DEEP GEOLOGIC

REPOSITORY

FOR OPG's LOW & INTERMEDIATE LEVEL WASTE

Postclosure Safety Assessment (V1): Features, Events and Processes

July 2009

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NWMO DGR-TR-2009-05

Quintessa INTERA SENES Consultants Limited

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

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Preliminary

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July 2009

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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 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.

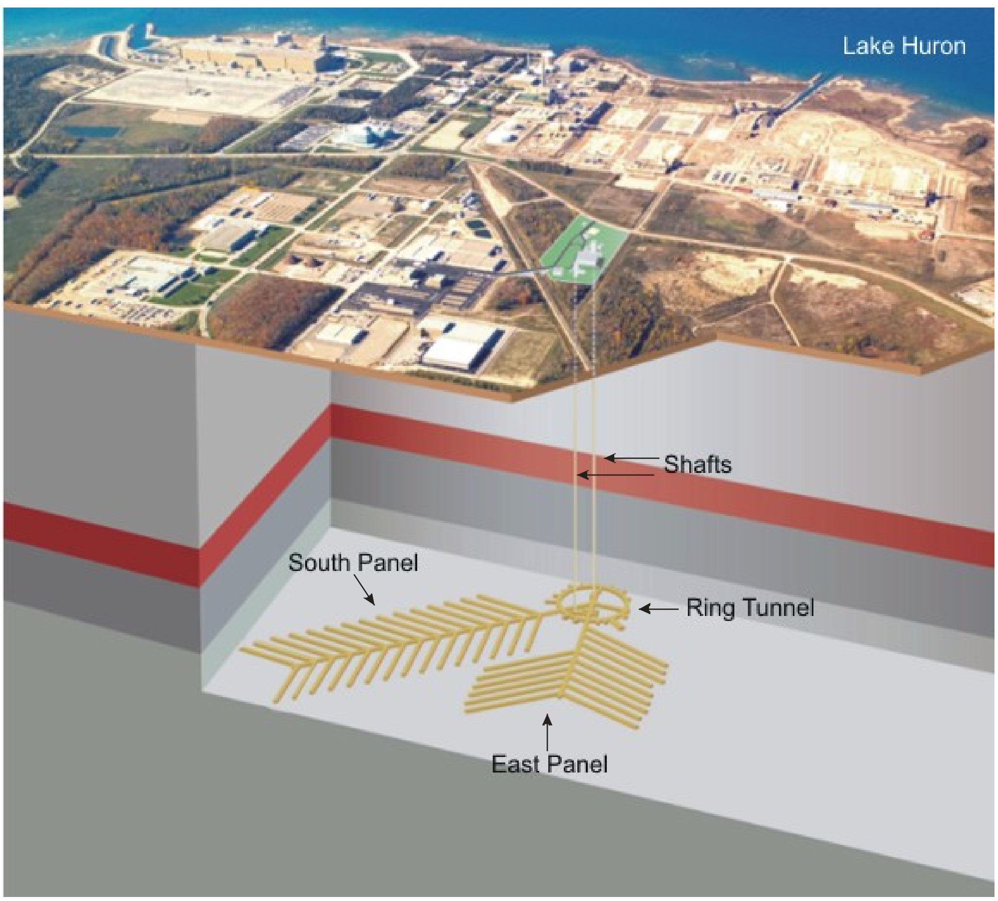

Figure 1-1: The DGR Concept at the Bruce Site

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 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 System and its Evolution report (Little 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).

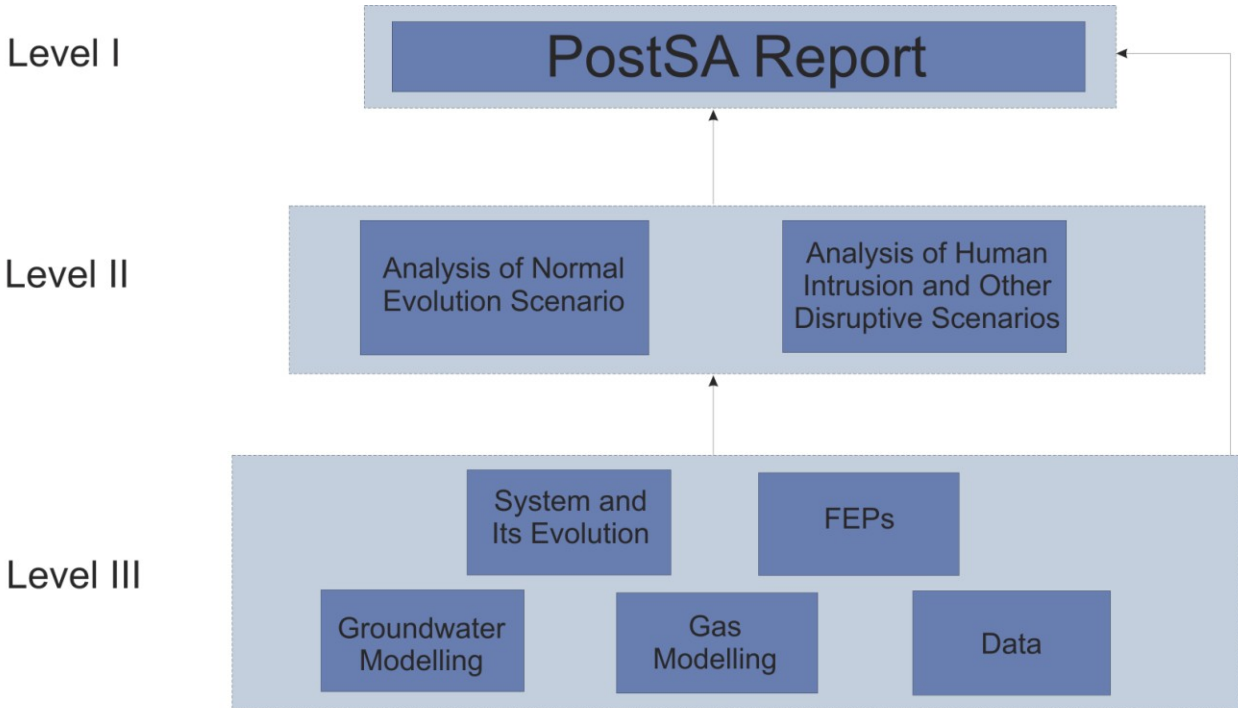

Figure 1-2: Document Structure for the Version 1 Postclosure Safety Assessment

1.1 PURPOSE AND SCOPE

The purpose of this report is to describe the features, events and processes that have been considered in the Version 1 SA and the reason(s) for their inclusion/exclusion from the SA.

The SA requires consideration of a wide range of factors that could potentially affect the behaviour of the repository, its contaminants and its environment over the time periods of interest. These factors may be features of the repository or site (e.g., waste type, rock thickness), events (e.g., earthquakes) or processes (e.g., sorption), and are known collectively as FEPs. They can be used as input for scenario development and subsequent conceptual model development for the safety assessment.

However, not all potential FEPs are necessarily included in a given safety assessment. This report starts with a structured and comprehensive list of possible FEPs, and then indicates whether and why these are included or excluded from consideration in the Version 1 SA.

The following time periods of interest can be identified.

- From closure of the DGR in 2062 to the time when institutional controls are considered to be no longer effective. During this period, institutional controls will be in place to prevent inadvertent human intrusion. A reference value of 300 years is adopted for the minimum period over which such controls, as well as societal memory, are effective, consistent with current international practice (see Section 3.8 of the Postclosure SA main report, Quintessa et al. 2009).
- The subsequent period up to the next glacial maximum, which is anticipated to occur around 100 ka. Following an initial period of global warming, it is expected that the DGR will be affected by ice sheet development resulting from cooling of the earth's climate (Peltier 2008).
- The subsequent period up to 1 Ma over which the DGR will be affected by a series of ice-sheet advances and retreats.
- The subsequent period up to 10 Ma that might need to be considered, albeit in a stylised manner, in order to demonstrate that the SA calculations encompass the time period when the maximum impact is expected to occur. Such extended timescales need to be considered due to the long half-lives of certain radionuclides considered in the assessment, the potential timescales over which the repository might resaturate once closed, and the slow groundwater travel times.

The FEPs presented in this report and the associated discussion are based on the understanding of the site derived from the information available at the time of the development of the Version 1 SA concerning the waste and waste package (the August 2008 inventory report, OPG 2008), the repository design (the May 2008 conceptual design report, Hatch 2008), the geological setting (data provided by the Geosynthesis team during 2008, Gartner Lee 2008a,b,c, Damjanac 2008, Hobbs et al. 2008 and Sykes et al. 2008), and the surface environment (assorted reports such as CSA 2008, BEAK 2002, Benovich 2003, OPG 2005a, Davis et al. 1993 and Garisto et al. 2004a).

The FEPs will be reviewed and updated in future iterations of the SA, in light of the results of the Version 1 SA, the on-going site characterisation programme (Intera 2006 and 2008), and quantitative screening of certain FEPs that might be undertaken as part of the future assessments.

1.2 REPORT OUTLINE

The report is organised as follows:

- the approach taken to develop the DGR-specific FEP list and screen that FEP list is described in Section 2;
- an overview of the DGR FEP list structure is provided in Section 3;
- the use of the FEP list in the Version 1 SA is explained in Section 4; and
- the description and screening of each FEP is provided in Section 5.

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

2 APPROACH USED FOR FEP LIST DEVELOPMENT AND SCREENING

There is considerable international precedent for developing a list of potential FEPs and using this as a structured basis for assessing factors to consider in a given safety assessment.

The FEPs presented in this report were generated from the following.

- IAEA (2004): The International FEPs List for Near-Surface Radioactive Waste Disposal Facilities. The structure of this FEPs database follows the structure of the international FEPs database developed by the OECD Nuclear Energy Agency (NEA 1999). The FEPs in this compilation were used where they were found to be relevant for the DGR. If necessary, they were modified to represent deep geological conditions.
- Garisto et al. (2004b): Third Case Study - Features, Events and Processes. The structure of this FEPs database also follows the structure of the international FEPs database developed by the OECD Nuclear Energy Agency (NEA 1999). The FEPs taken from the Third Case Study were modified to represent Low and Intermediate Level Waste (rather than spent fuel), the conceptual design of the DGR, and the site-specific geosphere and biosphere at the DGR site.
- Penfold et al. (2002): Improved Safety Assessment Modelling of Immobilised LLW Packages for Disposal. Appendix D. Prepared for Ontario Power Generation. Additional FEPs mentioned in this report were evaluated as well.

The FEPs compiled from the above documents were updated to include knowledge gained from recent studies and from international experience (see Appendix A). The FEPs were also updated to reflect information specific to the proposed DGR site and design, such as waste characteristics, repository factors and its surrounding site-specific geosphere and biosphere as summarised in the System and its Evolution report (Little et al. 2009) and the Data report (Walke et al. 2009b), and their supporting references. The review process included a check to ensure that all FEPs of potential relevance had been included in the FEP list.

