however, more than half of Baie du Doré is located in the Underwood Creek watershed. The Underwood Creek watershed does not interact with any discharges from the Bruce site. The largest drainage area in the Regional Study area is the Saugeen River watershed, located north of the Underwood Creek watershed. The Saugeen River discharges to Lake Huron near Port Elgin. The Saugeen River watershed does not interact with any discharges from the Bruce site.

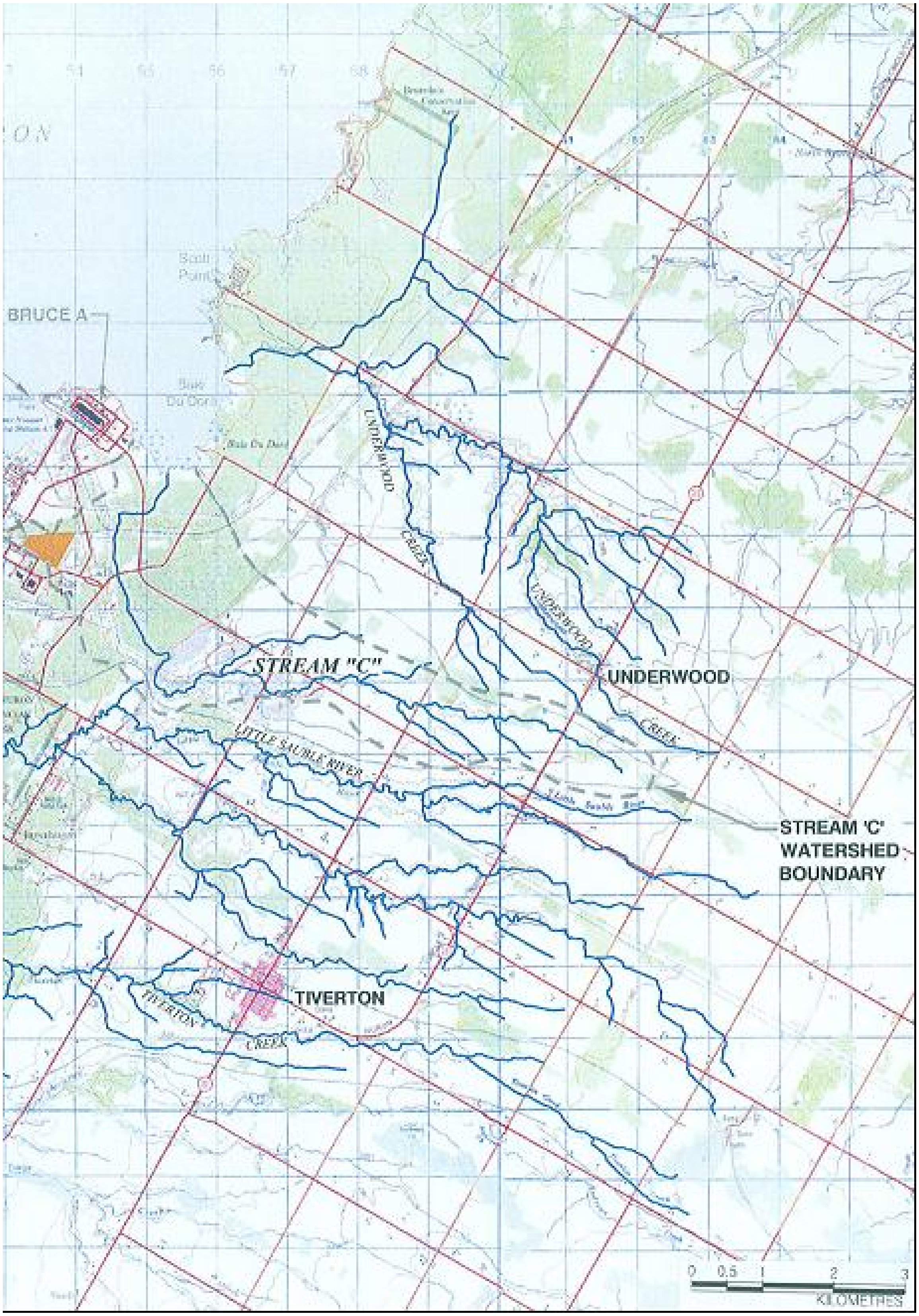



**Figure 2-20: Stream "C" Watershed from WWMF RWS EA (OPG 2005)**

There are no major rivers in the Regional Study Area, but there is an extensive network of small rivers and creeks. The largest river is the Saugeen River that enters Lake Huron at Southampton, 26 km to the northeast. There are two small east-to-west drainage courses entering the lake adjacent to the site: Underwood Creek and Stream “C” empty into Baie du Doré to the north and the Little Sauble River, which forms the southern boundary of Inverhuron Provincial Park, empties into Inverhuron Bay to the south.

Lake Huron is a typical, cold and deep oligotrophic lake. Near shore, a depth of about 6 m is reached at a distance of 460 to 610 m from the shore, whereas a 9 m depth is encountered 60 to 150 m further offshore. The lake contains about 3,500 $km^3$ of water, covering an area of 59,600 $km^2$. Average outflows from the lake represent less than 5% of the total lake volume per year, resulting in a hydraulic retention time of about 22 years. Currents in the lake are generally in the order of 10 cm $s^{-1}$, or two orders of magnitude greater than the through-flow velocity, and the predominant lake-wide circulation in the main basin is cyclonic (anti-clockwise).

Baie du Doré, located along the northern portion of the Bruce site, is an embayment within the Local Study Area (see Figure 2-21). It is characterised by shallow depths and rock outcrops. The habitat of the bay is protected from Lake Huron by two major shoals. Nevertheless, the shoreline remains subject to wave action and ice scour. Wetland areas exist at the head of the bay and are set back from the shoreline. However, they are connected to the bay through outflow channels. These wetlands provide a nursery and spawning habitat for many Great Lakes species and are very productive. Average water temperatures in Baie du Doré are generally 2ºC warmer than those in the open lake, but it is often much more than 2ºC warmer during the summer.

**Figure 2-21: Baie du Doré Pictured from Scott Point**

Stream “C” is a cool water stream that is located east of the WWMF boundary and flows in a northerly direction to Baie du Doré. Stream “C” is characterised as a slow-flowing stream with riffle and pool habitat throughout (see Figure 2-22). The stream has a mean width of 3.0 m with maximum depths ranging from 0.15 m to 0.8 m. Aquatic vegetation is plentiful throughout the reach consisting primarily of submergents and a small emergent component. Riparian vegetation is dominated by overhanging grasses that provide some shade to the stream.

**Figure 2-22: Stream "C" at the Site Boundary**

Also in the Local Study Area, a small wetland (4 ha) is located east of the WWMF boundary. A ditch, known as the Railway Ditch (see Figure 2-23), flows around the edge of the wetland and continues into Stream "C" beyond the wetland. The wetland has experienced yearly fluctuations in water levels and occasionally has small areas of open water.

**Figure 2-23: The Railway Ditch**

The Railway Ditch is approximately 5 m wide at the top of the bank with a wetted width of 3 m and a mean water depth of 0.15 m. The Railway Ditch has naturalised and the side slopes of the ditch are stabilised with natural vegetation cover including grasses, trees, shrubs and cattails, as seen in Figure 2-23. The presence of cattails throughout much of the ditch provides a highly stable ditch bed and serves to reduce water velocity, thus minimising erosion and increasing the rate of settling for sediments that may enter the ditch system.

### 2.4.3 Water Quality

A comprehensive Lake Huron water-sampling program in the Regional Study Area found that water samples collected in Lake Huron showed little variation temporally or spatially, and were within Provincial Water Quality Objectives. They showed low nutrient levels. Monitoring results for water supply plants that draw water from Lake Huron at Kincardine, Port Elgin and Southampton give tritium concentrations of up to 17 Bq $L^{-1}$ and gross beta concentrations of 0.07 Bq $L^{-1}$ (Bruce Power 2008). Monitoring results for the lake and streams local to the Bruce site give tritium concentrations of up to 108 Bq $L^{-1}$ and total beta concentrations of up to 0.24 Bq $L^{-1}$. Monitoring results for shallow wells show tritium concentrations up to 70 Bq $L^{-1}$ and gross beta concentrations (excluding low-energy beta emitters) up to 0.04 Bq $L^{-1}$.

The Site Study Area defined by the WWMF RWS EA (OPG 2005) included the WWMF property and the Railway Ditch. Water sampling along the Railway Ditch found elevated concentrations of metals including Cr, Cu, Fe, V and Zn, in some samples. However, there is no evidence of metal contamination in the soils or groundwater at the WWMF. Therefore, there does not appear to be a source at the WWMF that would contribute to the elevated levels of metals in the Railway Ditch.

### 2.4.4 Water Supply

The towns of Port Elgin, Kincardine and Southampton, located on the shores of Lake Huron within the Regional Study Area, have municipal water supply plants that obtain water from Lake Huron, as does the MacGregor Point Provincial Park.

Most of the rural population within the Regional Study Area obtains its water from private or communal wells, including the Village of Tiverton, the Hamlet of Underwood and some residences of Scott Point, Woodland Court Trailer Park, and Lime Kiln Cottages. Many inland cottages have water wells and septic tanks, although some lakefront properties have direct intakes from the lake. The Brucedale Conservation area campsites and Inverhuron Provincial Parks are supplied by wells. In the Kincardine Municipality there are approximately 1000 wells (Golder 2003). Water is drawn principally from the Shallow Bedrock Groundwater Zone from depths of between 30 and 100 m.

### 2.4.5 Sediment

The lake includes four main zones of depositional sediments, underlying the deeper waters of Georgian Bay, and the southern, western and central basins (Stephenson et al. 1995). The surface sediments in depositional zones are fine-grained, composed mainly of clay and silt-sized particles. Erosional zone sediments in shallower waters and inshore areas are more complex, comprising sands, lag sands and gravels. Sediments in the North Channel are likely similar to sediments in Georgian Bay.

The sediment in Stream “C” is composed of a mix of boulder/cobble (30%), sand/gravel (10%) and clay/silt (60%).

Sediment samples from Lake Huron were collected during 2002 and 2003 at various locations within the Site, Local and Regional Study Areas, and at a background location in Goderich. In the background samples, $^{134}$Cs and $^{60}$Co (usually only attributable to reactor operation) were not detected. Also in the background samples, naturally occurring $^{40}$K was reported in the range 181 to 251 Bq kg$^{-1}$ dry sediment, and $^{137}$Cs concentrations ranged from 0.3 to 0.5 Bq kg$^{-1}$ dry. $^{137}$Cs is a product of both fallout from atmospheric nuclear testing and reactor operations, and its concentration varies widely in the environment.

In the three Study Areas, the major component of activity in sediments is naturally occurring radionuclide $^{40}$K at concentrations in the range 240 to 450 Bq kg$^{-1}$ dry. $^{134}$Cs concentrations were below detection limits.

In the Regional Study Area (i.e., sediment from Southampton and Sauble Beach), $^{137}$Cs was measured at 0.7 to 1.2 Bq kg$^{-1}$ dry, and $^{60}$Co was less than the detection limit. Near the inner boundary of the Regional Study Area (Baie du Doré, Scott Point and Inverhuron Bay), $^{137}$Cs concentrations were higher, in the range of 1.1 to 8.7 Bq kg$^{-1}$ dry, and $^{60}$Co was just above the detection limit.

### 2.4.6 Soil

In the Regional Study Area, the surficial deposits below the Algonquin Bluff and underlying the Bruce site include silty to clayey till of the Elma (Catfish Creek) sequence overlying the bedrock surface. This till sequence varies in thickness up to approximately 15 m and locally contains interbedded sequences of sand, as determined from investigations at the WWMF site.

The till below the Algonquin Bluff is locally overlain by sand and gravel beach deposits related to the former glacial Lake Algonquin and Lake Nipissing shorelines. The glacial Lake Nipissing shoreline is marked by the less prominent Nipissing Bluff situated below the Algonquin Bluff. These deposits have been locally exploited for aggregate at pit locations along the Algonquin Bluff. The shoreline areas also include deposits of till and areas of boulders, exposed by shore erosion of this till. Areas of bog and cedar swamp also occur in poorly drained areas below the Algonquin Bluff and elsewhere within other poorly drained forested areas.

The overburden underlying the Local Study Area is composed of a comparatively complex sequence of surface sand and gravel from former beach deposits overlying clayey to sandy silt glacial till with interbedded lenses of sand of variable thickness. Near the shoreline, thin deposits of sand, gravel and boulders overlie the bedrock and bedrock locally outcrops.

The distribution of overburden thickness overlying the bedrock throughout the Local Study Area was assessed through contouring of the available geotechnical borehole information for the site previously compiled in 1986/87 by Ontario Hydro and subsequently updated for a few additional drillholes. In general terms, the thickness of overburden throughout the site varies from about 4.5 m beneath the northwestern half of the site to a maximum of 15 to 20 m within a localised area in the central eastern portion of the site in the vicinity of the WWMF.

The area of surficial deposits within the Bruce site (i.e., the Site Study Area) that has been most intensively investigated hydrogeologically lies within the WWMF. Generally, the WWMF site area is underlain by 13 to 18 metres of surficial deposits overlying bedrock which varies in elevation between 171 mASL and 177 mASL. The overburden thickness beneath the North Storage Area is approximately 13 to 15 m. The overburden thickens to approximately 18 m beneath the East Storage Area. The bedrock surface elevation is approximately the same beneath both storage areas varying between 172.5 mASL and 175.5 mASL. Overall, the bedrock surface beneath the WWMF slopes gently northeastward at approximately 1%, reflecting a glaciated erosional surface.

The overburden thickness in the vicinity of the proposed DGR site, located north of the WWMF, varies between about 12 and 15 m. The overburden in this area consists of a complex sequence of surface sand and gravel overlying a dense glacial till, locally interbedded with sand lenses or layers. The top 2 to 4 m of the glacial till unit is weathered. Underlying this brown weathered till horizon, there is an unweathered grey till comprised of dense silty sand to very hard clayey silt till with sand and boulders.

In general, there is a shallow layer of topsoil, typically about 30 cm, overlying silt till (Patrick and Romano 2001). There are occasional regions of peat-like materials. Soil and subsoil is generally firm to stiff and dense. Moisture varies, but the soil is generally moist and often wet or even saturated.

Note that there is no published information on the mineralogy associated with the soils constituting the top 30 cm of the biosphere. It is apparent however that there are both sandy and loamy/clayey soils present.

Recent monitoring results from the Local Study Area (Bruce Power 2008) provide dry weight soil concentrations for Cs-137 and K-40 in garden soils, lakeshore soils and inland soils. Average concentrations of up to 7.5 Bq $kg^{-1}$ are recorded for Cs-137 and up to 670 Bq $kg^{-1}$ for K-40. Provincial background soil concentrations of up to 1.4 Bq $kg^{-1}$ and 560 Bq $kg^{-1}$ are recorded for Cs-137 and K-40, respectively.

### 2.4.7 Land Use

Current land uses on the Bruce site are restricted to those associated with the nuclear operations and support activities.

The region around the Bruce Site is mainly used for agriculture, recreation and some residential development. Farmland accounts for around 60% of the land use in the county, with many cattle farmers, as well as farmers of pigs and sheep, and crops such as oats, barley, canola and hay. Local people also hunt wild animals including deer and waterfowl. Farms and rural populations often obtain water from wells. The lake provides water for larger communities, and is used for recreational and commercial fishing, and boating.

The nearest population centre is Inverhuron (population of around 750) about 4 km to the southwest of the DGR site. Larger towns are Port Elgin (population of over 7000) about 20 km to the northeast, and Kincardine (population of around 12000), 15 km to the southwest.

Archaeological sites exist in the vicinity showing that it was settled around 2000 years ago by the Iroquois Nation, and occupied by the Ojibway Tribe when Europeans settled in the 1800s. Two areas of archaeological interest exist on the Bruce Site, neither close to the DGR site.

There is some mineral extraction for sand and gravel in the region. Four disused quarries exist in the controlled development zone around the Bruce Site.

The traditional territory of the Ojibway in the Saugeen region covers the watersheds bounded by the Maitland River and the Nottawasaga River east of Collingwood, an area that includes the Bruce Peninsula and Grey and Bruce Counties. The Chippewas of Saugeen reserve is approximately 40.78 $km^2$ situated on Lake Huron, at the base of the Bruce Peninsula about 3 km northeast of Southampton. The Chippewas of Nawash reserve occupies 63.81 $km^2$ on the eastern shore of the Bruce Peninsula on Georgian Bay.

### 2.4.8 Biota

#### 2.4.8.1 Terrestrial Plants

The Regional Study Area is located within the Huron Ontario section of the Great Lakes, St. Lawrence Forest Region. Although Bruce County contains a number of large forested areas and wetlands, providing core habitat for a variety of wildlife species, much of the Regional Study Area consists of agricultural land. Consequently, few natural terrestrial features or wildlife corridors exist. There are remnant forested areas that are primarily associated with the Lake Huron shoreline, watercourse valleys, areas with steep topography and poorly drained sites.

Inverhuron Provincial Park, located immediately south of the Bruce site, contains primarily early succession and second growth vegetation communities resulting from past disturbances. The most mature forest within the park is found along the Little Sauble River near the river mouth. A sand dune succession system is also present. The Scott Point Provincially Significant Life Science A.N.S.I. (Area of Natural and Scientific Interest) is a complex of small coastal wetlands consisting of swamp, marsh, fen, shoreline bluffs and beach ridges.

Several distinct vegetation ecosites have been identified within the Local Study Area, the most common being:

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

No rare or unique vegetation species have been identified within these ecosites.

The WWMF site (part of the Site Study Area) is vegetated with balsam fir, sugar maple and American beech. There is also a meadow and wetland area on the site.

#### 2.4.8.2 Wildlife

Fish community monitoring has been conducted within the Regional Study Area since 1961. A total of 85 species has been recorded during these on-going field investigations. The fish community comprises two major types: those that range broadly throughout the region and Lake Huron, and use the area on an occasional basis; and those that are confined to nearshore areas for most of their life stages. The latter fish community includes yellow perch, smallmouth bass, northern pike, spottail shiner and bowfin. During various times of the year, fish species move in and out of the nearshore area. When rapid temperature fluctuations occur during windy periods, warm water fish often move out deeper into the lake.

The lake-wide fish community includes species that prefer open lake or deep coastal habitats such as round whitefish, lake whitefish, lake trout, and deepwater sculpin. These fish spawn at depths greater than 2 m and make use of the nearshore area most frequently for spawning, but also for foraging and nursery functions. Seasonal migrations into the nearshore areas occur during the winter months for feeding and limited spawning.

The Local Study Area provides habitat for a variety of wildlife, including birds, mammals, reptiles and amphibians.

Baie du Doré provincially significant wetland (within the Local Study Area) provides habitat for an overwintering population of bald eagles which are rare to uncommon in Ontario. Other rare species reported in the Baie du Doré area include the horned grebe, great egret, canvasback, redhead and Caspian tern. Under normal conditions, mudflat habitat is available for use by migratory shorebirds in the late summer as lake water levels decline.

Evidence of habitat use by numerous bird species has been recorded in the Site Study Area. Confirmed breeding species include black-capped chickadee, chipping sparrow, and American robin. Other recorded bird species include wood thrush, American goldfinch, common yellowthroat, killdeer, northern flicker Eastern kingbird, song sparrow, red-eyed vireo and wild turkey.

Incidental and cursory observations of mammals within the Site Study Area have identified habitat use by star-nosed mole, meadow vole, groundhog, red and gray squirrels, eastern chipmunk, woodland jumping mouse, skunk, snowshoe hare, eastern cottontail, little brown bat, porcupine, raccoon and white-tailed deer. Historical evidence of beaver activity was also noted. Muskrats and their dens, as well as an active water shrew den, have been observed along the Railway Ditch.

Amphibian and reptile species observed in the Local Study Area include the northern spring peeper, American toad, northern leopard frog, green frog, gray treefrog, wood frog, yellow-spotted salamander and redback salamander. Spotted turtle, which is rare to uncommon in Ontario and listed as vulnerable by the MNR (Ministry of Natural Resources), has been reported in Baie du Doré. A Bioinventory Study (LGL 2002) also listed midland chorus frog, mudpuppy, and midland painted turtle, as well as eight species of reptiles. The most widespread reptile, based on observation, was the eastern garter snake.

Some of the same herpetofauna have been observed at the site, primarily at the Railway Ditch. Species include green frogs, leopard frogs, northern watersnakes, garter snakes and a painted turtle. American toad, spring peeper, and gray treefrog have been previously recorded in the general area.

A number of active crayfish burrows have also been identified throughout the Bruce site, particularly along the wetted edge of the portion of the drainage ditch. Leeches and snails have also been found at many sites along the Railway Ditch.

#### 2.4.8.3 Aquatic Plants

There is a high diversity of habitats in Baie du Doré wetland complex (part of the Local Study Area). Predominant vegetation types within the marsh areas include yellow water lily, tamarack, rushes, cattails and sedges, cedar, shrubby cinquefoil, vetches and mosses.

In a 2000-2001 study, three provincially rare plant species were recorded: beach grass, ram's head lady's slipper, and beaked spike rush. All three of these species occur along Baie du Doré shoreline.

Within the Site Study Area, the dominant vegetative cover in the Railway Ditch is cattails, but other aquatic vegetation found in the ditch includes sedge, pondweed, watercress, water plantain, bulrush and arrowhead. Dense mats of muskgrass thrive in the open pool areas of the ditch along with filamentous green algae.

#### 2.4.8.4 Valued Ecosystem Components

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

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

## 2.5 UNCERTAINTIES

This section has provided a description of:

- the existing and future wastes to be disposed in the DGR;
- the proposed construction, operation and closure of the DGR;
- the DGR's present-day geological setting;
- the present-day surface environment in the vicinity of the DGR.

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

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

Most waste categories are relatively homogeneous in their physical characteristics, especially compacted wastes, incinerator ash, resins and sludges, and retube wastes. However, non-processible wastes could be quite diverse in characteristics. The volumes of metal and concrete are well defined, but quantities of other materials (e.g. cellulosics) are uncertain. Some physical characteristics of wastes, such as their moisture content and hydraulic conductivity, have been estimated, and are uncertain. However, it is unlikely that these parameters will have a significant effect on overall postclosure impacts.

Concentrations of radionuclides and non-radioactive contaminants are subject to a degree of uncertainty as they are based on waste-type-specific sampling and scaling factors, rather than direct measurement of each waste package. This approach is routinely used by other waste management organisations (IAEA, 2009). As the contaminants of most interest are present in the wastes at low levels, they can vary between packages, with log-dispersion of 5-10 in the overall range typically observed (OPG 2008). However, averaged across the many packages in the repository, the total inventories will have much less uncertainty.

The construction phase of the DGR is expected to take approximately five to seven years. The operations phase will then last about 40 to 45 years based on the operating life of the current nuclear fleet. This will be followed by a decommissioning phase (including dismantling surface facilities and sealing the shaft), which is expected to take about six years. Therefore, the earliest plausible closure of the DGR is end of 2062. This is the start time for the postclosure safety assessment (i.e., over 50 years from the present). Over such a timescale, it is likely that some changes could occur to the waste arisings, the construction, operation and closure of the DGR, and the surface environment in the vicinity of the DGR (changes to the geological setting over such timescales are very unlikely). It is assumed for this safety assessment that such changes will be minor and that the wastes, repository and surface environment at closure are as described in Sections 2.1, 2.2 and 2.4.

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

Although the waste, repository and surface environment can be considered to be comparatively well characterised, there are more significant uncertainties associated with the present-day geology of the site. A programme of work is currently being undertaken to characterise this (Intera 2006, 2008) and the Phase 1 results from the programme have already been incorporated. Nevertheless, the following key areas of uncertainty need to be recognised:

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

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These uncertainties are addressed in the safety assessment through the development and assessment of different conceptual models.

In addition, it is recognised that there is limited direct information on the extent of fracturing at the site-scale. The primary evidence for the lack of faults is the agreement of the site stratigraphy with regional data, the close alignment of the rock formations between the three deep boreholes which triangulate the DGR site, and the results of the 2-D seismic reflection survey[6]. The latter in particular did not identify any firm features over an area extending several hundred metres beyond the DGR footprint. The seismic survey did note two possible features outside the DGR area based on limited data; these could potentially be local, closed fractures, and will be investigated by a borehole in 2009.

There is, however, significant indirect evidence that there is and has been no significant permeable local or subregional fracturing for a long time. This includes the observed over and under groundwater pressures, and the chemical evidence for very limited mixing of formation groundwaters. The high regional horizontal stresses would also tend to close any vertical fractures that might form. Small horizontal fractures are only sparsely present in the deep rock cores from boreholes DGR-1 and DGR-2. Consequently the potential presence of significant permeable vertical faulting within the site model is considered not credible.

[6] Note that boreholes DGR-3 and DGR-4 and the 2-D seismic survey were recently completed and these data were not available for the Geosynthesis reports.

## 3. EXTERNAL FACTORS AFFECTING THE EXPECTED EVOLUTION OF THE DGR SYSTEM

The DGR system and its evolution are affected by various external, internal and contaminant factors (Figure 3-1). These factors may be further categorised as features, events or processes (FEPs). For example, an earthquake is an external event, carbon steel waste package is an internal feature, and sorption is a contaminant process.

The internal and contaminant factors are situated within the spatial boundaries of the DGR system, whereas the external factors originate outside these boundaries. The external features, events or processes (EFEPs) provide the system with both its boundary conditions and with factors that might cause change in the system. If these external factors can significantly affect the system within the assessment timescale, they can be considered to be scenario-generating FEPs (IAEA 2004) in the sense that whether they occur or not (or the extent to which they occur) could define a particular future scenario that should be considered within the postclosure safety assessment.

A list of potential External and Internal FEPs relevant to the DGR system has been developed (Garisto et al. 2009). This FEP list is based on lists developed in other programmes, such as the international FEPs database developed by the OECD Nuclear Energy Agency (NEA 1999), the IAEA's ISAM FEP list (IAEA 2004), and the FEP list used in OPG's Third Case Study (Garisto et al. 2004). The list identifies 53 External FEPs and almost 200 Internal FEPs.

The External (scenario-generating) FEPs are listed in Table 3-1. Those that are likely to affect the DGR system and its evolution are identified and discussed in this section. The effects of less likely external FEPs that might lead to abnormal degradation and loss of containment (Disruptive Scenarios) are considered in Section 8.

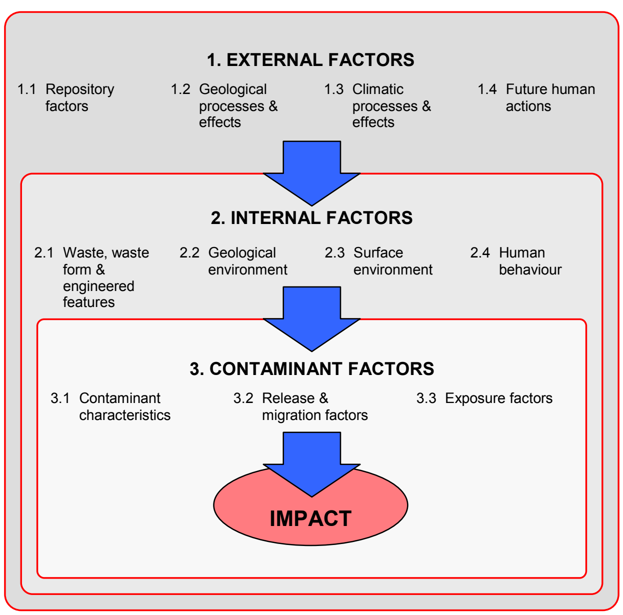



**Figure 3-1: External, Internal and Contaminant Factors**

**Table 3-1: External FEPs considered (Garisto et al. 2009)**

| | | |
|---|---|---|
| 1.1 | Repository Factors | |
| | 1.1.01 | Site investigations |
| | 1.1.02 | Design of repository |
| | 1.1.03 | Schedule and planning |
| | 1.1.04 | Construction |
| | 1.1.05 | Operation |
| | 1.1.06 | Waste allocation |
| | 1.1.07 | Repository closure |
| | 1.1.08 | Quality assurance |
| | 1.1.09 | Repository administrative control |
| | 1.1.10 | Accidents and unplanned events |
| | 1.1.11 | Retrievability |
| | 1.1.12 | Repository records and markers |
| | 1.1.13 | Monitoring |
| 1.2 | Geological Processes and Effects | |
| | 1.2.01 | Tectonic movement |
| | 1.2.02 | Orogeny |
| | 1.2.03 | Seismicity |
| | 1.2.04 | Volcanic and magmatic activity |
| | 1.2.05 | Metamorphism |
| | 1.2.06 | Hydrothermal activity |
| | 1.2.07 | Denudation and deposition (large-scale) |
| | 1.2.08 | Diagenesis |
| | 1.2.09 | Pedogenesis |
| | 1.2.10 | Salt diapirism and dissolution |
| | 1.2.11 | Hydrological response to geological changes |
| | 1.2.12 | Geomorphologic response to geological changes |
| | 1.2.13 | Deformation (elastic, plastic or brittle) |
| 1.3 | Climate Processes and Effects | |
| | 1.3.01 | Global climate change |
| | 1.3.02 | Regional and local climate change |
| | 1.3.03 | Sea-level change |
| | 1.3.04 | Periglacial effects |
| | 1.3.05 | Local glacial and ice-sheet effects |
| | 1.3.06 | Warm climate effects (tropical and desert) |
| | 1.3.07 | Hydrological response to climate changes |
| | 1.3.08 | Ecological response to climate changes |
| | 1.3.09 | Human behavioural response to climate changes |
| | 1.3.10 | Geomorphologic response to climate changes |
| 1.4 | Future Human Actions (Active) | |
| | 1.4.01 | Human influences on climate |
| | 1.4.02 | Social and institutional developments |
| | 1.4.03 | Knowledge and motivational issues (repository) |
| | 1.4.04 | Drilling activities |
| | 1.4.05 | Mining and other underground activities |
| | 1.4.06 | Un-intrusive site investigations |
| | 1.4.07 | Surface excavations |
| | 1.4.08 | Site development |
| | 1.4.09 | Archaeology |
| | 1.4.10 | Water management (groundwater and surface water) |
| | 1.4.11 | Explosions and crashes |
| | 1.4.12 | Pollution |
| | 1.4.13 | Remedial actions |
| | 1.4.14 | Technological developments |
| | 1.4.15 | Deliberate human intrusion |
| 1.5 | Other External Factors | |
| | 1.5.01 | Impact of meteorites and human space debris |
| | 1.5.02 | Evolution of biota |

The External FEPs in Table 3-1 have been reviewed, in light of information from the assessment context (documented in Section 3 of Quintessa et al. 2009) and the system description and its supporting documents (Section 2 of the current report), to identify those that should be included or excluded from consideration when considering the expected evolution of the DGR system over the timescale of interest (1,000,000 years). The resulting list of included/excluded External FEPs considered for the DGR is given in Table 3-2, together with a brief justification for their inclusion/exclusion in the assessment. More information is provided in the Version 1 FEPs report (Garisto et al. 2009).

Analysis of the External FEPs shows that the DGR is largely unaffected due to its depth (680 m below the ground surface). Although the effects of climate change resulting from continuing glacial and inter-glacial cycling are likely to cause major changes in the surface and near-surface environment, the DGR itself is intentionally isolated from the main consequences of climate change. A range of geoscientific observations can be used to provide evidence that the formations at these depths have been isolated from surface changes through the nine glacial cycles that have affected the Bruce site in the last one million years. For example, geochemical data indicate that brines in the Deep and Intermediate Bedrock Groundwater Zones are ancient and that glacial meltwaters have not penetrated to depths >130 m (Hobbs et al. 2008). In addition, results of transient palaeoclimate groundwater flow simulations undertaken by Sykes et al. (2008) for the Laurentide glacial episode (~120 ka to 10 ka BP) showed that heads in the Ordovician and Cambrian formations were little affected by Laurentide glacial loading and unloading.

The analysis of the External FEPs shows that the DGR might be impacted by two External FEPs:

- the stresses due to the loading and unloading of ice-sheets; and
- the occurrence of large earthquakes possibly resulting from the ice sheets.

Both of these mechanical factors could cause rockfall within the rooms in the repository and/or a reduction of the performance of the shaft sealing materials.

In addition to climate change, the surface and near-surface environment at the Bruce site is likely to be affected by future human actions resulting in land use change and the drilling of shallow water wells.

**Table 3-2: Status of External FEPs for the Expected Evolution of the DGR System**

| | External FEP | | Status* | Comment |
|---|---|---|---|---|
| 1.1 | Repository Factors | | | |
| | 1.1.01 | Site investigations | Included | Available data from previous site characterisation are included. All site investigation boreholes are appropriately sealed. |
| | 1.1.02 | Design of repository | Included | The DGR is built consistent with the description provided in Section 2.2, which is based on the Hatch (2008) conceptual design. |
| | 1.1.03 | Schedule and Planning | Included | DGR is operated from 2016 to 2056 and finally closed in 2062 (Section 3.8 of Quintessa et al. 2009). Account taken for decay of radioactivity prior to 2062. |
| | 1.1.04 | Construction | Included | DGR is constructed as described in Section 2.2.1. |
| | 1.1.05 | Operation | Included | DGR is operated as described in Section 2.2.2. |
| | 1.1.06 | Waste allocation | Included | LLW and ILW wastes are disposed in separate emplacement rooms that are laid out in the configuration describe in Section 2.2.1.3. |
| | 1.1.07 | Repository closure | Included | Closure of the DGR is undertaken under OPG's quality assurance programme and is consistent with the description provided in Section 2.2.3. |
| | 1.1.08 | Quality Assurance | Included | Construction, operation, monitoring and closure of the DGR are undertaken under OPG's quality assurance programme. |
| | 1.1.09 | Repository administrative control | Included | Controls remain effective for 300 years following DGR closure (Section 3.8 of Quintessa et al. 2009). |
| | 1.1.10 | Accidents and unplanned events | Excluded | Accidents and unplanned pre-closure events that could impact the long-term safety of the repository are unlikely. If they were to occur, then they would be mitigated before the repository was closed. |
| | 1.1.11 | Retrievability | Excluded | No retrieval-specific features are included in the DGR design that could impact the long-term safety of the repository, although it is noted that the absence of backfill in the repository rooms and tunnels would simplify retrieval operations. |
| | 1.1.12 | Repository records and markers | Included | Any repository records are effectively maintained for 300 years following DGR closure (Section 3.8 of Quintessa et al. 2009). |
| | 1.1.13 | Monitoring | Excluded | Monitoring during and after closure is carried out such that it has no consequences for the long-term safety of the DGR. |
| 1.2 | Geological Processes and Effects | | | |
| | 1.2.01 | Tectonic movement | Excluded | Site is in a tectonically stable region away from tectonic plate margins with no tectonic activity over the timescales of interest (Section 2.3). |

| External FEP | | Status* | Comment |
|---|---|---|---|
| 1.2.02 | Orogeny | Excluded | No orogenic activity over the timescales of interest due to the site's location (Section 2.3). |
| 1.2.03 | Seismicity | Included | Earthquakes will occur over the timescales of interest. However, as the area is not a seismically active region, the likely magnitude, frequency and distance of earthquakes would limit their impact at the repository location (Section 2.3.5). |
| 1.2.04 | Volcanic and magmatic activity | Excluded | No volcanic or magmatic activity over the timescales of interest due to the site's location (Section 2.3). |
| 1.2.05 | Metamorphism | Excluded | No processes occur over the timescales of interest that will cause metamorphism (Section 2.3). |
| 1.2.06 | Hydrothermal activity | Excluded | Site is geologically stable and no drivers of hydrothermal activity are present over the timescales of interest (Section 2.3). |
| 1.2.07 | Denudation and deposition (large-scale) | Excluded | It is unlikely that large-scale denudation or deposition will occur over the timescales of interest due to low relief topography and low elevation relative to sea level. There is no direct evidence of significant erosion in the past one million years. Small-scale (a few tens of metres) sediment/rock erosion and deposition are likely to occur due hydrological and ice-sheet processes. |
| 1.2.08 | Diagenesis | Excluded | Diagenesis that would have an effect on repository safety is unlikely over the timescales of interest. |
| 1.2.09 | Pedogenesis | Included | Ice-sheet advance and retreat associated with glacial/ interglacial cycling will result in removal and formation of soils over the timescales of interest. The development of soils can impact the nature of plants established in the soils and the uptake of radionuclides by the plants. |
| 1.2.10 | Salt diapirism and dissolution | Excluded | No salt deposits are located in the immediate vicinity of the site (Section 2.3.2). Historically, there were salt deposits but these have already been dissolved over a long period in the distant past. |
| 1.2.11 | Hydrological response to geological changes | Excluded | Although hydrological/hydrogeological changes will occur, these will be driven by climate change (see 1.3.07) rather than geological change. |
| 1.2.12 | Geomorphologic response to geological changes | Excluded | Although geomorphologic changes will occur, these will be driven by climate change (see 1.3.10) rather than geological change. |

| | External FEP | | Status* | Comment |
|---|---|---|---|---|
| | 1.2.13 | Deformation (elastic, plastic or brittle) | Included | Although deformation due to tectonic movement and orogeny is unlikely over the timescales of interest due to the site's tectonically stable location, deformation due to loading from ice-sheets is likely. Peltier (2008) has estimated that the peak pressure resulting from an ice-sheet over the site might reach 25 MPa and the associated maximum crustal depressions might be in excess of 500 m. An initial assessment of the geomechanical response to ice-sheet loading has identified its potential to cause rockfall in the repository excavations. |
| 1.3 | Climate Processes and Effects | | | |
| | 1.3.01 | Global climate change | Included | After an initial period of human-induced global warming, it is likely that Quaternary glacial/interglacial cycling continues (Section6.3). |
| | 1.3.02 | Regional and local climate change | Included | Regional/local climate responds to global climate change resulting in continuation of glacial/interglacial cycling on regional/local scale after initial period of human-induced global warming (Section 6). |
| | 1.3.03 | Sea level change | Excluded | Changes in sea level do not affect the site due to its elevated continental location. |
| | 1.3.04 | Periglacial effects | Included | Occur during colder climate states experienced during the glacial/interglacial cycling that is likely to occur at the site over a one million year timeframe. In particular, this would include permafrost development (Section 6.3). |
| | 1.3.05 | Local glacial and ice-sheet effects | Included | Ice-sheets are likely to cause a range of local effects. These include crustal deflection, change in rock stress (and possible earthquake initiation), changes in surface and near-surface hydrology (see 1.3.07), ecosystems (see 1.3.08), human behaviour (see 1.3.09), and surface topography (see 1.3.10). |
| | 1.3.06 | Warm climate effects (tropical and desert) | Excluded | Climate change does not result in development of tropical or hot desert conditions at the site due to its northerly latitude. There is no evidence of tropical or hot desert conditions having been present at the site during the Quaternary. Initial period of human-induced global warming will not result in extreme temperature rise resulting in tropical or desert conditions. |

| | | External FEP | Status* | Comment |
|---|---|---|---|---|
| | 1.3.07 | Hydrological response to climate changes | Included | Glacial/interglacial cycling impacts on the hydrological conditions in the Superficial and Shallow Bedrock Groundwater Zones. It is very unlikely that previous glaciations had any significant impact on groundwater flow in the Intermediate and Deep Bedrock Groundwater Zones. Key responses are: permafrost formation (but only a few tens of metres), short-lived meltwater events (which may intrude into the Shallow Bedrock Groundwater Zone and have geochemical consequences) and the formation of a major proglacial lake over the site during ice-sheet retreat (Section 6.3). |
| | 1.3.08 | Ecological response to climate changes | Included | Flora and fauna at the site change in response to glacial/interglacial cycling (Section 6.3). |
| | 1.3.09 | Human behavioural response to climate changes | Included | Human behaviour changes in response to glacial/interglacial cycling (Section 6.3). |
| | 1.3.10 | Geomorphologic response to climate changes | Included | Glaciation results in significant changes to the present-day landforms found at the site (Section 6.3). |
| 1.4 | Future Human Actions (Active) | | | |
| | 1.4.01 | Human influences on climate | Included | Global warming is likely to delay the onset of the next glacial event that affects the site (Section 6.3). |
| | 1.4.02 | Social and institutional developments | Included | Repository controls on the development of the site are effective for 300 years following DGR closure (Section 3.8 of Quintessa et al. 2009). Once controls are no longer effective, land use change at the site is likely (see also 1.4.08). |
| | 1.4.03 | Knowledge and motivational issues (repository) | Excluded | Inadvertent human intrusion into the DGR is unlikely due to its depth and the lack of resources at the site. |
| | 1.4.04 | Drilling activities | Included | Once controls are no longer effective, the drilling of shallow water wells in the area is likely over the assessment timescale since such wells currently exist in the region around the site (Section 2.4.4) (see also 1.4.10).<br>The drilling of deep exploration boreholes at the site that penetrate to the depth of the repository is unlikely. The depth (680 m below ground surface) and relatively small footprint of the DGR will mean that the annual probability of such a borehole intruding into an emplacement room would be very low (less than $10^{-5}$ taking a rate of occurrence of $10^{-10}$ $m^{-2}$ $a^{-1}$ - Gierszewski et al. (2004), and an emplacement room area of 5.2 $10^4$ $m^2$ – Walke et al. 2009b). |

| | External FEP | | Status* | Comment |
|---|---|---|---|---|
| | 1.4.05 | Mining and other underground activities | Excluded | No mining since no economically viable mineral resources at site. Other underground activities are unlikely at site because the geology is uniform across a large area and so there is nothing unique at this site. |
| | 1.4.06 | Un-intrusive site investigation | Excluded | No direct impact on repository safety. |
| | 1.4.07 | Surface excavations | Excluded | No direct impact on repository safety due to depth of repository. |
| | 1.4.08 | Site development | Included | Site land use changes are likely once institutional controls are no longer effective (see also 1.4.02). Land uses in the previously controlled area are likely to become consistent with the wider region. In turn, this is likely to be consistent with the land uses currently found in the area surrounding the Bruce site (i.e., predominantly agriculture and recreation – Section 2.4.7). |
| | 1.4.09 | Archaeology | Excluded | No direct impact on repository safety due to depth of repository. |
| | 1.4.10 | Water management (groundwater and surface water) | Included | The drilling of shallow water wells in the area is likely over the assessment timescale once controls are no longer effective (see also 1.4.04). Wells in the deeper groundwater zones are very unlikely since the groundwater in these zones is not potable (Section 2.3.3.2 and 2.3.4). There is present-day abstraction of groundwater in the area from the Shallow Bedrock Groundwater Zone for domestic and agricultural purposes (Section 2.4.7). Lake Huron could also be used as a source of water. |
| | 1.4.11 | Explosions and crashes | Excluded | Surface explosions and crashes would have no direct impact on repository safety due to depth of repository. Postclosure explosions in the repository are unlikely due to absence of an ignition source and oxygen. |
| | 1.4.12 | Pollution | Excluded | Impact of surface contaminants on the wastes disposed in the DGR is likely to be insignificant because of the repository depth and buffering capacity of the rocks above the repository. |
| | 1.4.13 | Remedial actions | Excluded | Remedial actions are unlikely following closure of repository, and if they occurred then the effects on the repository would need to be assessed at that time based on the specific remediation. |
| | 1.4.14 | Technological developments | Excluded | Consistent with the recommendations of ICRP (2000), Section 7.5.4 of CNSC (2006) states that human habits and characteristics should be based on current lifestyles. Therefore technological developments are not considered. |
| | 1.4.15 | Deliberate human intrusion | Excluded | Excluded by assessment context (Section 3.4.2 of Quintessa et al. 2009) consistent with recommendations of ICRP (2000). |
| 1.5 | Other External Factors | | | |

| External FEP | | Status* | Comment |
|---|---|---|---|
| 1.5.01 | Impact of meteorites and human space debris | Excluded | Excluded due to low probability (due to relatively small repository footprint) and low consequence (due to depth of repository). |
| 1.5.02 | Evolution of biota | Excluded | No evolution of humans assumed, consistent with ICRP's recommendation to apply the concept of (present-day) Reference Man to the disposal of long-lived solid radioactive waste (ICRP 2000). Similarly, no evolution of non-human biota assumed. General characteristics of biota are assumed to remain similar to current biota. |

* Status – *Included* means that this factor is considered in the Normal Evolution Scenario. *Excluded* means that this factor is not considered in the Normal Evolution Scenario
.

# 4. EXPECTED EVOLUTION OF THE WASTE AND REPOSITORY

## 4.1 CONTAMINANT INVENTORY

The total activity of radionuclides and the amount of chemical species in the LLW and ILW waste streams at closure are presented in Section 2.1, based on the latest available waste characterisation information provided in OPG (2008). The selected radionuclides and chemical species are based on the results of contaminant screening calculations as explained in the Data report (Walke et al. 2009b).

Contaminants are likely to be available in concentrations that are low in comparison to the bulk materials present. Therefore their behaviour is dictated by the geochemical evolution of the repository, discussed in the following section. However, the inventory of contaminants in the DGR will, itself, evolve with time. The two mechanisms involved are migration and decay/degradation. Contaminant migration is determined by the overall evolution of the repository and therefore is discussed as a key issue later in this section. Decay is an intrinsic property of the contaminants themselves.

Radionuclides will decay to stable isotopes with a characteristic half-life. The radioactivity of the waste will therefore change with time (Figure 4-1 and Figure 4-2).

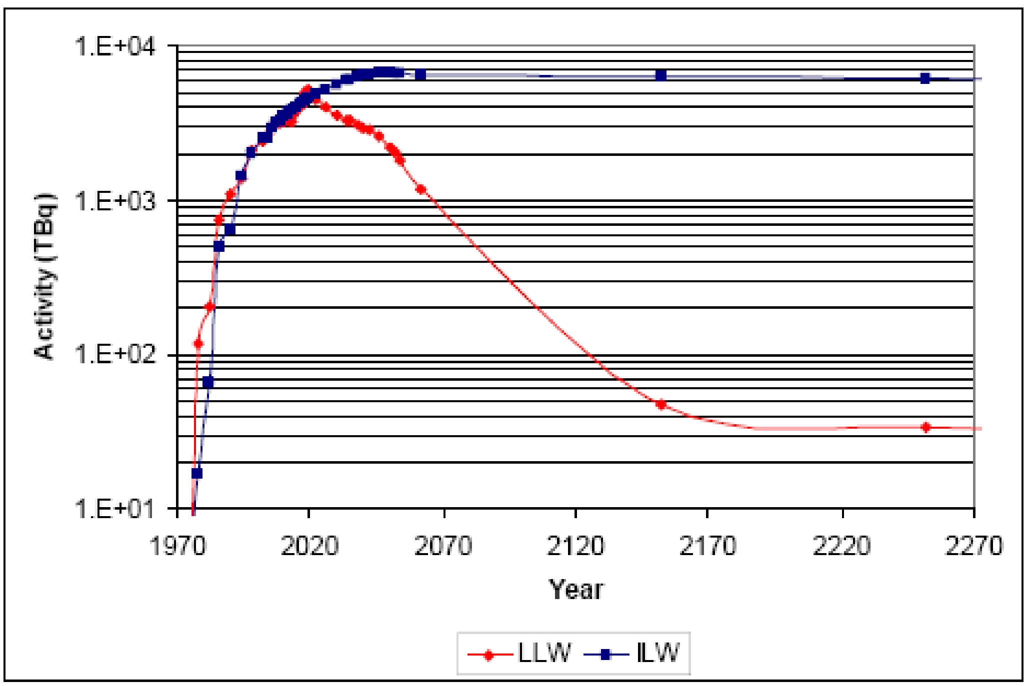



**Figure 4-1: Decay Corrected Activity for Operational L&ILW (after OPG 2008)**

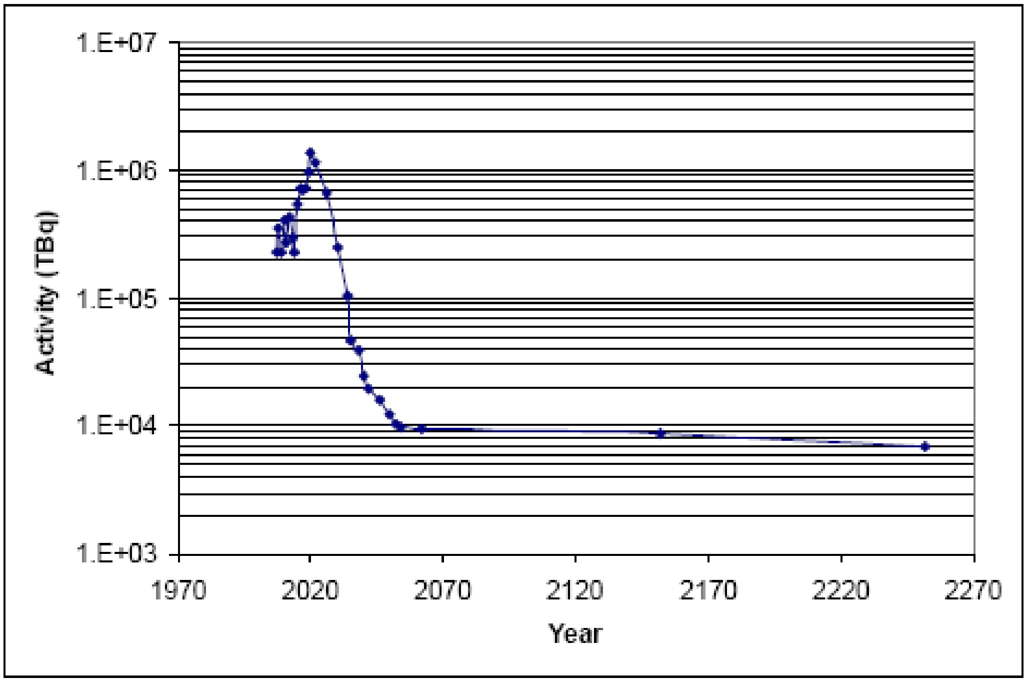



**Figure 4-2: Decay Corrected Activity for Refurbishment Waste (after OPG 2008)**

Figure 4-1 and Figure 4-2 show that the total amount of radioactivity in the LLW will decay to about 0.2 of the peak value after 50 years. Following a period of 250 years after the peak (in about 2020), the radioactivity will have decayed to about 0.01 of the amount present initially. Similarly, Figure 4-1 shows that the total radioactivity of ILW will decay, though at a slower rate than the radioactivity in the LLW owing to the presence of more radionuclides with longer half-lives. The radioactivity of refurbishment wastes initially decays even more rapidly due to the substantial inventory of short-lived activation products such as Co-60 and Fe-55 (Figure 4-2).

The status of non-radioactive species will be dependent on the conditions in the repository. Their potential toxicity will depend on their chemical form. For the purposes of the safety assessment, non-radioactive contaminants are cautiously taken to be initially present in the most harmful chemical form that is consistent with the materials present.

Some species (e.g., organic contaminants) will degrade. Even organics such as dioxins, that are often considered to be quite stable, are expected to degrade on assessment timescales; for example, data suggests effective half-lives of around 100 years in the surface environment (Adriaens et al. 1996). Other contaminants (e.g. heavy metals) will not significantly change over the entire assessment period, but may become locked into immobile mineral forms.

## 4.2 CHEMICAL AND BIOLOGICAL EVOLUTION

Chemical and biological reactions in the waste and repository engineering materials will result in substantial evolution of the repository materials. The nature of the reactions will be dependent on the materials present in the wastes and engineered structures (see Sections 2.1 and 2.2), and the chemistry of groundwater (see Section 2.3.4).

The chemical conditions in the repository can be expressed in terms of key parameters, namely: pH, redox state, salinity, $pCO_2$, total inorganic carbon content (TIC), $SO_4$ concentration and quantities of any mineral precipitates (e.g. calcite in cementitious materials). These factors influence, in particular, the characteristics of contaminant release and migration.

Key materials of interest include metals (in particular ferrous metals), organic materials, cementitious materials and engineered barrier materials (such as bentonite-sand, cement, and asphalt). Each will evolve over the period of interest as a result of the characteristic reactions discussed in this section. In general, it is expected that the high solute concentrations in the groundwater entering the repository will resist chemical changes due to strong buffering reactions.

The evolution of the repository is also affected by the availability of groundwater (which is needed for microbial reactions or corrosion) (Section 4.3). The quantity of groundwater in the repository is a function of the porewater pressure in the rock, the gas pressure in the repository, and the properties of the host rock (which is of low permeability and limited porosity, and so limits inflow). The gas pressure itself is dependent on the rate of water inflow as well as the rock permeability, and likely would act to decrease the water inflow rate.

The following chemical and biological processes are likely to be the most important to consider in the repository.

1) Corrosion of steel, resulting in the consumption of $O_2$ and water, and the generation of $H_2$ (some of which may be labelled with H-3). The process can result in the degradation of containers and rockbolts, and release of radionuclides.
2) The leaching and carbonation of cements. Leaching will cause increases in local pH, porosity and specific surface areas of the solid phases, thereby changing the sorption and solubility conditions that control the mobility of radionuclides. Leaching will also ultimately result in an increase in permeability of cementitious barriers. Carbonation will, to some extent, tend to counteract these processes by armouring cementitious phases and protecting them from leaching.
3) The microbiological degradation of the organic wastes and the associated generation of $CO_2$ and $CH_4$ (which may be labelled with C-14 and/or H3).

These processes will result in the general evolution of the redox conditions from aerobic to anaerobic. The generation of gases (most importantly $CH_4$ and $CO_2$ from organic degradation, and $H_2$ from corrosion) will act to increase gas pressure and reduce pH. This reduction in pH will also result from the formation of organic acids but is expected to be offset by the leaching of concrete in the repository and anaerobic corrosion of steels. There will be an increase in salinity in the repository due to the ingress of saline porewater from the host rock and the consumption of initial water in the wastes during anaerobic corrosion of steels. The anticipated evolution of key geochemical parameters is summarised in Table 4-1.

**Table 4-1: Summary of the Expected Evolution of Key Geochemical Parameters**

| Parameter | LLW Rooms | ILW Rooms | Concrete | Bentonite | Asphalt | Engineered Fill | EDZ |
|---|---|---|---|---|---|---|---|
| **pH** | Likely to be similar to background (up to pH 7) with potential increase in pH due to degradation of cement on ceilings, walls and floors and in wastes being offset by decrease caused by acidity induced by $H_2$, $CO_2$ and/or organic acids from waste package degradation. | Likely to be slightly higher than LLW rooms due to increased amount of concrete associated with waste packaging. Local to cementious waste packages higher pH conditions can be expected to develop. | Rapid increase of pH > 13 in concrete pore fluids, decreasing to ~12.5 and then to pH ~10 and eventually to pH of ambient groundwater. | Front of high pH moving a few cm into bentonite from concrete monoliths/bulkheads. pH = 6.5-8 in rest of bentonite. | Front of high pH moving up to a few cm into asphalt from concrete monoliths/bulkheads. pH of free water need not be considered in unaltered asphalt owing to zero porosity (though a small uptake of water into the asphalt structure is likely). | Due to relatively high permeability of fill and surrounding geosphere, assumed to equilibrate with ambient groundwater over $10^2$ y. | Unchanged from initial conditions (except where the EDZ is adjacent to cementitious materials in which case there may be a small (< 1 pH unit) increase). |
| **Redox** | Initially oxidising, becoming anaerobic over $10^2$ y. Redox defined by anaerobic steel corrosion (Eh = -400 mV at pH 7). If steel is subsequently consumed redox conditions are expected to return to natural values buffered by pyrite – aqueous $SO_4$ and ferroan carbonate – hematite (expected to lie in the range -150 mV to 0 mV) | Initially oxidising, becoming anaerobic over $10^2$ y. Redox defined by anaerobic steel corrosion (Eh = -400 mV at pH 7). If steel is subsequently consumed redox conditions are expected to return to natural values buffered by pyrite – aqueous $SO_4$ and ferroan carbonate – hematite (expected to lie in the range -150 mV to 0 mV) | Initially oxidising, becoming anaerobic over $10^2$ y due to equilibration with ambient groundwater. | Initially oxidising, becoming anaerobic over $10^2$ y due to pyrite dissolution in bentonite and equilibration with $Fe^{2+}$ in smectite. | Entirely anaerobic, except at interfaces during initial $10^2$ y, owing to very low permeability and exclusion of oxygen | | Initially oxidising, becoming anaerobic over $10^2$ y. Initial oxygen consumption by pyrite oxidation and aerobic steel corrosion. Subsequently redox defined by anaerobic steel rock bolt corrosion (Eh = -400 mV at pH 7). |

| Parameter | LLW Rooms | ILW Rooms | Concrete | Bentonite | Asphalt | Engineered Fill | EDZ |
|---|---|---|---|---|---|---|---|
| **Salinity** | Increase in salinity as high salinity porewater enters the repository and the initial water in the wastes is consumed by anaerobic corrosion of steel. | Increase in salinity as high salinity porewater enters the repository and the initial water in the wastes is consumed by anaerobic corrosion of steel. | Will become comparable with background levels with time. | Will become comparable with background levels with time. | Will become comparable with background levels with time. | | No significant change with time. |
| **$pCO_2$** (Defined by TIC at given temperature and pH) | Net increase initially ($10^2$ years) due to degradation of organics. Net decrease thereafter due to conversion of $CO_2$ to $CH_4$. | Net decrease due to conversion of $CO_2$ to $CH_4$ and Ca $CO_3$. | Minor decrease due to carbonation of cement. | Minor decrease due to carbonation of cement at the bentonite/concrete interface. | Minor increase due to conservative assumption of microbial breakdown at interfaces; no change in bulk asphalt | | As per ILW or LLW according to location. |
| **Total inorganic carbon (TIC)** | Net increase initially ($10^2$ years) due to degradation of organics. Net decrease thereafter due to conversion of $CO_2$ to $CH_4$. | Minor decrease due to carbonation of cement (any $CO_2$ entering the ILW rooms in the gaseous phase from elsewhere in the repository would be consumed rapidly after dissolution). | Minor decrease due to carbonation of cement. | Minor decrease due to carbonation of cement at the bentonite/concrete interface. | Minor increase due to conservative assumption of microbial breakdown at interfaces; no change in bulk asphalt | | Unchanged from initial conditions. |
| **$SO_4$ concentration** | $SO_4$ totally consumed due to microbial reaction with $H_2$ over $10^2$ years. | $SO_4$ totally consumed due to microbial reaction with $H_2$ over $10^2$ years. | No significant change with time. Minor exchange of $SO_4$ for $OH^-$ in cement. | No significant change with time. Minor exchange of $SO_4$ for $OH^-$ in cement at the bentonite/concrete interface. | No significant change with time. Possible minor reduction if microbial degradation occurs at interfaces. | | Repository EDZ: $SO_4$ totally consumed due to microbial reaction with $H_2$ over $10^2$ y. Shaft EDZ: no significant change with time. |
| **Porosity** | No significant change with time. | No significant change with time. | Possible slow net increase due to leaching. | Porosity decrease at alteration front in bentonite due to mineral precipitation. | No significant change with time. | | No significant change with time. |

| Parameter | LLW Rooms | ILW Rooms | Concrete | Bentonite | Asphalt | Engineered Fill | EDZ |
|---|---|---|---|---|---|---|---|
| **Main mineral precipitates** | Calcite growth associated with cement carbonation. Iron oxyhdroxide growth on iron components during initial oxic conditions and ultimately under anoxic conditions will produce magnetite and siderite. | Calcite growth associated with cement carbonation. Possible ettringite/gypsum growth in cement. Iron oxyhdroxide growth on iron components during initial oxic conditions and ultimately under anoxic conditions may produce magnetite and siderite. | Calcite growth associated with cement carbonation. Possible growth of ettringite/ gypsum in cement. Iron oxyhdroxide growth on iron components during initial oxic conditions and ultimately under anoxic conditions may produce magnetite and siderite. . | Calcite growth associated with cement carbonation. Migration of C-S-H - zeolite front through bentonite. | Possible minor precipitation of sulphide minerals at interfaces if microbial degradation occurs. | | Iron oxyhdroxide growth on rock bolts during initial oxic conditions and ultimately under anoxic conditions may produce magnetite and siderite. |

The processes associated with each of the key groups of materials in the emplacement rooms, repository tunnels and shafts are discussed in more detail in the following sub-sections.

### 4.2.1 Corrosion of Metals

There are a number of different metallic materials present in the repository, in the form of waste container materials (typically carbon-steel, galvanised steel, or stainless steel), as structural components (such as carbon-steel rails and rock bolts), or as wastes (Zr-based retube wastes and large components such as steam generators and copper alloy heat exchangers).

For the postclosure safety assessment, these materials are classified as belonging to one of the following four corrosion categories:

1. un-passivated carbon-steel (carbon-steel, painted carbon-steel, galvanised steel and copper alloy);
2. passivated carbon-steel (comprising carbon-steel overpacked in concrete, rebar, and rock bolts all of which are in contact with alkaline cementitious pore fluids that will result in the formation of a passive oxide film);
3. passive alloys (all stainless steels and austenitic Ni-alloys, including alloys such as Inconel 600 used in steam generator tubes); and
4. zirconium alloy (Zr alloy pressure tubes and calandria tubes).

These different categories represent alloy classes with a range of corrosion rates, ranging from the rapidly corroding ("active") materials, such as carbon-steel, to the more-slowly corroding passive materials, such as the steam generator and pressure tube alloys. As an illustration of the relative rates of corrosion, a 1 mm thick section of material would corrode under anaerobic conditions in times ranging from of the order of 500 years for the active alloys to 100,000 years for the most-passive alloys.

In aqueous environments, corrosion is an electrochemical process involving the coupling of at least a single anodic reaction (e.g., the dissolution of carbon-steel (Fe) as ferrous ions ($Fe^{2+}$)) and the cathodic reduction of at least one oxidant (e.g., $O_2$, $H_2O$, or $H^+$). These electrochemical reactions will occur in the thin water layers formed in sufficiently humid atmospheres, with the threshold relative humidity for corrosion typically being in the range 60-70% (Shreir 1976). Therefore, corrosion of the metallic waste forms and containers will start during the operational phase, and continue with repository closure.

The mechanisms of corrosion of metallic surfaces under humid and inundated conditions are slightly different. Although many of the same reactions occur under both sets of conditions, the relative importance of different processes is affected by the difference in the rates of mass transport and differences in the chemistry of the aqueous phase. For example, the mass transport of $O_2$ to the corroding surface is typically higher for unsaturated surfaces exposed to humid air than for submerged surfaces, resulting in higher rates of aerobic corrosion. This effect is somewhat offset, however, by the greater propensity for the formation of (protective) corrosion product films in the thin liquid layer as super-saturation of the aqueous phase with respect to corrosion products is more readily achieved.

#### 4.2.1.1 Corrosion of Ferrous Metals

Over a relatively short period of time (less than 10 years), corrosion of the ferrous materials results in the consumption of $O_2$ in the closed repository and the evolution from aerobic to anaerobic conditions. The aerobic corrosion of iron-based materials can be described by the reaction:

$$4Fe + 3O_2 + 2H_2O = 4\text{"}FeOOH\text{"} \quad (4\text{-}1)$$

where "FeOOH" represents a generic ferric oxyhydroxide species, which may also contain groundwater species (Cl, $SO_4^{2-}$, $CO_3^{2-}$) in various forms of green rust. As the environment becomes anoxic, the Fe(III) corrosion products will likely be converted to magnetite rather than $Fe(OH)_2$ via reactions like:

$$2FeOOH + Fe \Rightarrow Fe_3O_4 + H_2 \quad (4\text{-}2)$$

Uncorroded ferrous metals will also form magnetite through anaerobic corrosion processes such as:

$$3Fe + 4H_2O \Rightarrow Fe_3O_4 + 4H_2 \quad (4\text{-}3)$$

After the oxygen is consumed, the redox potential will be defined by the next most-dominant redox couple, which in turn depends on the concentrations of the redox agents and their corresponding rates of reaction. Given the large inventory of Fe-based materials in the repository, the most likely redox-controlling couple is the Fe(II)/Fe(III) couple.

The hydrogen gas that is liberated can accumulate and contribute to the increase in gas pressure in the repository.

The degradation of organic materials, discussed in Section 4.2.2, will increase the partial pressure of $CO_2$ ($pCO_2$) initially, and may therefore stabilize siderite ($FeCO_3$) as the principal corrosion product:

$$Fe + CO_2 + H_2O \Rightarrow FeCO_3 + H_2 \tag{4-4}$$

At an early stage during the evolution of the repository environment, it is likely that sulphate will be reduced to sulphide as a result of microbial activity. Much of the sulphide formed will be precipitated as iron sulphide due to the excess Fe(II) in the system:

Ferrous iron + Dissolved sulphide => "FeS" (4-5)

where "FeS" represents amorphous Fe(II) sulphide, most likely non-stoichiometric.

4.2.1.2 Corrosion of Other Metals

Re-tubes wastes consist mainly of various Zr alloys used as pressure tube materials. The release of activation products within the waste requires the corrosion of the Zr alloy matrix. Under aerobic conditions, the corrosion of Zr is described by:

$$Zr + O_2 \Rightarrow ZrO_2 \tag{4-6}$$

and under anoxic conditions by:

$$Zr + 2H_2O \Rightarrow ZrO_2 + 2H_2 \tag{4-7}$$

Other metals will be present within the repository, such as aluminium, chromium and copper. However, these will not have a significant impact on either the repository environment or the release of radionuclides due to the dominance of Fe (the corrosion of which accounts for the vast majority of the $H_2$ generated) and Zr (the corrosion of which will result in the slow release of activation products from the Zircaloy matrix).

### 4.2.2 Degradation of Organic Materials

The organics present in the various DGR waste forms can be broadly classified as being cellulosic waste (generally comprising paper and other similar material) and "plastic" waste (comprising less-biodegradable organics, such as plastics and resins).

Cellulose is a polymer of glucose and can be represented by the general stoichiometry $[C_6H_{10}O_5]_n$. In the presence of microbes, cellulose is hydrolysed to glucose ($C_6H_{12}O_6$):

$$[C_6H_{10}O_5]_n + [H_2O]_n \Rightarrow [C_6H_{12}O_6]_n \tag{4-8}$$

with the rate of hydrolysis of cellulosic material being one to two orders of magnitude faster than that for the "plastic" wastes. Hydrolysis reactions will occur both in the unsaturated phase (in the thin liquid films adsorbed on the surface of the wastes) and in the bulk groundwater phase. Glucose, in turn, can be microbially decomposed into $CH_4$ and $CO_2$ according to:

$$C_6H_{12}O_6 \Rightarrow 3CH_4 + 3CO_2 \quad (4\text{-}9)$$

This is a key process for the DGR as it results in the liberation of large volumes of gas into the repository void. However, in the presence of $H_2$ generated from metal corrosion, $CO_2$ can be reduced to $CH_4$

$$CO_2 + 4H_2 \Rightarrow CH_4 + 2H_2O \quad (4\text{-}10)$$

This process is potentially important as it results in the conversion of five moles of gas to one mole, and can act to restrain the gas pressure in the repository. It is catalysed by a specific group of methanogenic bacteria.

Whilst biodegradation of cellulosics is well established, biodegradability of resins is uncertain.

- A large body of opinion considers that there would be little degradation of resins under anaerobic repository conditions. In general, the resins are found to be resistant to both chemical and biological degradation. For example, Torstenfelt (1989) reviewed the stability of ion exchange resins in a cementitious environment and noted that the resins are very stable from attack by polar, oxidising or reducing agents.
- However, there is also a substantial body of evidence for the degradation of resins presented in the literature (e.g. Bowerman et al. 1988; Evans, 2000; Bracke et al. 2004). For example, Bowerman et al. (1988) observed that the rate of biochemical attack on resins was very low, but following irradiation (1 MGy Co-60) and/or loading with organic acid anions such as EDTA, citrate, or oxalate, their susceptibility to alteration increased.

In the present safety assessment, resin degradation is treated conservatively, assuming that all the resins do degrade and using a similar treatment to that for cellulose although with a lower reaction rate. This approach maximises the amount of gas generated in the repository.

Note that the degradation of the organics (but not the corrosion of steel) requires the presence of an active anaerobic microbial community. However, the rock porewater around the repository is highly saline and not favourable for microbes – and tests of the host rock formations do not exhibit appreciable microbial activity (Stroes-Gascoyne and Hamon 2007). Although the wastes themselves will contain microbes and some water, at some point the saline conditions of the surrounding rock will control the chemistry and possibly inhibit further microbial activity. This would affect both the production of gas through Equation 4-9 as well as the reduction through Equation 4-10.

The organic degradation also means that there could be significant variations in the chemistry of the water within the repository due to the resulting increased $CO_2$, $CH_4$, Fe(II) and $H_2S$ (e.g., decreased pH).

### 4.2.3 Degradation of Cementitious Materials

Where there are cementitious materials, pH will increase due to leaching of cement through hydrolysis of portlandite:

$$Ca(OH)_2 \Rightarrow Ca^{2+} + 2OH^- \quad (4\text{-}11)$$

and incongruent dissolution of the C-S-H gel. Karlsson et al. (1999) state that there is 420 kg of hydrated cement paste in 1 $m^3$ of concrete. This amount of cement paste is able to liberate up to 8000 moles of $OH^-$ (from both portlandite and C-S-H gel leaching). Saturation of concrete with groundwater therefore leads to the development of a hyperalkaline (pH > 12.5) pore fluid.

The pH decreases with time in accordance with leaching of progressively less-soluble solids. In the long-term, pH in concrete pore fluids is defined by the incongruently soluble C-S-H gel, with pH progressively decreasing from 12.5 to < 10.

The stability of cement pastes in saline solutions and brines has been investigated and Glasser et al. (1999) found that portlandite solubility increases with increasing NaCl content. The presence of a $MgSO_4$ brine component will lead to at least partial replacement of Ca and $OH^-$ in the cement, forming brucite ($Mg(OH)_2$) and gypsum ($CaSO_4.2H_2O$), and resulting in an overall decrease in pH of the coexisting fluid:

$$Ca(OH)_2 + Mg^{2+} + SO_4^{2-} + 2H_2O \Rightarrow Mg(OH)_2 + CaSO_4.2H_2O \qquad (4\text{-}12)$$

Brucite is less soluble than its calcic counterpart, portlandite, and buffers pH ≤ 10. Similar reactions occur with the C-S-H gel component of the cement. At high ionic strength, anhydrite ($CaSO_4$) is expected to form instead of gypsum. Glasser et al. (1999) noted that, in a mixed brine, these reactions are accelerated relative to those in either salt (NaCl, $MgSO_4$) separately. Sodium chloride enhances the solubility of both $Mg(OH)_2$ and $CaSO_4.2H_2O$.

Minor amounts of chloride from brine will be consumed in cement, through the reaction of $3CaO.Al_2O_3$ in the cement paste with $CaCl_2$ in the aqueous phase:

$$3CaO.Al_2O_3 + CaCl_2(aq) + 10H_2O \Rightarrow 3CaO.Al_2O_3.CaCl_2.10H_2O \qquad (4\text{-}13)$$

As a consequence, up to 90 % of $Cl^-$ in cements is present as solid chloroaluminate and not in the pore fluid. There is a direct relationship between the capacity of cement to 'bind' chloride ions and its $3CaO.Al_2O_3$ content.

Any increase of temperature above ambient will accelerate ageing and crystallisation of the C-S-H gel component of the cement paste, producing solids such as jennite, tobermorite, and afwillite (Glasser et al. 1999). These phases are likely to condition coexisting pore fluids to a lower pH and induce some contraction and/or shrinkage of the cement paste.