The basic structure of each FEP is as follows:

- Description: provides brief explanation of the FEP and its key components;
- Screening Analysis: discusses relevance of the FEP to the DGR and the conceptual models developed for the Version 1 SA (which are documented 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); and
- FEP Screening: lists the scenarios (if any) in which the FEP is included in the associated conceptual model(s). Note that inclusion of a FEP in a conceptual model does not necessarily imply its inclusion in the related mathematical model since it might be decided to simplify the mathematical model by excluding the FEP or subsuming it into another FEP. The FEPs included in the mathematical models are presented in the Normal Evolution Scenario Analysis report (Walke et al. 2009a), the Human Intrusion and Other Disruptive Scenarios Analysis report (Penfold and Little 2009), and the

supporting Groundwater Modelling report (Avis et al. 2009) and the Gas Modelling report (Calder et al. 2009)[1].

Consistent with international practice (Appendix A), the screening in of FEPs for the scenarios and associated conceptual models is conducted based on the following criteria:

- the FEP should be relevant to the DGR system (i.e., to the types of wastes being sent for disposal, the design of the repository, and/or the geological/geographic setting);
- the FEP should not have the same effect as another, the overall definition of which may be more appropriate (i.e. each FEP should be unique);
- the FEP should be relevant to the SA's assessment context given in the Version 1 SA postclosure safety report (Quintessa et al. 2009), especially the prevailing regulatory guidance; and
- the FEP should not have both low probability and low consequence.

The scenarios (and their associated titles) considered in the Version 1 SA are documented in the System and its Evolution report (Little et al. 2009) and are summarised below.

Normal Evolution Scenario		Expected evolution of the system. Considers evolving repository conditions and the impact of anthropogenic greenhouse warming and continuing glacial and interglacial cycling on biosphere and geosphere.
Disruptive ("What if") Scenarios	Human Intrusion	Inadvertent intrusion into the DGR via an exploration borehole.
	Severe Shaft Seal Failure	Representing a poorly performing shaft seal system.
	Open Borehole	Site investigation borehole poorly sealed.
	Extreme Earthquake	DGR system impacted by seismic activity resulting in the reactivation of a vertical fault.

In contrast to the IAEA FEP list (IAEA 2004), the DGR FEP list does not include the Assessment Context category of FEPs. This is because the FEPs are already discussed in the assessment context section (Section 3) of the Version 1 Postclosure SA main report (Quintessa et al. 2009).

[1] It is planned that, in future iterations of the SA, the FEPs included in the mathematical models will be audited against those in the associated conceptual model and an explanation provided as to why any FEPs have been excluded from the mathematical model or subsumed into another FEP.

3 THE DGR FEP LIST

Category	FEP	FEP
1. EXTERNAL FACTORS		
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)

Category	FEP	FEP	
	1.4.04	Drilling activities	
	1.4.05	Mining and other underground activities	
	1.4.06	Un-intrusive site investigation	
	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	
2. REPOSITORY SYSTEM FACTORS			
2.1	Waste, Waste Form & Engineered System		
	2.1.01	Waste inventory	
		2.1.01.01	Radionuclide content
		2.1.01.02	Chemical content
	2.1.02	Waste-form characteristics	
		2.1.02.01	Metallic wastes
		2.1.02.02	Organic wastes
		2.1.02.03	Non-metallic, inorganic wastes
	2.1.03	Waste-packaging characteristics	
		2.1.03.01	Containers
		2.1.03.02	Overpacks
	2.1.04	Emplacement room and access and ring tunnel characteristics	
		2.1.04.01	Roofs and walls
		2.1.04.02	Floors
		2.1.04.03	Rock bolts
		2.1.04.04	Sealing walls
		2.1.04.05	Backfill
	2.1.05	Shaft characteristics	
		2.1.05.01	Lining
		2.1.05.02	Backfill
		2.1.05.03	Plugs
		2.1.05.04	Rock bolts
	2.1.06	Mechanical processes and conditions (in wastes, emplacement rooms, tunnels and shafts)	
		2.1.06.01	Packaging collapse
			A Steel failure
			B Concrete failure
		2.1.06.02	Material volume changes
			A Concrete shrinkage/expansion
			B Bentonite swelling
			C Corrosion products
		2.1.06.03	Emplacement room/tunnel collapse

Category	FEP	FEP	
		2.1.06.04	Container movement
		2.1.06.05	Fracture formation
		2.1.06.06	Stress-corrosion cracking
		2.1.06.07	Gas explosion
		2.1.06.08	Influence of climate change
	2.1.07	Hydraulic/hydrogeological processes and conditions (in wastes, emplacement rooms, tunnels and shafts)	
		2.1.07.01	Resaturation/desaturation
		2.1.07.02	Water flow
		2.1.07.03	Gas-mediated water flow
		2.1.07.04	Failure of drainage system
		2.1.07.05	Fracturing of repository components due to hydraulic pressure
		2.1.07.06	Coupled hydraulic processes including temperature, chemical or electrical gradients
		2.1.07.07	Influence of climate change
	2.1.08	Chemical/geochemical processes and conditions (in wastes, emplacement rooms, tunnels and shafts)	
		2.1.08.01	pH conditions
		2.1.08.02	Eh conditions
		2.1.08.03	Chloride and sulphate conditions
		2.1.08.04	Corrosion
			A General
			B Localised
			C Galvanic
		2.1.08.05	Polymer degradation
		2.1.08.06	Mineralisation
			A Leaching
			B Chloride attack
			C Sulphate attack
			D Carbonation
		2.1.08.07	Precipitation reactions
		2.1.08.08	Chelating agent effects
		2.1.08.09	Colloid formation
		2.1.08.10	Osmotic effects
		2.1.08.11	Chemical concentration gradients
		2.1.08.12	Influence of climate change
	2.1.09	Biological/biochemical processes and conditions (in wastes, emplacement rooms, tunnels and shafts)	
		2.1.09.01	Microbial growth and poisoning
		2.1.09.02	Microbially/biologically mediated processes
		2.1.09.03	Microbial/biological effects on evolution of redox (Eh) and acidity/alkalinity (pH).
		2.1.09.04	Influence of climate change
	2.1.10	Thermal processes and conditions (in wastes, emplacement rooms, tunnels and shafts)	
		2.1.10.01	Radiogenic, chemical and biological heat production from the waste packages
		2.1.10.02	Heat production from engineered features
		2.1.10.03	Temperature evolution
		2.1.10.04	Temperature dependence of processes,

Category	FEP	FEP	
			A Mechanical
			B Hydraulic
			C Chemical
			D Biological
		2.1.10.05	Influence of climate change
	2.1.11	Gas sources (in wastes, emplacement rooms, tunnels and shafts)	
		2.1.11.01	Radioactive decay
		2.1.11.02	Metal corrosion
		2.1.11.03	Organic waste degradation
		2.1.11.04	Cement degradation
		2.1.11.05	Asphalt degradation
	2.1.12	Radiation effects (in wastes, emplacement rooms, tunnels and shafts)	
	2.1.13	Extraneous materials effects	
	2.1.14	Nuclear criticality	
2.2	Geological Environment		
	2.2.01	Stratigraphy	
	2.2.02	Host lithology	
	2.2.03	Disturbed zone (in geosphere)	
		2.2.03.01	Emplacement rooms and tunnels
		2.2.03.02	Shafts
	2.2.04	Large-scale discontinuities (in geosphere)	
		2.2.04.01	Faults and shear zones
		2.2.04.02	Fractures and joints
		2.2.04.03	Dykes
	2.2.05	Mechanical processes and conditions (in geosphere)	
		2.2.05.01	Geomechanical properties
		2.2.05.02	Current stress regime
		2.2.05.03	Future stress regime
	2.2.06	Hydraulic/hydrogeological processes and conditions (in geosphere)	
		2.2.06.01	Hydraulic properties
		2.2.06.02	Current hydraulic potentials and gradients
		2.2.06.03	Future hydraulic potentials and gradients
	2.2.07	Chemical/geochemical processes and conditions (in geosphere)	
		2.2.07.01	Mineralogical properties
		2.2.07.02	Geochemical properties
		2.2.07.03	Effects of engineered barriers
		2.2.07.04	Effects of climate change
	2.2.08	Biological/biochemical processes and conditions (in geosphere)	
	2.2.09	Thermal processes and conditions (in geosphere)	
		2.2.09.01	Thermal properties
		2.2.09.02	Effects of waste and repository materials
		2.2.09.03	Effects of climate change
	2.2.10	Gas processes and effects (in geosphere)	
		2.2.10.01	Gas sources (excluding waste and repository materials)
		2.2.10.02	Gas migration
		2.2.10.03	Gas dissolution
		2.2.10.04	Gas-induced fracturing

Category	FEP	FEP	
	2.2.11	Geological resources (in geosphere)	
	2.2.12	Undetected features (in geosphere)	
2.3	Surface Environment		
	2.3.01	Topography and morphology	
	2.3.02	Biomes	
	2.3.03	Soil and sediment	
		2.3.03.01	Surface soils
		2.3.03.02	Overburden
		2.3.03.03	Aquatic sediments
	2.3.04	Near-surface aquifers and water-bearing features	
	2.3.05	Terrestrial surface-water bodies	
		2.3.05.01	Wetlands
		2.3.05.02	Lakes and rivers
		2.3.05.03	Springs and discharge zones
	2.3.06	Coastal features	
	2.3.07	Marine features	
	2.3.08	Atmosphere	
	2.3.09	Vegetation	
	2.3.10	Animal populations	
	2.3.11	Climate and weather	
	2.3.12	Hydrological regime and water balance (near-surface)	
	2.3.13	Erosion and deposition	
	2.3.14	Ecological/biological/microbial systems	
	2.3.15	Biotic intrusion	
2.4	Human Behaviour		
	2.4.01	Human characteristics (physiology, metabolism)	
	2.4.02	Age, gender and ethnicity	
	2.4.03	Diet and fluid intake	
		2.4.03.01	Farming diet
		2.4.03.02	Hunter/gatherer diet
		2.4.03.03	Other diets
	2.4.04	Habits (non-diet-related behaviour)	
	2.4.05	Community characteristics	
		2.4.05.01	Community type
		2.4.05.02	Community location
		2.4.05.03	Water source
	2.4.06	Food preparation and water processing	
	2.4.07	Dwellings	
	2.4.08	Natural/semi-natural land and water use	
	2.4.09	Rural and agricultural land and water use	
	2.4.10	Urban and industrial land and water use	
	2.4.11	Leisure and other uses of environment	
3. CONTAMINANT FACTORS			
3.1	Contaminant Characteristics		
	3.1.01	Radioactive decay and in-growth	
	3.1.02	Organics and potential for organic forms	
	3.1.03	Chemical/organic toxin stability	