Some inorganic carbon in the repository (in gaseous and aqueous phases) will be precipitated in concrete materials. $CO_2$ dissolved in groundwater will be involved with the carbonation of portlandite, producing calcite:

$$Ca(OH)_2 + CO_2 \Rightarrow CaCO_3 + H_2O \qquad (4\text{-}14)$$

In some instances a protective layer will consequently be formed on the cement/concrete surface. In addition, $pCO_2$ will decrease and the activity of water will increase as a result of this reaction. The availability of $CO_2$ for this reaction will be limited by competing reactions: reaction between $CO_2$ and the carbonate host rock, and microbial reduction of $CO_2$ with $H_2$ to form $CH_4$.

Reaction of cement and concrete with sulphate in groundwater is likely to cause swelling and cracking due to solid volume changes associated with the conversion of portlandite ($Ca(OH_2)$) and C-S-H to ettringite ($Ca_6Al_2(SO_4)_3(OH)_{12}.26H_2O$) and /or gypsum ($CaSO_4.2H_2O$):

$$6Ca(OH)_2 + 2Al^{3+} + 3SO_4^{2-} + 26H_2O = Ca_6Al_2(SO_4)_3(OH)_{12} : 26\,H_2O \quad (4\text{-}15)$$

Ettringite formation requires 3 moles of sulphate and 2 moles of Al, and thereby consumes 6 moles of portlandite (or the equivalent amount of Ca from C-S-H gel). The net solids volume change is +356 %, on the basis that both Al and S are present in the aqueous phase.

### 4.2.4 Evolution of Bentonite

Compacted bentonite will saturate with ambient groundwater and swell, as illustrated in Figure 4-3.

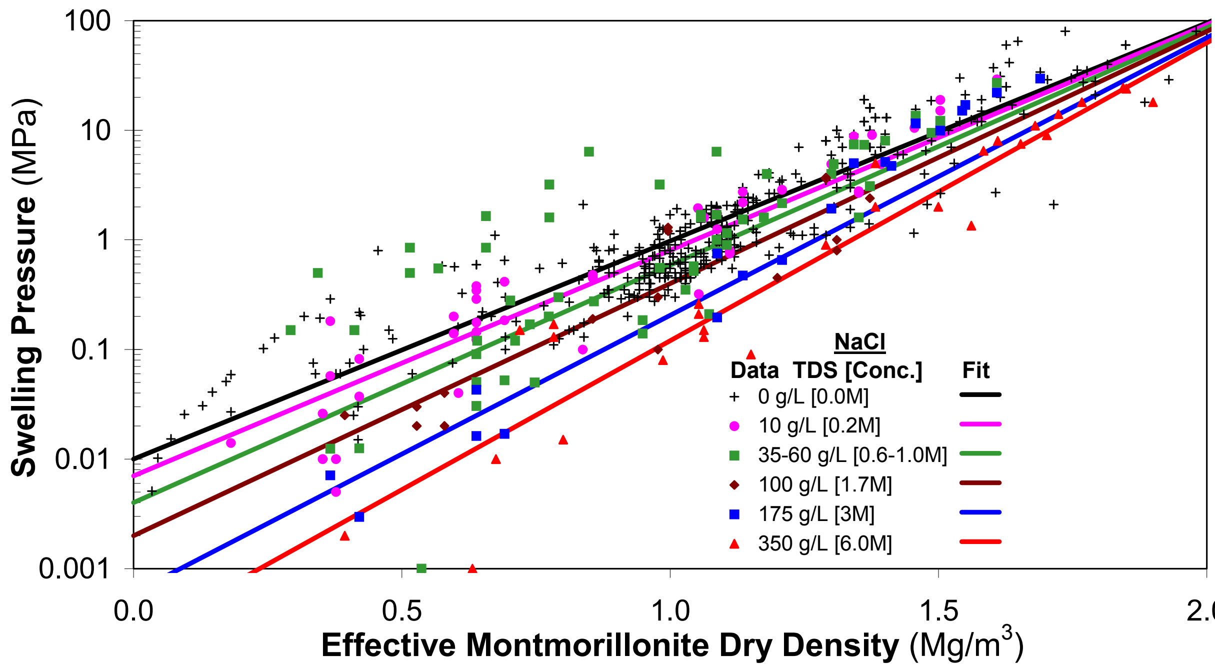



**Figure 4-3: Swelling pressure as a function of clay density and salinity in smectite-based sealing materials; the TDS is based on NaCl solution (after Baumgartner 2006)**

At the interface with concrete, the clay minerals in the bentonite will be destabilised by the elevated pH of pore fluids within the concrete. Above pH 10, deprotonation of neutral aqueous silica species serves to increase silicate solubility. $OH^-$ ions also catalyse the rate of aluminosilicate dissolution by weakening Al-O bonds, such that the rate of dissolution is typically proportional to $[OH^-]^{0.5}$. A simple mass balance for the dissolution of montmorillonite at high pH is as follows:

$$Na_{.33}Mg_{.33}Al_{1.67}Si_4O_{10}(OH)_2 + 4.68OH^- + 2H_2O \rightarrow \quad (4\text{-}16)$$
$$0.33Na^+ + 0.33Mg^{2+} + 1.67Al(OH)_4^- + 4\ HSiO_3^-$$

which implies that dissolution of one mole of montmorillonite consumes 4.68 moles of $OH^-$. If MX-80 bentonite contains roughly 90 wt % montmorillonite, then montmorillonite dissolution can account for ~12 moles of $OH^-$ per kg of (dry) bentonite. However, as identified by Takase (2004), the mass balance issue is complicated by the nature of the potential secondary products of the cement-bentonite interaction. Growth of secondary minerals will contribute to consumption or generation of $OH^-$. An example is precipitation of tobermorite, which will enhance the pH buffering capacity of the bentonite and decrease the degree of montmorillonite dissolution by consuming hydroxyl ions:

$$5Ca^{2+} + 6HSiO_3^- + 4OH^- + 5.5H_2O \Rightarrow Ca_5Si_6H_{21}O_{27.5} \quad (4\text{-}17)$$

In contrast, the precipitation of minerals such as analcime:

$$Na^+ + Al(OH)_4^- + 2HSiO_3^- \Rightarrow NaAlSi_2O_6 + 2OH^- + 2H_2O \quad (4\text{-}18)$$

or zeolites will generate $OH^-$, prolong the duration of the hyperalkaline alteration, and potentially increase the amount of montmorillonite dissolution, thereby increasing the spatial scale of alteration.

In this regard, it is likely that there will be a difference between alteration of bentonite at pH > 12 and that at lower pH. Mineralogical alteration at pH > 12 is dominated by the growth of calcium silicate hydrate solids, such as tobermorite, whereas alteration at pH < 12 is typified by zeolites (Savage et al. 2007). Secondary mineral formation at pH < 11 (i.e., at pH conditions typical of low-pH cement) will therefore be zeolitic, and thus tend to extend the zone of alkaline alteration. However, the availability of silica will be limited compared to higher-pH conditions because montmorillonite will not dissolve as readily (see Equation 4-16) and so the extent of the alteration zone will be restricted.

The degree of bentonite alteration is sensitive to a number of factors, such as the precise rate and mechanism of montmorillonite dissolution under conditions that are close to equilibrium, the variation of porosity and permeability with time, the composition of cement pore fluids, and the assumed crystallinity and types of secondary minerals (Savage et al. 2007). Essentially, a front of alteration will move by diffusion through the bentonite, controlled by the changing physical properties with time. This front may move a few tens of cm into the bentonite over a 1000-year timescale according to the mass and composition of the bentonite and cement, and groundwater composition (Savage et al. 2007; Gaucher et al., 2004). These processes are usually accompanied by a decrease in porosity and may thus be self-limiting in terms of spatial scale and so alteration would not extend beyond a few tens of cm, even over extended time periods. This mineral alteration will likely lead to embrittlement of the bentonite and a loss of swelling pressure within the altered zone.

### 4.2.5 Evolution of Asphalt

Other than aggregates or sand, asphalt consists of four different components, often referred to as bitumen: saturated hydrocarbons; aromatic hydrocarbons; resins; and asphaltenes. Under anaerobic conditions, resins and asphaltenes are more or less unaffected by micro-organisms (Pettersson and Elert 2001) unless the surfaces of the asphalt are exposed to flowing water (Pedersen 2001), which is not expected to occur in the DGR following asphalt emplacement. Brodersen et al. (1991) state that with the present knowledge about biodegradation of bitumenised waste, biodegradation seems to be of minor importance for the long-term evolution of asphalt. Miller et al. (2000) cite numerous natural asphalts that have survived intact for tens of thousands of years.

Although asphalt is a hydrophobic material, water can be transported into the asphalt matrix (Pettersson and Elert 2001). This process is usually described as diffusion of water vapour. Water uptake does not only take place in water-saturated systems but also in humid air. However, unless there are impurities (e.g. mineral fillers such as fly ash, hydrated limestone or stone dust), the water uptake is negligible. In summary, from the available evidence, it seems very unlikely that asphalt degradation will occur in the DGR system. Any degradation would be extremely slow, with the degradation products being $CO_2$ and $CH_4$ with volatile fatty acids as intermediates.

## 4.3 HYDRAULIC EVOLUTION

Construction of the repository will draw down the porewater heads around the excavated tunnels and emplacement rooms. At the time of repository closure, the emplacement rooms will be essentially free of significant liquid water accumulations but the atmosphere will be humid and moisture will be present in some wastes. If there is sufficient moisture in the vapour phase of the repository (expected for relative humidities greater than around 60%, surfaces will be wetted by a thin adsorbed water layer of the order of a few nm thick (equivalent to a few tens of water molecules).

Following closure, the repository's resaturation profile will be determined by the rate of inseeping water, the rate of gas generation by degradation of organic matter and corrosion of metals (Section 4.2), and the rate at which gas migrates from the repository, either as free phase gas or dissolved in water (Section 4.7). The gas generation rate will not be constant, but will vary over time in a way that depends upon the inflow of water to support the corrosion and microbial degradation reactions. It is anticipated that there will be significant gas generation within the repository due to the corrosion of metals and microbial degradation of organic wastes. As gas is generated in the repository the gas pressure will rise more rapidly than would occur due to resaturation and reduction of the gas headspace alone. Therefore, the repository will likely only partly resaturate before resaturation ceases.

If gas generation continues and the gas pressure increases above hydrostatic pressure, then the repository will begin to desaturate as the water is pushed back into the rock. If the gas pressure in the repository rises above hydrostatic pressure (plus the host rock gas entry pressure), then gas will begin to permeate into the rock adjacent to the repository.

The rate of migration or loss of gas from the repository will depend on which processes dominate. With the low permeability, low porosity geosphere at the Bruce site, it is likely that the repository would not fully resaturate for hundreds of thousands or even millions of years. It is possible that at sufficiently high gas pressures, other processes may lead to faster gas loss, such as potentially the influence of ice-sheet loading, or gas-mineral reactions, or other processes activated by high gas pressure. These processes have not yet been evaluated. Eventually gas generation will cease due to complete consumption of metals and organics. The gas pressure in the repository will decrease due to migration of bulk gas into the geosphere and dissolution of gas into groundwater, and the repository will slowly resaturate. In the long term, the repository is likely to contain a significant fraction of predominantly $CH_4$ gas at around hydrostatic pressure (due to the conversion of $H_2$ and $CO_2$ to $CH_4$), similar to what occurs in (larger) natural gas fields in sedimentary rocks.

## 4.4 MECHANICAL EVOLUTION

### 4.4.1 Emplacement Rooms and Repository Tunnels

The following mechanical processes are likely to occur in the repository at some point:

- deformation and "slumping" of waste containers due to corrosion; and
- rockfall.

Slumping of the waste containers in the emplacement rooms will occur as the containers at the bottom of the stacks corrode and loose their mechanical strength. The entire set of containers will eventually slump, albeit constrained by adjacent containers and the remaining bulk of the lower containers and their waste.

Failure of the rock will eventually occur as the rooms are not backfilled. Geomechanical modelling of the stability of the repository (Damjanac 2008) indicates that, under the influence of in-situ stress and internal gas pressure, the degradation of the rock is such that damage propagates up to at most 7 m above the roof of the emplacement rooms and tunnels (assuming no support) over the timescales considered (100 ka). The maximum extent of rockfall 100 ka after excavation is estimated to be 2.5 m, assuming no additional loading (e.g., seismic shaking or ice-sheet loading).

Consideration has also been given to seismic events. Those considered included a **M**5.5 event at 15 km from the repository and a **M**7 event at 50 km. The analysis shows that if the event were to occur 100 ka after construction, most of the damaged rock mass would be shaken down. However, it is noted that most of the EDZ would have formed after only about 15 ka, so, in safety assessment terms, a conservative assumption would be to assume a collapse of about 7 m at 15 ka, in response to an earthquake. Damjanac (2008) does not consider the potential effects of more frequent but lower magnitude earthquakes, nor the consequences of repeated glaciations, nor long-term shaft stability. However, it is anticipated that further work will be undertaken to address these issues.

Rock collapse, induced by seismic events and/or ice-sheet loading/unloading, 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 height of the collapse zone is anticipated to extend to 20 m above the emplacement rooms and 30 m above the access tunnels, taking around 45 ka and 75 ka to develop respectively (Appendix A). More conservative estimates suggest that the height of the collapse zone could be 50 m for the emplacement rooms, taking 0.8 Ma to develop, and 70 m for the access tunnels, taking 1 Ma to develop.

These considerations can be used to determine a potential sequence and timing of rockfall events for consideration in the safety assessment. Appendix A presents more details, and a quantitative treatment of rockfall events.

### 4.4.2 Shafts

The chemical and biological processes that operate on the shaft materials (Section 4.2) can result in a number of physical changes which in turn will affect the mechanical evolution of the shaft and its materials. The physical changes include the following.

- Cracking due to precipitation of ettringite in concrete and embrittlement of bentonite. Cracking will lead to a change in the porosity, but the most significant change will be to the hydraulic conductivity.
- Changes in concrete porosity due to precipitation. Changes in the porosity will also result in changes in the hydraulic conductivity, effective diffusivity and retardation factor.
- Changes in bentonite swelling pressure. Changes in the swelling pressure will lead to changes in the porosity, and hence the hydraulic conductivity, effective diffusivity and retardation factor. The swelling pressure against the shaft walls will also affect the quality of the seal at this interface between material types.
- Microbial degradation of asphalt possibly leading to porosity increase, embrittlement and cracking. Cracking could lead to a change in the porosity and the hydraulic conductivity.

Changes in the mechanical properties will be most significant for the concrete monoliths at the bases of the shafts and the concrete bulkheads which occur at various intervals up through the shafts (Figure 2-6). As these concrete monoliths and bulkheads degrade, their mechanical strength will tend to decrease and they might be physically disrupted leading to fracturing and increases in hydraulic conductivity.

In addition to being affected by chemical and biological processes, the performance of the shaft materials could be affected by the geomechanical impacts of an overlying ice-sheet. The consequences are related to changes in physical properties resulting from fracturing due to loading/unloading (primarily changes in hydraulic conductivity and porosity) that will influence the process of groundwater and gas migration of contaminants.

#### 4.4.2.1 Seals in the Deep Bedrock Groundwater Zone

The components of the shaft seal system in the Deep Bedrock Groundwater Zone are overlain by the shaft backfill in the Intermediate and Shallow Bedrock Groundwater Zones. The lithostatic pressures will increase with depth, and therefore will be greatest in the shaft backfill within the Deep Bedrock Groundwater Zone. Compaction of shaft backfill by overlying materials will be greatest in the Deep Bedrock Groundwater Zone.

The densities of the materials proposed for backfilling the shafts are generally a little lower than those of the geosphere lithologies (Walke et al. 2009b), and, with the exception of the concrete bulkheads, the backfill materials will be considerably less stiff than the rock. This density difference means that at a given elevation the lithostatic pressure in the shaft will be a little lower than in the geosphere, and the geosphere rock will try to relax into the shaft, compressing the less stiff shaft backfill. This relaxation will be negligible compared with the relaxation caused by forming the open shafts, and will not result in any further enhancement of the EDZ. Opposing these phenomena there may be stress imparted by the backfill on the adjacent geosphere within the sections of the shaft sealed with bentonite sand. Swelling of the bentonite will induce some lateral stress on the geosphere and will tend to close fractures in the EDZ. The swelling bentonite may also penetrate some of the fractures, depending on their orientation and connectivity to the shaft. The shaft bulkheads may also impact stress on the geosphere, if they act as a ‘hard point’ where the geosphere is relaxing and squeezing the backfill above and/or below the bulkhead.

Hatch (2008) describes how concrete bulkheads will be keyed into the geosphere at various elevations within the shafts, removing much of the EDZ in the process (and the outer EDZ in the case of the water-stops). Since the shaft seal materials underlying the concrete bulkheads will not have been compacted by a weight equal to the final overburden there will tend to be some residual downwards stresses imparted on the bulkheads by the overlying backfill, i.e., the backfill under the bulkhead will tend to compact under the weight of the overlying material, and hence the bulkhead will want to 'bow' as its middle tends to subside and the edges are pinned by the geosphere. However, since there are a number of bulkheads along the length of the shafts, any residual downward stress will be limited by the amount of material between bulkheads.

Where the underlying material is a bentonite/sand mixture, these residual downwards stresses will tend to be cancelled by the upward stresses due to the swelling pressure. However, this effect is complicated because of the great variation in swelling pressure with water uptake and the fact that the swelling pressure will change with time. Where a bentonite/sand mixture is present above and below a concrete bulkhead, the swelling pressures will tend to cancel. For the bulkhead overlying the asphalt, the residual downward stresses will be enhanced by the swelling pressure of the overlying bentonite/sand mixture.

The bulkheads are designed to withstand these pressures; however, as the concrete degrades and its mechanical properties change, it may potentially be disrupted by any pressure differentials. These pressure differentials include those imparted by the gas pressure within the repository in the context of the monoliths at the bases of the shafts.

#### 4.4.2.2 Seals in the Intermediate Bedrock Groundwater Zone

The lithostatic (overburden) pressures in the shaft sealing system will be lower in the Intermediate Bedrock Groundwater Zone than in the Deep Bedrock Groundwater Zone and swelling pressures will be more significant relative to the lithostatic pressure. Changes in swelling pressure may therefore be more significant in terms of the overall shaft seal system performance than in the Deep Bedrock Groundwater Zone.

#### 4.4.2.3 Seals in the Shallow Bedrock Groundwater Zone

Lithostatic (overburden) pressures in the shaft sealing system will be lowest in the Shallow Bedrock Groundwater Zones. The shaft seal system design does not include any bentonite in the shallow zone so there will not be any swelling pressure, unless transmitted from the underlying intermediate geosphere, in particular following any mechanical degradation of the concrete bulkhead separating the Intermediate and Shallow Bedrock Groundwater Zones.

## 4.5 THERMAL EVOLUTION

The temperatures in the repository will vary as a result of both processes operating within the repository itself and thermal effects in the surrounding geosphere. This section considers only the former effects; thermal effects in the geosphere are considered in Section 5.1.

Overall, there will be little radiogenic heating in the L&ILW (including reactor refurbishment waste) present in DGR at the time of closure (Figure 4-4). Some of the retube wastes contain relatively high concentrations of Co-60 and, if emplaced in the repository before this isotope has decayed substantially, could potentially attain locally elevated temperatures. The effect will be short-lived owing to the rapid decay of Co-60, and, if necessary, these wastes could be stored for longer at the surface prior to emplacement. Peltier (2004) notes that the natural geothermal heat flux in the vicinity of the Bruce site is 80 W $m^{-2}$ which equates to 23 kW for the overall area of the repository footprint (Hatch 2008). So radiogenic heating in the repository will be negligible.

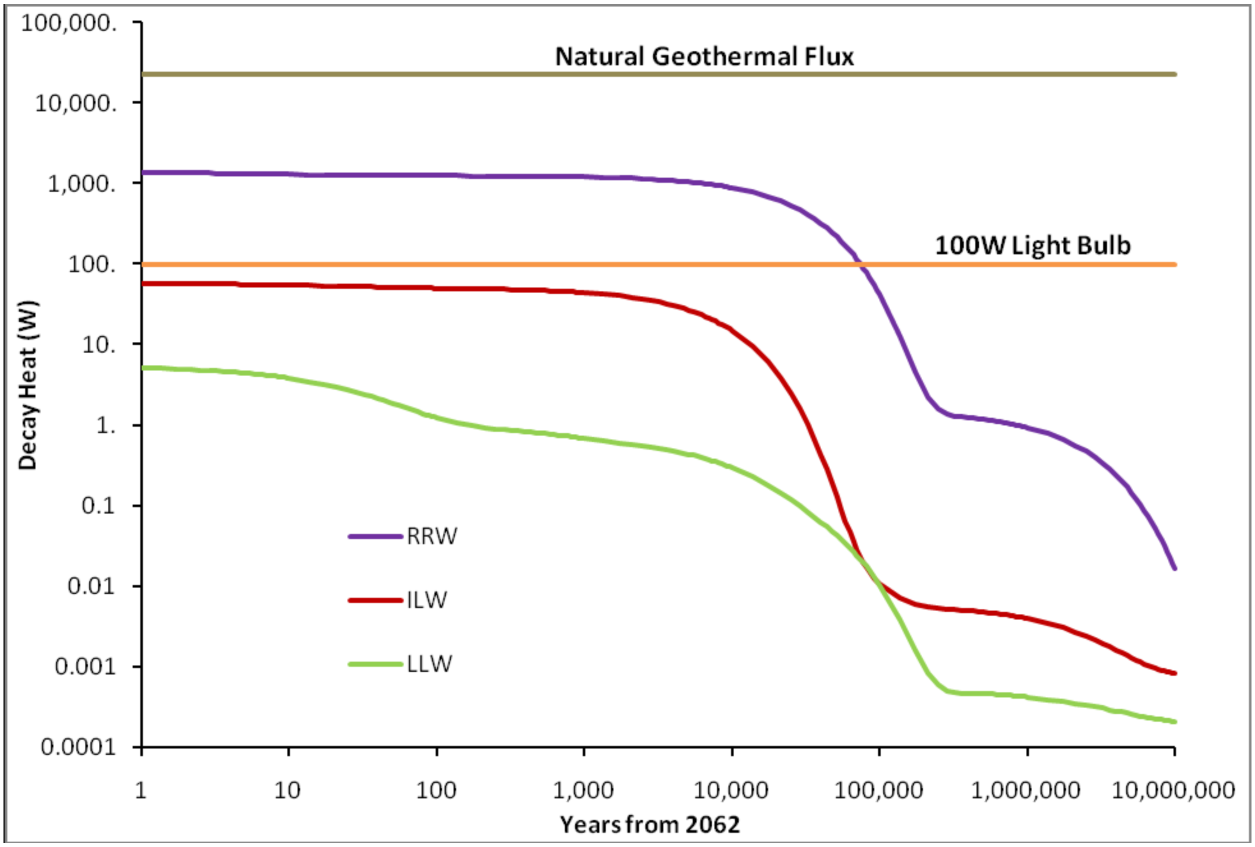



**Figure 4-4: Total Decay Heat of the Waste as a Function of Time**

Hydration of cementitious materials is an exothermic reaction that will cause temperatures to rise during the initial period. The DGR will contain large quantities of cementitious materials for structural purposes, but construction will largely take place well before the repository is closed, therefore most cements will have completed hydration and cooled. The exception relates to the concrete monoliths and bulkheads that will seal the repository.
Corrosion of waste metals, and decomposition or degradation of organic materials will be in progress at the time of repository closure (Section 4.2.2), and can be expected to emit some heat.

Overall, heat production is not expected to have a significant effect given the very large thermal sink of the surrounding rock and the limited heating effect (e.g. a few degrees centigrade as a result of decay heat from retube wastes). Therefore, it is expected that there will not be any significant temperature gradients in the repository postclosure, and, in the absence of glacial and interglacial cycling, conditions will remain close to the ambient host rock temperature given in the Data report (Walke et al. 2009b) of about 20 $^{o}$C. The effects of glacial and interglacial cycling on repository temperature are considered in Section 5.1.

## 4.6 CONTAMINANT RELEASE

### 4.6.1 Contaminant Release Processes

A range of potential mechanisms may lead to the release of contaminants from the disposed wastes. These mechanisms do not require fully water-saturated conditions in order for the radionuclides to be released from the wastes themselves. The conditions within the repository will always be humid, so that release is possible before saturated conditions are attained.

#### 4.6.1.1 Leaching

Radionuclides that contaminate the surfaces of solid materials readily come into contact with any water that enters the wastes. The extent to which surface contaminants enter the water is controlled by surface reactions such as surface complexation and cation exchange (e.g. in ion exchange resins), but could include mobilisation and subsequent dissolution of contamination in particulate form. These are treated together in an empirical relationship referred to as sorption. The most important controls on leaching are those that will evolve as a result of the chemical and biological processes discussed in Section 4.2. These include pH, redox and salinity (TDS), which affect the distribution of elements among aqueous species.

The extent to which a particular element will be leached depends to a large extent upon the charge of the dominant species in which the element occurs. Similarly, the aqueous chemistry will affect the sorption characteristics of the mineral surfaces. The characteristics of the solids themselves will also impact greatly upon the extent to which leaching occurs. The specific surface area, surface charge and characteristics of surface complexes (particularly the abundance of OH: groups) will particularly influence the extent of leaching and the characteristics of the species that may leached.

#### 4.6.1.2 Diffusion, Corrosion and Degradation

Radionuclides that are contained within the matrix of solid materials will only be able to enter the water by diffusion through the material in which they are embedded, or as a result of corrosion (in the case of metals) or degradation of the material in question (e.g., by microbially mediated breakdown of organic material). Corrosion and degradation processes are discussed in Section 4.2.

#### 4.6.1.3 Radioactive Gas Generation

Radioactive decay of actinides will produce gaseous progeny radionuclides (Rn-222, Rn-220), which may diffuse relatively easily, but are short lived.

Radioactive $CO_2$ and $CH_4$ may be generated through the incorporation of C-14 and H-3 into these gases. Radioactive water vapour and hydrogen gas may also be generated through the incorporation of H-3. C-14 and H-3 may also be incorporated into other minor gaseous phases (e.g., $H_2S$) in the DGR, although these minor gases are not considered to be significant in terms of contaminant release.
The majority of H-3 is present as surface contamination in the form of tritiated water in the LLW waste streams. It is also present in the ILW resins mostly as tritiated water (roughly ~70%) and as 'fixed' activity (i.e., an integral part of the waste materials themselves). H-3 is only present as 'fixed' activity in the ILW metallic wastes (such as irradiated core components and retube wastes). H-3 present as surface contamination will be released by diffusion of gaseous H-3 as HTO out of the unsaturated waste containers. In saturated waste containers, H-3 present as

surface contamination will be released in the aqueous phase. H-3 can exchange between groundwater and water vapour (gas) in the repository. H-3 present as fixed activity is released by diffusion of tritiated hydrogen gas out of the wastes materials, and subsequently out of the waste containers. The tritium associated with hydrogen gas may subsequently ion-exchange with hydrogen in water vapour and be microbially incorporated into methane.

The majority of the C-14 inventory is in ILW resins. C-14 is present mostly (roughly 85%) as carbonate/bicarbonate for ILW resins. The rest is incorporated into resins as the organic form. C-14 is also present as an activation product in ILW steels (retube wastes). Some amount of C-14 is present in carbonate/bicarbonate as surface contamination on the LLW cellulosic and plastic wastes.

C-14 radiolabelled $CO_2$ and $CH_4$ gases are produced through the microbial degradation of both saturated and unsaturated LLW cellulosic & plastic wastes, and ILW resins & filters. C-14 release from metals is congruently controlled by corrosion. Corrosion can occur in both the saturated and unsaturated wastes. For metallic wastes, C-14 is likely to be released from the saturated wastes as bicarbonate and carbonate ions, whilst in the unsaturated zone, C-14 is incorporated in iron corrosion products (e.g. sorbed on to ferrous hydroxides and incorporated into siderite and potentially green rusts) and is released to water once the wastes become saturated.

If C-14 is associated with carbides in the metaliferous wastes, as opposed to being in the elemental form, it could be congruently released from the unsaturated wastes as radiolabelled methane. However, this is not considered in the Version 1 conceptual model. C-14 associated with carbonate and bicarbonate ions in the repository waters can exchange with $CO_2$ in the repository atmosphere. C-14 associated with $CO_2$ in the repository atmosphere may subsequently be microbially metabolised to $CH_4$ by reaction with $H_2$ gas. This process continues until all the $H_2$ gas in the repository has been consumed.

#### 4.6.1.4 Solubility Limitation

The limit on an element’s solubility is determined by the equilibrium constant for the dissolution of the solubility-limiting solid phase and the equilibrium constants for the formation of other soluble species, usually complexes. The solubility-limiting solid phase is the most thermodynamically stable solid that can form under the prevailing conditions (Chambers et al. 1995). Concentrations of most contaminants will be sufficiently low that solubility limits will not be reached, although some locally high concentrations could result in temporary solubility limitation (e.g., within waste packages and overpacks) under certain conditions (particularly of pH, Eh and concentrations of complexing ions as discussed below). This in turn can control the rate of radionuclide release from waste into the repository water.

An increasing pH tends to decrease the solubilities of radioelements. This is because many of the most stable solid phases are hydroxides, and increasing the concentration of hydroxyl ions in solution will drive the solubility equilibrium towards the solid phase, reducing the solution concentration of the radioelement. The DGR is likely to operate at around neutral pH to slightly acidic pH, with little capacity to buffer pH internally at more alkaline values (because there will be relatively small quantities of cement present). As a result, it is expected that there will be little control of solubilities through pH, except in limited, localised pH environments (e.g., those associated with cement-based waste packages).

The anaerobic conditions expected to prevail in a repository from shortly after closure (negative Eh) drive the most stable oxidation state to a lower level (for elements such as actinides and technetium where alternatives exist). In general, the lower the oxidation state, the lower the limiting solubility.

Some solubilities of radioelements are increased by the presence of complexing ions. One example would be the effect of carbonate ions on uranium solubility. Another is the impact of complex organic acids generated by the decomposition of cellulosic wastes on the solubility of plutonium (Greenfield et al. 1997).

### 4.6.2 Influence of Mechanical Processes on Contaminant Release

The mechanical processes discussed in Section 4.4 could influence the release of contaminants from the wastes in the following ways.

- Rockfalls and corrosion of waste containers are likely to cause breaching of the containers.
- A slumped column of waste containers, or compression following a rockfall, could release the waste form, causing the waste to be more rapidly exposed to the groundwater.
- Corrosion products are likely to have larger specific volumes than uncorroded materials, leading to expansion. The stresses caused by such expansion are likely to affect the integrity of containers.

These mechanical processes lead to the opportunity for more prompt contaminant release to groundwater and gas due to the failure of the waste container and any overpacking. However, most waste packages in the repository are not intended to be fully sealed and the lifetime of waste containers is expected to be relatively short in comparison with the overall assessment timeframe. Consequently, a cautious but reasonable assumption can be adopted in which it is assumed that all wastes are available for contact by repository water immediately following closure of the DGR.

### 4.6.3 Influence of Temperature on Contaminant Release

The limited scope for heating in the repository means that it is reasonable to assume that there will be little temperature variation, and processes can be considered to take place at the ambient temperature of around 20 $^{o}$C.

## 4.7 MIGRATION AND RETARDATION

Radionuclides released from the waste packages, will enter the water and/or gas in the emplacement rooms. The distribution of elements between the gaseous and aqueous phases will reflect their chemistry. The quantity of water and gas present will vary with time as the repository gradually resaturates.

Contaminants in **water** can migrate from the emplacement rooms into the surrounding rock and the shafts and their associated EDZs by diffusion and advection. Provided water is present in the DGR, diffusion will occur through surfaces contacted by the water. As the repository resaturates, the area over which diffusion occurs will therefore increase. Diffusion will occur from the repository in all directions. Advection will, however, only occur if driven by hydraulic and/or gas pressure.

Contaminants in **gas** can be released by: dissolution into water in and surrounding the repository and subsequent advection and diffusion in groundwater/porewater, and advective transport of bulk gases, e.g., via the shafts and their associated EDZs especially prior to resaturation. The extent to which the advective movement of bulk gases occurs is dependent upon the pressures within the repository.

The migration of most contaminants in groundwater through rocks is usually significantly retarded by sorption. Sorption data specific to the DGR conditions (saline groundwater, Ordovician limestone) has not yet been directly measured. However, measurements in somewhat similar systems, including the saline environment at WIPP, indicate that sorption will help retain important radionuclides in the DGR. The chemical characteristics of seven elements of potential importance in the postclosure safety assessment and their sorption properties are summarised in Table 4-2. A review of sorption values is documented in the Data report (Walke et al. 2009b).

**Table 4-2: Chemical Characteristics and their Influences on Sorption for Selected Elements**

| Element | Chemical characteristics | Sorption characteristics |
|---|---|---|
| C | Under most deep groundwater conditions inorganic carbon will be dominantly in the form of $HCO_3$-<br><br>At lower pH, $H_2CO_3$ may be significant or even dominant (pH < 6.2)<br><br>At higher pH, $CO_3^{2-}$ may be significant or even dominant (pH > 10.1)<br><br>Under very reducing conditions, carbonate may be reduced to $CH_4$<br><br>Carbonate is a major component of solid carbonate mineral phases (most commonly calcite, dolomite and siderite) and may therefore partition between these phases. | Adsorption onto Fe-oxyhydroxides and carbonate minerals may be significant<br><br>Adsorption is largely independent of ionic strength, especially for the $CO_3^{2-}$ ion, indicating strong inner-sphere co-ordination<br><br>Carbonate and bicarbonate form complexes with certain metal ions; such complexation may reduce the degree of sorption to mineral surfaces<br><br>$CH_4$ is not likely to be significantly sorbed onto inorganic solids; sorption onto organic materials may occur<br><br>Significant sorption does not occur at very acidic pH values due to the formation of neutral $H_2CO_3$.<br><br>Sorption increases at higher pH as $HCO_3^-$ becomes stable and able to sorb onto positively-charged sites on the surface.<br><br>Sorption decreases at even higher pH because $CO_3^{2-}$ is repulsed from increasingly negatively-charged surfaces |
| Cl | Not typically significantly bound in aqueous complexes and generally considered to be “conservative” (that is not participating extensively in water/rock reactions) | Sorption is extremely weak and often undetectable |
| Ni | Can exist in oxidation states ranging from | Shows pH-dependent sorption onto many solid |

| Element | Chemical characteristics | Sorption characteristics |
|---|---|---|
| | -1 to +4, but in natural groundwaters the dominant form is Ni(II) and it is not readily affected by redox reactions. In crystal structures $Ni^{2+}$ readily substitutes for $Mg^{2+}$, $Mn^{2+}$, $Fe^{2+}$, $Cu^{2+}$ and $Co^{2+}$. In aqueous solutions, an aqua complex, $[Ni(H_2O)_6]^{2+}$, may form readily.<br><br>Complexes occur with many other organic and inorganic ligands, such as $Cl^-$, $CO_3^{2-}$, $SO_4^{2-}$; salts with almost all common inorganic anions occur.<br><br>At pH < 9, speciation is usually $Ni^{2+}$-dominated, but contributions from $NiOH^+$, $Ni(OH)_2^0$, and $Ni(OH)^{3-}$ increase with increasing pH.<br><br>In the presence of $HS^-$ sulphide phases may form, and $Ni^{2+}$ can substitute for $Fe^{2+}$ in pyrite ($FeS_2$).<br><br>NiO and $Ni(OH)_2$ are theoretically solubility-limiting solid phases, but nickel sulphides and silicates may be more important solubility-limiting solid phases in nature. | phases, reflecting pH-dependent aqueous speciation and mineral surface charges. Sorption onto Fe / Mn oxides and hydroxides is generally strongest. Sorption onto feldspar and clays is weak.<br><br>Sorption occurs by both cation exchange and surface complexation mechanisms. Little sorption will occur at low pH, where $Ni^{2+}$ is the dominant specie and mineral surfaces are positively charged. As pH increases towards near-neutrality sorption becomes much more significant owing to less positively-charged hydrolysed nickel species becoming more abundant and mineral surfaces developing a net negative charge. Increasingly negative mineral surface charge at progressively higher pH, leads to increasing sorption with increasing pH. At very high pH, negatively charged species such as $Ni(OH)_3^-$ become increasingly abundant and mineral surfaces become more net negatively charged, leading to less sorption at very high pH. Competition between $Ni^{2+}$ and alkaline earth cations ($Ca^{2+}$ and $Mg^{2+}$) may influence sorption strongly at lower pH. |
| Zr | Most common oxidation state: +4<br><br>Dominant species at pH < 4: $Zr(OH)_3^+$, $Zr(OH)_2^{2+}$<br><br>Dominant species at pH 4-12: $Zr(OH)_4^0$<br><br>Dominant species at pH >12: $Zr(OH)_5^-$ | Typically shows strong sorption onto mineral phases<br><br>Sorption should decrease with increasing pH since at high pH (>10), most mineral oxide surfaces will be negatively charged and dominant aqueous Zr species will be $Zr(OH)_5^-$. |
| Nb | Nb(V) is the dominant oxidation state<br><br>At near-neutral pH, $Nb(OH)_5^0$ dominates<br><br>At high pH (>10) $Nb(OH)_6^-$ dominates<br><br>At lower pH values, hydrolysis decreases and there may be significant complexation by acid anions (e.g. $SO_4^{2-}$, $Cl^-$, $PO_4^{3-}$, etc.)<br><br>Nb may also form polymeric oxo anions (e.g. $[H_2Nb_6O_{19}]^{6-}$ and $[HNb_6O_{19}]^{7-}$) | Sorption of Nb is expected to be strong particularly when there are oxide/hydroxide surfaces present<br><br>The behaviour reflects the very strong tendency to hydrolyse<br><br>At pH >10, most mineral oxide surfaces are negatively charged and increasing abundance of $Nb(OH)_6^-$ at increasing pH suggests that sorption should decrease |
| U | Oxidation states of U(VI) and U(IV), though only the latter expected under repository conditions | Sorption controlled by surface complexation in many cases<br><br>Consistent with strong sorption onto Fe-oxides |

| Element | Chemical characteristics | Sorption characteristics |
|---|---|---|
| | Dominant species at pH < 7 $U^{4+}$ (reducing conditions) and $UO_2^{2+}$ (oxidizing conditions)<br><br>Dominant species at neutral to slightly alkaline pH are hydrolysed species such as $U(OH)^{3+}$, $U(OH)_2^{2+}$ and $UO_2(OH)^+$<br><br>Anionic species such as $UO_2(OH)_4^{2-}$ are increasingly important in more alkaline conditions; carbonate complexes can be important if there are significant carbonate concentrations present | and clays<br><br>Sorption is lowest at acidic pH, but increases sharply as the pH is increased to near-neutral<br><br>At alkaline pH >9, sorption sometimes observed to drop |
| Np | Oxidation states of Np(III), Np(IV), Np(V), Np(VI) and Np(VIII) occur in aqueous systems<br><br>Np(IV) and Np(V) will dominate most groundwater zones; at near neutral pH the transition occurs at about 200 mV<br><br>At acidic pH $Np^{4+}$ and $NpO_2^+$ will dominate<br><br>At increasing pH, Np is increasingly hydrolysed to $Np(OH)_3^+$, $Np(OH)_2^{2+}$ and $NpO_2(OH)_0$<br><br>At alkaline pH negative species form e.g. $NpO_2(OH)_2^-$, or carbonate complexes if there is sufficient carbonate | Np sorption under aerobic conditions is lower than under anaerobic conditions<br><br>Np sorbs particularly on Fe- and Mn- oxides, carbonate minerals and apatite<br><br>Moderate Np sorption occurs on biotite, chlorite, clay minerals, zeolites and pyrite<br><br>Some sorption occurs on feldspars and quartz<br><br>Np sorption is lowest at acidic pH<br><br>With increasing pH, sorption increases sharply to a maximum at near neutral pH<br><br>As pH increases further (>9) sorption decreases, particularly if carbonate is present.<br><br>Np(IV) sorption is much stronger than Np(V) sorption (>2 orders of magnitude)<br><br>Np forms aqueous carbonate complexes and increased carbonate concentrations causes reduced sorption<br><br>At near-neutral pH, Np sorption is independent of ionic strength<br><br>At acid pH, high ionic strength probably causes reduced sorption. |

Rockfalls or the slumping of corroded containers would promote localised contaminant migration in groundwaters. However, such processes are not considered significant for the overall migration of contaminants from the repository.

Temperature gradients can cause convective (buoyancy-driven) flow of water, or pressure-driven flow of gas. But Section 4.5 indicates that no significant temperature gradients are expected in most of the repository. In and around the shafts, a temperature gradient may exist, associated with the curing of concrete plugs (in particular the large concrete monoliths that are planned). These effects on gas and water flow are expected to be minor and short-lived.

## 4.8 INTERFACES WITH THE GEOSPHERE AND BIOSPHERE SUB-SYSTEMS

The processes within the waste and repository will influence the geosphere by:

- the migration of gases from the repository into the surrounding host rock;
- the migration of dissolved solutes from the repository into the host rock;
- the open repository volume that will draw in porewater during the resaturating phase;
- the gas pressure in the repository affecting surrounding rock stresses; and
- rockfall into the repository affecting the surrounding rock integrity and stress distribution.

The waste and repository interfaces directly with the biosphere through the shaft. This is a potential path for radionuclide release and gas release.

## 4.9 UNCERTAINTIES

The main uncertainties concerning the wastes and repository sub-system are as follows.

Initial contaminant concentrations and waste volumes are effectively managed through waste characterisation and are reasonably well known. The chemical form and physical location of contaminants within the wastes, and the physical properties of the wastes, are uncertain. However, for most wastes, these sources of uncertainty are not significant since the wasteform itself is not assumed to be a barrier. For the primary Zr-93 containing waste, the relevant properties of the wastes are well known.

The evolution of repository conditions with time is a key source of uncertainty, and in particular the resaturation and gas pressure evolution. These in turn are key in determining the availability and partitioning of contaminants (e.g., C-14) (and therefore the timescales relevant to their potential release), together with the relative potential importance of the gas and groundwater migration pathways. Uncertainties in resaturation and gas pressure are due primarily to uncertainties concerning:

- the volumes and rates of gas generation;
- the hydrogeological properties of the host rock;
- the gas transport properties of the host rock; and
- the influence of glaciation on an unsaturated repository.

At long times, the impact of ice-sheet loading and unloading on the stability of the emplacement rooms is uncertain. However, the rooms will eventually fill with rubble and self-stabilize at levels that are not expected to be significant. In effect, the initial void space in the open rooms will be distributed across a somewhat larger volume of rock, but the primary host rock barrier will remain.

With respect to contaminant transport, the main uncertainties are due to the hydrogeological properties of the shaft EDZ, and with the sorption rate of contaminants onto the shaft sealing materials.

# 5. EXPECTED EVOLUTION OF THE GEOSPHERE

## 5.1 THERMAL EVOLUTION

As noted in Section 4.5, the heat generated from the degradation of waste packages and the decay of radionuclides will have minimal impact on the temperature of the geosphere surrounding the repository.

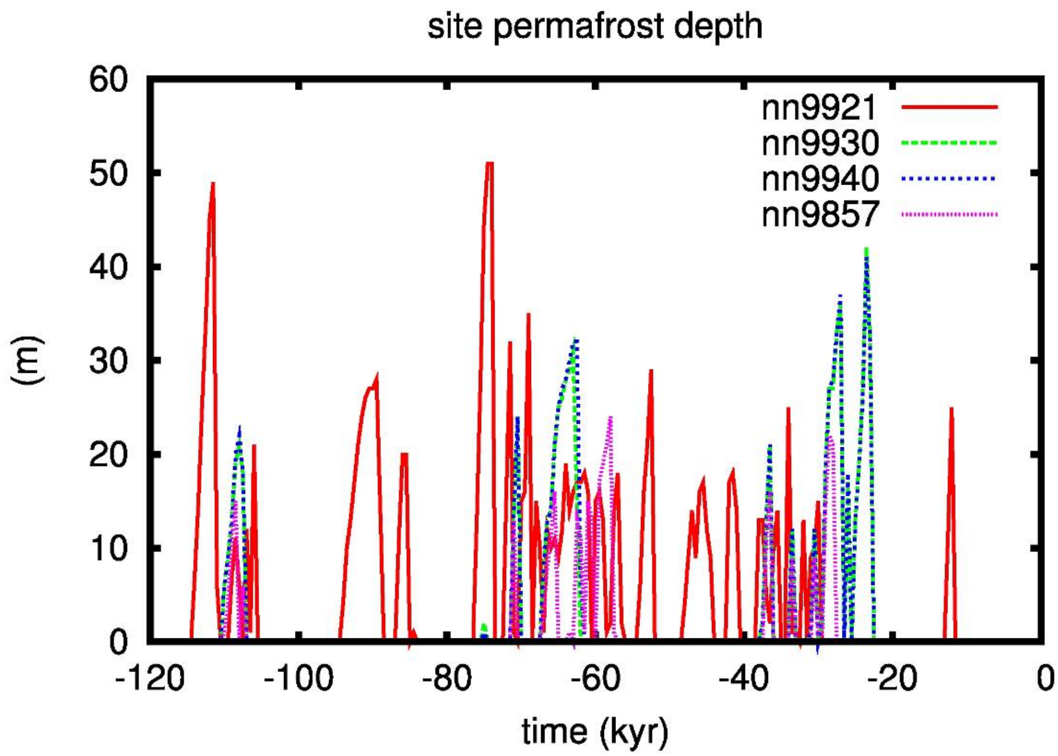
Climate change will affect the near-surface region, but have very little effect on the deep geosphere which will remain with stable temperatures for tens of thousands of years.

In the longer term, thermal changes in the geosphere will be driven by the glacial and interglacial cycling discussed in Section 6. A fall in surface temperature will cause the upper part of the geosphere to cool and eventually the development of permafrost (Peltier 2004). The permafrost will normally form before an ice-sheet although the pattern of formation can be complex. Once an ice-sheet has formed, the temperature evolution beneath the ice-sheet depends upon the insulating effect of the ice and the geothermal heat flow (Peltier 2004). The geothermal heat flow is likely to be effectively constant over the timescale of interest, but the insulating effect of the ice will depend upon the thickness of the ice-sheet. Consequently, the temperature at depth beneath the interface between the earth and the ice is likely to vary over time and permafrost may be either present or absent.

Thus, the picture that emerges is that the temperature in the geosphere will decrease as the climate cools, and long before the ice front reaches the site. After the ice front has crossed the site, the temperature may then increase once more, though conditions will remain cooler than they were prior to glaciation. Then, when the ice retreats, the temperatures will increase and eventually return to their pre-glaciation values. The temperature changes at the depth of the repository will lag behind, and be smaller than, the temperature changes at shallower depths.

Peltier (2008) has applied the University of Toronto Glacial System Model to examine the impacts of glaciation at the DGR site over the last 120,000 years. Eight models have been developed that provide acceptable fits to the historic data. As expected, the precise temperature changes and thickness of permafrost development varied with time owing to variable climatic cooling and/or different ice thickness. The general picture that emerges from the results is that the permafrost thickness rarely exceeded 60 m (Figure 5-1) and annual average, earth surface temperatures at the site ranged between -4 °C and +10 °C (Figure 5-2). Simplistically assuming the same temperature gradient as found at the site today, a -4 °C earth surface temperature would result in a temperature at the depth of the repository of around 9 °C, compared with the current value of around 20 °C. Calculations have not yet been undertaken to determine whether such changes in repository temperature could occur given the depth of the repository, and the timescales over any temperature changes might occur.

The thermal evolution of the geosphere can impact the solubility of aqueous and gaseous contaminants since solubility is generally temperature dependent. The solubility of gases in pore waters increases with a decrease in temperature. Therefore, the diffusive flux of most dissolved gases will depend partially on the in-situ temperatures. When all other conditions (pH, salinity etc) are held constant, the solubility product of minerals typically increases with increasing temperature, although there are certain major exceptions, e.g., carbonate minerals and gibbsite (aluminium hydroxide). Thus, a decrease in temperature due to permafrost penetration will decrease the solubility equilibria for most minerals but increase the solubility of carbonate minerals due to the increased solubility of $CO_2$(aq). However, it is probable that these temperature effects will be very small.



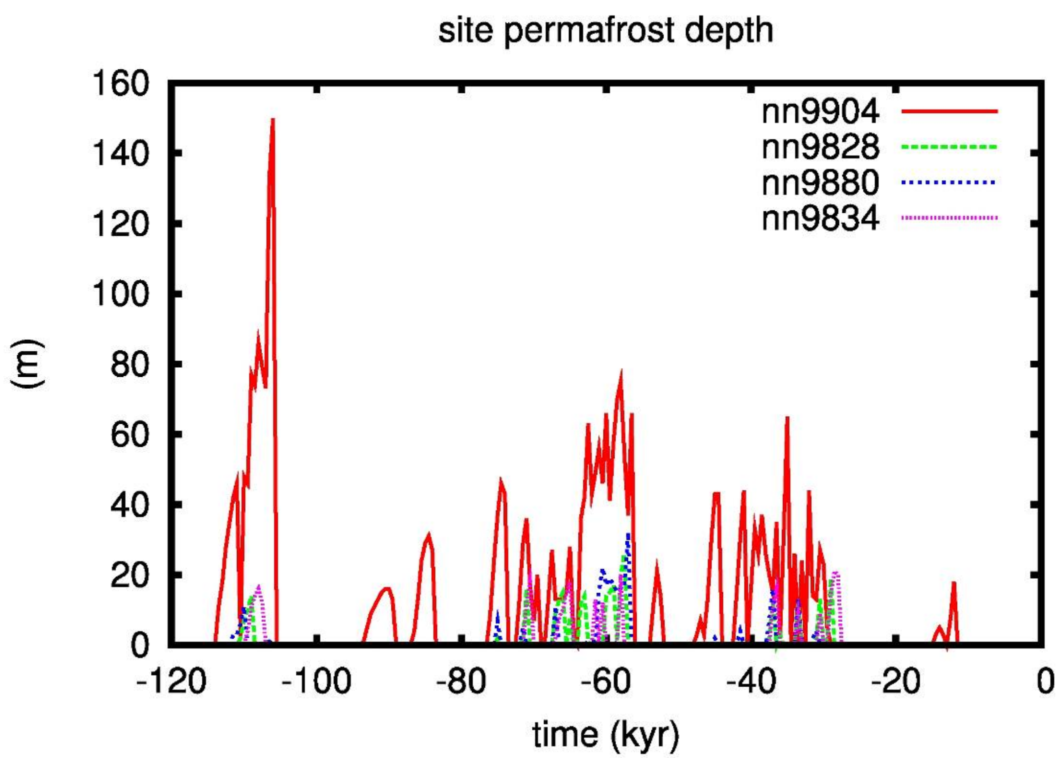




**Figure 5-1: Simulated Permafrost Depth at the Bruce Site over the Last Glacial Cycle for the Eight Cases Consistent with Historical Data (Peltier 2008)**

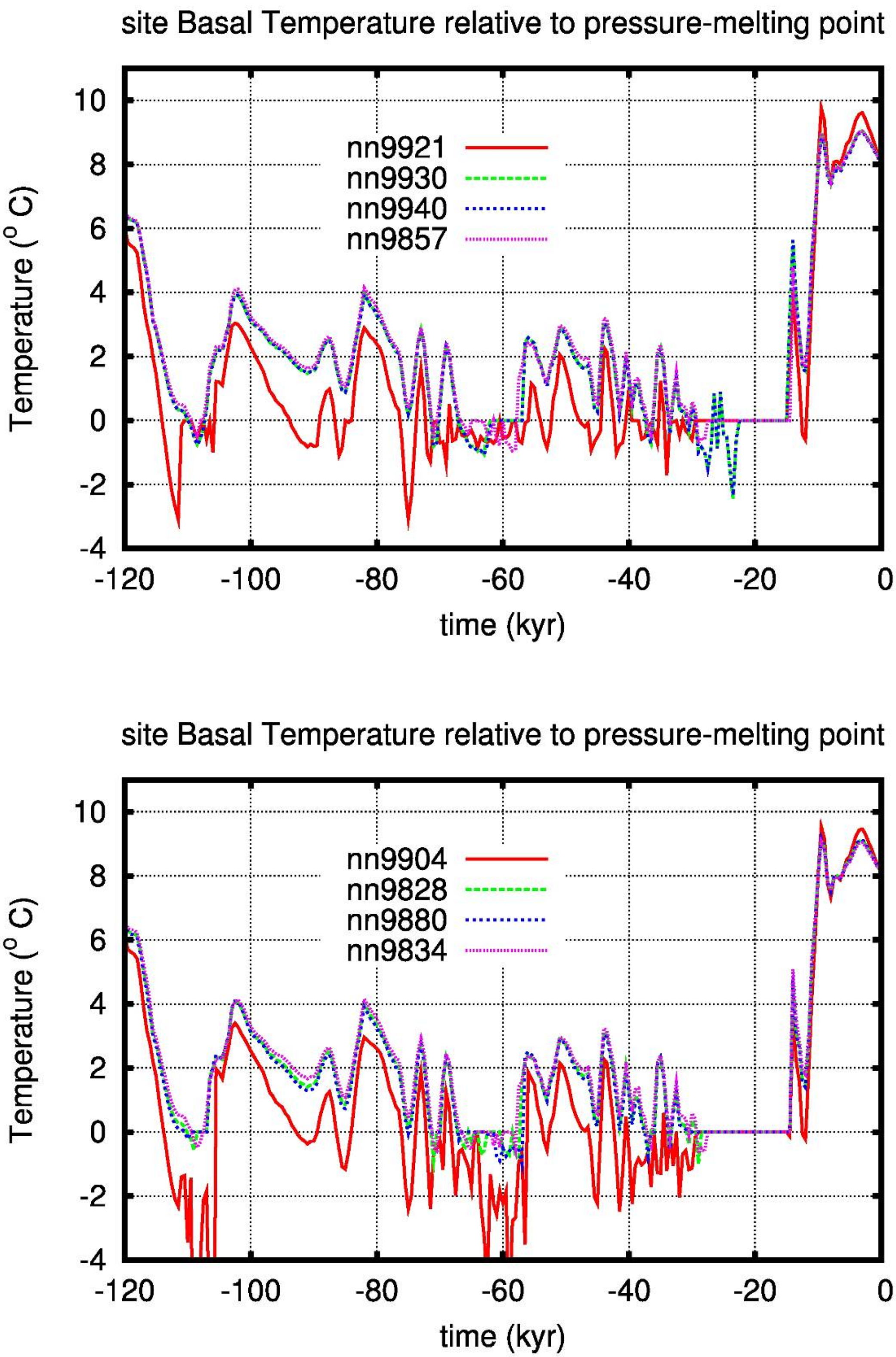



**Figure 5-2: Simulated Temperatures at Earth Surface at the Bruce Site over the Last Glacial Cycle for the Eight Cases Consistent with Historical Data (Peltier 2008)**

## 5.2 MECHANICAL EVOLUTION

The host sedimentary rocks are stable and extend laterally for hundreds of kilometres. Their current stress regime reflects the lithostatic weight of the rocks in the vertical direction, and steady long-term tectonic forces in the horizontal directions. On a regional scale, these will only change after tens of thousands of years due to the added stresses from glaciation, particularly in the vertical direction.

On the site scale, the excavation of the repository will cause redistribution of rock stresses, which could influence the development and/or evolution of pathways for groundwater and gas migration.

### 5.2.1 Geosphere Surrounding the Emplacement Rooms and Repository Tunnels

The rock stresses in the geosphere surrounding the repository will change with repository excavation and then, as the internal pressure within the repository increases due to generation of gas and inflow of groundwater, with repository re-pressurisation. Gas pressures might exceed hydrostatic pressure, delaying complete resaturation for hundreds of thousands of years of years. Ultimately the pressure in the repository and surrounding geosphere will equilibrate at hydrostatic pressure. Damjanac (2008) has undertaken geomechanical modelling studies of the stability of the repository and surrounding geosphere. These have been summarised in Section 4.4.1. Basically, there will be rockfall into the open space in the rooms and tunnels at long times, until the combination of rockfall and residual waste package materials form a self-supporting equilibrium.

### 5.2.2 Geosphere Surrounding the Shafts

The shaft excavation activity can induce damage in the surrounding rock, depending on the excavation method used, and therefore the roadheader excavation method is proposed for use in the deep low-permeability rock formations in order to minimize such damage (Hatch 2008). The stress redistribution created by shaft excavations will also cause rock damage to develop. The response of the rock to these stresses depends on the rock properties. The volume of rock altered by the combined effects of excavation-induced damage and stress relief damage is referred to as the Excavation Damaged Zone (EDZ).

Because the deep stress field is likely to be anisotropic at the DGR site (Section 2.3.6), the EDZ will have an elliptical geometry around the shaft (in the horizontal plane). The creation of fractures and cracks within the host rock around the shafts will, in turn, increase rock permeability by up to a few orders of magnitude relative to the undisturbed host rock permeability. The effect is largest near the surfaces of the shafts and then decreases rapidly with distance into the rock. The extent of the EDZ and the impacts on the rock properties are discussed by Damjanac (2008) and Walke et al. (2009a,b).

### 5.2.3 Impact of Ice-sheets

Glacial cycles will cause the rock to be depressed and rebound due to the loading and unloading caused by the advance and retreat of ice-sheets. Figure 5-3 shows the surface elevation at the site over the last 120 ka as simulated by the University of Toronto Glacial System Model and indicates a maximum depression of around 500 m at the last glacial maximum (Peltier 2008). This depression occurs over a large regional or continental scale and, due to the large scale over which it is developed, tends to be aseismic and not associated with significant displacements along fractures.

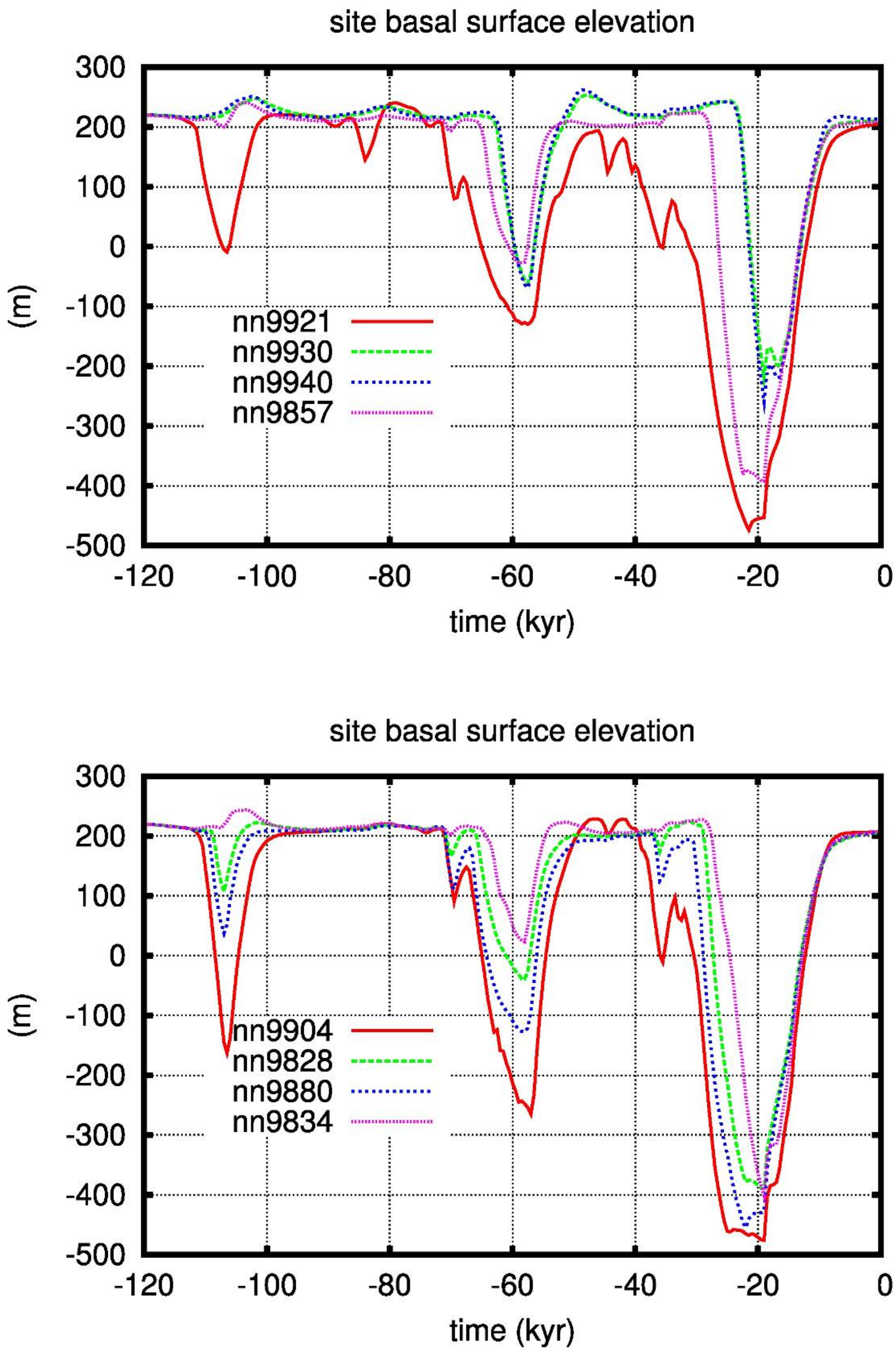
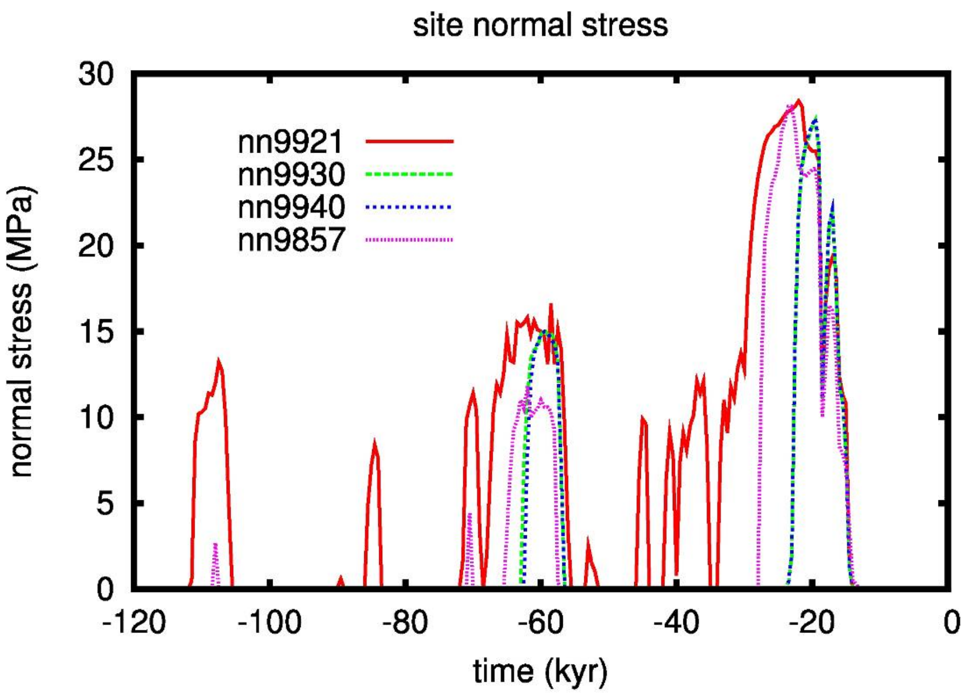



**Figure 5-3: Simulated Earth Surface Elevation at the Bruce Site over the Last Glacial Cycle for the Eight Cases Consistent with Historical Data (Peltier 2008)**

During the glacial advance over the site, there will be local stress changes. In advance of the ice sheet there will be a forebulge which will change stresses at least in the top rock layer. With the ice-sheet on the site, the normal stresses will be increased due to the weight of the ice; Peltier (2008) has estimated normal stresses increases of up to 30 MPa (Figure 5-4). The normal stress at repository level is about 17 MPa in the absence of an ice sheet.



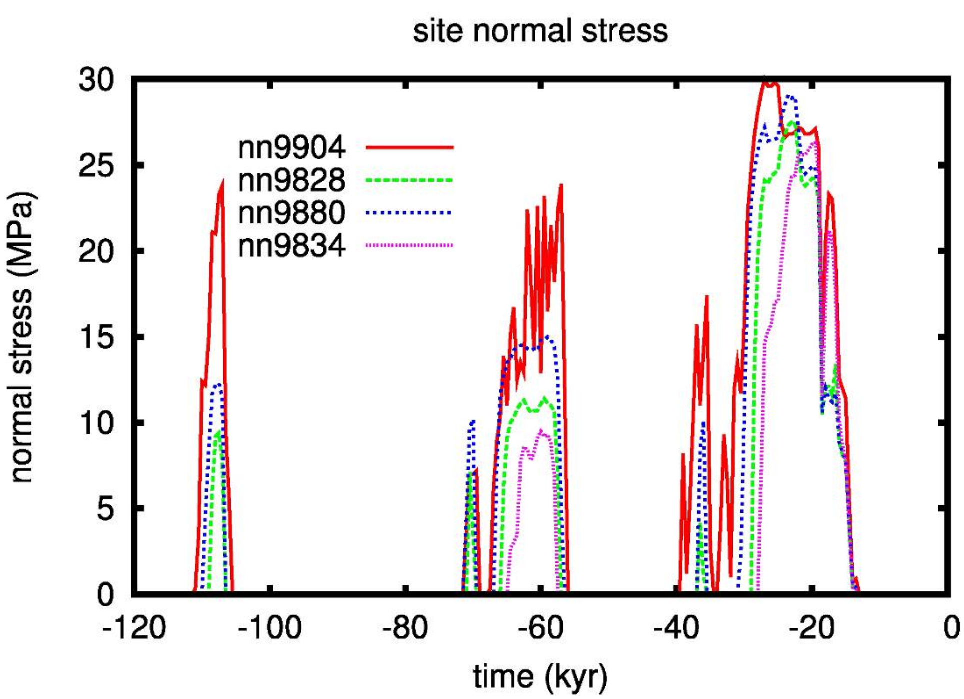




**Figure 5-4: Simulated Normal Stresses at the Bruce Site over the Last Glacial Cycle for the Eight Cases Consistent with Historical Data (Peltier 2008)**

Seismic activity, which is normally low in this area located in the middle of a continental craton, may be triggered by rapid crustal uplift and the release of stresses after the retreat of an ice-sheet (Wu 1998). Such activity is expected to cause localised rather than large-scale movements but nevertheless might cause the extension of existing faults from outside of the area of the DGR into the area of interest, or it might re-open or enhance any existing faulting in the vicinity of the DGR. However, there is evidence indicating that there is no significant vertical or horizontal faulting in the vicinity of the DGR site now, and that no significant faulting happened during previous glaciation cycles during the past million years, including the extension or long-term opening of existing faults (Sykes et al. 2008).

## 5.3 HYDRAULIC EVOLUTION

The present-day groundwater flow regime is described in Section 2.3.3. Climate change would affect the near-surface region, but is unlikely to have a significant effect on the deep geosphere which would remain stable for tens of thousands of years based on the majority of the data and analysis currently available from the 'Geosynthesis' reports (see Gartner Lee 2008c and supporting reports). In the longer term, its evolution will be affected by glacial and interglacial cycling through its effects on recharge, surface water bodies and the advance and retreat of ice-sheets.

### 5.3.1 Effects of Recharge

There is topographically-driven sub-horizontal flow in the Superficial Groundwater Zone and in the upper part of the Shallow Bedrock Groundwater Zone, with recharge from infiltration and discharge to surface waters (local streams, wetlands, and Lake Huron). Flows in this part of the system will be sensitive to changes in climatic conditions that influence groundwater recharge, i.e. precipitation (amount, form and temporal distribution), evapotranspiration, runoff / drainage (natural and anthropogenic) and cold climate effects such as the quantity of snow fall, sublimation, and rate of spring snow melt. A reduction in groundwater recharge would tend to result in a lowering of the water table in the recharge areas (topographic highs) with a consequent reduction in the hydraulic gradient and hence flow rates. This may be compensated to some extent by a decrease in surface water levels.

Increases in recharge will have the opposite effect; however, the impacts will be self-limiting because under present-day conditions, the amount of meteoric precipitation that can infiltrate the rock is small compared with the amount occurring as runoff (Thorne and Gascoyne 1993). Relatively little increase in hydraulic gradient is possible from increased meteoric precipitation (McMurry et al. 2003).

Changes in recharge are expected to have no significant impact on the Intermediate and Deep Bedrock Groundwater Zones due to their hydraulic isolation from the overlying zones.

### 5.3.2 Effects of Local Surface Water Bodies

Groundwater flows in the Superficial and Shallow Bedrock Groundwater Zones will also be affected by changes in the spatial location of surface water bodies and their water levels, since they are in hydraulic connection with the underlying geosphere. Surface water levels can be affected by changes in precipitation, evapotranspiration, runoff, etc., but also erosion / sedimentation and by changes in eustatic sea level in response to global warming / cooling and hence the volume of water in the world's oceans. However, the Bruce site and the Great Lakes are sufficiently elevated, and sufficiently disconnected from the sea, that their extent is unlikely to be directly affected by changes in eustatic sea level.

The spatial extent and levels of surface water bodies will be affected by glaciation both in terms of the impacts of erosion and deposition on the topography, but also isostatic depression and rebound of the land surface (see Section 5.2.3). During the last glaciation cycle, modelling results (Peltier 2008) and field evidence indicate that a large freshwater lake existed in the vicinity of the current site (except when covered by the ice-sheet). So although the details of the shoreline and extent of Lake Huron will change in the future, it is reasonable to assume that a large lake will generally be present in the vicinity of the DGR site.

Changes in the local surface water bodies are expected to have no significant impact on the Intermediate and Deep Bedrock Groundwater Zones due to their hydraulic isolation from the overlying zones.

### 5.3.3 Effects of Ice-sheet Advance and Retreat

In the cooling stage of a glacial cycle, there could be widespread formation of permafrost and possibly reduced precipitation, which would significantly decrease recharge and alter the shallow flow system hydraulic gradients (Peltier 2002, 2004). However, by analogy to historical glacial conditions, the results of Peltier (2008) indicate that future permafrost at the DGR site would typically be only a few tens of metres thick; sufficient to reduce recharge significantly but insufficient to freeze the entire thickness of the active groundwater system. Generally, permafrost is not continuous unless the depth of permafrost exceeds 60 to 90 m (Brown and Pewe 1973).

Even under permafrost climate conditions, features such as taliks might form: these are regions of open, unfrozen ground, and typically are sustained under deeper surface water bodies. Around the Bruce site, the Lake Huron bed would likely remain unfrozen, and would continue to form a discharge location for the Shallow Bedrock Groundwater Zone.

Regions of permafrost would eventually be covered by an ice-sheet, either by the flow of an ice-sheet over the site or by the in-situ accumulation of snow. It is presently estimated that the maximum thickness of an ice-sheet that would cover the proposed DGR site would be approximately 3 km (Peltier 2008).