Category	FEP	FEP	
	3.1.04	Inorganic solids/solutes	
	3.1.05	Volatiles and potential for volatility	
	3.1.06	Noble gases	
3.2	Contaminant Release and Migration Factors		
	3.2.01	Contaminant release pathways	
	3.2.02	Water-mediated migration of contaminants	
		3.2.02.01	Water-mediated effects (repository)
			A Advection
			B Molecular diffusion
			C Dispersion
		3.2.02.02	Water-mediated effects (geosphere)
			A Advection
			B Molecular diffusion
			C Dispersion
			D Matrix diffusion
		3.2.02.03	Water-mediated effects (biosphere)
			A Groundwater discharge to biosphere
			B Infiltration
			C Capillary rise
			D Transport by surface run-off
			E Transport by interflow
			F Transport in surface-water bodies
		3.2.02.04	Multiphase transport processes
	3.2.03	Solid-mediated migration of contaminants	
	3.2.04	Gas-mediated migration of contaminants	
	3.2.05	Atmospheric migration of contaminants	
	3.2.06	Microbially/biologically-mediated processes, effects on contaminant release and migration	
	3.2.07	Animal-, plant- and microbe-mediated migration of contaminants	
	3.2.08	Human-action-mediated migration of contaminants	
	3.2.09	Colloid-mediated migration of contaminants	
	3.2.10	Dissolution, precipitation and mineralisation	
		3.2.10.01	Dissolution and Precipitation (repository)
		3.2.10.02	Dissolution and Precipitation (geosphere)
		3.2.10.03	Dissolution and Precipitation (biosphere)
		3.2.10.04	Change in mineralisation
	3.2.11	Speciation and solubility (contaminant)	
		3.2.11.01	Speciation and solubility (solubility limitation, repository)
		3.2.11.02	Speciation and solubility (solubility limitation, geosphere)
		3.2.11.03	Speciation and solubility (solubility limitation, biosphere)
		3.2.11.04	Solubility changes caused by chemical interaction between waste and pore water
		3.2.11.05	Solubility changes caused by change in temperature
		3.2.11.06	Species equilibrium change caused by change in temperature

Category	FEP	FEP	
	3.2.12	Sorption and desorption (contaminant)	
		3.2.12.01	Sorption and desorption (repository)
		3.2.12.02	Sorption and desorption (geosphere)
		3.2.12.03	Sorption and desorption (biosphere)
		3.2.12.04	Chemical reactions caused by adsorption or desorption
		3.2.12.05	Anion exclusion effects
		3.2.12.06	Sorption change caused by change in temperature
	3.2.13	Complexing agent effects (contaminant)	
		3.2.13.01	Organics
		3.2.13.02	Chelating agents
		3.2.13.03	Microbes
	3.2.14	Food chains and uptake of contaminants	
3.3	Exposure Factors		
	3.3.01	Contaminant concentrations in drinking water, foodstuffs and drugs	
	3.3.02	Contaminant concentrations in non-food products	
	3.3.03	Contaminant concentrations in other environmental media	
	3.3.04	Exposure modes	
		3.3.04.01	Exposure of humans
		3.3.04.02	Exposure of biota other than humans
	3.3.05	Dosimetry and biokinetics	
		3.3.05.01	Dosimetry and biokinetics for humans
		3.3.05.02	Dosimetry and biokinetics for biota other than humans
	3.3.06	Radiological toxicity/effects	
		3.3.06.01	Radiological toxicity/effects for humans
		3.3.06.02	Radiological toxicity/effects for biota other than humans
	3.3.07	Chemical toxicity/effects	
		3.3.07.01	Chemical toxicity/effects for humans
		3.3.07.02	Chemical toxicity/effects for biota other than humans
	3.3.08	Radon and radon daughter exposure	

4 THE USE OF THE DGR FEP LIST IN THE VERSION 1 SA

The DGR FEP list has two main uses in the assessment.

1. The Category 1 FEPs (i.e., External Factors) are used in the System and its Evolution report (Little et al. 2009) to identify potential scenarios for consideration in the assessment. These external factors 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, they can be considered to be scenario-generating FEPs, in the sense that whether they occur or not (or the extent to which they occur) can define a particular future scenario that should be considered within the assessment.

2. The Category 2 FEPs (i.e., Repository System Factors) and Category 3 FEPs (i.e., Contaminant Factors) are used to ensure that the conceptual models developed to assess the scenarios have included all the potentially relevant internal FEPs. The conceptual model and associated FEP audit for the Normal Evolution Scenario is described in Walke et al. (2009a), whereas the models and audits for the Disruptive Scenarios are described in Penfold and Little (2009).

The FEP descriptions and screening analyses associated with the list also provide additional information to that given in the other Postclosure Safety Assessment documents (such as the System and its Evolution report, Little et al. 2009) on the FEPs and their relevance to the Version 1 SA.

5 FEP DESCRIPTION AND SCREENING ANALYSIS

1. EXTERNAL FACTORS

Definition

Features, events and processes (FEPs) with causes or origin outside the repository system, i.e. natural or human-induced factors of a more global nature and their immediate effects on the performance of the disposal system. Included in this group are decisions related to repository design, operation and closure since these are outside the temporal boundary of the repository domain for the purpose of the postclosure safety assessment.

The external FEPs (EFEPs) are generally not influenced (or are only weakly influenced) by processes within the repository domain. In developing conceptual and mathematical models of the repository, external factors are often represented as boundary conditions or initiating events and processes.

"External Factors" is divided into five categories as follows:

1.1 Repository Factors
1.2 Geological Processes and Effects
1.3 Climate Processes and Effects
1.4 Future Human Actions (Active)
1.5 Other External Factors

1.1 Repository Factors

Description
Factors related to decisions taken, and events occurring during the life cycle of the repository (e.g. design, construction, operation, closure and decommissioning) that could have an influence on the postclosure performance of the facility and therefore have to be considered in the safety assessment process.

The "Repository Factors" category of FEPs is outside the temporal boundary of the disposal system domain and predominantly associated with the pre-operational and operational period of the repository. These factors are an example of the interdependencies that exist between these periods and the postclosure period and give rise to issues of how to treat these interdependencies in the safety assessment process.

"Repository Factors" is a category of External Factors in the DGR FEP List and is divided into individual FEPs as follows:

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 Records and Markers

1.1.13 Monitoring

1.1.01 Site Investigations

Description

Investigations carried out to characterise the repository site, whether conducted prior to excavation or during subsequent construction and operation.

These activities establish baseline conditions and provide data for the safety assessment. Results from previous safety assessments using information from site investigation can contribute to decisions made on subsequent activities, such as a decision to proceed with excavation at a candidate site or a decision on the repository design. The extent of site investigation also affects the degree of uncertainty associated with the assessment modelling.

Screening Analysis

Available data from the current site characterisation is being used in the Version 1 assessment (see Sections 2.3 and 2.4 of the System and its Evolution report, Little et al. 2009 and Sections 5 and 6 of the Data report, Walke et al. 2009b). Results of future site characterisation studies will be used in future assessments.

For the Open Borehole Scenario, it is assumed that a site investigation borehole is left open or poorly sealed. All other scenarios assume that any site investigation activity undertaken to characterise the DGR site has no detrimental impact on safety.

FEP Screening

Include FEP in all scenarios.

1.1.02 Design of Repository

Description

Assumptions regarding the design of the repository including both the safety concept, i.e. the general features of design and how they are expected to lead to a satisfactory performance, and the engineering specification for excavation, construction, operation and closure.

Screening Analysis

The DGR design assessed in the Version 1 SA is documented in Section 2.2 of the System and its Evolution report (Little et al. 2009) and Section 4.1 of the Data report (Walke et al. 2009b) and is based on the Hatch conceptual design (Hatch 2008).

Design modifications (e.g. including the consideration of backfilling of repository rooms and tunnels) are considered in variant calculations for the Normal Evolution Scenario.

FEP Screening

Include FEP in all scenarios.

1.1.03 Schedule and Planning

Description

The sequence of events and activities occurring during repository excavation, construction, waste emplacement and sealing.

Relevant events may include phased excavation of emplacement rooms and emplacement of wastes, backfilling, sealing and closure of sections of the repository after wastes are emplaced and monitoring activities to provide data on the transient behaviour of the system or to provide input to the final assessment. The sequence of events and time between events may have implications for long-term performance, e.g. decay of activity, material corrosion and degradation, chemical and hydraulic changes during the operational phase.

Screening Analysis

The repository is assumed to be closed by 2062, i.e. 45 years after it receives its first consignment of waste. The SA considers the evolution of the repository, e.g. radioactivity and gradual resaturation, from 2062 onwards. Account is taken of radioactive decay prior to 2062. No other schedule is considered in the Version 1 SA. See Section 3.8 of the Postclosure Safety Assessment report (Quintessa et al. 2009).

FEP Screening

Include FEP in all scenarios.

1.1.04 Construction

Description

Factors related to the excavation of shafts, tunnels, disposal galleries, silos, etc. of a repository, the stabilisation of these openings, and the installation and assembly of structural elements. It may be necessary to examine the consequences of the use of poor construction techniques not being detected by quality control.

Screening Analysis

It is assumed for all scenarios, other than the Severe Shaft Seal Failure Scenario, that the DGR is constructed as described in Section 2.2.1 of the System and its Evolution report (Little et al. 2009) and Section 4.1 of the Data report (Walke et al. 2009b) under an appropriate quality assurance regime.

Poor construction techniques could impact on the performance of the repository. Therefore, the Severe Shaft Seal Failure Scenario includes consideration of enhanced permeability of the Excavation Damaged Zones (EDZs) in the shafts that could result from poor construction.

FEP Screening

Include FEP in all scenarios.

1.1.05 Operation

Description

The placing of waste packages in their final positions within the repository. One issue of concern is the potential for faulty emplacement of waste packages (e.g. containers). Containers might be damaged during handling, leading to premature failure and contaminant releases.

Screening Analysis

It is expected that the waste packages are placed in the repository to the design specifications described in Section 2.2.2 of the System and its Evolution report (Little et al. 2009) under an appropriate quality assurance regime that prevents their faulty emplacement. However, the effects of unexpected premature failure and contaminant releases that could be result from faulty emplacement of waste packages are investigated in a variant calculation for the Normal Evolution Scenario.

FEP Screening

Include FEP in all scenarios.

1.1.06 Waste Allocation

Description

Describes the assumptions regarding the allocation of wastes to the repository, including waste type(s) and amount(s).

Screening Analysis

The L&ILW to be disposed in the DGR is described in Section 2.2.2 of the System and its Evolution report (Little et al. 2009) and Section 4.1 in the Data report (Walke et al. 2009b). See also *Waste Inventory FEPs [2.1.01].* However, the only distinction made in the location of wastes is between the South Panel (LLW) and East Panel emplacement rooms (ILW and certain LLW).

FEP Screening

Include FEP in all scenarios

1.1.07 Repository Closure

Description

Factors related to the end of waste disposal operations and the sealing of tunnels and shafts. These closure activities are undertaken mainly to prevent human access into and limit the migration of contaminants from the repository.

It may be necessary to examine the consequences of the use of poor closure techniques not being detected by quality control. It may also be necessary to consider the potential for degraded performance of shaft and borehole seals, particularly over the long time frames over which those seals might contribute to safety.

Screening Analysis

The SA assumes that the repository is closed consistent with the description provided in Section 2.2.3 of the System and its Evolution report (Little et al. 2009) and Section 4.2 in the Data report (Walke et al. 2009b). It is assumed that closure of the DGR is undertaken under OPG's quality assurance programme.