Ice-sheet development will result in mechanical loading of the geosphere (Section 5.2.3) and isostatic depression of the ground surface, both below the ice sheet and for many tens or even hundreds of km beyond the ice sheet margins. While the mechanical component of the loading will be transmitted almost instantaneously through the rock, the hydraulic component will be transmitted at a rate proportional to the hydraulic diffusivity (equal to the rock hydraulic conductivity divided by its specific storage). As the geosphere is compressed, the heads will increase resulting in flow (predominantly in the Shallow Bedrock Groundwater Zone) laterally to, and discharge at, the ice-sheet margins. However, discharge might not actually be able to occur at the ice-sheet margins due to the presence of permafrost, and will therefore tend to occur some distance further away. Around the DGR site, discharge would likely be to the local large lake (Lake Huron or its successor). Ice sheet loading will close fractures in the Shallow Bedrock Groundwater Zone, decreasing the hydraulic conductivity of this zone. The groundwater flow rates within the Shallow Bedrock Groundwater Zone to the ice sheet margins will be a function of this reduced hydraulic conductivity and the increased head gradients in response to ice sheet loading.

Hydrogeological conditions during glaciation also would differ depending on whether the ice-sheet was cold-based or warm-based. As long as there was no melting associated with the ice-sheet (cold-based conditions), groundwater recharge would be inhibited. A warm-based ice-sheet is one in which temperatures are above freezing at the ice-rock interface. It can occur due to several processes: (a) an increase in ground temperature at the ice-rock interface due to geothermal heating coupled with the insulating effect of the ice itself, (b) pressure-dependent ice melting due to the thickness of the ice-sheet, or (c) atmospheric warming (end of glacial cycle). Sub-glacial groundwater flow patterns associated with warm-based conditions are likely to involve increased volumes of water and more rapid shallow groundwater movement than under pre-glacial or cold-based conditions.

If the base of the ice-sheet is melting, liquid water would be present at the interface between the ice and the rock surface. The water would be under pressure due the hydraulic head in the ice-sheet itself, which could affect the groundwater flows and geochemistry by moving large volumes of low-salinity and possibly oxidising meltwater through the hydraulically active part of the flow system in the rock (McMurry et al. 2003). The maximum depth to which the fresh water penetrates the geosphere will tend to be associated with the advective pathline from the point of melting furthest from the ice margin. However, the weight of overlying ice will be greatest here and will therefore tend to close fractures in the bedrock and reduce the hydraulic conductivity. The presence or absence of meltwater tunnels at the base of the ice-sheet could also impact the movement of the meltwater. Such tunnels could be important routes for the release of water pressures developed at the base of the ice-sheet.

A secondary control on the depth of meltwater penetration will be the density contrast with the geosphere, dependent on relative salinity and temperature controls. Since the surface boundary conditions are dynamically evolving, the groundwater flow system is unlikely to reach steady state and the maximum depth of freshwater penetration might never be realised – particularly for the low permeability Intermediate and Deep Bedrock Groundwater Zones.

As the ice-sheet retreats, rapid melting of the ice can be expected. Modelling by Peltier (2008) indicates that meltwater generation is confined to temporally discrete events largely constrained to a short period of time after glacial maxima. A rate of around ten to a few tens of cm per year have been estimated (Figure 5-5). As the weight of the ice is removed, and the rock relaxes, under-pressures will develop, i.e., heads below equilibrium with the current surface conditions. The hydraulic conductivity of the Shallow Bedrock Groundwater Zone will return to values similar to pre-glacial conditions as fractures re-open. Isostatic rebound of the ground surface would occur slowly, taking tens of thousands of years to fully recover.

Depending on site-specific properties such as permeability and groundwater salinity, the time required for the groundwater system to stabilise following deglaciation is likely to vary from hundreds of years to ten thousand years or longer. For example, coupled hydro-mechanical modelling of post-glacial responses by Chan et al. (2003) indicated that hydrostatic pore pressures in low-permeability rock would take tens of thousands of years to dissipate following ice-sheet retreat.

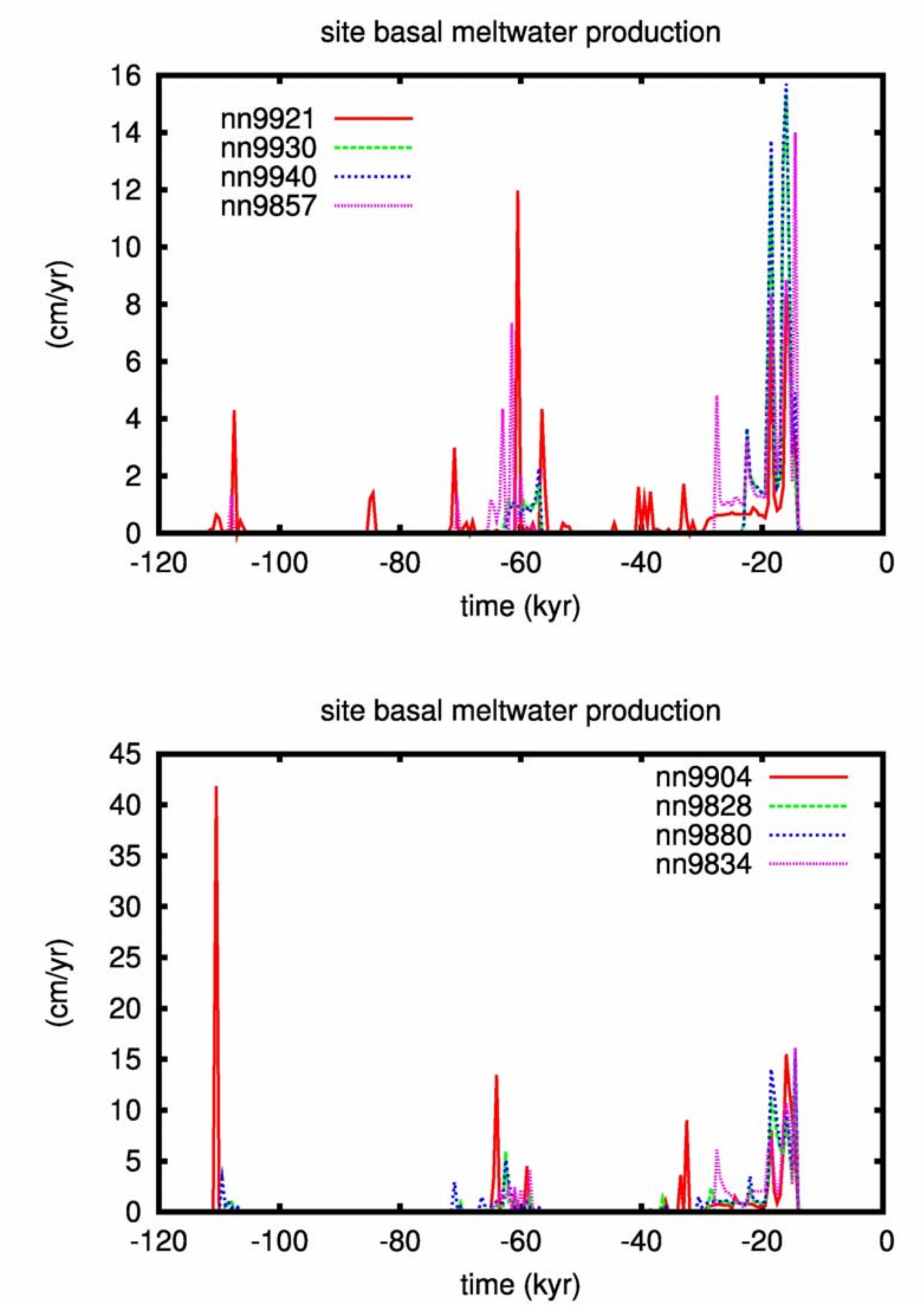



**Figure 5-5: Simulated Basal Meltwater Production at the Bruce Site over the Last Glacial Cycle for the Eight Cases Consistent with Historical Data (Peltier 2008)**

The current under-pressures observed in the Ordovician rock formations may be due to the glacial unloading. However, transient palaeoclimate groundwater flow simulations undertaken by Sykes et al. (2008) for the the Laurentide glacial eposide (~120 ka to 10 ka BP), based on the NN9930 model of Peltier (2008), show that the under-pressures are unlikely to be associated with the last Laurentide glacial episode. The low permeability of the majority of the geological formations, combined with the near-horizontal layering and anisotropy all act to limit the depth to which the pressure signal can be transmitted within the duration of the glacial episode. Alternative mechanisms identified by Sykes et al. (2008) that potentially explain the Ordovician underpressures are:

- mechanical unloading in response to erosion;
- the presence of a gas phase within the pores (i.e., partial saturation);
- changes in the regional stress field (in which case the disequilibrium heads must be ancient due to the tectonic history of the region); and
- osmosis (in which case the hydraulic conductvity of the rock must be too low for Darcy's law to apply).

## 5.4 CHEMICAL EVOLUTION

At the repository horizon, the present-day chemical conditions in the geosphere are isolated and buffered by several hundred metres of low permeability rock. Regional geochemical studies (Hobbs et al., 2008) indicate that the deep geosphere has not been significantly affected by the passage of previous glaciations, and it is not expected to be affected by future ones.

On a site scale, the repository and the waste packages will present a change in the chemical conditions. An equilibrium will develop between the rock and repository chemistry on long time scales.

### 5.4.1 Impact of the Repository

#### 5.4.1.1 Evolution of Gas Chemistry

Gas generation, primarily $CH_4$, $CO_2$ and $H_2$, will occur within the repository due to microbially mediated degradation (producing $CO_2$ and $CH_4$) and corrosion (producing $H_2$) of the wastes and packaging. Over time these gases will migrate into the surrounding host rock. There are also some natural gas and trace liquid hydrocarbons present in the Middle Silurian and Ordovician formations at the Bruce site.

The primary gas species in the long term will be methane, which is generally unreactive with the host sedimentary rocks, as demonstrated through natural gas fields in similar rocks elsewhere in Southern Ontario.

The quantity of $CO_2$ in the repository is expected to generally be low due to microbially mediated reduction with $H_2$ to form $CH_4$. There could be minor reactions between the small quantity of $CO_2$ in the repository and rock minerals; particularly carbonates within the limestones and dolomites.

#### 5.4.1.2 Evolution of Mineralogy

Large-scale mineralogical changes resulting from geosphere interaction with the repository materials and wastes that would significantly effect the migration of fluids and transported solutes are considered to be very unlikely. The deep porewaters are reducing, of very high total dissolved solids, and buffered by the rock minerals. Therefore, reaction with repository materials is not likely to alter the major chemistry to such an extent that repository fluids will drive large-scale mineralogical changes.

It is expected that any mineralogical changes that do occur are likely to involve localised mineral precipitation/dissolution in the immediate vicinity of the repository. Evolution of the geosphere mineralogy adjacent to the repository including the EDZ is discussed below.

#### 5.4.1.3 Evolution of Geosphere Mineraology Adjacent to the Repository

The precise chemical evolution of the geosphere adjacent to the repository including the EDZ is presently uncertain owing to limited site-specific data and the fact that many coupled processes will control this evolution. However, the impacts associated with these interactions are expected to be small and not likely to detrimentally affect the performance of the repository.

During excavation and the operational phase, dewatering of the repository and thus drying of the EDZ may result in the precipitation of salts such as halite and gypsum in fractures or joints or open porosity associated with the EDZ. These precipitation reactions could be very important in sealing any such features and reducing permeability.

Equally, dissolution of minerals could result in the increase of rock permeability. The alteration would most probably involve the following kinds of reactions:

- dissolution of carbonate minerals, by reactions such as:

  $CaCO_3(s) + CO_2(g) + H_2O \rightarrow Ca^{2+} + 2HCO_3^-$

- oxidation of pyrite, while the repository is operational and in the few years post-closure when oxygen remains, according to reactions such as:

  $FeS_2(s) + 3.5O_2(g) + H_2O \rightarrow Fe^{2+} + 2SO_4^{2-} + 2H^+$

- alteration of feldspars, by reactions such as:

  $Ca_{0.6}Na_{0.4}Al_{1.6}Si_{2.4}O_8 + 5.4H^+ + CO_2(aq) \rightarrow 0.6Ca^{2+} + HCO_3^- + 2.2H_2O + 0.4Na^+ \ 1.6Al^{3+} + 2.4\ SiO_2(aq)$; and

- cation exchange involving expandable clay minerals.

Small amounts of sulphide minerals (pyrite and sphalerite) occur within some rock samples from the Cobourg Formation from the Bruce site (Table 2-8). There is a possibility that due to ingress of oxygen during excavation and operation of the DGR, localised oxidation will cause the generation of some acidity. This acidity will be neutralised by reaction with the calcareous host rock which will buffer the pH. This reaction will tend to increase porosity and permeability in the EDZ.

During the operational phase and immediately following repository closure, the undisturbed geosphere immediately surrounding the repository will be oxidized only if atmospheric oxygen is not entirely consumed by oxidation reactions (principally involving pyrite) within the EDZ. Only under these circumstances could there be acidification of porewater by the oxidation of sulphide minerals (principally pyrite) in the rock beyond the EDZ.

Following closure, $CO_2$ generated by the microbially mediated degradation of the wastes will dissolve in the repository waters and porewaters, leading to some dissolution of the calcareous host rock, which will act to buffer the pH. Therefore there is not expected to be a significant change in the pH of the repository waters and porewaters. Dissolution of carbonate minerals will tend to increase porosity and permeability in the EDZ.

Reaction of $CO_2$ with concrete in the wastes and repository engineering, and microbial reduction of $CO_2$ with $H_2$ forming $CH_4$ will act as competing sinks for $CO_2$. Therefore reaction between $CO_2$ and the host rock may be limited. Reduction in the $CO_2$ partial pressure due to reaction with concrete and microbial reduction, combined with the generation of aqueous iron (II) through corrosion reactions, may result in precipitation of minerals such as siderite (iron II carbonate) in both the repository waters and EDZ porewaters.

Alteration of feldspars could be more extensive, but these reactions are much slower than carbonate dissolution reactions, and feldspars only constitute a minor component of the Ordovician rocks (Table 2-8). Cation exchange reactions coupled to the pH evolution of the groundwater in the repository would be minor, since expandable clay minerals are present only in relatively minor quantities.

Characteristic products of any EDZ oxidation would be Fe- oxyhydroxide minerals. These solids are expected to be generated principally as a result of sulphide mineral oxidation (which would release Fe). However, the carbonate minerals present in the rock may contain Fe(II) and Mn(II). Any dissolution of these minerals while oxygen is still present in the repository may also be accompanied by oxidation of Fe- and Mn- to produce Fe- and Mn- oxyhydroxides. The mineral products of such oxidation reactions would have high specific surface areas. Potentially any radionuclides that might migrate through the EDZ could sorb on these minerals. These precipitates will also tend to clog fractures in the EDZ, thereby offsetting the increase in porosity and permeability due to dissolution to an extent.

### 5.4.2 Effects of Ice Sheets

#### 5.4.2.1 Evolution of Groundwater and Porewater Chemistry

An extended period of global warming with elevated levels of $CO_2$ might affect the chemical properties of the uppermost near-surface waters, with increased dissolution and total dissolved solids, but the influence would not penetrate deeply due to the buffering capacity of the rock.

The extent and magnitude of geochemical changes during any glacial cycle will depend on the site-specific conditions of the geosphere and of the particular glacial episode. Changes will be most evident in the shallow, hydraulically active portion of the flow system, where oxygenated, low-salinity meltwaters will have the potential to react with redox-sensitive elements or to cause dissolution or precipitation of minerals in fractures (Guimerá et al. 1999).

For example, geochemical and isotopic data from the Lac du Bonnet batholith (Gascoyne 2000) indicated that only the upper, actively circulating groundwater system was affected by past glaciations, with deeper, denser, high-salinity waters remaining near-stagnant. In this batholith, the upper 200 metres of bedrock contains low-salinity, oxidising groundwaters which have H-3 and C-14 levels up to near-modern values and a warm-climate (present-day) $^{2}H$ -$^{18}O$ isotopic signature, indicating residence times of tens to thousands of years at most. At greater depths from about 200 to 400 m, a transition zone is observed in which groundwaters become more saline and in which geochemical modelling indicates either incursions by glacial meltwater (Laaksoharju et al. 2000) or a mixing by freezeout from deep permafrost formation (Zhang and Frape 2002). These moderate-depth groundwaters have a cool-climate isotopic signature that corresponds to the last glacial cycle (McMurry et al. 2003).

A generally similar pattern is observed across the Southwestern Ontario and central and eastern Michigan. Geochemical evidence (Hobbs et al. 2008) indicates that glacial or younger recharge is most often identified in shallow (<130 m) environments. The deepest glacial recharge has been observed at depths of up to 300 m along the northern and western margins of the Michigan Basin. It is interesting to note that the majority of samples are dated to the Last Glacial Maximum or younger, consistent with modelling results of Peltier (2008) and transient palaeoclimate groundwater flow modelling undertaken by Sykes et al. (2008). Some of the lower permeability till deposits contain waters of glacial age that were trapped when the sediments were deposited, as do drift aquifers that are confined by low permeability tills and clays.

Salinity and hence the groundwater age increases with depth in the Shallow Bedrock Groundwater Zone. Porewaters in the deep and intermediate zones are very old, confirming the stability of these zones (Hobbs et al. 2008) and lack of glacial influence. However, site-specific data are not yet available for the DGR site.

The deep groundwater chemistry is likely to be essentially invariant except locally near the repository and shaft, where it will be influenced by interactions with dissolved solutes from the repository materials (wastes, packaging, concrete, bentonite-sand and asphalt), as well as gases generated in the repository (see Section 4).

#### 5.4.2.2 Evolution of Mineralogy

Enhanced recharge of fresh oxidising waters under glacial conditions, particularly during glacial retreat, would affect the geochemistry of the surface groundwater zone. Redox sensitive minerals such as pyrite might be oxidised to produce oxide and oxyhydroxide mineral phases, whereas the low-salinity water is expected to dissolve and leach at least some of the minerals initially present. Whilst rock porosity would generally increase as a result of these processes, the net effect on permeability is more difficult to predict because the secondary minerals that form will at least partly occlude the porosity. Additionally, the secondary oxide and oxyhydroxide phases would tend to have higher specific surface areas and sorption capacities than the original oxidized minerals, thereby increasing the ability of the rock to retard radionuclide migration. Thus, a combination of positive and negative effects on system performance is expected. However, the net impact is considered to be insignificant in terms of system performance and contaminant transport, since the intermediate and deep geosphere form the major barrier to contaminant transport.

## 5.5 GAS MIGRATION

As microbial degradation of organic wastes and corrosion of metaliferous wastes proceeds, the repository gas pressures will increase (Section 4). Gas can migrate from the repository and through the geosphere by a number of processes:

1. diffusion of gas molecules in water;
2. advection of water containing dissolved gas;
3. movement of gas as a discrete phase within the original (or primary) pore space of the material;
4. movement of gas as a discrete phase within natural fracture porosity of the material;
5. movement of gas as a discrete phase within stress- or pressure-induced microscopic porosity in the rock matrix (pathway dilation); and
6. movement of gas as a discrete phase within stress- or pressure-induced macroscopic fractures (gas-induced fractures).

Processes (1), (2), and (3) are considered relevant for the Bruce geosphere. Field evidence suggests that the Ordovician host rock is largely unfractured, so natural fracture porosity system transport (process (4) above) can be excluded. It is expected that in-situ gas pressures will not exceed lithostatic pressures and so processes (5) and (6) can also be excluded.

Processes (1) and (2) will be dominant as long as the gas generation rate is lower than the diffusive and advective flux of dissolved gas resulting in gas pressures below hydrostatic pressure. For process (3), gas must be generated at a rate that is greater than that which can be carried away by the diffusive and advective flux of dissolved gas, resulting in transport in a separate gas phase. Movement of bulk gas will occur at a faster rate within the shafts and EDZ compared with the geosphere, due to their relatively high hydraulic conductivity. Dissolution of gas into groundwater, and potentially also exsolution of gas from groundwater, will occur along geosphere and shaft / shaft EDZ pathways.

Under future glacial conditions, the presence of continuous frozen ground, either due to permafrost or covering by a cold-base ice-sheet, would restrict the release of gas from the geosphere into the biosphere. Gas would be driven to migrate laterally within the Shallow Bedrock Groundwater Zone and would partially dissolve in groundwater depending on its solubility and the gas pressure.

## 5.6 OTHER PROCESSES

### 5.6.1 Biological processes

Microbes are often found in deep geospheres. Possible processes that could affect contaminant properties include the following.

- Anaerobic bacteria could modify groundwater composition, affecting the pH and Eh and subsequently increasing or decreasing contaminant sorption and solubility. In general, they will act to create more reducing conditions, including consumption of any oxygen.
- Microbes could remove gases permeating from the repository, including $H_2$, $CO_2$ and $O_2$.
- Micro-organisms might metabolise or serve directly as organic complexing agents that can change solubilities and sorption properties of contaminants released from the repository.

Microbiological activity in the deep rock formations at the DGR site will be limited by the paucity of available nutrients in the geosphere, i.e., nitrogen and phosphate, and the high salinity conditions. Their role in radionuclide migration will be further constrained by the low porosity of these zones. A core sample from the Cobourg limestone formation was analysed for the presence of viable and culturable microbes; preliminary results found an absence of culturable indigenous organisms (Stroes-Gascoyne and Hamon 2007).

#### 5.6.2 Colloids

Colloids occur naturally in groundwaters and surface waters. They could enter the repository with groundwater, or be produced in the repository as rock flour from the use of explosives or drilling during repository construction. Colloids may also form in the repository during degradation of the wastes or engineered barrier materials. For example, colloid formation may be promoted by steep chemical gradients within the repository system, such as at an interface where the Eh or pH changes abruptly because of chemical or biological activity. Colloid stability generally decreases as ionic strength (salinity) increases.

Colloids may influence contaminant transport by serving as a mobile carrier of otherwise highly-sorbing (and therefore potentially immobile) contaminants. Colloid transport can be affected by anion exclusion which can prevent their movement through small pores. Colloids can also act as a retardant when they agglomerate, by plugging pore spaces which are too small to permit ingress and thereby affecting the hydraulic conductivity of the backfill and rock.

Colloids are not expected to be significant in the transport of contaminants through the DGR geosphere for the following reasons.

- Given the high salinity of the Deep and Intermediate Bedrock Groundwater Zones (Section 2.3.4), colloids are expected to be unstable and so susceptible to agglomeration and dissolution.
- The very small pore size and low permeability of the Ordovician sediments is expected to prevent migration of colloids by filtering.
- The transport of any colloids is expected to be a diffusion process since diffusion rather than advection is considered the primary mechanism of contaminant transport within the Deep Bedrock Groundwater Zone. The diffusion coefficients for the colloids would likely be smaller than for true solutes.

#### 5.6.3 Solubility

The formation of stable aqueous species will increase elemental solubility limits, promoting the dissolution and transport of contaminants. Conversely, a reduction in the stability of aqueous species, or increase in the stability of a solid phase, will lead to precipitation and decreased transport. These effects will be influenced by groundwater composition, and hence their occurrence will depend on the location in the geosphere. In addition, these effects will change with time in response to evolution of the groundwater and temperature (Section 5.1).

#### 5.6.4 Sorption

The migration of most contaminants in groundwater through rocks is usually significantly retarded by sorption, although the saline conditions in the lower parts of the geosphere might limit sorption. Sorption data have not yet been directly measured at the Bruce site. However, measurements in somewhat similar systems, including the saline environment at WIPP, indicate that sorption will help retain contaminants in the geosphere. A review of sorption values, including sorption on limestones and shales, is documented in the Data report (Walke et al. 2009b). Sorption properties are summarised in Table 4-2.

#### 5.6.5 Denudation and Deposition

It is unlikely that large-scale denudation or deposition will occur over the 1 Ma timescale of interest to the DGR project, due to the site's low relief topography and low elevation relative to sea level.

Geosynthesis work to date indicates there is no direct evidence from site investigation of significant erosion in the past one million years. As noted in Section 2.3.3.2, erosion of hundreds of metres since the Mississippian period (359 to 318 Ma BP) has been proposed as a possible explanation of the pattern of excess and deficient hydraulic pressures currently seen at the site. However, there are other potential explanations of these pressures that do not involve such large-scale erosion, and these erosions would anyway have occurred a long time ago.

Small-scale (a few tens of metres) sediment/rock erosion and deposition is likely to occur due to hydrological processes, wind and particularly glacial processes. Denudation and deposition are assumed to approximately balance one another, such that the repository depth below ground level will not change by more than a few tens of metres over the next million years.

### 5.7 INTERFACES WITH THE WASTE/REPOSITORY AND BIOSPHERE SUB-SYSTEMS

The most important effects of the geosphere on the repository (including wastes) occur as a result of resaturation. Groundwater from the geosphere will infiltrate into the repository and promote:

- degradation of the waste packages;
- generation of gases from degradation of waste packages; and
- release of radionuclides from the waste.

The geosphere will influence the biosphere, except when there is widespread permafrost which will effectively disconnect the biosphere from the geosphere. In the absence of permafrost, these influences are likely to occur as a result of:

- groundwater discharge to the surface at natural discharge locations (e.g., into lake sediment) or through wells or open boreholes;
- gas discharge to the surface.

### 5.8 UNCERTAINTIES

The main uncertainties in the geosphere sub-system are summarised below.

The timing and duration of glacial periods and the extent of permafrost and associated impacts are uncertain. However, insight is provided by the continental scale glacial models of the last 120,000 years developed by Peltier (2008), by application of these models to future conditions and by global climate change models. The results presented in Peltier (2008) indicate that due to elevated $CO_2$ concentrations, ice-sheet growth will not be initiated during the next

Milankovitch solar insolation minimum, and therefore the DGR site will remain de-glaciated until beyond the next minimum, some 60,000 years into the future.

Disequilibrium hydraulic heads have been observed in the Intermediate and Deep Bedrock Groundwater Zones at the DGR site. Their presence is an indication that the host rock is low-permeable and unfractured. Although contaminant transport will be diffusion dominated in the rock, advection might occur in the more permeable shafts/EDZ due to head gradients. The future evolution of these heads, including their response to future glacial cycles, is uncertain since their cause is not yet clear.

There are expected to be major changes in the Shallow Bedrock Groundwater Zone (within about 180 m of the surface). This is a relatively conductive zone, and therefore will respond to changes in climate-based recharge rates in the short term, and the presence of overlying bodies such as a proglacial lake or ice-sheet in the long term. The exact details of the future surface hydrology and the Shallow Bedrock Groundwater Zone are therefore uncertain. However, it is likely that the water flowing through this zone will discharge quickly, and primarily to a nearby large surface water body such as the current lake.

The geosphere conceptualisation and parameters are dominantly based on regional (and Southern Ontario) information, interpolated to the DGR site. There are presently only limited site-specific data to support the geosphere conceptualisation or parameters for zones below the Shallow Bedrock Groundwater Zone. In particular, while the hydraulic permeability in the intermediate and deep rock formations is low, the value is uncertain and currently two alternative conceptual models have been proposed.

Given the saline groundwater conditions, significant uncertainty surrounds the potential sorption of contaminants onto the host rock, which has the potential to retard contaminant migration.

The shaft EDZs may play a key role in contaminant migration for both the groundwater and gas pathways. Assumptions described here with respect to size and permeability represent best estimates based on EDZ studies from other sites.

Although erosion and deposition are not expected to alter the geosphere pathlength significantly over the next million years, the extent of net erosion is uncertain. Further data regarding geosphere erosion rates over the last million years would be valuable to provide confidence that the geosphere barrier is unlikely to be significantly reduced in response to erosion.

# 6. EXPECTED EVOLUTION OF THE BIOSPHERE

## 6.1 APPROACH

Over the timescale over which the DGR system evolution is to be considered (i.e., 1,000,000 years), it is unrealistic to predict human habits and behaviour. Further, major changes to the surface and near-surface environment are also likely to occur over such timescales, either as a result of natural changes such as glaciation or as a result of future human actions.

Thus, in order to estimate the potential impacts in the future, a series of assumptions relating to the biosphere and its evolution must be made. Some of these assumptions will necessarily be arbitrary to some extent. However, such assumptions must be consistent with providing a reasonable level of assurance regarding the potential impact of the DGR on humans and the environment.

In particular, any description of the biosphere that is adopted for radiological impact assessment should be considered a ‘reference’ or ‘assessment’ biosphere that acts as a ‘measuring instrument’ for evaluating representative indicators of the potential long-term radiological impact of the repository.

A systematic process (the ‘Reference Biosphere Methodology’) for establishing a logical audit trail to justify the scope, constituents and definition of such biospheres was developed in Phase II of the Biosphere Model Validation Study (BIOMOVS II 1996) for use in the assessment of deep geologic repositories. It has been subsequently tested and enhanced under the International Atomic Energy Agency’s International Programme on Biosphere Modelling and Assessment Methods (BIOMASS) (IAEA 2003) and the BIOCLIM project of the European Commission (BIOCLIM 2004). It is helpful to take the methodology into account when considering the representation and documentation of biosphere evolution. In particular, the practical, three-step approach used for the identification of future biosphere systems (Figure 6-1) is applied in Sections 6.2, 6.3 and 6.4.

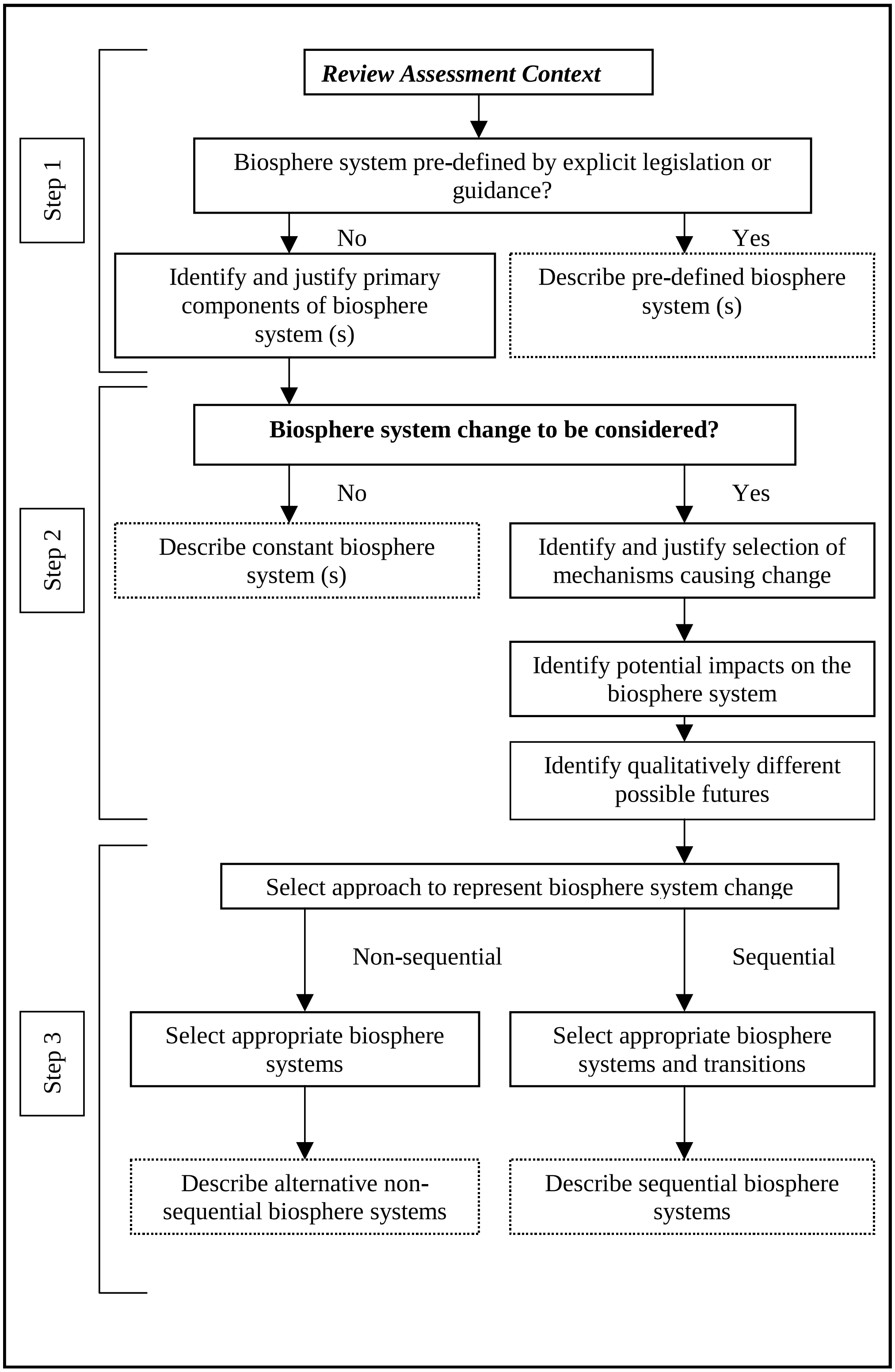



**Figure 6-1: Decision Tree for Use in the Identification and Justification of Biosphere Systems (IAEA 2003).**

A consequence of the application of the BIOMASS approach is that this section of the report has a somewhat different structure from the repository and geosphere evolution sections (Sections 4 and 5) and their focus on the thermal, hydraulic, mechanical and chemical evolution of the repository and geosphere.

## 6.2 CONSIDERATION OF THE ASSESSMENT CONTEXT

With respect to the assessment context, as documented in Quintessa et al. (2009), there is no explicit or pre-defined biosphere system(s) to be considered. However, the context does constrain the definition of the assessment biosphere to a certain extent by the following.

- The purpose of the biosphere assessment is to assess the postclosure radiological and non-radiological safety of the proposed DGR at the Bruce Site.
- The primary postclosure safety indicators are: radiological impact on humans as represented by the annual individual effective dose to an average adult member of a hypothetical potential exposure group expected to receive the highest annual dose (i.e., the critical group) from each scenario that is assessed; radiological impact on non-human biota identified through the evaluation of site-specific Valued Ecosystem Components (VECs); and environmental concentrations of hazardous substances.
- A range of representative exposure groups needs to be considered in order to allow confirmation of the identification of the critical group and to illustrate the range of doses that might be received by different exposure groups. Their habits and characteristics should be based on reasonably conservative and plausible assumptions that consider current lifestyles.
- The assessment is to be carried out to a point in time that allows a clear demonstration that the peak calculated impacts have been reached (CNSC 2006).

Since the assessment context does not pre-define the biosphere system, it is necessary to identify and justify the primary components of the present-day biosphere system both at a local and regional scale (i.e., proceed down the left-hand side of Step 1 shown in Figure 6-1). The principal components of the present-day biosphere system are described in Section 2.4.

Given the long timescales to be considered, it is necessary to give consideration to biosphere system change (i.e., proceed down the right-hand side of Step 2 shown in Figure 6-1) and to identify mechanisms of change and the possible future biosphere systems.

## 6.3 CONSIDERATION OF BIOSPHERE CHANGE

### 6.3.1 Mechanisms of Change

#### 6.3.1.1 Introduction

The BIOMASS programme identified seven External FEPs that can act as mechanisms of global change in the biosphere which can then propagate change down to the regional and local scales (IAEA 2003). These are listed below together with their reference number in the FEP list given in Table 3-1 and whether they are included or excluded from consideration in the DGR Normal Evolution Scenario as a consequence of the External FEPs identification process documented in Garisto et al. (2009) and summarised in Section 3 and Table 3-2.

- Orogeny (FEP 1.2.02) – excluded.
- Seismicity (FEP 1.2.03) – excluded.
- Volcanic and magmatic activity (FEP 1.2.04) – excluded.
- Global climate change (FEP 1.3.01) – included.
- Human influence on global climate (FEP 1.4.01) – included.
- Social and institutional developments (FEP 1.4.02) – included.
- Impact of meteorites (FEP 1.5.01) – excluded.

Global climate change is the principal External FEP causing long-term environmental change in the biosphere. Human influence on global climate, and social and institutional developments, will have important impacts on the biosphere. These are discussed further below.

#### 6.3.1.2 Global Climate Change

In the past million years, Canada has experienced approximately nine cycles of glaciation and deglaciation (melting), with relatively short interglacials between them (Peltier 2008). The last glaciation began at about 120,000 years before the present and reached its maximum extent about 21,000 years ago. At that time, more than 97 percent of Canada was covered by ice, primarily the Laurentide ice-sheet. The final retreat of the ice-sheet occurred between approximately 9,000 and 6,500 years ago.

Understanding gained from evidence from past ice-sheets, in particular the most recent, can be used to provide information on the likely effects of future ice-sheets on the Bruce site. To this end, work using the University of Toronto Glacial Systems Model (UoT GSM) has been undertaken to describe the evolution of the Canadian land mass in response to glacial events over the last 120,000 years up to present (Peltier 2008). The work is limited to exploring the details of historical glacial events, mainly because it is necessary to constrain the modelling in many important respects with data from the historic record. The work indicates that the site will be affected substantially by the development, presence, and retreat of an ice-sheet.

A range of conclusions are identified by Peltier (2008) that are important in framing the response of the DGR system to climate change for the purposes of safety assessment modelling. Principally, these are:

- calculated permafrost depth at the site has not been substantial historically, typically being tens of metres in depth (Figure 5-1);

- meltwater generation is confined to temporally discrete events largely constrained to a short period of time after glacial maxima, at rates of around ten to a few tens of cm per year (Figure 5-5);
- the calculations indicate that the site is likely to be covered with a proglacial lake in periods of retreat, which may reach considerable depth (tens of metres) and which gradually retreats in response to uplift (Figure 6-2);
- crustal deflection of more than 500 m is computed at the last glacial maximum (Figure 5-3); and
- three distinct glacial maxima can be identified over the last 120,000 years (Figure 5-3 and Figure 5-5).

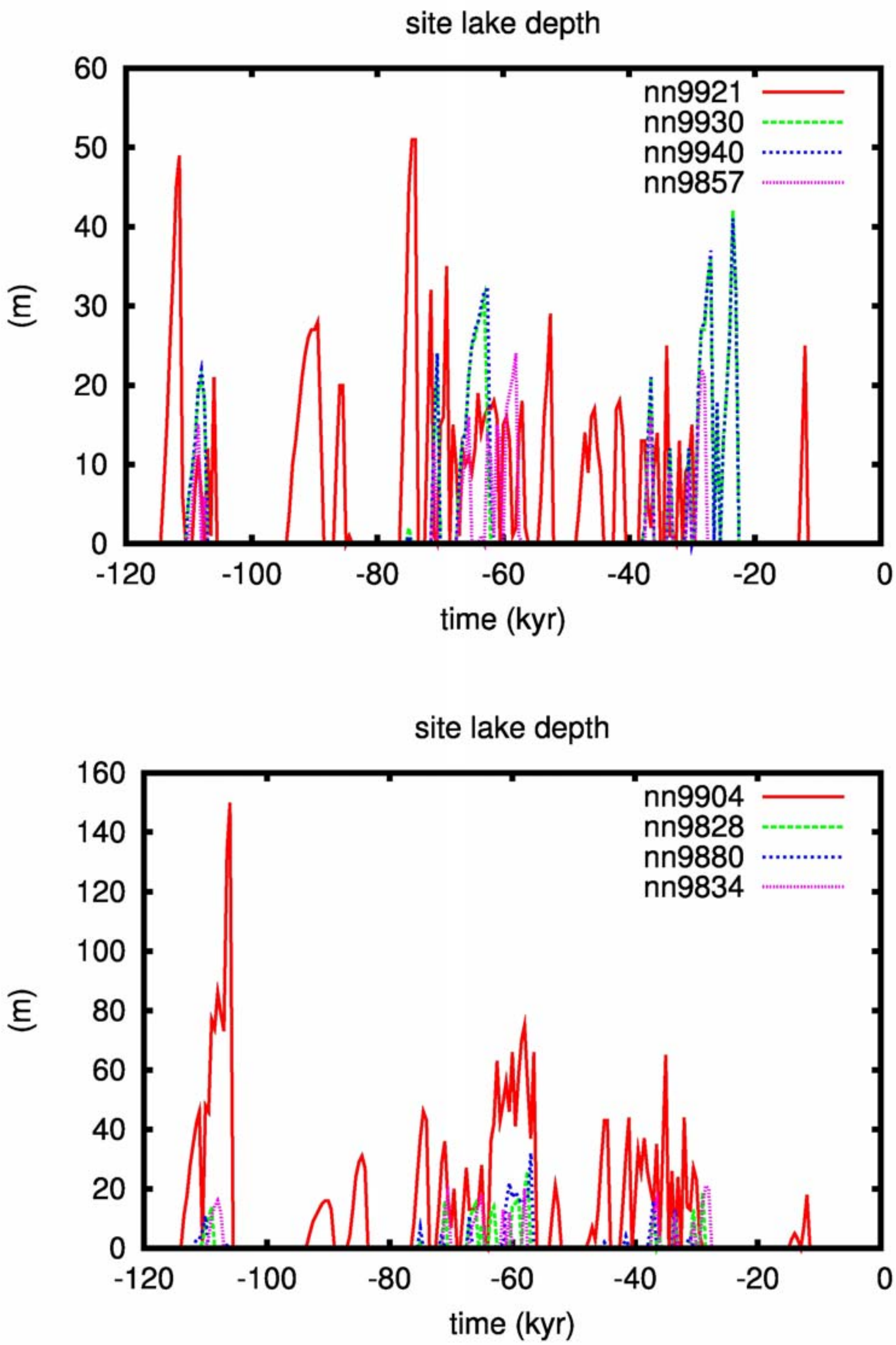



**Figure 6-2: Simulated Proglacial Lake Depth at the Bruce Site over the Last Glacial Cycle for the Eight Cases Consistent with Historical Data (Peltier 2008)**

#### 6.3.1.3 Human Influence on Global Climate

There is a growing body of evidence that man-made emissions of gases such as carbon dioxide and methane are enhancing global warming (IPCC 2007).

In the near term (i.e., on the scale of centuries or perhaps a thousand years), global warming is likely to cause average annual global surface temperatures to increase by several degrees Celsius, with the increase being rather greater at high northern latitudes. The resulting changes in meteoric precipitation could affect the surface and near-surface environments and could change patterns of human activity. Such global warming will also result in a global sea level rise of several metres. Although the sea level rise is unlikely to impact the site (due to its elevated inland location), the impacts of temperature and precipitation changes on the surface and near-surface systems might be locally important. For example there could be changes in Lake Huron water levels and therefore changes in the current shoreline, streams and wetlands.

In the longer term, the effects are more uncertain. However, Peltier (2008) notes that the initiation of a glacial episode in the next 60,000 years could be inhibited. Long-term climate modelling in the BIOCLIM project (BIOCLIM 2004) also indicated that no significant glaciations would occur for considerably longer than 60,000 years (and potentially well in excess of 100,000 years). Ultimately, however, it is expected that carbon dioxide levels will return to historic levels and glacial-interglacial cycling, on a characteristic timescale of around 100,000 to 120,000 years, will be re-established (BIOCLIM 2004).

#### 6.3.1.4 Social and Institutional Developments

Potentially significant social and institutional developments include:

- changes in planning controls and environmental legislation;
- demographic change and urban development;
- changes in land use; and
- loss of records or societal memory of the DGR location and hazards.

Societal knowledge of the DGR is likely to provide control for at least 300 years from the closure of the DGR (see Section 3.8 of Quintessa et al. 2009). Thereafter, it is assumed for the assessment that the land uses in the previously controlled area is likely to become consistent with the wider region around the Bruce site (i.e., predominantly agriculture and recreation – Section 2.4.7).

### 6.3.2 Potential Changes to the Biosphere

#### 6.3.2.1 Changes in Surface Features and Processes

*Topography*

The current-day topography around the Bruce Site and the larger region is relatively flat. It is expected that a relatively low-lying topography with bluffs (representing former lake shorelines), or hills due to glacial moraines, will be maintained during subsequent ice-sheet advances and retreats.

*Lake*

Lake Huron is a dominant feature in the present-day biosphere at Bruce. Modelling results (Peltier 2008) and field observations indicate that there has been a large lake in this area for a considerable period, althought the size, lake levels, and possibly flow outlet have varied. Although the details of the shoreline and extent of Lake Huron will change in the future, it is expected that a large lake will generally be in the vicinity of the DGR site, except during periods of glacial maxima when the area will be overridden by an ice-sheet.

Changes in the size of the lake will have consequences for surface and groundwater conditions, and also changing the areas of land that can be utilised by humans.

*Streams and Wetlands*

There are currently streams and wetlands present in the vicinity of the site (Section 2.4.2). Future climate change will affect surface water systems and their associated sediment. Changes in precipitation, evapotranspiration and the lake margin location, associated with general climate evolution (including global warming), will be reflected in an evolving pattern of surface drainage with the associated erosion and deposition of sediment. The presence of an ice-sheet will change the nature of “surface” flows. Ice margin effects will also be significant, especially during retreat when there are likely to be large volumes of meltwater and the presence of a proglacial lake over the site. Sediment can also be eroded and deposited during the advance/retreat of an ice-sheet. Consequently, the presence and character of surface water courses and their associated sediment will be dynamic, especially in the periods before and after ice-sheet cover occurs.

*Soil*

The migration of streams and changes in the location of lake margins will result in the exposure/submersion of sediment/soil. In addition to the effects of changes in location of surface water courses, soils and lake sediments will be affected by the advance and retreat of an ice-sheet through erosive and depositional processes and subsequent pedogenesis. The soils currently found at the Bruce site have developed from former lake bed sediments exposed by the recession of the Lake Huron shoreline following the retreat of the last ice-sheet to affect the site.
The flow of water through the soils will be affected by: the climate, through its effect on precipitation and evapotranspiration rates; and the hydraulic characteristics of the soil, which in turn can be affected by the climate through the formation of permafrost (Figure 5-1).

#### 6.3.2.2 Changes in Biota

The current distribution of biota in the vicinity of the Bruce site is described in Section 2.4.8. This distribution can be expected to evolve as a result of natural and human-induced climate change. The climate is currently in a warm phase of the glacial cycle and is expected to warm further in the next millenium, due to global warming, resulting in some changes to the nature and distribution of biota in the vicinity of the Bruce site. Thereafter, during glacial cycling, the climate is likely to oscillates between cool and warm periods as it has for the past 1 Ma. During the cool periods, the ecosystem is expected to evolve to approximately resemble that currently present at inland tundra locations at higher latitudes in central Canada.

#### 6.3.2.3 Changes in Human Behaviour

Once controls are no longer effective in preventing land use change at the Bruce site, it is likely that land use will change to be consistent with that in the surrounding area (i.e., predominantly agriculture and recreation). Furthermore, wells could be drilled into the Shallow Bedrock Groundwater Zone on the site since the water in the upper parts of this zone is potable and such wells currently exist in the region around the site (Section 2.4.7). Wells in the deeper groundwater zones are not credible since the groundwater in these zones is not potable (Section 2.3.3.2 and 2.3.4).

Natural and human-induced climate change will also impact human behaviour. It is likely that, for some periods of the glacial cycle, conditions will be sufficiently inhospitable that permanent human habitation is very unlikely. However, for the remaining periods, when permanent habitation is feasible, human habits can be expected to remain broadly the same as found today; the main differences being the parameter values that describe the human habits (e.g., the ingestion rates of different foodstuffs and the occupancy rates in different parts of the biosphere system). Present-day practice at farms and individual households in the area is to obtain water from wells rather than the lake or other surface water sources (Section 2.4.4). The wells are typically no more than 50 m deep. During climate conditions in which there is some formation of permafrost it may be necessary to obtain water from other sources such as the lake because the available water supply may be constrained by the permafrost, and the deeper waters below the permafrost are likely to be saline.

### 6.3.3 Biosphere Evolution

From consideration of the above mechanisms of change and the associated potential changes, the following illustrative description of the evolution of the biosphere system through a series of stylised biosphere states has been developed for consideration in the current safety assessment.

Following closure of the repository, controls will remain effective for a period of at least 300 years. As noted in Section 6.3.2.3, once controls are no longer effective, land uses will become consistent with the present-day practices in the wider region. Although the DGR system will be affected by global warming in the short term (i.e., on the scale of centuries or perhaps a thousand years), the associated changes will not be significant from the perspective of the postclosure safety assessment since they will not modify the fundamental nature of the biosphere system and its processes. However, global warming will mean that the onset of the next glacial cycle may not occur for at least 60,000 years resulting in there being only one glacial maximum with a potentially reduced intensity in the glacial/interglacial cycle over the next 100,000 to 120,000 years rather than the three maxima experienced over the last 120,000 years (Peltier 2008).

Following the onset of climatic cooling, the climate will become drier and the present-day temperate ecosystem will gradually evolve into a tundra ecosystem characterised by sparse vegetation such as lichens, grasses, sedges and arctic-adapted low-lying plants, and dwarf shrubs and discontinuous permafrost. The timescale over which this evolution will occur is uncertain, but previous work for a slightly more northerly latitude has suggest that it could be up to a few thousands of years (McMurry et al. 2003). This tundra period is likely to be the predominant biosphere state during a glacial cycle.

With further cooling, the land surface temperature will fluctuate around the freezing point, but eventually the average annual surface temperature will drop below 0°C, and snow will begin to accumulate without melting. An ice-sheet will start to advance over the site, developing to a maximum thickness of 3 km. Where the ice and snow provide adequate insulation against heat loss from the earth's interior, the interface between the ice and the underlying solid earth will reach temperatures that are at or slightly below freezing.

Towards the end of the glacial cycle, the ice-sheet will start to retreat relatively rapidly by melting, resulting in voluminous discharges of meltwater. Regionally, this will be likely to lead to the formation of large proglacial lakes, erosion of poorly resistant rocks and sediments in some locations, and deposition of thick layers of glacially derived sediments elsewhere.

Subsequently, further warming will result initially in the re-establishment of tundra conditions, and the eventual warming to present-day temperatures resulting in the re-establishment of a temperate ecosystem. Based on historical records, the warm conditions will persist for about 20,000 years until another cooling period initiates the next cycle of glaciation.

This new cycle of glaciation will have a different behaviour in detail, due in part to the different solar insolation variations in the future. However it is sufficient to model it based on the previous historic cycle modelled by Peltier (2008) including its three glacial maxima, as this cycle includes the key aspects of a glacial cycle. This results in the following sequence of biosphere states:

> temperate => tundra => glacial => post-glacial => tundra => glacial => post-glacial => tundra => glacial => post-glacial => tundra => temperate

For assessment purposes, this sequence of glacial/interglacial cycling is repeated for the remainder of the assessment timeframe with a periodicity of around 100,000 to 120,000 years, consistent with historic records over the Late Quaternary (Peltier 2008).

### 6.3.4 Biosphere States

From the above description of the evolution of the biosphere, four biosphere states can be identified:

- temperate;
- tundra;
- glacial; and
- post-glacial.

Each state has been defined to represent a configuration of the system that is reasonably likely to occur during the evolution of the biosphere, and is of interest in relation to assessing the safety of the DGR system.

6.3.4.1 Temperate

The temperate biosphere state is illustrated in Figure 6-3.

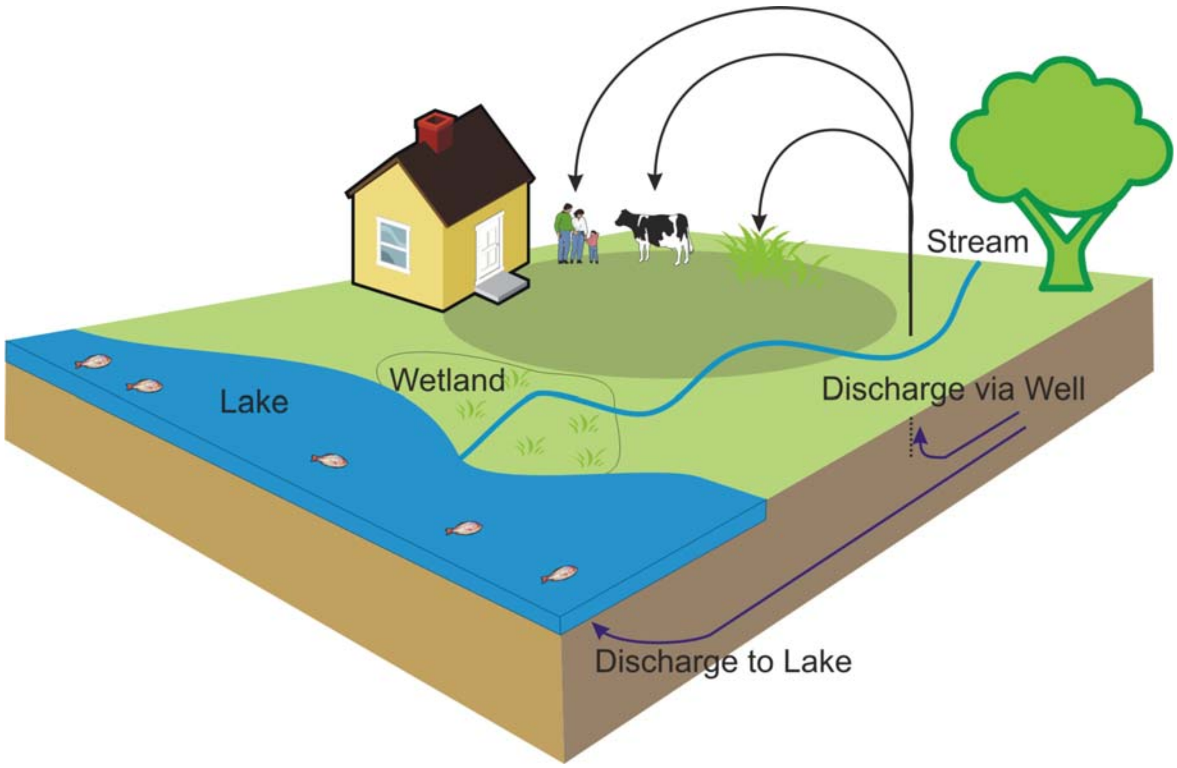



**Figure 6-3: Illustration of the Temperate Biosphere State**

The characteristics of the soils, surface waters and biota are similar to the present day. Human habits are the same as at the present day, with the land being used for agricultural and recreational purposes. Groundwater discharges to the lake and could be pumped from a well in the Shallow Bedrock Groundwater Zone. Well-water is used for agricultural and domestic purposes. Wetlands and other natural environments are sources of wild food.

6.3.4.2 Tundra

The tundra biosphere state is illustrated in Figure 6-4.

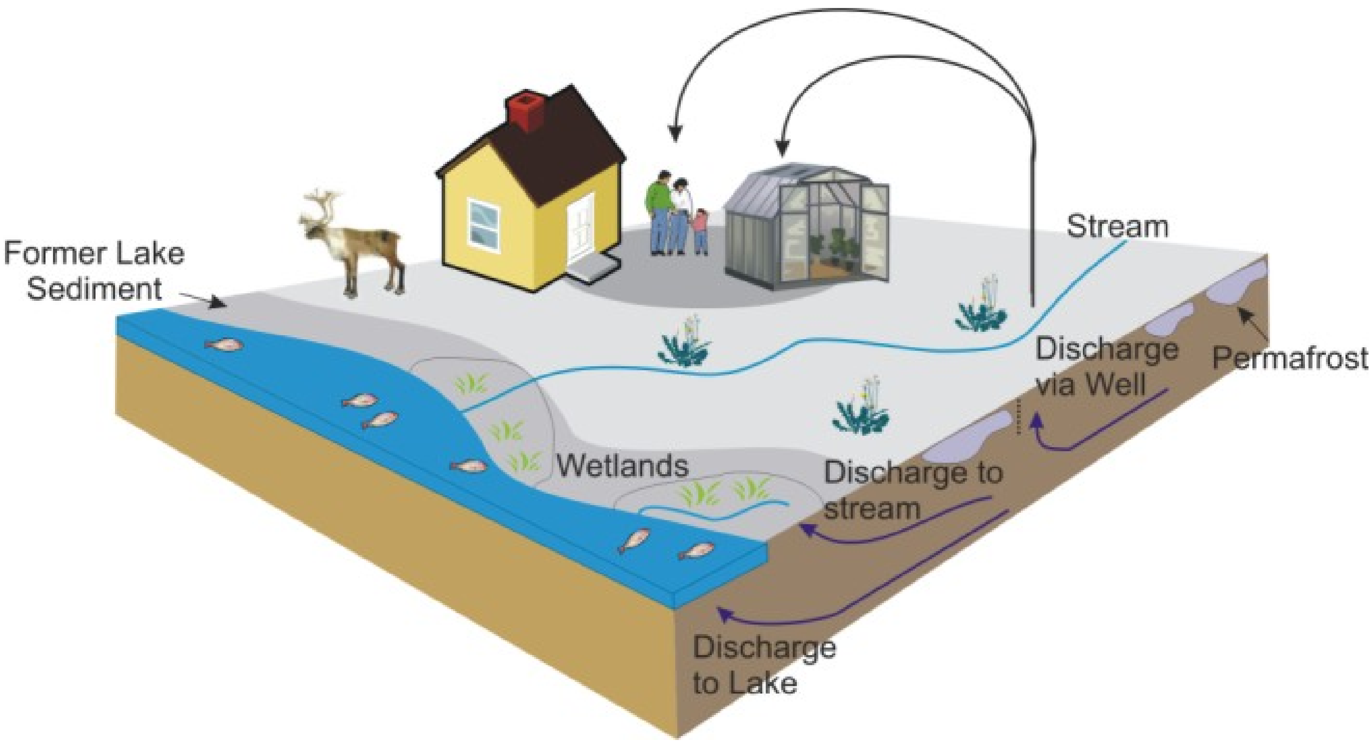



**Figure 6-4: Illustration of the Tundra Biosphere State**

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. Any permafrost that might be present would be discontinuous and limited to less than a few tens of metres. The biota that are present are comparable with the biota found in present-day tundra environments.

Human habitation is be 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.

Groundwater continues to discharge to the lake and the retreat of the lake may lead to some limited discharge of water from the Shallow Bedrock Groundwater Zone to a stream. 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.

6.3.4.3 Glacial

The glacial biosphere state is illustrated in Figure 6-5.

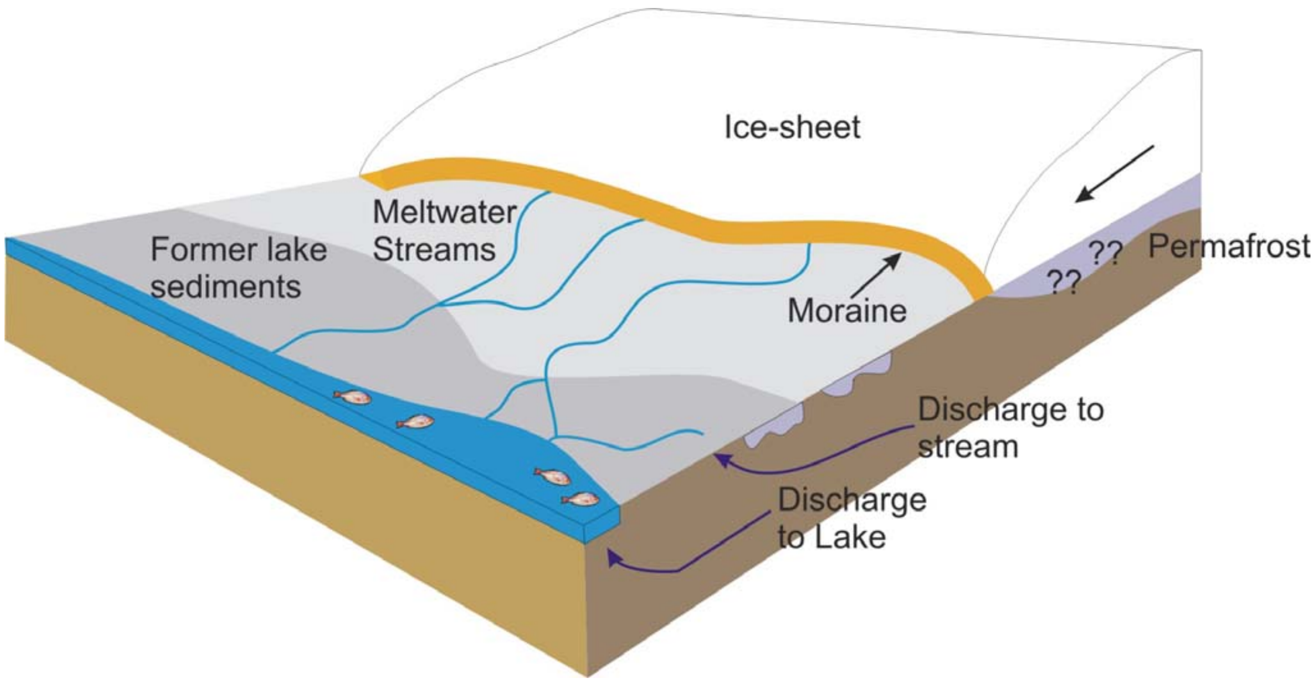



**Figure 6-5: Illustration of the Glacial Biosphere State**

The ice-sheet will approach and pre-glacial effects will become evident and the biota more limited. The lake may also continue to retreat due to reduced precipitation, exposing sediments. However, this retreat could be mitigated by meltwater coming from a warm-based ice-sheet, especially if other lobes of the ice-sheet cut off the water outlet. As the ice-sheet advances sediments will be eroded due to the action of the ice and meltwater, and moraines (accumulations of unconsolidated soil and rock) will develop at the front of the ice-sheet. Groundwater releases are expected to continue to the lake basin and also potentially to other surface waters that may form in advance of the ice-sheet (if warm-based). Permafrost might continue to develop but it is likely to remain discontinuous and is unlikely to extend to a depth in excess of 60 m. If the ice-sheet is warm based, the permafrost is likely to disappear as the ice-sheet advances over the site. Recharge to the shallow groundwater will decrease if the ice-sheet is cold-based, and increase if it is warm-based.

Self-sufficient permanent human habitation in the region is very unlikely as the environment will be harsh and inhospitable, especially once the site has been overrun by the ice-sheet. Prior to the site being overrun by the ice-sheet, there might be some limited use of resources in the region (e.g., the lake) by temporary visitors (e.g. fishermen, nomadic people).

6.3.4.4 Post-glacial

The post-glacial biosphere state is illustrated in Figure 6-6.

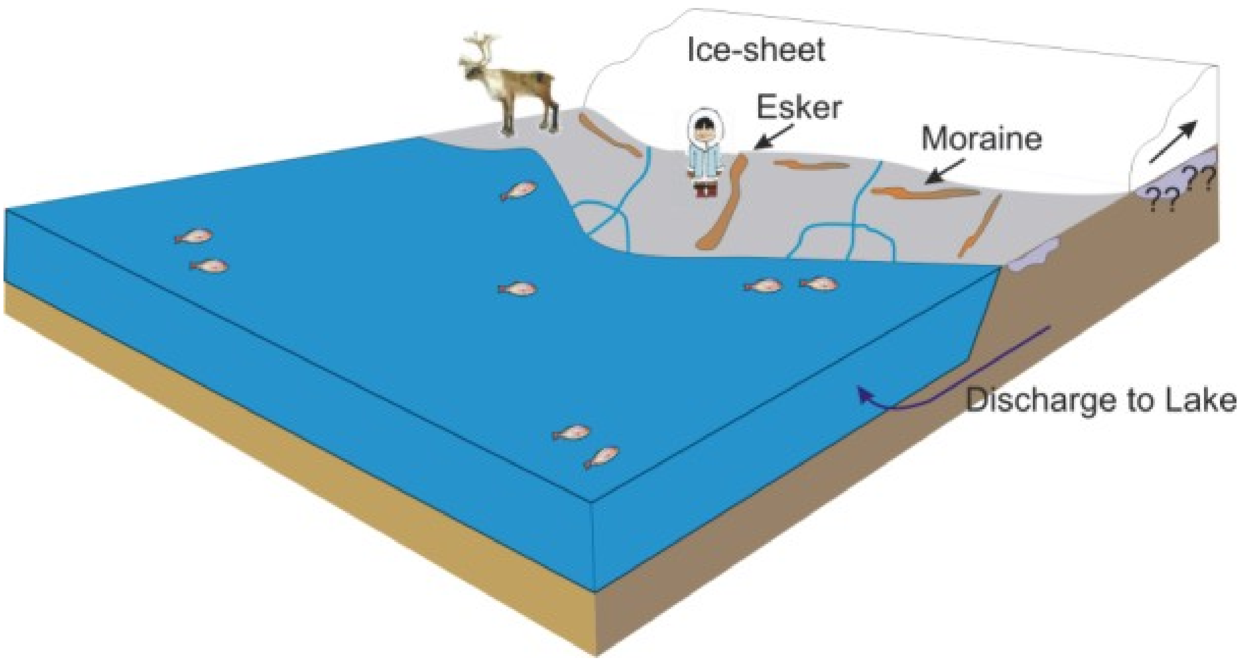



**Figure 6-6: Illustration of the Post-glacial Biosphere State**

Peltier (2008) indicates that following the retreat of the ice-sheet from the site, a proglacial lake is likely to form as a result of various factors including the production of glacial meltwater and the depression of the land. The retreating ice-sheet also has the potential to result in a network of meltwater streams. There will be substantial disruption of the surface environment, with redistribution of sediments resulting from the ice-sheet deposition. There will be long eskers of sand and gravel from subglacial meltwater streams, large alluvial fans of sands and clays from meltwater outflow in some areas, and large moraines marking ice lobe boundaries. The proglacial lake is expected to eventually overlie the site completely for a period, before gradually receding as a result of ameliorating climatic conditions and isostatic rebound. Sediments will become exposed. These will gradually weather and develop into soil.

Some nomadic animals (e.g., caribou herds, migratory birds) will be present and vegetation will be limited to a few hardy species. There could be a transient presence of people who make use of the local resources (e.g., fish and nomadic animals).

### 6.3.5 Sequence of Future Biosphere Change

The analysis of historic climate change effects undertaken by Peltier (2008) can be reviewed and simplified in order to determine basic trends that can be used in a safety assessment representation of the sequence of future climate change at the Bruce site. Projecting past patterns of climate change forward in time is valid because the key initiators of glacial cycles, variations in the Earth's orbit, have a characteristic timescale. This is known as the Milankovitch effect. A key period of 41 ka is associated with the temporal variability in orbital obliquity (the precession of the spin axis with respect to the plane of the ecliptic). A dominantly 100 ka periodic variation of orbital eccentricity modulates the amplitude of the processional effect. This means that, whilst characteristic timescales can be identified, the magnitude of glaciations varies. However, the Milankovitch theory does not fully explain the dominant 100 ka periodicity of observed in the Quaternary.

Figure 6-7 to Figure 6-10 present the simplified patterns of change for sea level, site basal temperature, permafrost depth and crustal depression calculated for the last full glacial cycle, considered by Peltier (2008). These figures have been developed by judgement from the reported results of Peltier's ensemble of model runs, seeking to identify the key trends, and representative measures of sea-level, temperature, permafrost and crustal depression corresponding to the Bruce site.