The Normal Evolution Scenario represents reference assumptions on closure and degradation of shaft seals over time. The Open Borehole Scenario considers what if a borehole is not sealed or is poorly sealed. The Shaft Seal Failure Scenario considers the consequences of degraded performance of the shaft seals.

FEP Screening

Include FEP in all scenarios.

1.1.08 Quality Assurance

Description

Quality assurance and control procedures and tests during the design, construction, operation and closure of the repository, including the manufacture of the waste forms, containers and engineered features.

Screening Analysis

It is assumed for all scenarios that a quality assurance and control programme is implemented to ensure that containers and seals are designed, constructed, filled and emplaced properly. However, the programme does not detect flaws in the construction of the shaft seals (for the Severe Shaft Seal Failure Scenario) or in the borehole seals (for the Open Borehole Scenario).

FEP Screening

Include FEP in all scenarios but does not detect errors for the Severe Shaft Seal Failure and Open Borehole Scenarios.

1.1.09 Repository Administrative Control

Description

The administrative measures, and time period, used to control events at or around the repository site during the operational period and after closure.

The responsibility for administrative control of the site, and the type of administrative control, may vary depending on the stage in the repository lifetime. There may be implications on *Scheduling and planning [1.1.03], Quality assurance [1.1.08]* and *Maintenance of records and markers [1.1.13].*

Screening Analysis

For the SA, it is assumed that adequate administrative control exists to ensure closure in 2062. Thereafter, it is assumed that controls are maintained for a period of 300 years to prevent inadvertent human access (see Section 3.8 of Postclosure Safety Assessment report, Quintessa et al. 2009).

After this period, it is assumed that controls are no longer effective. The possibility of intrusion into the repository subsequent to controls being no longer effective is considered in the Human Intrusion Scenario but not in any other scenarios.

FEP Screening

Include FEP in all scenarios.

1.1.10 Accidents and Unplanned Events

Description

Events that occur during excavation, construction, waste emplacement and closure, and that are unplanned or of an accidental nature, which might have an impact on long-term performance or safety of the repository.

Examples of such events and potential effects include:

- explosions in or near the repository, fires, flooding and other destructive events that could affect the rock integrity or lead to short- or long-term impacts on the accessible environment from contaminants in air and pumped water (see also *Explosions and crashes [1.4.11]*);
- mishandling or lack of procedural adherence could damage the container or other components of the engineered barriers during transport and emplacement, leading to early releases or enhanced transport of contaminants (see also *Operation [1.1.05]);*
- rockfalls and rockbursts in the repository rooms and tunnels (see also *Emplacement roof/ tunnel collapse [2.1.06.03]*);
- sabotage or theft of the containers, seals, etc. could compromise the long-term performance of the repository. Examples include explosions changing rock integrity, terrorist activity associated with the strategic value of fissionable material, and activities aimed at preventing the use or closure of the facility.

Screening Analysis

These events are not included in the postclosure SA as it is reasonable to assume that any deleterious effects would be remedied during the operation of the repository, and corrective actions would be taken so that long-term performance of the repository is not impaired.

FEP Screening

Screened out.

1.1.11 Retrievability

Description
Related to any special design, emplacement, operational or administrative measures that might be applied to enable or ease retrieval of wastes.

Repository designs may specifically allow for retrieval or rule it out. In some cases, an interim period might be planned between waste emplacement and final repository sealing, during which time retrieval is possible. Issues of concern include retrieval options that degrade repository performance, and options that may hinder subsequent decisions for retrieval. A related issue is discussed under *Deliberate Human Intrusion [1.4.15].*

Screening Analysis
The DGR waste package acceptance criteria include minimum service lifetimes for the packages of 15 years for LLW and 30 years for ILW (NWMO 2009). These provide easier retrieval during the operational period, if needed, but these minimum lifetimes do not affect postclosure performance. Otherwise, there are no retrieval-specific features included in the DGR design.

An important design feature that would simplify retrieval operations is the lack of backfill in rooms and access tunnels. However, although this feature is important and needs to be included in the analyses, it is not present specifically because of retrievability.

FEP Screening
Screened out.

1.1.12 Repository Records and Markers

Description

Refers to the retention of records of the content and nature of the repository after closure and also the placing of permanent markers at or near the site.

These records and markers would allow future generations to recall the existence and nature of the repository following closure, and influence events such as future intrusion into the repository. The loss of such records and markers might increase the likelihood of inadvertent intrusion some time in the future (see *Future Human Intrusion Actions FEPs [1.4]).*

Screening Analysis

It is expected that the DGR presence will be recorded in various institutional records, including at least municipal Kincardine, county and provincial records and possibly national and international records. It is also expected that a robust marker would be included at the site at closure.

The specific details have not been decided, and will likely not be finalised until the DGR closure phase 50 years from now. However, it is likely that durable records could be provided that would ensure that future generations would remain aware of the presence of the repository for some time. Furthermore, the local population would have a societal memory of the site that would also likely last for several generations.

Consistent with international practice, it is assumed in this assessment that records and markers are effective for 300 years, and no credit is taken for subsequent times.

FEP Screening

Assume records and markers are effective for 300 years for all scenarios.

1.1.13 Monitoring

Description

Monitoring that is carried out during operations or following closure of parts of the repository or the entire repository. It includes monitoring for operational safety and also monitoring of parameters related to the long-term safety and performance of the repository.

Screening Analysis

A monitoring programme will be in place during the operation of the facility (Section 3.13, Conceptual Design Report, Hatch 2008). After closure, there would be a further period of monitoring to confirm that the DGR is performing as expected (Section 2.6.5, DGR Project Description, OPG 2005b).

The monitoring programme will be designed and operated so as not to compromise long-term safety. Therefore, for the Normal Evolution Scenario it will have no effect on the postclosure system.

However, to assess the possible negative effects from monitoring of the repository, the Open Borehole Scenario is considered in which it is assumed that a monitoring borehole is left open or is poorly sealed, potentially providing a pathway through the host rock.

FEP Screening

Included only in the Open Borehole Scenario.

1.2 Geological Processes and Effects

Description
Factors related to the long-term processes arising from the wider geological setting and their effects on the performance of the repository.

The "Geological Processes and Effects" category of FEPs refers to regional geological processes and effects, which generally are outside the temporal and spatial boundaries of the disposal system domain.

"Geological Processes and Effects" is a category of External Factors in the DGR FEP List and is divided into individual FEPs as follows:

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)

1.2.01 Tectonic Movement

Description

Refers to the movement of the lithosphere (the Earth's outermost layer or surface rock) because of the underlying movement of the crustal plates.

These movements give rise to large-scale processes such as continental drift, mountain building (orogeny), crustal deformation, faulting, folding and subduction. They typically occur over periods of millions of years. Their effects may appear as small-scale gradual movements or creep, but they are also associated with earthquakes and volcanic activity. Potential effects on a repository system include modification of groundwater flow and contaminant transport pathways, movement of a container, and damage to the repository structure or seals.

Screening Analysis

Active tectonic plate margins are the locus of most tectonic activity worldwide. In contrast, the DGR is in the Bruce Megablock (Figure 2.3 of Gartner Lee 2008a), which is very stable tectonically, being virtually aseismic (Figure 6.3 of Gartner Lee 2008b). The pre-Cambrian basement rock beneath the repository is located in the interior of the large North American tectonic plate, which is one of the most tectonically stable regions on the planet. The DGR site is located over 1000 km from the nearest plate margin. At the current spreading rates the North American plate is unlikely to collide with another plate resulting in orogeny potentially followed by the development of a new tectonic regime for many tens of millions of years (Figure 3.1 of Gartner Lee 2008a).

Earthquakes are discussed in *[1.2.03] Seismicity*.

FEP Screening

Include FEP in the Extreme Earthquake Scenario only.

1.2.02 Orogeny

Description

Factors related to the formation of mountains (orogeny), the potential for orogeny and its effects on the performance of the repository.

Screening Analysis

Orogenesis generally occurs at tectonic plate margins where different plates are in contact. The DGR site is located in the interior of the large North American tectonic plate. Orogenic activities at the margins of the North American plate are not expected to occur for tens of millions of years (see *[1.2.01] Tectonic Movement*) and therefore within the time frame of the assessment (around 1 Ma, although some illustrative calculations are taken out to 10 Ma in order to demonstrate peak impacts have been reached – see Postclosure Safety Assessment report, Quintessa et al. 2009).

FEP Screening

Screened out.

1.2.03 Seismicity

Description

Release of accumulated geologic stress via rapid relative movements within the Earth's crust, usually along existing faults or geological interfaces. Seismic events are most common in tectonically active or volcanically active regions at or near crustal plate margins.

The potential effects of seismic events on the repository include liquefaction of the backfill materials, shaking and damage to the containers and seals, rockfalls in the repository, modification of the properties of the EDZ, and extension or creation of fractures near the repository. The geosphere might be affected by the growth of existing faults or the creation of new faults, with consequent changes in groundwater flows and possibly groundwater composition. Potential effects on the biosphere include tidal waves (tsunamis), liquefaction of soil, formation of new discharge areas, alteration of river courses and destruction of dams. Multiple events occurring close together in time might have effects that are not simply additive.

Observations have shown that the effects and magnitude of a seismic event are greater at the surface than underground.

Screening Analysis

The Bruce Megablock is virtually aseismic (Figure 6.3 of Gartner Lee 2008b). The annual probability of occurrence of an event of $M \geq 6$ within a 20 km radius of the Bruce Site is approximately once in 800,000 years (with an uncertainty of a factor of three on this return period) (Gartner Lee 2008b). Global studies suggest that rare intra-plate earthquakes can have magnitudes as large as M7, but occur extremely infrequently (Gartner Lee 2008b). Based on Gutenberg-Richter relationship (Gartner Lee 2008b), it can be anticipated that the probability of an M7 event is a factor of ten lower than that of an M6 event. Seismic reactivation of existing faults is a remote possibility.

Nevertheless, low magnitude seismic events ($M \leq 5$) will occur over the timescales of thousands of years and could be triggered by ice-sheet loading and unloading (see Section 2.3.5 of the System and its Evolution report, Little et al. 2009).

FEP Screening

Include FEP in all scenarios, although only the Extreme Earthquake Scenario considers a high magnitude ($M \geq 6$) event in the DGR region.

1.2.04 Volcanic and Magmatic Activity

Description

Intrusion of magma (molten rock) into the crust, possibly reaching the Earth's surface.

A volcano is a vent or fissure in the Earth's surface through which magma may flow, and solid and plastic fragments, liquid droplets and hot gases can be expelled. Mantle and lithospheric hot spots and rifts correspond to weak areas in the Earth's crust that may give rise to similar phenomena. The high temperatures and pressures associated with volcanic and magmatic activity may result in permanent changes in the surrounding rocks (see also *Metamorphism [1.2.05]*).

Effects on the geosphere could include activation, creation and sealing of faults, changes in topography, changes in rock stress, deformation of rock and changes to groundwater composition and temperatures. Volcanic and/or magmatic activity may drive hydrothermal circulation. The repository may be disrupted indirectly owing to changes in temperature, groundwater flow or groundwater chemistry that are caused by magmatism. Direct effects on the repository include disruption by intersection of repository rooms by a magmatic dike or fracture caused by volcano-tectonic activity. Flowing magma and/or associated fluids that intersect the repository and that also reach the surface may give rise to dispersion of wastes in a plume of volcanic ejecta and in lava flows.