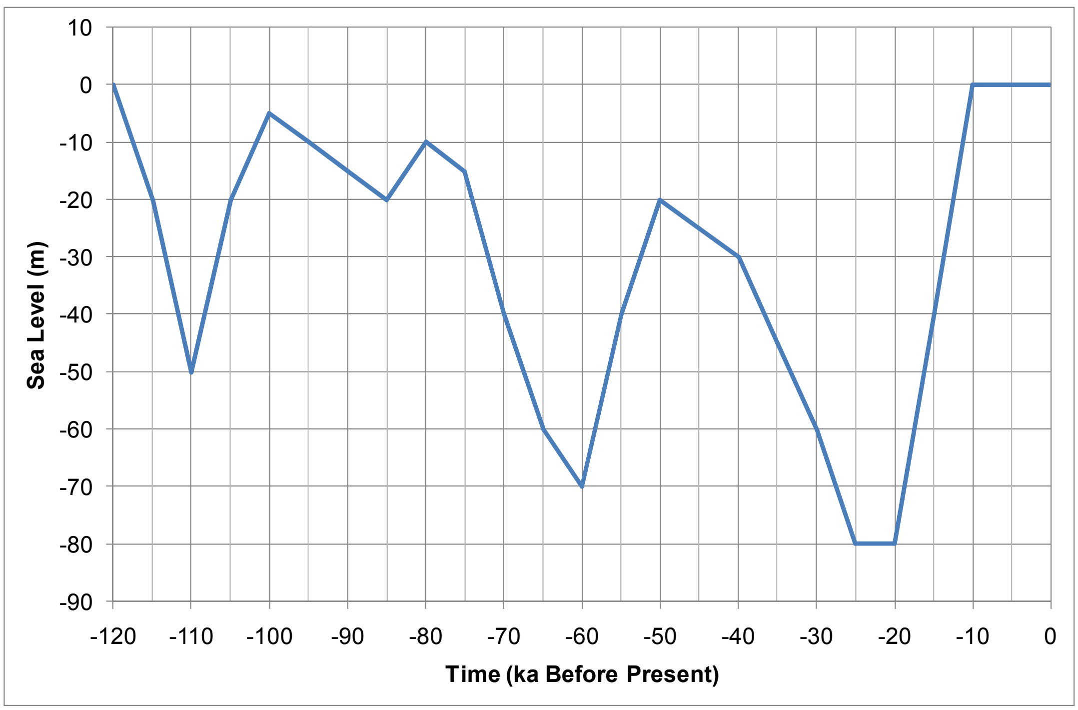



**Figure 6-7: Simplified Historic Pattern of Sea-level Change**

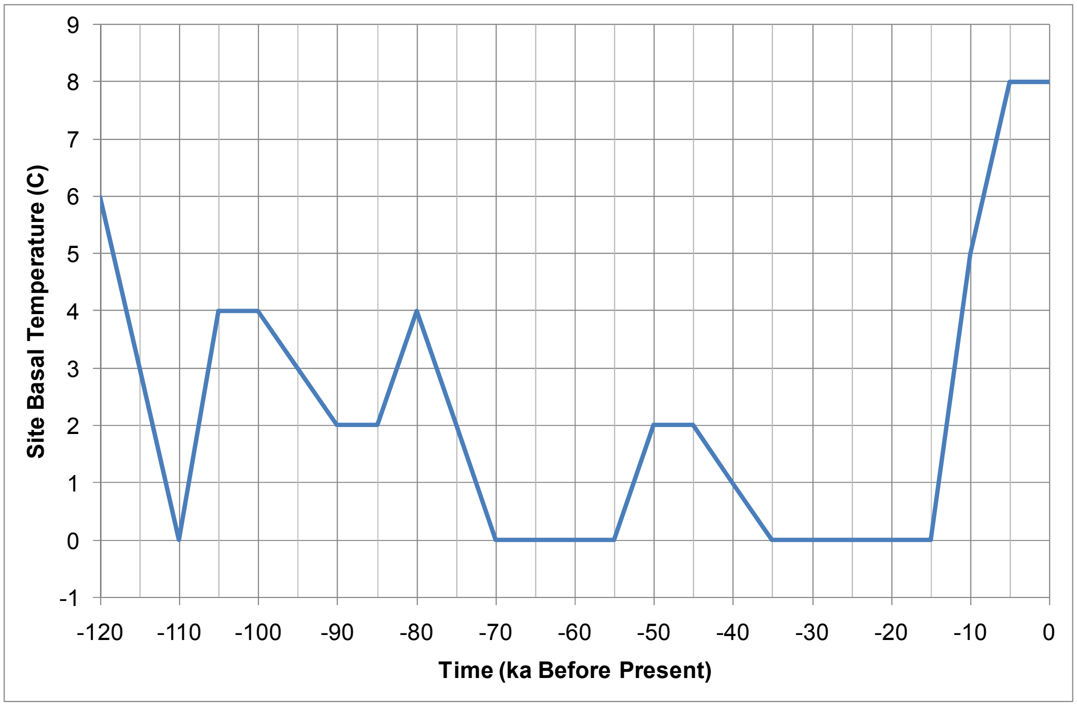



**Figure 6-8: Simplified Historic Pattern of Surface Temperature at the Bruce Site**

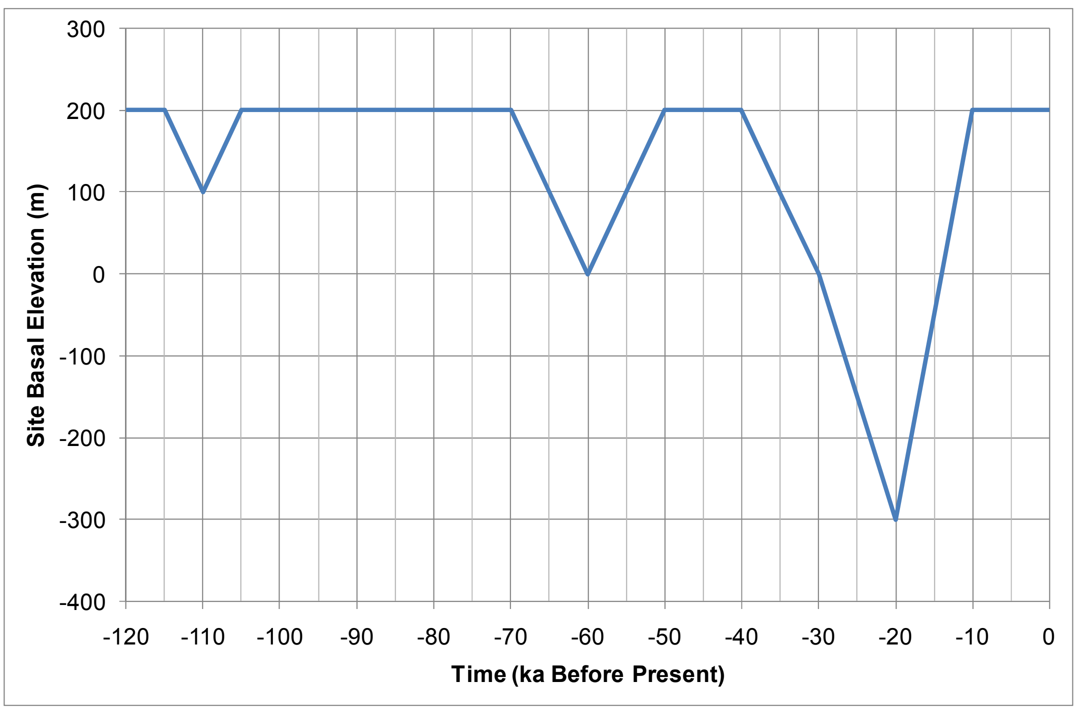



**Figure 6-9: Simplified Historic Pattern of Crustal Deflection at the Bruce Site**

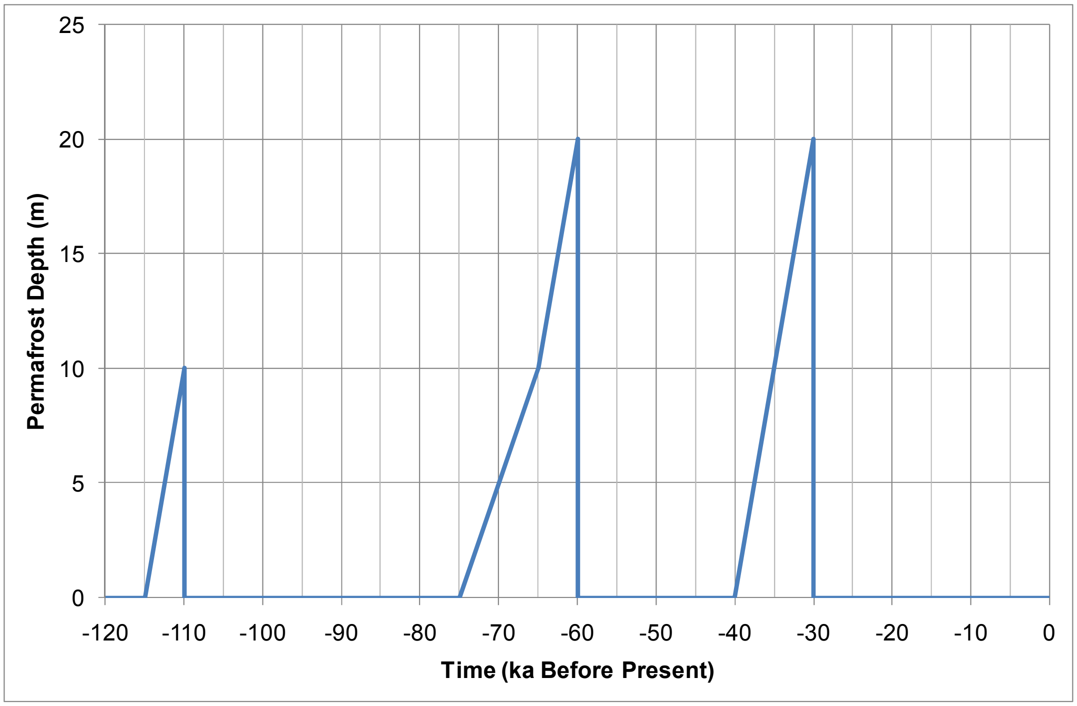



**Figure 6-10: Simplified Historic Pattern of Permafrost Depth at the Bruce Site**

It is clear that three glaciation maxima occurred, peaking at approximately 110ka, 60ka and 20 ka BP, with varying magnitude (the 20 ka BP event being by some margin the most severe). Some of Peltier's model runs also indicate a notable near-glaciation at about 90 ka BP.

Throughout most of the last glacial cycle, site basal temperatures were below 4 $^{O}$C, with only the last 10 ka showing temperatures that would comfortably correspond to a temperate climate. During this cycle (i.e. unaffected by global warming effects) the climate during the rest of the period is tundra or glacial in nature at the Bruce site.

A simplified sequence of climate states can be assigned using the biosphere states identified in Section 6.3.4 and is shown in Figure 6-11. This corresponds to typical climatic variations, with no influence of increased greenhouse gas concentrations due to human activity. There is some uncertainty as to whether the 41 ka or 100 ka periodicity will dominate in the future (the former dominated during the last few million years, but the latter has been most prevalent during the last 800 ka). Peltier's results are presented on a 120 ka timescale and therefore, for consistency with these, this timescale is adopted as being representative, although it is noted that variations will occur.

The UoT GSM does not take account of the influence of global warming as a result of the increased concentrations of atmospheric greenhouse gases. No detailed information on the impact of global warming at the Bruce Site is therefore available. However, Peltier (2008) notes that glacial cycles in the next 60 ka could be inhibited (in practice, this could be even longer, depending on the rate at which greenhouse gases are removed from the atmosphere). Furthermore, work on long-term climate modelling using Earth Models of Intermediate Complexity (EMICs) by the BIOCLIM project (BIOCLIM, 2004) indicate that no significant glaciations would occur for considerably longer than 60 ka (potentially well in excess of 100 ka).

If consideration is given to global warming in the assessment modelling, it is therefore reasonable to assume that temperate conditions persist at the Bruce site for 60 ka before there is a possibility for the historical pattern of glaciations to recommence, as illustrated in Figure 6-12. The rest of the sequence is based on the pattern shown in Figure 6-11, but projected forward in time with the first 60 ka assumed to be temperate. This is more appropriate than shifting the entire sequence forward by 60 ka, as it retains consistency with orbital forcing of glacial cycles.

Subsequent cycles are then assumed to follow a pattern similar to that experienced in the last 120 ka (shown in Figure 6-11).

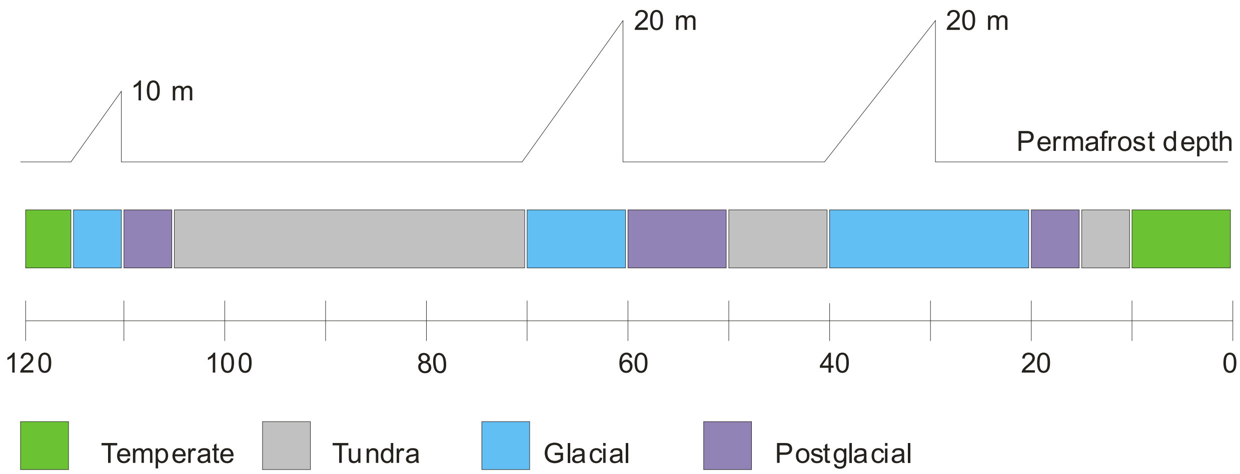



**Figure 6-11: Simplified Sequence of Past Climate States and Permafrost**

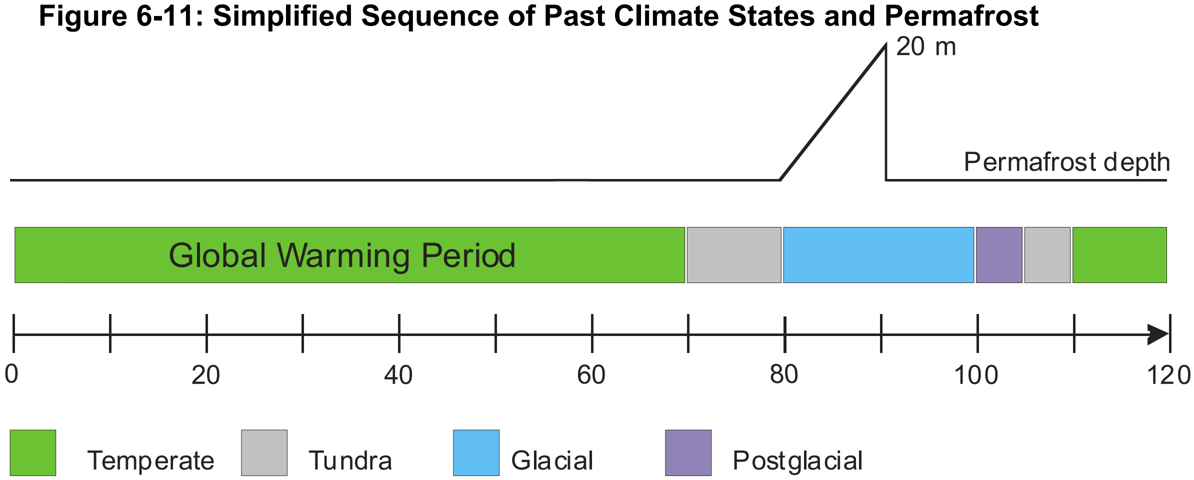



**Figure 6-12: Assumed Sequence of Climate States and Permafrost Depth with Global Warming for the Next 120 ka**

## 6.4 REPRESENTATION OF BIOSPHERE SYSTEM CHANGE

The final step in the identification and justification of the biosphere system is the selection of an approach to represent biosphere system change in the development of assessment biospheres.

The choice of approach is a modelling decision that is discussed in the Normal Evolution Scenario Analysis report (Walke et al. 2009a) rather than this system description and evolution report.

## 6.5 INTERFACES WITH THE REPOSITORY AND GEOSPHERE SUB-SYSTEMS

It is expected that there will be no direct impact of the biosphere on the waste for the Normal Evolution Scenario due to the isolation of the waste from the biosphere and its processes provided by the depth of the repository (680 m). Nevertheless, there could be a limited number of indirect impacts such as the increased loading and associated stresses at depth resulting from an ice-sheet causing rockfall in the repository rooms and tunnels. Furthermore, since the access and ventilation shafts are part of the repository system and they extend up from the level of the emplacement rooms through the geosphere to the surface environment, the repository system can be considered to have a direct interface with the biosphere.

The interface between the geosphere and biosphere is important to consider in any safety assessment since its nature can have a significant impact on the release of contaminants from the geosphere into the biosphere. It is particularly important to consider the impact of the environmental changes on the geosphere-biosphere interface (GBI).

Contaminant releases into a biosphere consistent with that currently found at the site can be expected to occur via the following pathways:

- groundwater discharge via the Shallow Bedrock Groundwater Zone into a lake;
- groundwater wells near the repository in the Shallow Bedrock Groundwater Zone; and
- gaseous releases into the atmosphere above the repository, primarily focussed around the Main and Ventilation Shafts.

However, with evolution of the biosphere described above, the nature of the GBI can be expected to change. With the onset of cooler conditions, the location of contaminant discharge is expected to be redirected, for example to former lake bed sediments exposed due to a fall in lake level (see Section 6.3.2.1). The advance and subsequent retreat of ice-sheets over the site is likely to cause significant changes in the configuration of the biosphere and the nature of the Shallow Bedrock Groundwater Zone, due to the effects of erosion and deposition caused by the ice-sheet and its associated meltwaters. The response of surface-water and groundwater systems may also be complex (see discussion in Section 5.3). Therefore, a number of GBIs could be envisaged for the post-glacial biosphere state in addition to the lake and well GBIs identified for the present-day state:

- groundwater discharge via the Shallow Bedrock Groundwater Zone into a stream/river;
- groundwater discharge via the Shallow Bedrock Groundwater Zone into a marsh; and
- groundwater discharge via the Shallow Bedrock Groundwater Zone to a lake shore.

## 6.6 UNCERTAINTIES

As noted in Section 6.1, there are significant uncertainties associated with the evolution of the biosphere arising from various sources such as uncertainties associated with the timing and effects of future glacial-interglacial cycles, and the inability to predict human habits and behaviour and the impacts of human actions on environmental change over the timescales of interest. Therefore, any descriptions of the biosphere in the long term must inevitably be speculative. In order to manage these uncertainties, an illustrative sequence of biosphere states has been considered.

The stylised approach deals with these uncertainties at a simple level by presenting clear assumptions that cover the range of outcomes and are cautious in nature. However, even with this approach it is noted that some uncertainties remain unresolved that have the potential to affect calculated results significantly. Most notably, the potential nature of the discharge to surface is important, as terrestrial discharges are substantially more significant, radiologically, than releases to the lake. Associated with this uncertainty is the potential location and size of the lake over the whole glacial cycle. Other areas of uncertainty, such as soil and sediment characteristics and human land use, are directly related to the lake location.

# 7. THE EXPECTED EVOLUTION OF THE DGR SYSTEM: THE NORMAL EVOLUTION SCENARIO

The guidelines for the preparation of the Preliminary Safety Report and Environmental Impact Statement (EIS) required for the DGR (CEAA and CNSC 2009) and the guidance on assessing the long-term safety of radioactive waste management (CNSC 2006) both identify the need for the postclosure safety assessment to include a scenario of the normal (or expected) evolution of the of the site and facility with time that is based on reasonable extrapolations of present-day site features and receptors' lifestyles. This scenario should include the expected evolution of the DGR system and its degradation (loss of barrier function) with time.

The expected evolution of the DGR system has been described in Sections 3 to 6 in terms of:

- the external FEPs affecting the expected evolution of the system (Section 3);
- the internal FEPs affecting the expected evolution of the repository (Section 4);
- the internal FEPs affecting the expected evolution of the geosphere (Section 5); and
- the internal FEPs affecting the expected evolution of the biosphere (Section 6).

The role of this section is to synthesise the information provided in Sections 3 to 6 in order to provide a high-level narrative of the expected evolution of the DGR system that can be used to inform the subsequent development of conceptual models.

Section 3 identifies the following external (scenario generating) FEPs as needing to be considered in the Normal Evolution Scenario:

- climate change with initial global warming, and subsequent reversion to the glacial and interglacial cycling experienced over the last million years;
- seismic events with a moment magnitude of less than 6;
- the development of soils from unconsolidated parent material (particularly after the retreat of ice-sheets);
- the deformation of rocks (including the EDZ) and shaft materials due to loading from ice-sheets; and
- land use change once institutional controls are no longer effective.

Taking these external FEPs into account, together with the internal FEPs discussed in Sections 4 to 6 and the FEPs report (Garisto et al. 2009), the following description of the Normal Evolution Scenario has been developed.

## 7.1 OVERALL SYSTEM EVOLUTION

The construction, operation, monitoring and closure of the DGR will be undertaken under OPG's quality assurance programme and is consistent with the description provided in Section 2.2. Following closure of the repository, some combination of active and passive institutional controls (e.g., monitoring, planning controls, and markers) remains effective for a reference period of 300 years (Section 3.8 of Quintessa et al. 2009). Once institutional control becomes ineffective, it is assumed that land uses in the previously controlled area become consistent with the wider region. In turn, this is likely to be consistent with the land uses currently found in the area surround the Bruce site (i.e., predominantly agriculture and recreation) (Section 2.4.7).

Although global warming is likely in the near term (i.e., over the next thousand years), it is expected that its impact will not be significant from the perspective of the postclosure safety assessment because:

- the inland location of the Bruce site means that sea level rise does not impact the site;
- the hydraulic isolation of the repository and the deep geosphere from the surface and near-surface systems prevent the effects of any temperature and precipitation changes impacting the repository and the deep geosphere; and
- releases of contaminants are very unlikely to occur from the repository over such a timescale due to the isolation provided by the geosphere and shaft seals.

However, global warming does delay the onset and duration of the next glacial episode, which does not occur for 60,000 years (Peltier 2008) and has a curtailed duration of 40,000 to 60,000 years. Around 60,000 years, a cooling in surface temperature occurs resulting in the transition from present-day temperate conditions through tundra to glacial conditions. A warming in surface temperature then occurs resulting in the retreat of the ice-sheet from the site and the development of a proglacial lake and the subsequent re-establishment of tundra conditions. Further warming results in the eventual re-establishment of temperate conditions. These warm conditions persist until another cooling period initiates the next cycle of glaciation around 100,000 to 120,000 years from present. This new cycle of glaciation will not be affected to the same extent by global warming and so will have characteristics similar to the historic cycle modelled by Peltier (2008) including its three glacial maxima. This sequence of glacial/interglacial cycling is repeated for the remainder of the assessment timeframe with a periodicity of around 100,000 to 120,000 years, consistent with historic records over the Late Quaternary (Peltier 2008).

## 7.2 WASTE AND REPOSITORY EVOLUTION

The evolution of the repository can be divided into three phases:

1) an aerobic humid period immediately following closure of the repository during which the levels of oxygen in the repository decrease due to degradation of the waste packages;
2) an anaerobic humid period during which degradation of waste packages continues, and repository is unsaturated or partly saturated; and
3) an anaerobic inundated period following resaturation of the entire repository.

The aerobic humid phase is expected to be relatively short, with the main consequence being the removal of oxygen and establishment of anaerobic conditions in the repository.

During the anaerobic phases, the waste packages (i.e., wastes, containers and any overpacks) in the repository degrade at differing rates due to corrosion and microbial degradation. If sufficient water is present, the carbon steel containers will degrade significantly on timescales of decades to centuries, whereas other packages (e.g., those with stainless steel containers or concrete overpacks) might take thousands of years. At this point, the waste and the radionuclides can be contacted by groundwater that has entered the repository. The extent of contact depends on the resaturation level.

Most wasteforms will release radionuclides relatively easily into the repository water on contact. However radionuclides within the concrete packages (resins, retube waste) will be affected initially by low solubility due to high pH. Corrosion resistant wasteforms such as Zircaloy will only release radionuclides and other contaminants very slowly.

Although the rocks are expected to be quite sturdy around the non-backfilled emplacement rooms, it is expected that some rockfall from the ceilings of the emplacement rooms and repository tunnels will occur periodically, possibly due to seismic and/or glacial events. This process will continue intermittently, over periods of tens of thousands of years, until the volume of collapsed rock has increased sufficiently to support the roof of the void. The maximum extent of rock collapse is expected to be 20-30 m above the original ceiling, although if extreme assumptions are made, it could reach 70 m.

The concrete block walls at the entrances to the emplacement rooms are not constructed to be water/air tight and can be expected to provide a limited barrier to water mixing (i.e. diffusion) and no effective barrier to gas mixing.

The shafts contain a sequence of seals of concrete, bentonite-sand and asphalt that will limit migration of contaminants in gas and water through the shafts and their associated EDZs. The performance of these seals in terms of resistance to gas and water flow is not expected to degrade in the Deep and Intermediate Bedrock Groundwater Zone due to the stable geological environment. However, the concrete seals in the Shallow Bedrock Groundwater Zone are expected to degrade due to the faster flow conditions promoting leaching and dissolution and due to mechanical stress from ice-sheet loading and unloading.

The degradation of the waste packages results in the generation of gases, primarily hydrogen, carbon dioxide and methane, over a period of many thousands of years. Initially, the rate of gas generation is likely to be greater than the rate of gas loss due to the low permeability of the host rock. Although there might be an initial decrease in gas pressure in the repository as oxygen is consumed in the oxidation of iron, and hydrogen and carbon dioxide are converted to methane, the gas pressure will build up due to waste degradation to exceed natural steady-state pressure. Thereafter, pressures decrease slowly to natural steady-state pressure level due to gas dissolution in the repository, gas migration from the repository up the shafts and into the geosphere, gas reactions, and a virtual cessation of gas generation in the repository. From then onwards, gas pressure is practically constant – being just below natural steady-state pressure due to gas migration from the repository being balanced by some continuing low level of gas generation and pressurisation from resaturating water.

This evolution of gas pressure affects the rate of resaturation of the repository. Initially there is seepage of water into the repository up to the point at which the gas pressure reaches the natural steady-state pressure. For a period thereafter, which may last for hundreds of thousands of years, no water flows into the repository and water is likely to be driven out of the repository by high gas pressure. After gas pressures fall below the natural steady-state pressure, water seeps once more into the repository resulting in its gradual resaturation.

Repository gases may contain H-3 and C-14, and radon gas will also be generated. In addition, I-129, Cl-36 and Se-79 may be volatilised or potentially methylated[7]. These radionuclides can be released as bulk gas phase via the shafts and associated EDZs, and the host rock. Gases will also dissolve into repository water and migrate from the repository in the groundwater. The rate of bulk and dissolved gas migration is slow due to the relatively low permeability and small area of the shafts, and the very low permeability of the host rock.

[7] Microbially mediated reactions in surface soils can lead to the methylation of I, Cl and Se, forming volatile compounds, i.e. $CH_3Cl$, etc. Similar reactions could potentially occur in a repository.

Contaminants will be also released from the wastes into repository water. Diffusion of contaminants will take place through any surface contacted by repository water, transporting contaminants into the EDZ and thence the geosphere. The release of contaminants will therefore increase as the repository resaturates. Transport of contaminated water will take place in the shafts and their associated EDZs. This might have a comparatively significant advective, as well as diffusive, component due to the driving head provided by the pressurised Cambrian formation that underlies the DGR. However, the relatively small cross-sectional area of the shafts limits the contaminant mass that can migrate via this route. Contaminants may also be released to the host rock, although this is expected to be diffusion dominated due to the low permeability of the host rock.

## 7.3 GEOSPHERE EVOLUTION

The deep sedimentary rocks were laid down over 400 million years ago. These rock formations are thick, laterally extensive, and stable.

The repository is a local perturbation to the deep rock. There will be a ‘halo’ region around the repository where there will be some effects from the repository on the host rock, such as some alteration of the porewater chemistry, redistribution of stresses, and increased gas content in the pores.

On a larger scale, the key process in geosphere evolution is glaciation. Within the past million years these rocks have endured multiple glaciations and this glacial cycling is expected to continue. Although global warming will result in changes in groundwater recharge and flow in the Shallow Bedrock Groundwater Zone in the short term (i.e., over the next thousand years), it is expected that the impacts will not be significant from the perspective of the postclosure safety assessment other than the delay in the onset of the next ice-sheet advance (Section 7.1).

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 glacial loading and unloading. Changes in the stress regime might result in repository rockfall, as described in Section 7.2.

Significant changes are likely to occur in the Shallow Bedrock Groundwater Zone due to the glacial and interglacial cycles. As the climate cools, the recharge to the shallow groundwater decreases due to reduced precipitation and an increased proportion of precipitation becoming surface runoff due to spring snowmelt. Discontinuous permafrost develops in the Shallow Bedrock Groundwater Zone and with time extends down to several tens of metres depth. The permafrost will not, therefore, substantially impact on the conductivity of the Shallow Bedrock Groundwater Zone. The arrival of a warm-based ice sheet is likely to result in the melting of the upper parts of the permafrost layer. The water might be under high pressure due to the weight of the overlying ice and might affect hydrogeology and groundwater chemistry by moving large volumes of low-salinity and possibly oxidising meltwater through the Shallow Bedrock Groundwater Zone. The amelioration of the climate as the glacial cycle continues results in the retreat of the ice sheet, and the melting of the permafrost. It is likely that proglacial meltwater lakes will be present.

It is unlikely that large-scale denudation or deposition will occur over the timescales of interest due to low relief topography and low elevation relative to sea level. There is no direct evidence from site investigation of significant erosion in the past million years. Small-scale (a few tens of metres net) sediment/rock erosion and deposition is likely to occur due to hydrological processes, wind and particularly glacial processes.

The Bruce site is in a tectonically stable region and is expected not to be subjected to seismic events with a moment magnitude of greater than 6. Nevertheless, seismic events will occur during the timescales of interest and are expected to be one of the causes of repository rockfall within the emplacement rooms and tunnels. Other potential consequences of seismic activity, such as reactivation and long-term opening of existing faults, are very unlikely. No evidence of open faults has been found in the vicinity of the repository, and they are not evaluated in the Normal Evolution Scenario.

Contaminants will migrate by diffusion through the Deep Bedrock Groundwater Zone, and then into the Intermediate and Shallow Bedrock Groundwater Zones. Groundwater in the Deep and Intermediate Bedrock Groundwater Zones is either stagnant or very slow moving, in large part due to the low permeability of the rock. However, there is currently some uncertainty over the magnitude of the (low) rock permeability, and the cause(s) of the vertical head distribution in the Deep and Intermediate Bedrock Groundwater Zones. Further uncertainties relate to the potential extent of advective flow in the more permeable Guelph, Salina A0 and Salina A2 evaporite formations in the Intermediate Bedrock Groundwater Zone. These have the potential to limit the vertical migration of contaminants into the Shallow Bedrock Groundwater Zone, but the magnitude, direction and future evolution of these flows are uncertain. These uncertainties will have to be taken into account when developing conceptual models of contaminant transport.

Contaminant transport in the Shallow Bedrock Groundwater Zone will be advection dominated and contaminated groundwater will discharge into the near-shore zone of Lake Huron or its successor. The nature of transport in this region may be affected during glacial cycles through the introduction of large volumes of low-salinity and possibly oxidising meltwater and changes in the groundwater discharge location.

## 7.4 BIOSPHERE EVOLUTION

Due to the robustness of the DGR system, most of the contaminants are expected to be isolated and contained in the repository and deep geosphere. Any release to the biosphere would be at low concentrations and at very long times. Therefore, one consequence of this robust repository is the need to consider the biosphere over timescales in which glacial-interglacial cycling is likely to occur. Given the considerable uncertainties associated with the resulting evolution of the biosphere, a ‘reference’ biosphere approach has been used, in which stylised representations of the biosphere are used to allow illustrative estimates of potential repository impact to be made.

Contaminants could reach the biosphere in low concentrations through transport in gas and groundwater.

Peak fluxes of contaminated gas into the biosphere are expected over timescales of between 10,000 and 100,000 years reflecting the depth of the DGR and the low permeability of the host rock and shafts. Beyond this point, radioactive decay will have reduced the remaining C-14 to negligible levels.

Peak fluxes of contaminated groundwater into the biosphere are expected to occur much later than for gas releases (potentially in excess of 1,000,000 years) due to the depth of the DGR, its slow resaturation, the low permeability of the host rock and shafts, and retardation of certain contaminants in the geosphere.

Four future biosphere states are identified.

- **Temperate** - the characteristics of the biosphere and habits of the humans are similar to those found in the vicinity of the site today. The land is used for agricultural and recreational purposes and water is pumped from a well in the Shallow Bedrock Groundwater Zone and used for agricultural and domestic purposes. The wetlands and other natural environments are sources of wild food.
- **Tundra** - the characteristics of the biosphere and habits of the humans are similar to those found in present-day tundra ecosystems. Any permafrost present is discontinuous and limited in depth to less than a few tens of metres. Groundwater continues to discharge from the Shallow Bedrock Groundwater Zone into the lake and is pumped from a well. In addition, retreat of the lake due to reduced precipitation results in exposure of lake bed sediment and may lead to some limited discharge of groundwater to a stream. Human habitation is feasible, but reduced temperature and precipitation means that limited agriculture occurs and there is greater reliance on wild foods than in the temperate system. Exposure pathways associated with well water would remain possible for domestic and limited agricultural use.
- **Glacial** – self-sufficient permanent human habitation in the region is very unlikely as the environment is harsh and inhospitable. Prior to the site being overrun by the ice-sheet, there may be some use of resources in the region (e.g., the lake) by temporary visitors (e.g. fishermen, nomadic people) and releases of groundwater are expected to continue to the lake basin and also potentially to other water bodies that may form in advance of the ice-sheet (if warm based). As the ice-sheet advances, sediments are eroded due to the action of the ice and meltwater, and moraines develop at the front of the ice-sheet.
- **Post-glacial** - a proglacial lake is likely to form and to eventually overlie the site completely for a period, before gradually receding as a result of ameliorating climatic conditions and isostatic rebound. The retreating ice-sheet will result in a network of meltwater streams, which will redistribute sediments resulting from ice-sheet deposition. Human habitation is unlikely initially as the exposed rocks and sands do not support life, but in due course soils develop, plants return, and migrating animals and birds, and fish, support nomadic humans.

# 8. OTHER POSSIBLE EVOLUTIONS OF THE DGR SYSTEM: DISRUPTIVE SCENARIOS

In addition to consideration of the Normal Evolution Scenario, the guidelines for the preparation of the Preliminary Safety Report and Environmental Impact Statement (EIS) required for the DGR (CEAA and CNSC 2009) and the guidance on assessing the long-term safety of radioactive waste management (CNSC 2006) both identify the need for the postclosure safety assessment to consider additional scenarios (disruptive scenarios) that examine the impacts of unlikely disruptive events that lead to possible penetration of barriers and abnormal degradation and loss of containment. As such, the Disruptive Scenarios identified in this section of the report consider various very unlikely "what if" cases that are designed to test the robustness of the DGR system to scenarios that result in the breaching or extreme degradation of geosphere and/or engineered barriers.

## 8.1 IDENTIFICATION OF DISRUPTIVE SCENARIOS

A set of Disruptive Scenarios has been identified through evaluating the potential for external FEPs identified in Table 3-1 to compromise the DGR's isolation or containment and associated safety arguments. The various external FEPs that might compromise these safety functions and associated arguments are listed and screened in Table 8-1 to identify those that need to be considered further. The identified failure mechanisms can be grouped into four Disruptive Scenarios as discussed below and summarised in Table 8-2.

The DGR is sited in an area of low economic resource potential, it has a small footprint, and is at a depth of 680 m. This limits the range of human activities that could directly impact the closed repository to a borehole unintentionally drilled into the repository as part of a future geological exploration programme. Even this situation has a low probability of occurrence (less than $10^{-5}$ $a^{-1}$, using a rate of borehole drilling of $10^{-10}$ $m^{-2}$ $a^{-1}$, i.e., one deep borehole per 100 years per 10 km x 10 km area - Gierszewski et al. (2004), and an emplacement room plan area of around 52,400 $m^2$ – Walke et al. 2009b). Nevertheless, it is recognised in Table 8-1 that the possibility of inadvertent human intrusion by this method cannot be ruled out once controls on the use of the site are no longer effective and over the long timescales of interest to the safety assessment[8]. Such a borehole would provide an enhanced permeability pathway to surface environment and potential for direct exposure to waste. The scenario that represents these conditions is referred to as the **Human Intrusion Scenario**.

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

**Table 8-1: External FEPs Potentially Compromising DGR Isolation and Containment**

| Safety Argument | Potentially compromised by | Need to consider as failure mechanism |
|---|---|---|
| The location of the DGR at a depth of 680 m underground, absence of economically viable natural resources, and no drinking water below 100 m provide excellent isolation from the biosphere | Near-surface design adopted (FEP 1.1.02). | **No**, only deep design being considered for the DGR (Section 2.2.1) |
| | Meteorite impact (FEP 1.5.01). | **No**, due to low probability (due to relatively small repository footprint) and low consequence (due to depth of repository) |
| | Exploration borehole penetrates into repository providing enhanced permeability pathway to surface environment (FEP 1.4.03 and 1.4.04). | **Yes**, although the depth and relatively small footprint of the DGR will mean that the annual probability of such a borehole intruding into the DGR will be very low. |
| | Mining and other underground activities resulting excavation in the vicinity of the repository (FEP 1.4.05). | **No**, due to absence of economic resources at or below repository level. |
| | Deliberate human intrusion into repository (FEP 1.4.15). | **No**, assessment context (Section 3.4.2 of Quintessa et al. 2009) excludes deliberate human intrusion consistent with recommendations of ICRP (2000) |
| | Could discover previously undiscovered resources or exploit existing rocks that have become an economically viable resource. These new resources are exploited by drilling or mining at or below repository level (FEP 1.4.04 and 1.4.05). | **No**, the host rocks are laterally extensive and uniform in properties. The lack of resources seen at the site is consistent with regional information. Even if the existing rocks became viable, the DGR site is unlikely to be the mine site because of the large lateral extent of the host rocks, which extend to shallower depths elsewhere. Impact of drilling is already considered under exploration borehole (FEP 1.4.04). |
| The host rock is old, stable and predictable | High magnitude seismic event results in reactivation of undetected fault and/or failure of shaft seals which provides enhanced permeability pathway to surface environment (FEP 1.2.03). | **Yes**. Technical work is currently being undertaken to evaluate the potential of seismic events on the DGR system. Ahead of the results of this work, it is prudent to consider seismic events as a potential failure mechanism. |
| | Other external geological processes disrupts the DGR system, i.e., tectonic movement (FEP 1.2.01), orogeny (FEP 1.2.02), volcanic and magmatic activity (FEP 1.2.04), metamorphism (FEP 1.2.05), hydrothermal activity (FEP 1.2.06), diagensis (FEP 1.2.08) and salt diapirism and dissolution (FEP 1.2.10). | **No**, since precluded by site's location and assessment timescales (see Table 3-2). |

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

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

| Safety Argument | Potentially compromised by | Need to consider as failure mechanism |
|---|---|---|
| A repository can be built and operated safely using internationally proven and accepted technologies | Poor construction techniques impact on the performance of the repository and shaft EDZ providing enhanced permeability pathway to surface environment (FEP 1.1.04). | **Yes**, although application of OPG's quality control will ensure that poor construction is very unlikely. |
| | Repository and shaft poorly sealed providing enhanced permeability pathway to surface environment (FEP 1.1.07). | **Yes**, although application of OPG's quality control will ensure that poor sealing is very unlikely. Nevertheless, long-term performance of seals may deviate from that expected due to unexpected processes. |
| | Site investigation/monitoring borehole not properly sealed providing enhanced permeability pathway to surface environment (FEP 1.1.01 and 1.1.13). | **Yes**, although application of OPG's quality control will ensure that poor sealing is very unlikely. Nevertheless, long-term performance of seals may deviate from that expected due to unexpected processes. |

**Table 8-2: Potential Failure Mechanisms and Associated Scenarios**

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

A second scenario category can be determined that is also related to human activities, but in relation to the reliability of the construction and closure of the repository. This can also be used to test or demonstrate the robustness of the DGR design. Specifically, the Normal Evolution Scenario takes account of the role of engineered barriers and assumes their performance meets design specifications; it includes an expected degree of degradation of the seals with time. However, it is unlikely but possible that the materials may not be fabricated appropriately and this may not be detected by the DGR quality control procedures, or the long-term performance of materials may deviate significantly from that expected due to unexpected physical, chemical and/or biological processes. Either situation could result in poorer than anticipated performance in the engineered barriers resulting in an enhanced permeability pathway to the surface environment. The shaft seals are the most important engineered barriers, so a “what if” scenario is considered in which the materials have the properties of engineered fill (crushed rock), and is referred to as the **Severe Shaft Seal Failure Scenario**. It is difficult to assign a probability to the scenario as there is limited basis for determining whether the materials would perform poorly. However, given the quality control measures that will be applied to the DGR project, backed up by supporting work, it would be expected to be very unlikely.