Screening Analysis

Active tectonic plate margins, including rifts and subduction zones, are the locus of most seismic and volcanic activity worldwide. In contrast, the Bruce Megablock, in which the Ordovician host rocks are located, is very stable tectonically, being virtually aseismic (Gartner Lee 2008b).

Volcanic activity in the interior of the tectonic plate is very unlikely for at least another 20 million years, because the site location is part of a vast, stable cratonic region where the Earth's heat flux is low (Jaupart et al. 1998). Assuming that relative plate motions continue as they are today, volcanic activity may develop again in approximately 20 million years. At that time, the southwestern edge of the Canadian Shield may pass over a mantle plume ("hot spot") that is currently associated with volcanic eruptions and fumaroles in the Snake River Plain and Yellowstone area of the western U.S. (Wood and Kienle 1990, Müller et al. 1993).

FEP Screening

Screened out.

1.2.05 Metamorphism

Description

The processes by which rocks are changed by the action of pressure and/or heat beneath the Earth's surface. Metamorphism may occur due to burial, in the vicinity of *volcanic and magmatic activity [1.2.04]* or in the vicinity of active faulting.

The past metamorphic history of a host rock may be important to understanding its present- day characteristics and future evolution. Ongoing metamorphism can activate, create or seal faults; change topography and rock stress; deform rock structures; and alter groundwater composition, temperatures and pressures. Metamorphism can also alter the mineralogical and physical properties of rock; for instance, shale is composed of thin layers of fine-grained sediment, most of which is clay minerals, and can be altered by metamorphism to slate, a more compact and harder rock. Many metamorphic reactions involve dehydration or hydration of solid minerals. These reactions add or remove water to the pore space. Some reactions may release other fluids from the solid phase, such as CO_2, gaseous hydrocarbons and liquid hydrocarbons. The changes in the quantities and/or characteristics of pore fluids that occur may cause anomalous pressures and pressure gradients to develop.

Screening Analysis

The Ordovician host rocks are sedimentary and may be subject to metamorphic processes if volcanic activity were to occur. However, no volcanic activity is expected for 20 million years (see *Volcanic and Magmatic Activity [1.2.04]*). Therefore, there is neither particularly susceptible rock, nor the temperatures and pressures needed for metamorphism to occur in the host rock over the time frame of the assessment (around 1 Ma, although some illustrative calculations are taken out to 10 Ma in order to demonstrate peak impacts have been reached – see Postclosure Safety Assessment report, Quintessa et al. 2009). The Bruce site will be subject to glacial loading over the assessment timeframe, but this will cause insufficient pressure to induce metamorphism.

FEP Screening

Screened out.

1.2.06 Hydrothermal Activity

Description

Processes associated with high temperature groundwaters, including buoyancy (density-driven groundwater flow) and alteration of minerals in the rocks through which the high temperature groundwater flows. These processes are often complex and strongly coupled; for example mineral precipitation and/or alteration could cause fracture infilling, thereby impeding groundwater flow, and potentially modifying groundwater salinity, resulting in the occurrence of a new set of mineral alteration reactions, and so forth. Depending upon the enthalpy of the hydrothermal fluids and the pressure gradients along flow paths, fluid phase changes (principally boiling and condensation) may occur. The hydrothermal fluids may also transport a wide range of dissolved gases (CO_2, H_2S, etc.). These gases may exsolve in response to changing temperature and pressure conditions along a flow path.

Groundwater temperature is determined by a wide range of processes including fluid mixing, phase changes and the thermal properties of the rock. Important influences are large-scale geological and hydrogeological properties of the rock, such as the location of geothermal heat sources, thermal conductivity, location of recharge and discharge areas and hydraulic conductivity.

Screening Analysis

The DRG is located in Ordovician sediments in southwestern Ontario. The heat flux is low across the Pre-Cambrian basement rocks, resulting in a temperature at the proposed repository depth of 20.75 ºC (Walke et al. 2009b). Therefore, geosphere-driven hydrothermal processes act too slowly to be of concern over the Postclosure SA time period (around 1 Ma, although some illustrative calculations are taken out to 10 Ma in order to demonstrate peak impacts have been reached – see Postclosure Safety Assessment report, Quintessa et al. 2009).

FEP Screening

Screened out.

1.2.07 Denudation and Deposition (large-scale)

Description

The large scale (geological) removal and accumulation of rocks and sediments, with associated changes in topography and hydrological conditions at the repository site surface.

This factor is concerned with processes (such as glaciation or massive river erosion such as gave rise to the Grand Canyon) that could result in localised incisions that remove large volumes of rock from a small area or broader-ranging actions that remove large volumes of surface soil and rock from a widespread area. It also includes subsequent deposition of the eroded material on lake bottoms and in river deltas. Related processes are discussed under *Erosion and Deposition [2.3.13]*, and related glaciation effects under *Local Glacial and Ice-sheet Effects [1.3.05]*.

Screening Analysis

Figure 7.1 of Gartner Lee (2008a) indicates that based on the organic maturity of the palaeozoic rocks elsewhere in the Michigan Basin, circa 1500 m of material must have been eroded since the end of the Carboniferous (~300 Ma BP) as the sedimentary layers on the site have been progressively raised due to tectonic activity. Due to the current flat topology around the Bruce site and the low elevation relative to sea level, it is expected that there will be little net erosion at the site over the next one million years.

The potential for large-scale denudation and deposition is being considered as part of the Geosynthesis programme and the results will be available for the next iteration of the SA.

FEP Screening

Screened out. Re-evaluate in light of the Geosynthesis work for the next iteration of the SA.

1.2.08 Diagenesis

Description

The processes by which deposited sediments at or near the Earth's surface are formed into rocks by compaction, cementation and crystallisation, i.e. under conditions of temperature and pressure normal to the upper few kilometres of the Earth's crust. Diagenesis refers to processes occurring within the host rock subsequent to initial sedimentation. See also *Metamorphism [1.2.05],* which generally occurs at greater depths and at higher temperatures.

Screening Analysis

For the SA, it is expected that there will not be significant physical and chemical changes to the rock properties over the assessment period given the mineralogy of the rocks and the associated temperatures at the depth of the DGR. Diagenesis driven by *Denudation and Deposition (large scale) [1.2.07]*, *Hydrothermal Activity [1.2.06]* and *Volcanic and Magmatic Activity [1.2.04]* are unlikely to occur since these FEPs have been screened out.

FEP Screening

Screened out.

1.2.09 Pedogenesis

Description

Pedogenesis relates to the origin and development of soils, with reference to the factors responsible for the formation of “solum”, or true soil, from unconsolidated parent material.

Pedogenesis may affect biosphere uptake and near-surface system evolution as it involves geohydrologic, atmospheric and biological processes (burrowing animals, plant roots activity/invasion) at or near surface on time scales of a few hundred to thousands of years.

Screening Analysis

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.

FEP Screening

Include FEP in all scenarios.

1.2.10 Salt Diapirism and Dissolution

Description

The large-scale evolution of salt formations. Salt diapirism is the lateral or vertical intrusion or upwelling of a salt formation into overlying strata. Dissolution of the salt may occur where the salt formation is in contact with groundwater.

Screening Analysis

Regionally, there are significant salt formations in the Michigan basin. Salt is mined commercially at Goderich, about 50 km from the Bruce site. These major salt deposits are present in the Salina B, D, E and F Formations.

Regionally, the salt / evaporite deposits in the Salina B Formation were much thicker when originally deposited, and covered a much greater area of the Michigan basin. However, they were significantly dissolved during the late Silurian leading to their present day distribution (Gartner Lee 2008a). Selective dissolution of these salts is interpreted to have led to the formation of collapse features in the overlying (younger) Devonian sediments at the margins of the Michigan basin. Similar collapse features have been located at three locations within 80 km of the DGR site, although their effects are confined to the Salina Formations.

There are no significant salt layers at the DGR site. Thin salt and evaporite layers are present in the Salina B Anhydrite, Salina A2 Evaporite, and Salina A1 Evaporite. These layers are only a few metres thick at the DGR site (Walke et al. 2009b). There is no evidence of collapse structures within the Salina Formations, or active salt dissolution more recently than the late Silurian, at the DGR site.

The Ordovician Formations do not contain significant salt deposits. They have been stable for millions of years, as illustrated by their regional uniformity. The repository will be constructed in the Ordovician sediments in the Lower Cobourg Formation. Due to the absence of significant salt formations in or below the Ordovician host rocks, no effects of salt diapirism or dissolution are expected at the site. There is no identified mechanism for salt diapirism to occur.

FEP Screening

Screened out.

1.2.11 Hydrological / Hydrogeological Response to Geological Changes

Description

Effects on regional groundwater flow and pressures arising from large-scale geological changes.

These effects could include changes in groundwater flow and pressures caused by the effects of erosion on topography, and changes to hydraulic properties of geological units caused by changes in rock stress or fault movements. Within and underlying low-permeability geological formations, hydrogeological conditions may evolve very slowly so they may have characteristics that reflect past geological conditions. In this case, the hydrogeological conditions are in a state of disequilibrium.

Screening Analysis

Initial groundwater head data from two site investigation boreholes drilled at the DGR site (DGR-1 and DGR-2) show a complex pattern of excess and deficient heads (see Figure 2-14 in the System and its Evolution report, Little et al. 2009). The major features of the head-depth profile are significant underpressures in the Ordovician and significant overpressures in the Cambrian. The specific cause(s) of the head profile are currently being investigated. At this stage of the project only a small number of site-specific head data have been collected; therefore it is too early to draw definitive conclusions. Possible causes include the following.

- Disequilibrium due to the history of ice-sheet loading and unloading, with different parts of the system being in different states of disequilibrium dependent on the timing, duration and magnitude of ice-sheet loading and unloading, formation depth, formation compressibility, and the hydraulic diffusivity of overlying formations. Regional groundwater flow modelling results (Sykes et al. 2008) for a transient palaeoclimate simulation of the Laurentide glacial episode (~120ka to 10ka BP) indicate that glacial melt waters did not penetrate below the Upper Silurian (Salina F), consistent with geochemical evidence (Hobbs et al. 2008). Although ice loading significantly affected heads in the Silurian and Devonian formations, heads in the Ordovician formations and Cambrian were only changed by a small amount. Since none of the earlier Quaternary glaciations are thought to have been significantly larger than the Laurentide glacial episode, the model results currently indicate that the disequilibrium heads at depth are unlikely to be due to Quaternary ice-sheet loading and unloading.
- The diequilibrium heads might reflect long-term sedimentary and tectonic processes such the erosion of over a kilometre of sediment since the end of the Carboniferous. Regional geochemical evidence which indicates that the groundwaters are ancient (Hobbs et al. 2008) suggests that this might be the case. From the regional geochemical trends, Hobbs et al. (2008) infer the brines in the Deep and Intermediate Bedrock Groundwater Zones of evaporated sea water origin, possibly emplaced 250 million years ago, 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.
- Alternatively, the disequilibrium heads may not be due to climate or geological changes. Alternative possible explanations include the presence of a gas phase within the pores (i.e. partial saturation) or osmosis (in which case the hydraulic conductvity of the rock must be too low for Darcy's law to apply).