Other human activities that could affect repository performance relate to monitoring and site investigation activities around the repository site. Several such boreholes will be sunk in the vicinity of the DGR down to and beyond the depth of the DGR during the site investigation and operational phases. Some of these may be retained for monitoring during the postclosure period. In all cases, the boreholes will be licensed through the Ontario Ministry of Natural Resources and they will be well outside the repository footprint. Furthermore, they will be sealed on cessation of site investigation/monitoring activities and consequently they will have no effect on the repository performance. However, if a deep borehole were not properly sealed, then it could provide a small but permeable pathway for the migration of contaminants from the repository. Like the Severe Shaft Seal Failure Scenario, such a situation would be expected to be very unlikely as good practice and quality control would prevent such a situation occurring. However, the situation is one of a limited number of potential events that could result in an enhanced permeability pathway to surface environment and therefore merits investigation as a threat to the containment function of the disposal system. The scenario is termed the **Open Borehole Scenario**. In common with the Severe Shaft Seal Scenario, it is difficult to assign a probability to the Open Borehole Scenario. However, given quality control measures that will be in place, it would be expected to be very unlikely.

Earthquakes are an external event of potential relevance to postclosure safety. As noted in Section 2.3.5, the DGR site is located in a seismically stable region, so large earthquakes are very unlikely and the repository is designed to handle the expected level of earthquakes for the area. However, the assessment timescales are such that a significant event with a moment magnitude **M** ≥ 6 may occur, even though its annual probability of occurrence within a 20 km radius of the Bruce Site is roughly once in 800,000 years (with an uncertainty of a factor of 3 on this return period), see Section 2.3.5. Such an earthquake could cause disruption to the repository, reduce the performance of the shaft seals, and reactivate a hypothetical fault in the vicinity of the DGR. Because the event could have a number of consequences, all resulting in enhanced permeability pathways to the surface environment, it is useful to assess it as a "what if" scenario, referred to as the **Extreme Earthquake Scenario**.

In order to build confidence that an appropriate set of disruptive (or "what if") scenarios has been identified using the safety function and argument approach described above, a complementary approach was also used. The approach involved reviewing each of the external FEPs identified in Table 3-1 to see whether, given the assessment context (specified in Quintessa et al. 2009) and the system description (given in Section 2), it was possible for it to have one or more alternative states to the state considered in the Normal Evolution Scenario. The results of this review are presented in Table 8-3. Those external FEPs with potential alternative states were then reviewed to see whether the alternative states would generate scenarios in addition to the Normal Evolution Scenario or could be covered by alternative conceptualisation of the Normal Evolution Scenario. The same set of four additional scenarios, identified using the safety argument approach, was identified (see Table 8-3).

Further confidence that an appropriate set of disruptive scenarios has been identified can be built by comparing the scenarios (additional to the "reference/base/normal evolution" scenario) considered in the postclosure safety assessments of other deep repositories. A review of a number of major assessments of deep repositories in other countries was undertaken. The results of the review are summarised in Table 8-4. It can be seen that, consistent with this assessment, most assessments have identified a limited number of additional scenarios that consider the degradation/failure of engineered and natural barriers by natural processes (e.g., earthquakes, climate change) and human actions (e.g., drilling, poor quality control). Although there are some scenarios identified in Table 8-4 that are not considered in the DGR Disruptive Scenarios, these are either not relevant to the Bruce site (e.g., volcanic activity, sea level rise, mining of resources) or have been included in the DGR's Normal Evolution Scenario (e.g., climate change, canister failure, gas generation).

**Table 8-3: Grouping of Alternative States for EFEPs into Additional Scenarios**

| | | EFEP | Potential for Alternative State(s) | Additional Scenario |
|---|---|---|---|---|
| 1.1 | Repository Factors | | | |
| | 1.1.01 | Site investigations | **Yes**, consider a site investigation borehole not being properly sealed | **Open Borehole** |
| | 1.1.02 | Design of repository | **Yes**, consider design alternatives such as grouting and backfilling | Can be covered by alternative conceptualisation of the Normal Evolution Scenario – no need for additional scenario |
| | 1.1.03 | Schedule and planning | **No**, only consider operational period to 2062 (see Section 3.8 of Quintessa et al. 2009) | - |
| | 1.1.04 | Construction | **Yes**, consider poor construction techniques impacting on the performance of the shaft seal | **Severe Shaft Seal Failure** |
| | 1.1.05 | Operation | **Yes**, consider damage of waste container during emplacement | Can be covered by alternative conceptualisation of the Normal Evolution Scenario – no need for additional scenario |
| | 1.1.06 | Waste allocation | **Yes**, consider alternative options of locating certain waste packages within the repository | Can be covered by alternative conceptualisation of the Normal Evolution Scenario – no need for additional scenario |
| | 1.1.07 | Repository closure | **Yes**, consider degraded performance of shaft seals | **Severe Shaft Seal Failure** |
| | 1.1.08 | Quality assurance | **No**, a quality assurance programme will be followed. However, some 'what if' states that could result from process errors that are undetected by quality assurance/quality control procedures are noted in 1.1.01, 1.1.04, 1.1.05 and 1.1.07. | - |
| | 1.1.09 | Repository administrative control | **No**, institutional controls will be in place following repository closure. Calculations for all postclosure scenarios will be undertaken from closure of the facility (2062) and so results can be produced for a range of different periods of effective institutional control without the need to generate alternative scenarios | -- |
| | 1.1.10 | Accidents and unplanned events | **No**, even if accidents and unplanned events occur, corrective actions will be taken to prevent any detrimental impacts on postclosure safety | - |
| | 1.1.11 | Retrievability | **No**, no retrieval-specific features included in the DGR design that could impact the long-term safety of the repository | - |

| | | EFEP | Potential for Alternative State(s) | Additional Scenario |
|---|---|---|---|---|
| | 1.1.12 | Repository records and markers | **No**, records will be in place following repository closure. Calculations for all postclosure scenarios will be undertaken from closure of the facility (2062) and so results can be produced for a range of different periods of record maintenance without the need to generate alternative scenarios | - |
| | 1.1.13 | Monitoring | **Yes**, consider monitoring borehole not being properly sealed | **Open Borehole** |
| 1.2 | Geological Processes and Effects | | | |
| | 1.2.01 | Tectonic movement | **No**, given the site's tectonically stable location and timescales of interest (Section 2.3). | - |
| | 1.2.02 | Orogeny | **No**, given site's location and timescales of interest (Section 2.3). | - |
| | 1.2.03 | Seismicity | **Yes**, severe seismic event could damage shaft seals or reactive faults. | **Extreme Earthquake** |
| | 1.2.04 | Volcanic and magmatic activity | **No**, given site's location and timescales of interest (Section 2.3). | - |
| | 1.2.05 | Metamorphism | **No**, given the timescales of interest (Section 2.3). | - |
| | 1.2.06 | Hydrothermal activity | **No**, given absence of drivers of hydrothermal activity over the timescales of interest (Section 2.3). | - |
| | 1.2.07 | Denudation and Deposition (large-scale) | **No**, due to low relief topography and low elevation relative to sea level. | - |
| | 1.2.08 | Diagenesis | **No**, significant diagenesis that would effect repository safety is unlikely over the timescales of interest | - |
| | 1.2.09 | Pedogenesis | **No**, already considered in Normal Evolution Scenario | - |
| | 1.2.10 | Salt diapirism and dissolution | **No**, salt deposits are not located in the vicinity of the site | - |
| | 1.2.11 | Hydrological response to geological changes | **Yes**, seismic activity reactivates fault | **Extreme Earthquake** |
| | 1.2.11 | Geomorphologic response to geological changes | **No**, given site's geologically stable location and timescales of interest (Section 2.3). | - |
| | 1.2.12 | Deformation (elastic, plastic or brittle) | **No**, already considered in Normal Evolution Scenario | **-** |

| | | EFEP | Potential for Alternative State(s) | Additional Scenario |
|---|---|---|---|---|
| 1.3 | Climate Processes and Effects | | | |
| | 1.3.01 | Global climate change | **No**, already considered in Normal Evolution Scenario | - |
| | 1.3.02 | Regional and local climate change | **No**, already considered in Normal Evolution Scenario | - |
| | 1.3.03 | Sea level change | **No**, already considered in Normal Evolution Scenario | - |
| | 1.3.04 | Periglacial effects | **No**, already considered in Normal Evolution Scenario | - |
| | 1.3.05 | Local glacial and ice-sheet effects | **No**, already considered in Normal Evolution Scenario | - |
| | 1.3.06 | Warm climate effects (tropical and desert) | **No**, northerly location of site precludes tropical or hot desert conditions | - |
| | 1.3.07 | Hydrological response to climate changes | **No**, already considered in Normal Evolution Scenario | - |
| | 1.3.08 | Ecological response to climate changes | **No**, already considered in Normal Evolution Scenario | - |
| | 1.3.09 | Human behavioural response to climate changes | **No**, already considered in Normal Evolution Scenario | - |
| | 1.3.10 | Geomorphologic response to climate changes | **No**, already considered in Normal Evolution Scenario | - |
| 1.4 | Future Human Actions (Active) | | | |
| | 1.4.01 | Human influences on climate | **No**, already considered in Normal Evolution Scenario | - |
| | 1.4.02 | Social and institutional developments | **No**, expect that land use change will not occur until institutional control is no longer effective. Although it is possible that certain changes in land use might be allowed during the institutional control period, it is expected that this will only occur if the change can be demonstrated to have no safety consequences. | - |
| | 1.4.03 | Knowledge and motivational issues (repository) | **Yes**, there is human intrusion into the DGR. | **Human Intrusion** |
| | 1.4.04 | Drilling activities | **Yes**, exploration borehole penetrates into the repository | **Human Intrusion** |
| | 1.4.05 | Mining and other underground activities | **No**, no resources at site and other underground activities are unlikely at site because the geology is uniform across a large area and so there is nothing unique at this site. | - |

| EFEP | | Potential for Alternative State(s) | Additional Scenario |
|---|---|---|---|
| 1.4.06 | Un-intrusive site investigation | **No**, no direct impact on repository safety | - |
| 1.4.07 | Surface excavations | **No**, no direct impact on repository safety due to depth of repository | - |
| 1.4.08 | Site Development | **No**, already considered in Normal Evolution Scenario | - |
| 1.4.09 | Archaeology | **No**, no direct impact on repository safety due to depth of repository | - |
| 1.4.10 | Water management (groundwater and surface water) | **Yes**, water is drawn from sources other than a well in the Shallow Bedrock Groundwater Zone (e.g., lake or river) | Can be covered by alternative conceptualisation of the Normal Evolution Scenario – no need for additional scenario |
| 1.4.11 | Explosions and crashes | **No**, surface explosions and crashes would have no direct impact on repository safety due to depth of repository. Rockfall might provide ignition source for gases in repository but impact on long-term safety expected to be minimal. | - |
| 1.4.12 | Pollution | **No**, impact of non-repository derived contaminants is expected not to be significant | - |
| 1.4.13 | Remedial actions | **No**, even if remedial actions are undertaken, it is expected that they do not have a detrimental impact on safety | - |
| 1.4.14 | Technological developments | **No**, only consider current lifestyles, consistent with CNSC (2006) | - |
| 1.4.15 | Deliberate human intrusion | **No**, assessment context (Section 3.4.2 of Quintessa et al. 2009) excludes deliberate human intrusion consistent with recommendations of ICRP (2000) | - |
| 1.5 | Other External Factors | | |
| 1.5.01 | Impact of meteorites and human space debris | **No**, due to low probability and low consequence in terms of repository safety | - |
| 1.5.02 | Evolution of biota | **No**, consistent with recommendations of ICRP (2000) | - |

**Table 8-4: Additional Scenarios Considered in Other Safety Assessments**

| Assessment | Reference | Additional Scenarios Considered |
|---|---|---|
| SAFIR 2 (Belgium) | ONDRAF/NIRAS (2001) | • Exploitation and exploratory drilling<br>• Greenhouse effect<br>• Poor sealing of repository<br>• Fault activation<br>• Severe glacial period<br>• Failure of engineered barriers<br>• Gas-driven transport |
| TILA-99 (Finland) | Vieno and Nordman (1999) | • Canister failure |
| Dossier Argile (France) | Andra (2005) | • Seal failure and defective plug<br>• Defective waste and spent fuel containers<br>• Borehole penetrating repository<br>• Functioning of repository greatly degraded |
| H12 (Japan) | JNC (2000) | • Climate and sea level change<br>• Borehole drilling<br>• Engineering defects |
| SAFE (Sweden) | SKB (2001) | • Climate change<br>• Barrier defects<br>• Borehole drilling |
| Opalinus (Switzerland) | Nagra (2002b) | • Gas pathways<br>• Borehole drilling |
| GPA (UK) | Nirex (2003) | • Borehole drilling |
| WIPP (USA) | USDoE (2004) | • Mining<br>• Borehole drilling |
| Yucca Mountain (USA) | USDoE (2002) | • Borehole drilling<br>• Seismicity<br>• Volcanic event |

## 8.2 DESCRIPTION OF DISRUPTIVE SCENARIOS

### 8.2.1 Human Intrusion Scenario

The Human Intrusion Scenario considers the same evolution of the DGR system as for the Normal Evolution Scenario with the only difference being the occurrence of human intrusion into the repository at some time after controls are no longer effective.

In this scenario, an exploration borehole is drilled down through the geosphere. Upon encountering the repository, the drilling crew registers a loss of drill fluid to the repository void if the repository pressure is less than the drill fluid pressure, or a surge of gas and/or slurry (water and some suspended waste) from the repository up the borehole if the repository pressure is greater than the drill fluid pressure. Current technology necessary to drill to 680 m depth would enable the drillers to ascertain the nature of the void that had been encountered, and to limit any significant upflow from the repository (e.g., this is standard practice in sedimentary rocks where one may encounter natural gas).

In an exploration borehole, the investigators would most likely collect samples or conduct measurements at the repository level, which would readily identify if there were still significant residual radioactivity (e.g. gamma logging is a routine borehole measurement). In this case the investigators would likely choose to close and seal the borehole, and ensure any surface-released materials were appropriately disposed (again, this is normal drilling practice). Sealing the borehole would avoid any further release of residual radioactivity direct to the surface. Under normal drilling, there would be little impact.

Nevertheless, the Human Intrusion Scenario considers the case where the intrusion is inadvertent, is not recognised to have occurred and no restrictions are imposed, and the borehole and drill site are not managed and closed to current standards. In this “what if” case,, contaminants can be released and humans and non-human biota exposed via three pathways: direct release to the surface of pressurised gas and slurry prior to sealing of the borehole; retrieval and examination of core samples contaminated with waste; and the long-term release of contaminated water from the repository into permeable geosphere horizons via degraded seal and casing in the exploration borehole. These releases result in the exposure of the drill crew, laboratory technicians (who examine the core), residents living near the site at the time of intrusion, and site residents who might occupy the site subsequent to the intrusion event.

### 8.2.2 Severe Shaft Seal Failure Scenario

The shafts represent a potentially important pathway for contaminant release, and therefore the facility design includes specific measures to provide a good shaft seal, taking into account the characteristics of the DGR system. The Normal Evolution Scenario considers the likely behaviour of the shaft seals and the shaft EDZs; it includes some expected degree of degradation of the seals with time. The Shaft Seal Failure Scenario considers the same evolution of the DGR system and the same exposure pathways and groups as the Normal Evolution Scenario, the only difference being that the performance of the shaft seals and shaft EDZs is very poor (e.g., the shaft seals have the hydraulic characteristics of engineered fill/crushed rock). In particular, it is assumed that the shaft seals and the shaft EDZs have physical and chemical properties of crushed rock from the time of closure of the repository. Like the other Disruptive Scenarios, the scenario is a bounding, “what if” scenario that is designed to investigate the robustness of the DGR system.

### 8.2.3 Open Borehole Scenario

Several site investigation/monitoring boreholes will be sunk in the vicinity of the DGR down to and beyond the depth of the DGR during the site investigation and operational phases. Some of these may be retained for monitoring during the postclosure period. In all cases, the boreholes will be licensed through the Ontario Ministry of Natural Resources and they will be outside the repository footprint. Furthermore, they would normally be sealed at the end of their useful lifetime. Consequently they would have no effect on the repository performance. However, the Open Borehole Scenario considers the consequences of a borehole not being properly sealed. Although sections of the borehole are likely to be cased, the casing is expected to have degraded by the time that contaminants are released from the repository, and so the borehole can be considered to be uncased.

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

### 8.2.4 Extreme Earthquake Scenario

An extreme seismic event or glacial loading/unloading, which resulted in the generation of an earthquake with a moment magnitude of **M** ≥ 6, might have the potential to cause the reactivation of a hypothetical fault and/or failure of shaft seals thereby providing an enhanced permeability pathway to surface environment. Technical work is currently being undertaken to evaluate the potential for such events having an impact on the DGR system. Until the results of this work are available, it is prudent to consider the effects of such extreme earthquakes, although it is important to recognise the low probability of such events and the speculative and pessimistic nature of the scenario.

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

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

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# APPENDIX A: ROCKFALL IN THE DGR

## A.1 INTRODUCTION

Over the assessment timescales of hundreds of thousands of years, it is expected that, in addition to the release of rock stresses resulting from the excavation of access tunnels and emplacement rooms, external events such as earthquakes and glaciations will induce loads on the rock. These events could lead to the collapse of rock into the open space in the DGR emplacement rooms and access tunnels. The resulting region of damaged rock will provide a locally enhanced pathway for contaminant migration.

It is therefore necessary to determine the potential extent of rockfall above the DGR.

## A.2 BACKGROUND

### A.2.1 GEOMECHANICAL ASSESSMENT

Damjanac (2008) has undertaken geomechanical modelling studies of the stability of the repository. At present, these use literature data on the rock properties. These studies indicate that, under the influence of gas pressure only, the degradation of the rock is such that damage propagates up to at most 7 m above the roof of the emplacement rooms and tunnels (assuming no support) over the timescales considered (100 ka). The maximum extent of rockfall 100 ka after excavation is estimated to be 2.5 m, assuming no additional loading (e.g., seismic shaking or glacial loading).

Damjanac (2008) also explores the effects of severe seismic events. Those considered included a M5.5 event at 15 km from the repository and a M7 event at 50 km. The analysis shows that if the event were to occur 100 ka after construction, most of the damaged rock mass would be shaken down. However, it is noted that most of the EDZ would have formed after only about 15 ka, so, in safety assessment terms, the most conservative assumption would be to assume a collapse of about 7 m at 15 ka, in response to an earthquake.

The seismic study did not consider the potential effects of more frequent but lower magnitude earthquakes. Also, Damjanac (2008) did not assess the consequences of repeated glaciations. These could be expected to have a number of important consequences such as:

- compaction of waste and rockfall in the rooms;
- further extension of the EDZ; and
- potentially frequent severe earthquakes following the ice-sheet retreat.

### A.2.2 ROCK BULKING FACTORS

A simple perspective on the maximum extent of rock collapse can be gained by considering the bulking factor for the rock, $B_f$, as discussed in Hatch (2008a). This is simply the ratio of the volume of rubble and the volume of rockfall. It can alternatively be expressed in terms of the height of rock collapse (H, m) and the height of the tunnel (h, m)

$$B_f = \frac{V_{Rubble}}{V_{Rockfall}} = \frac{H}{H-h} \qquad \text{(B-1)}$$

Hatch (2008a) report that bulking factors are found to range from about 1.25 to more than 1.6. The lower end of this range is most appropriate for the DGR host rocks since they are laminated and so would tend to break off in slabs which pack relatively efficiently (Hatch 2008a).

## A.3 HEIGHT OF ROCK COLLAPSE

The bulking factor approach can be used to obtain an estimate of the maximum height of roof/rock collapse. In making the calculations, account has been taken of the latest emplacement room and access tunnel specifications given in Hatch (2008b), as well as the Hatch (2008b) estimates of the packing efficiency of waste in rooms. It has been assumed for the purposes of the rockfall calculations that wastes typically have an initial voidage of 50% (the range varies from 30% to 90% - see Data report, Walke et al. 2009). The parameter values used in the calculations are shown in Table A-1.

**Table A-1: Parameters for Bulking Factor Calculations**

| Parameter | LLW rooms | ILW rooms (worst case) | ILW rooms (average) | Access tunnels |
|---|---|---|---|---|
| Room Height | 7.0 | 7.2 | 6.2 | 7.0 |
| Packing Efficiency | 63% | 15% | 43% | 0% |
| Initial Voidage in Waste | 50% | 50% | 50% | n/a |

These parameters have been used to estimate the theoretical height of rock collapse for a range of bulking factors. The range, plotted in Figure A-1, considers extreme bulking factor values of 1.1 and 1.8, noting that a more reasonable range is about 1.25 – 1.6.

The results show that for access tunnels, and some ILW rooms with low packing efficiency (about 15%), the height of rock collapse could approach 10 times the height of the tunnel/room if a very cautious bulking factor of 1.1 is selected. However, the theoretical height of rock collapse is much less when wastes are assumed to be present with typical packing efficiencies (63% for LLW, 43% for ILW on average). It is noted that, in this calculation it has been conservatively assumed that the rockfall compresses waste to the point at which it has no effective voidage.

A suitable reference assumption for rock collapse is to adopt a bulking factor of 1.25 (Hatch 2008a), with an extreme case using a value of 1.1. For alternative calculation cases in which some (or all) of the repository is backfilled, it is assumed that no rockfall occurs in the backfilled region. The EDZ will still form, although to a thickness of perhaps 4 m rather than 7 m (Damjanac 2008).

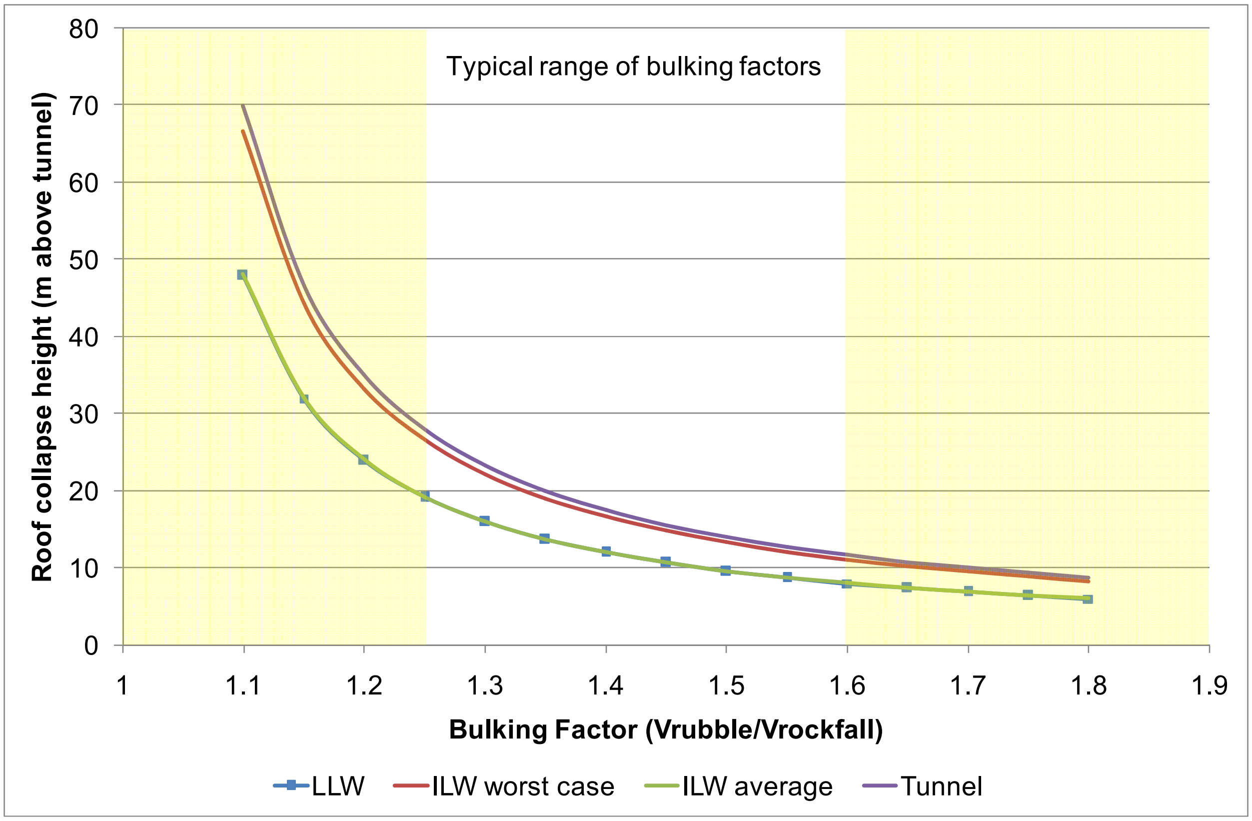


**Figure A-1: Theoretical Height of Rock Collapse based on Bulking Factors**

### A.3.3 SEQUENCE OF ROCK COLLAPSE EVENTS

#### A.3.3.1 Reference Case

For the reference case, the maximum extent of rock collapse considered for access tunnels is 30 m, with 20 m for emplacement rooms (these values are rounded up to the nearest ten metres) taking account of the bulking factor of 1.25.

It would be expected that rock collapse occurs as a sequence of smaller steps, in which an EDZ of up to about 7 m is formed, dislodged by an event, followed by formation of a new EDZ. An illustration of a time-dependent sequence of rock collapses is shown in Figure A-2. Here, it is assumed that:

- the extent of EDZ formation grows to about 7 m above the roof, reaching this value after about 15 ka based on Damjanac (2008); and
- after 15 ka, the entire EDZ collapses due to a seismic event, and a new EDZ begins to form.

The second assumption is necessary because Damjanac (2008) has not yet demonstrated whether or not lower magnitude, more frequent seismic events than those assessed would produce sufficient acceleration to dislodge the damaged rock. It is therefore cautiously assumed that an event with a frequency of 1/15,000 $y^{-1}$ or greater could dislodge the entire EDZ.

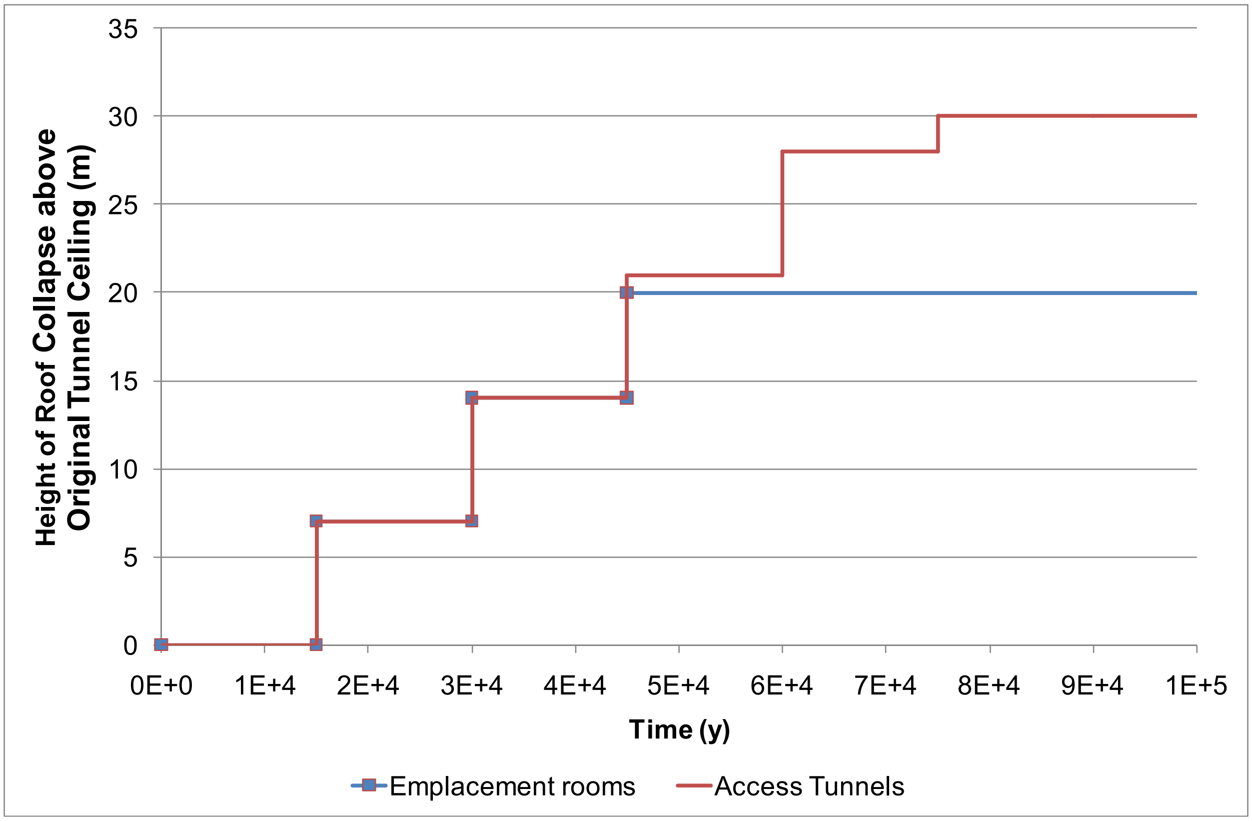


**Figure A-2: Reference Assumption for the Representation of Time-Dependent Rock Collapse**

Rock collapse is cautiously assumed to affect all tunnels and rooms (i.e. it is assumed not to be "patchy"). It is assumed that EDZ forms at both the side and base of the repository, but that these areas are not involved in rock collapse, with the exception of pillars. Over a certain height (tens of metres) it is likely that pillars will collapse, although this is not assumed to extend the overall height of rock collapse. However, after a certain point (say, the second assumed rock collapse) the properties of the pillars can be considered to be degraded to those of rubble. Similarly, it would be reasonable to assume that after the first rock collapse, key waste properties such as porosity are changed, and any packages that have not already failed (e.g., due to corrosion) are assumed to fail.

### A.3.3.2 Alternative Case 1

An alternative case can be considered in order to evaluate the consequences of a more conservative bulking factor of 1.1. This results in a theoretical maximum extent of rock collapse of 70 m for access tunnels and 50 m (rounded up) for emplacement rooms.

A time-dependent approach is suitable, continuing until the maximum extent of collapse has been reached. In this case the uncertainty in the frequency of events that could dislodge damaged rock is considered by adopting the reference events assessed by Damjanac (2008), with a frequency of $10^{-5}$ $y^{-1}$. The resulting sequence of events is illustrated in Figure A-3.

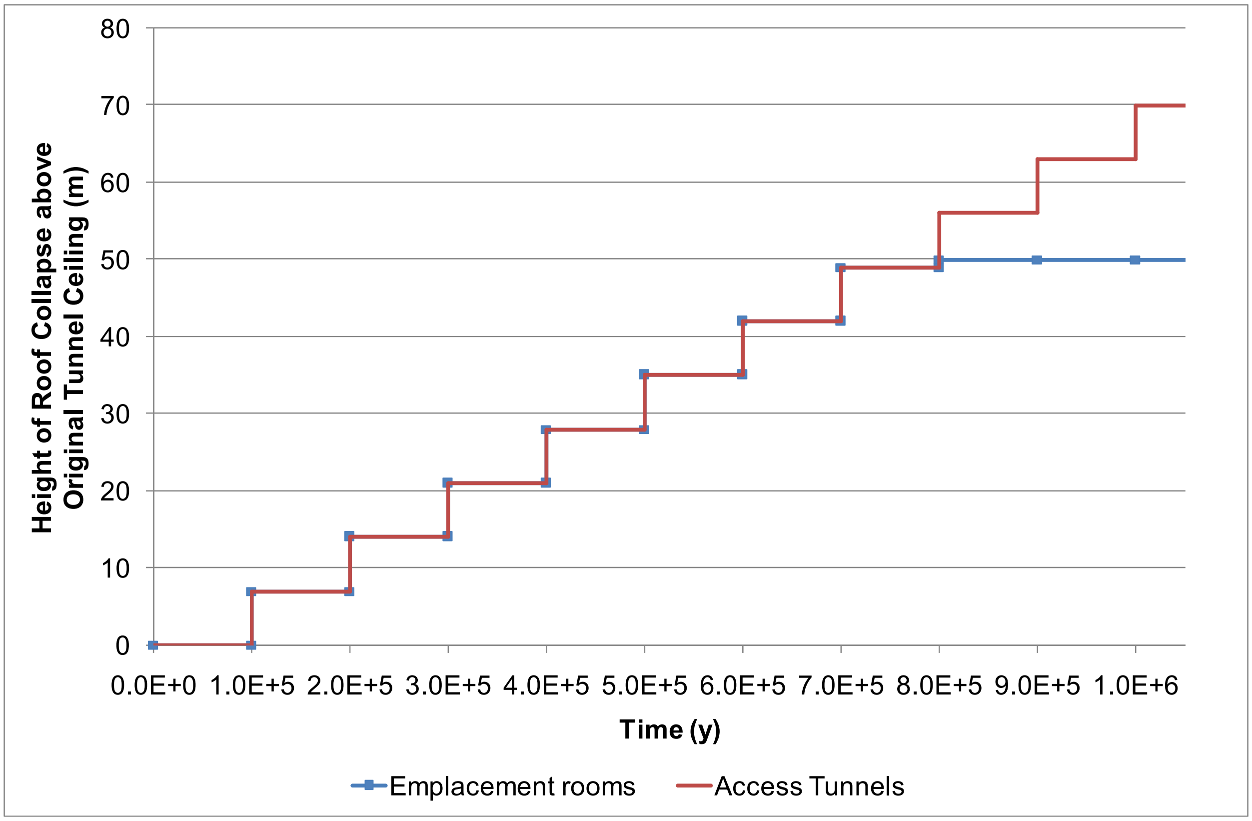


**Figure A-3: Proposed Extreme Assumption for the Representation of Time-Dependent Rock Collapse**

#### A.3.3.3Alternative Case 2

The safety assessment is considering various repository design options including repository backfilling. This option would involve emplacement rooms and tunnels that are backfilled with crushed excavated rock. The rock should provide sufficient mechanical stability to support the damaged rock and limit the potential for rock collapse. However, the waste is assumed to have a voidage of 50%, which could become compressed.

If it is cautiously assumed that the waste could be compressed completely (e.g. by ice-sheet loading), 1.3 m of the total height of the LLW rooms could be made available for collapsed rock, with 1.5 m in the ILW rooms, on average. The absence of wastes in the access tunnels means that they would be entirely filled with backfill and therefore not subject to significant rock collapse. Applying a conservative bulking factor of 1.1 implies a height of rock collapse of 12 m in LLW rooms and 16 m in ILW rooms, with an overall average of 14 m. On this, basis two rockfalls could occur associated with ice-sheet loading:

- to 7 m above the emplacement rooms after c. 100 ka; and
- a further 7 m rockfall to 14 m above emplacement rooms after c. 200 ka.

Access tunnels would be unaffected as the crushed rock is assumed to have sufficient mechanical strength to resist compression.

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