Although disequilibrium heads in the Deep and Intermediate Bedrock Groundwater Zones may be associated with sediment erosion since the Carboniferous, significant erosion is currently not anticipated over the assessment time scales, which are much shorter than the 360 Ma time period from the Carboniferous to the present day. Therefore there are not anticipated to be any significant hydrological / hydrogeological responses to geological changes. Assessment of processes related to this FEP is primarily a Geosynthesis activity. If the Geosynthesis evaluation indicates that significant changes in hydrological/hydrogeological conditions due to geological changes are expected, for example due to significant glacial erosion over the assessment timescales, then the current assumption will be reassessed.

Given the preliminary nature of site-specific information and its interpretation, the Version 1 SA has assumed that the any hydrological/hydrogeological changes will be climate rather than geologically driven. In particular hydrogeological changes are expected in the Shallow Bedrock Groundwater Zone in response to climate change (see *Hydrological Response to Climate Change [1.3.07]*).

As noted in *Tectonic Movement [1.2.01]*, reactivation of an existing fault by a high magnitude earthquake is a possibility, albeit remote. This could result in the fault acting as a relatively high permeability groundwater pathway through the geosphere. This is considered in the Extreme Earthquake Scenario.

<u>FEP Screening</u>

Screened out for all scenarios other than the Extreme Earthquake Scenario. Re-evaluate in light of the Geosynthesis work for the next iteration of the SA.

1.2.12 Geomorphologic Response to Geological Changes

Definition

Factors related to surface landform changes on a regional and local scale, i.e., the general configuration of the Earth's surface, caused by the geological changes listed in FEP *[1.2.01]* to FEP *[1.2.10]*.

Key concepts relevant to this FEP include the following.

- Structural landforms: Landforms that are created by massive earth movements due to plate tectonics and related processes (e.g. folding, thrusting, tectonic uplift and land subsidence). This includes landforms with some of the following geomorphic features: fold mountains, rift valleys, and volcanoes.
- Weathering landforms: Landforms that are created by the physical or chemical decomposition of rock through weathering. Weathering produces landforms where rocks and sediments are decomposed and disintegrated. This includes landforms with some of the following geomorphic features: karst, patterned ground, and soil profiles.
- Erosional landforms: Landforms formed by the removal of weathered and eroded surface materials by wind, water, ice-sheets, and gravity. This includes landforms with some of the following geomorphic features: river valleys, glacial valleys, and coastal cliffs.
- Depositional landforms: Landforms formed by the deposition of weathered and eroded surface materials. On occasion, these deposits can be compressed, altered by pressure, heat and chemical processes to become sedimentary rocks. This includes landforms with some of the following geomorphic features: beaches, deltas, flood plains, and glacial moraines.

Screening Analysis

The general topography of the land surface is currently assumed to be relatively constant and stable over the evaluation period and any changes will be climatically (see *Geomorphologic Response to Climate Change [1.3.10]*) rather than geologically driven due to absence of geological drivers. All but two of the geological FEPs (FEP *[1.2.01]* to FEP *[1.2.10]*) have been screened out and the two that have been included (*Seismicity [1.2.03]* and *Pedogenesis [1.2.09]*) are not expected to have a significant effect on the geomorphology.

Assessment of processes referred to in this FEP is primarily a Geosynthesis activity. If the Geosynthesis evaluation indicates that significant changes in landforms are expected due to geological changes, then the assumption will be reassessed.

FEP Screening

Screened out. Re-evaluate in light of the Geosynthesis work for the next iteration of the SA.

1.2.13 Deformation (elastic, plastic or brittle)

Description

The physical deformation of geological structures in response to geological forces such as *Tectonic movement [1.2.01]* and *Orogeny [1.2.02]*. This includes faulting, fracturing, extrusion and compression of rocks.

A fault is a large-scale discontinuity or fracture in the Earth's crust accompanied by displacement of one side of the fracture relative to the other. Fractures may be caused by compressional or tensional forces in the Earth's crust. Such forces may result in the activation and extension of existing faults and, less likely, the generation of new faults, or they may result in creep during excavation of the repository.

Void spaces could form or be closed by compressional forces. Rock might fall into existing void spaces (e.g., repository rooms and tunnels).

Screening Analysis

Although deformation due to tectonic movement and orogeny is unlikely over the timescale of interest due to the site's tectonically stable location, deformation due to loading from ice-sheets is likely (see *Local glacial and ice-sheet effects [1.3.05]*).

In addition, as described in *Seismicity [1.2.03]*, seismic reactivation of existing faults is a possibility, albeit remote.

FEP Screening

Include FEP in all scenarios.

1.3 Climatic Processes and Effects

Description:

Factors related to the long-term processes arising from global climate changes and consequent regional effects on the performance of the DGR.

"Climatic Processes and Effects" is divided into individual FEPs as follows:

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

1.3.01 Global Climate Change

Description

This refers to the global climate and its evolution in time. Climate is characterised by a range of factors, notably temperature and precipitation. A global climate change would lead to local changes around a repository (see *Regional and local climate change [1.3.02]*), and possibly subsequently affect the performance of the repository.

One important possible climate change is the onset of a new ice age. The last two million years of the Earth's climate have been characterised by glacial/interglacial cycling, which more recently has had a periodicy of about 100,000 years, and it is expected that this will continue.

The global climate could also change due to: global warming, possibly caused by elevated levels of greenhouse gases in the atmosphere; extended winters caused by dust generated by nuclear war, volcanoes or meteorite impacts; or other large-scale changes that might be attributed to changes in ocean current patterns, changes in the extent of snow and vegetation cover on the Earth's surface, and changes in the degree of cloud cover in the atmosphere.

Screening Analysis

The two main drivers for global climate change over the timescale of interest are greenhouse-gas concentrations and changes in insolation.

Current trends towards global warming, whether human-caused or not, are likely to lead to significant changes in global climate. These changes would in turn lead to local climate changes around a repository, as discussed in *[1.3.02].*

Also, global warming is likely to delay the onset of the next global glacial cycle (BIOCLIM 2004). However, the factors that initiate glacial cycles, such as periodic reduction in solar insolation due to earth orbital variations, will still be present. Therefore it is likely that glacial/interglacial cycling will resume in the long term, or at least prudent to assume that cycling will resume for postclosure SA. This has the potential to affect the repository.

FEP Screening

Include FEP in all scenarios.

1.3.02 Regional and Local Climate Change

Description

The climate at a repository site, on local or regional scale, and its evolution in time. Climate is characterised by a range of factors, but most notably temperature and precipitation.

Changes to the local climate can be:

- a long-lasting response to variations in *Global Climate Change [1.3.01];*
- regional climate fluctuations lasting a few years in response to processes such as the North Atlantic Oscillation; and
- normal fluctuations caused by seasonal and even daily variations in weather.

Climate change can occur as smooth or abrupt gradations from one climate state to the next. Climate change is not just concerned with the starting and ending states, because the processes that occur during the change between these states may also be important.

The responses to local climate change are discussed under *Periglacial effects [1.3.04], Local glacial and ice-sheet effects [1.3.05], Warm climate effects (tropical and desert) [1.3.06], Hydrological response to climate changes [1.3.07], Ecological response to climate changes [1.3.08*] and *Human response to climate changes [1.3.09].*

Screening Analysis

Potentially important for the DGR system, especially in the surface and near-surface systems.

In the near term (i.e., on the scale of centuries or perhaps a thousand years), global warming is likely to cause temperature and precipitation changes which in turn could impact the surface and near-surface systems, for example there could be changes in Lake Huron water levels and therefore changes in the current shoreline, streams and wetlands. There could also be changes in the local ecosystems and human behaviour.

Although global warming is likely to delay the onset of the next ice-sheet advance by tens of thousands of years, it is expected that glacial/interglacial cycling will resume in the long term. At the Bruce site location, it is expected that this will involve extended periods when the site is under periglacial conditions [see *1.3.04*] and also when the site is covered by an ice-sheet [see *1.3.05*].

FEP Screening

Include FEP in all scenarios.

1.3.03 Sea-level Change

Description

Changes in the sea level due to climate processes and effects may occur as a result of global (eustatic) or regional (isostatic) changes. For example, as ice-sheets melt, the ocean volume increases and sea levels rise (global change). At a given location, water level will also be affected by the regional vertical rebound movement of the land mass associated with ice-sheet unloading or rebound (see also *Local glacial and ice-sheet effects [1.3.05]*).

Screening Analysis

Changes in sea level do not affect the site due to its elevated continental location.

FEP Screening

Screened out.

1.3.04 Periglacial Effects

Description

The physical processes and associated landforms in cold but ice-sheet-free environments (ice covered effects are discussed in *Local glacial effects [1.3.05]*).

A key feature of such environments is the formation of large volumes of permanently frozen subsurface soils and rock, called permafrost. Permafrost layers will isolate the surface from the groundwater, forcing regional groundwater flows to discharge at local unfrozen zones (called taliks) under lakes or large rivers. A volume of high salinity water may form at the front of the permafrost freezing zone. Permafrost will also prevent meltwater, produced during seasonal thaws, from percolating downwards, resulting in a saturated surface layer and possibly mass movement of soil on slopes. A tundra climate, characterised by cold and wet conditions, may form in regions nearby, affecting natural biota, and the characteristics and lifestyle of humans.

The advance or retreat of ice-sheets will lead to a change to or from periglacial conditions. These will be accompanied by changes in drainage and watershed systems, which will affect near-surface groundwater flow, and changes in the plant, animal and human communities, which will affect potential exposure pathways.

Screening Analysis

By analogy to historical conditions for the regional area around the Bruce site, the results of modelling using the University of Toronto Glacial System Model (Peltier 2008) indicate that future permafrost at the DGR site would typically be up to a few tens of metres thick. Generally, permafrost is not continuous unless the depth of permafrost exceeds 60 to 90 m (Brown and Pewe 1973). Therefore it is likely that permafrost around the site may alter the local groundwater flow somewhat, but will not freeze the entire thickness of the Shallow Bedrock Groundwater Zone. Surface recharge and discharge can still occur.

The impact of periglacial conditions on the intermediate and deep groundwater flow systems is expected to be minimal because they will not become frozen, and because their salinity and low permeability will isolate them from changes in the Shallow Bedrock Groundwater Zone. Evidence from the site is expected to confirm that there has been no or limited effect of previous periglacial conditions in these systems.

FEP Screening

Include FEP in all scenarios.

1.3.05 Local Glacial and Ice-sheet Effects

Description

The effects of glaciers, including ice-sheets, within the region of a repository, e.g., changes in the surface topography, water flow paths and ground stresses.

Screening Analysis

As identified in *[1.3.02]*, during future glacial cycles, the repository site is expected to be covered periodically by ice-sheets. Peltier (2008) provides an illustration of future glacial cycles, based on historical glacial cycles. In particular, the site would be covered multiple times with ice-sheets ranging from 2 to 3 km in thickness at the site.

The presence of an ice-sheet will change hydraulic heads directly, imposing an additional head at the surface of up to the equivalent to the height of the ice-sheet. During and after the glaciation, the surface and shallow groundwater flow paths will change due to various effects, ranging from the changed gradients around the ice-sheet, to changes in the permeability of the shallow system due to permafrost.

The ice-sheets may cause the introduction of oxygenated water, possibly during the period of ice-sheet advance or retreat. The process could significantly alter groundwater compositions in the Shallow and even the Intermediate Bedrock Groundwater Zones, notably concentrations of oxygen or other electrochemical oxidants. This particular process is not expected at the level of the repository due to the low permeability of the rocks. The presence of old saline groundwater/ pore water shows that there is no geochemical signature of previous ice-sheets at the DGR depth at the site.

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 depression 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, and degradation in the performance of the shafts (Damjanac 2008).

Glaciation would bring about significant changes to the biosphere. Erosional and depositional processes associated with ice-sheet movement and with meltwaters beneath the ice mass and at the margins, can change the local surface topography. For instance, erosion can form valleys whilst sedimentation can form moraines and eskers (see also *Denudation and Deposition [1.2.07]*). There would also be consequences for local humans and other biota (see *Ecological response to climate changes [1.3.08]* and *Human behavioural response to climate changes [1.3.09])*.

FEP Screening

Include FEP in all scenarios.

1.3.06 Warm Climate Effects (Tropical and Desert)

Description

Related to warm tropical and desert climates, including seasonal effects, and meteorological and geomorphologic effects special to these climates.

If the regional climate becomes tropical, then the region may experience extreme weather patterns (monsoons, hurricanes) that could result in flooding, storm surges and high winds with implications on erosion. The high temperatures and humidity associated with tropical climates result in rapid biological degradation and soils are generally thick.

In more arid regions, total rainfall, erosion and recharge may be dominated by infrequent storm events. Desertification as a result of extended drought could lead to deforestation and loss of grassland; dust storms might become a common feature causing soil erosion; alkali flats might form causing the accumulation of salts and contaminants at the soil surface. A lowered water table would affect natural biota, and might also lead to the use of deep water-supply wells to support local agriculture (or to use of distant water supplies).

These changes may also be associated with rapid alteration of topography associated with enhanced effects of erosion.

Screening Analysis

The development of tropical/warm-desert conditions around the Bruce site is unlikely over the time frame of interest due to its northerly latitude and the dominance of glacial/interglacial cycling. Furthermore, there is no evidence of tropical or hot desert conditions having been present at the site during the Quaternary. The initial period of human-induced global warming is not expected to result in extreme temperature rise resulting in tropical or desert conditions. Therefore warm climate effects are not included in the SA.

FEP Screening

Screened out.

1.3.07 Hydrological Response to Climate Changes

Description

Related to changes in hydrology (including hydrogeology) in response to climate change in a region.

The hydrology of a region is closely coupled to climate. Climate controls the amount of precipitation and evaporation, seasonal ice and snow cover, and thus the soil water balance, degree of soil saturation, surface runoff, changes in sediment load characteristics and groundwater recharge. Vegetation and human actions may modify these responses. Potential effects include climate-induced evolution of surface-water bodies, such as the formation of lakes and rivers, or their loss by sedimentation and infilling, river-course meander and long-lasting flooding or drying of low lying areas.

Other effects are discussed separately under *Periglacial effects [1.3.04], Regional and local glacial and ice-sheet effects [1.3.05], Warm climate effects (tropical and desert) [1.3.06], Ecological response to climate changes [1.3.08] and Human response to climate changes [1.3.09]*. More specific effects on the disposal system are described under *Hydrological processes and conditions (repository and geosphere) [2.1.07 and 2.2.06]*, *Surface-water bodies [2.3.05]* and *Hydrological regime and water balance (near-surface) [2.3.12].*

Screening Analysis

Although it is considered that flow conditions in the Deep and Intermediate Bedrock Groundwater Zones at the DGR site will not be significantly altered by glacial/interglacial cycling (see FEP *[1.2.11]*), significant changes will occur in the Shallow Bedrock Groundwater Zone. 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.

As the climate cools further and arctic conditions become established, permafrost is expected to develop in the Shallow Bedrock Groundwater Zone. With the onset of full glaciation, the insulating effect of the ice sheet will tend to reduce the depth of permafrost, although permafrost could extend down several tens of metres (Peltier 2008).

The groundwater will be under pressure due to the weight of the overlying ice. The shallow groundwater (below any permafrost) will tend to flow towards the margins of the ice sheet, although it will likely discharge to glacier basal meltwaters before it reaches the ice sheet margins, which may be located hundreds of km from the DGR site. The amelioration of the climate following the glacial maximum results in the retreat of the ice-sheet, the melting of the permafrost, the re-establishment of groundwater flow throughout the Shallow Bedrock Groundwater Zone, the potential introduction of large volumes of low-salinity and oxidising meltwater into the groundwater system and the development of proglacial lakes.

FEP Screening

Include FEP in all scenarios.

1.3.08 Ecological Response to Climate Changes

Description

The regional ecosystem, i.e. microbial, plant and animal populations and their interactions, will change in response to climate changes.

Screening Analysis

Ecosystems are responsive to climate changes that occur over a range of time scales. The current ecosystem in the vicinity of the Bruce site can be expected to evolve as a result of global warming in the next millennium resulting in some, relatively minor, changes to the nature and distribution of biota. In the longer term, the glacial/interglacial cycling that will affect the site will result in more significant changes to the ecosystem found at the site. As the temperature cools, the ecosystem will evolve into a tundra system; further cooling will result in an arctic ecosystem. Following glacial retreat and the return of temperatures to present-day levels, it is assumed that an ecosystem similar to that observed at the site today is re-established.

FEP Screening

Include FEP in all scenarios.

1.3.09 Human Behavioural Response to Climate Changes

Description

Human behaviour (including habits, diet, size of communities and dwelling types and location) changes in response to climate changes.

Climate affects the abundance and availability of natural resources such as water and the types of crops that can be grown. It also affects the activities and needs of humans; for instance, a colder climate would likely increase the time spent indoors and heating fuel needs. The more extreme a climate, the greater the extent of human control over the resources required to maintain agricultural productivity, e.g., through the use of controlled agricultural environments (greenhouses). Some climate changes may be sufficiently extreme that the region becomes uninhabitable on a permanent basis. Conversely, some climate changes may make a region more attractive for human habitation. These latter effects would influence the location and habits of a critical group.

Screening Analysis

The characteristics of potential exposure groups will change as a result of climate changes. The effect of global warming in the next millennium on human behaviour can be expected to have some, relatively minor, impact on human behaviour. More significant impacts are expected as the climate cools in the longer term, with agriculture and forestry becoming less viable around the repository site. Small centres of human population may be maintained; e.g., with external supplies of food and energy to support other forms of resource development; or by subsistence hunting, fishing and trapping, such as is observed in present-day tundra communities. During the ice-sheet period, no human occupation is expected at the site. As the climate warms up again during the interglacial period, it is expected that agriculture and forestry become re-established, and communities would be re-established in the area.

FEP Screening

Include FEP in all scenarios.

1.3.10 Geomorphologic Response to Climate Change

Description

Factors related to surface landform changes on a regional and local scale, i.e. the general configuration of the Earth's surface, caused by the climate changes listed in FEP *[1.3.01]* to FEP *[1.3.06]*.

Key concepts, examples and related FEPs include the following.

- Periglacial landforms: Periglacial landforms can be subdivided into two main groups: slope landforms and patterned ground landforms. Slope landforms include cryoplanation terraces, gelifluction terraces, and cryopediments. These slope landforms are similar to slope landforms found in other warmer, semi-arid environments.
- Patterned ground landforms include thermokarsts, pingos, palsas, earth hummocks, and polygonal ground. Most of the patterned ground landforms are unique to the periglacial environment.
- Warm climates: The high temperatures and humidity associated with tropical climates result in soils that are generally thin (see FEP *[1.3.06]*).

Screening Analysis

This EFEP is closely associated with *Local glacial and ice-sheet effects [1.3.05*]. It is recognised that the glacial/interglacial cycling, which will occur over the timescales of interest, will result in significant changes to the surface and near-surface environment due to the effects of ice-sheet erosion and deposition (see Section 6.3.4 of the System and its Evolution report, Little et al. 2009).

FEP Screening

Include FEP in all scenarios.

1.4 Future Human Actions (Active)

Description

Factors related to human actions and regional practices associated with the postclosure period (future), which can potentially affect the performance of the natural (geological) and/or engineered barriers, and consequently the performance of the DGR.

The "Future Human Action" category of FEPs refers to human actions, which generally originate from outside the temporal and spatial boundaries of the disposal system domain. Included in this category of FEPs are thus intrusive actions, but not the passive behaviour and habits of the local population (see *Human Behaviour [2.4]*).

"Future Human Actions (Active)" is a category of the External Factors in the DGR FEP List and is divided into individual FEPs as follows:

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 investigation
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

1.4.01 Human Influences on Climate

Description

Human activities that could affect the climate on global or local scales.

Examples of such activities include the following.

- The greenhouse effect. Man-made emissions of gases such as carbon dioxide and methane have been implicated as factors in global warming. Concerns exist that the continued emission of such gases could lead to massive climate change. For example, if the Michigan Basin experienced a warmer and drier climate, this effect could act to delay or even prevent the next glaciation cycle.
- On a local scale, climate could be modified by human activities such as de-forestation or farming practices that involve extensive irrigation.
- It is also possible that there will be an active effort to maintain conditions close to the present ones; as is indicated by current efforts to reduce causes of global warming.

Screening Analysis

The impacts of temperature and precipitation changes associated with human-induced global warming on the surface and near-surface systems can 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 (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) in the BIOCLIM project (BIOCLIM 2004) indicate that no significant glaciations would occur for considerably longer than 60,000 years (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).

On a local scale, changes in regional land-use etc. are considered to have a less significant impact on climate.

FEP Screening

Include FEP in all scenarios.

1.4.02 Social and Institutional Developments

Description

Related to changes in social patterns and degree of local government, planning and regulation.

Potentially significant social and institutional developments include (see also *Site development [1.4.08]*):

- 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 repository location and hazards (see also *Repository records and markers [1.1.12]*).

Screening Analysis

As noted in *Administrative control [1.1.09]* assumptions, the SA assumes that societal knowledge of the DGR will provide control for some initial period, but cannot be relied on indefinitely to prevent inadvertent human intrusion into the site. It is assumed that institutional control is maintained for a period of 300 years to prevent inadvertent human access (see Section 3.8 of the Postclosure Safety Assessment report, Quintessa et al. 2009). Thereafter, controls are no longer in place to prevent land-use change at the site and it is assumed that land uses in the previously controlled area become consistent with the wider region. In turn, this is assumed to be consistent with the land uses currently found in the area surrounding the Bruce site (i.e., predominantly agriculture, recreation and forestry) (see System and its Evolution report, Little et al. 2009). It is also assumed that social and institutional developments can be impacted by climate change.

FEP Screening

Include FEP in all scenarios.

1.4.03 Knowledge and Motivational Issues (Repository)

Description

Factors related to the degree of knowledge of the existence, location and/or nature of the repository, including reasons (motivation) for deliberate interference with, or intrusion into, a repository after closure with complete or incomplete knowledge.

Some future human actions could directly or indirectly impact upon the repository performance. Examples of these actions are presented in FEPs *[1.4.03]* to *[1.4.10]*. The motivation for these actions may be associated with complete, incomplete or no knowledge of the repository.

Screening Analysis

Two factors need to be considered.

- Knowledge of the repository: this will be influenced by the institutional control measures put in place for the facility, e.g., the keeping of records and the placement of markers. This may provide information on the existence and location, nature and content of the facility. Knowledge of the repository may provide reasons (motivation) for human actions that may potentially affect the performance of the DGR. Deliberate human actions are those taken with knowledge of the existence and location of the radioactive waste repository, e.g., deliberate attempts to retrieve the waste, malicious intrusion and sabotage and are discussed under *Deliberate human intrusion [1.4.15]*.
- Inadvertent human action: this refers to those human actions taken without knowledge or with incomplete knowledge or awareness of the existence of the radioactive waste repository. These actions may lead to inadvertent human (accidental) intrusion into the facility and potentially affect the performance of the natural (geological) and/or engineered barriers, and consequently the performance of the repository.
  - Loss of records: One of the ways that can be used to reduce the probability of inadvertent human intrusion is to keep records of the facility’s existence, location, nature and content. If these records are lost, the probability of intrusion will increase.
  - Loss of markers (misinterpretation): One of the ways that can be used to reduce the likelihood of inadvertent human intrusion is to place durable markers on the site to identify the location of the repository. If these markers are lost or are misinterpreted (as a result of loss of records), the likelihood of intrusion will increase.

FEP Screening

Include FEP in Human Intrusion Scenario only.

1.4.04 Drilling Activities

Description

The possibility of any type of drilling activity in the vicinity of the repository, performed without knowledge of the repository. This category includes exploratory boreholes drilled in association with mining but not *Mining and other underground activities* [1.4.05]. It also includes boreholes drilled for water-supply wells. The subsequent management of abstracted water is discussed in *Water management (groundwater and surface water)* [1.4.10].

Boreholes may have been drilled before construction of the repository and their existence forgotten or their location unknown. Other boreholes might also be drilled after the presence of the repository or the existence of its potential hazards has been forgotten.

Drilling activities might be carried out for a number of reasons, including:

- the abstraction of water from aquifers;
- the exploration for mineral and energy resources;
- the production of geothermal energy;
- the injection of liquid wastes; and
- scientific studies.

Potential impacts include direct exposure to excavated waste or contaminated gas, water and rock, and creation of altered groundwater, gas and contaminant transport pathways between the repository and surface environment. In addition, the most exposed individuals might have different characteristics; for example, the drilling crew.

Screening Analysis

Water wells can be expected to be drilled into the Shallow Bedrock Groundwater Zone in the future (such wells currently exist in the region around the site). They are unlikely to penetrate beyond 100 m since the water is not potable (e.g., Figure 51 of Hobbs et al. 2008).

Exploration boreholes could be drilled down into the DGR. However, the drilling of such deep boreholes at the site is very unlikely. The depth (680 m), small footprint of the DGR's emplacement rooms (c. 0.05 km^2), and lack of minerals or unusual geologic features in the area mean that the annual probability of such a borehole intruding into the DGR would be very low. It can be estimated at around $5\ 10^{-6}\ a^{-1}$, assuming a rate of occurrence of $10^{-10}\ m^{-2}\ a^{-1}$ – equivalent to one deep borehole per 100 years per 10 km x 10 km area (Gierszewski et al. 2004).

It is possible that the repository might be detected by remote measurement methods, and be deliberately targeted for study. Again, the uniformity of the sediments and lack of interesting minerals or geologic features in the area would argue against deliberate surveys of the area. Furthermore, if the repository were detected as an anomaly and deliberately targeted, then the nature of the contact with the repository would likely be more carefully managed.

Such wells and boreholes would only be drilled on the site once controls were no longer effective.

FEP Screening

Shallow water wells are included in all scenarios. An exploration borehole penetrating the DGR is considered in the Human Intrusion Scenario.

1.4.05 Mining and Other Underground Activities

Description

The possibility of any type of mining or excavation activity carried out in the vicinity of the repository, taken without knowledge of the repository. These activities include conventional blasting and excavation practices, strip mining and solution mining. Mining activities that involve drilling of boreholes are discussed under *Drilling activities (human intrusion) [1.4.04]*.

Reasons for mining and related activities include:

- recovery of nearby natural resources such as minerals;
- excavation of another repository for the storage or disposal of nuclear waste;
- excavation for storage or disposal of other wastes (e.g., natural gas storage, CO_2 sequestration);
- excavation for storage of valuable material such as petroleum products; and
- construction of underground shelters for military purposes.

Potential impacts include direct exposure to *in situ* waste, excavated waste or contaminated water and rock, and modifications to the performance of the repository system by creation of a large zone of unsaturated rock, creation of altered groundwater and contaminant transport pathways, modification of groundwater composition such as the introduction of oxygenated surface water, and damage to the integrity of the host rock. These impacts would depend on the location of the activity relative to the repository; for instance, a down-gradient excavation might enhance groundwater flow through the repository whereas an up-gradient excavation might introduce nitrates (from blasting activities) and other contaminants into groundwater flowing through the repository. These activities could also alter the terrestrial recharge and discharge locations.

In addition, these activities could affect the characteristics of the critical group; for instance, the most exposed individuals might be miners.

Screening Analysis

Mining into or near the DGR is unlikely because the host rock at the site is of no economic interest. Use of repository host rock for natural gas storage is considered unlikely given the presence of more suitable host rocks elsewhere. Any exploration for such an application is covered by *Drilling Activities [1.4.04]*.

It is noted that contaminants may migrate from the DGR to geological layers above the repository depth, up to the near surface. However, mining between the DGR and the surface can also be ruled out, given the lack of resources of economic interest.

FEP Screening

Screened out.

1.4.06 Un-intrusive Site Investigation

Description

The possibility and consequences of airborne, surface or other remote investigations of a repository site after repository closure.

Such investigations, such as prospecting for geological resources, might occur after information on the location of a repository had been lost. The evidence of the repository, e.g. discovery of an old shaft and/or a magnetic anomaly (due to the large amount of metal in the repository), might itself prompt investigation, including research of historical archives.

Note that this EFEP excludes all drilling activities, including those that do not penetrate into the repository. Such activities are considered to be intrusive (i.e., penetrate into the geosphere) rather than un-intrusive and are covered by *Drilling activities [1.4.04]*.

Screening Analysis

Un-intrusive site investigations for any purpose are not considered because they would have no immediate, direct effect on the DGR or associated contaminants.

If the investigations led to further "intrusive" investigation or development, then the consequences of these latter actions are dealt with under separate FEPs. See, for example, *Drilling activities [1.4.04], Mining and other underground activities [1.4.05],* and *Water management (groundwater and surface water) [1.4.10].*

FEP Screening

Screened out.

1.4.07 Surface Excavations

Description

Human activities carried out in the surface environment that can potentially affect the performance of the repository. These activities are undertaken without knowledge of the existence of the repository. Activities related to water management are discussed specifically under *Water management (groundwater and surface water) [1.4.10]*.

Examples of human activities at the surface environment include:

- quarrying and trenching;
- excavation for industrial purposes such as construction of a building;
- residential and road construction; and
- major earthmoving projects, such as construction of dikes and dams (which could alter the landscape and expose subsoil, overburden or bedrock and change groundwater recharge and discharge locations or affect groundwater flow regimes).

Screening Analysis

The depth of the repository means that there is no direct impact of surface excavations on the repository. Excavation might occur into surficial deposits, which in turn might be contaminated with repository-derived radionuclides (via the groundwater pathway). However, the impacts of such excavations are expected to be significantly less than direct abstraction and use of the contaminated groundwater and less than the impacts of intruding directly into the DGR via an exploration borehole.

FEP Screening

Screened out.

1.4.08 Site Development

Description

Factors related to any type of human activities during site development that can potentially affect the performance of the repository or the exposure pathways after closure.

As used here, site development refers to alterations to the surface environment after memory of the repository has been lost.

Examples of site development include the following.

- Preparation for construction of roads, residential buildings (urban) or industries. This includes earthmoving works such as levelling of the site, which may include filling up or removing the top part of the site.
- Change in topography caused by human modification of the natural site drainage (e.g., levelling of the site for the construction of an airport).
- Changes in land use, for example reclamation/extension, agricultural activity, urbanisation, waste disposal site, etc.

Screening Analysis

See the rationale for FEP *[1.4.07]* for earthmoving/surface excavation activities.

Changes of the site land use following cessation of controls have to be considered (e.g., reversion to agricultural, forestry and recreational uses). Climate-driven changes also have to be considered (see *Human behavioural response to climate change [1.3.09]* and *Social and institutional developments [1.4.02]*).

Future receptors corresponding to future site developments are considered in the SA.

FEP Screening

Include FEP in all scenarios.

1.4.09 Archaeology

Description

Factors related to any type of human activities associated with archaeology that can potentially affect the exposure pathways at or near the repository site after closure.

Screening Analysis

This FEP refers to archaeological investigations for prehistoric artefacts associated with the Bruce site. However, given the 680 m depth of the repository, surface archaeological excavations would not impact the repository directly. It is conceivable, although unlikely, that future un-intrusive site investigation might identify the DGR as a magnetic anomaly and a site for potential archaeological investigation. This might result in the intrusion into the DGR via an exploration borehole – an event that is considered under *Drilling activities [1.4.04]*.

Archaeological excavation might occur into surficial deposits, which in turn might be contaminated with repository-derived radionuclides. Archaeological excavations are different from surface excavations (see FEP *[1.4.07]*), in the sense that one can assume the process will be much slower resulting in much longer exposure times to humans. However, it is expected that the impacts of such excavations would still be significantly less than direct pumping and use of the contaminated groundwater for food crops and animals, and less than the impacts of intruding directly into the DGR via an exploration borehole.

FEP Screening

Screened out.

1.4.10 Water Management (Groundwater and Surface Water)

Description

Groundwater and surface-water management including water extraction, reservoirs, dams, canals, pipelines, and river management. These activities are undertaken without knowledge of the existence of the repository. Similar human activities are discussed under *Site development [1.4.08]*.

Water-management activities have a wide range of possible effects on a repository system. For instance, the construction of dams, diversions, lakes or drainage systems for hydroelectric generation, irrigation, flood control etc., could alter the landscape and expose subsoil, overburden or bedrock, and change groundwater flow regimes such as recharge and discharge locations.

The use made of groundwater and surface water can also have significant effects on impacts to humans and the environment. Water may be extracted for human domestic use (e.g. drinking water, washing, heating), agricultural uses (e.g. irrigation, animal consumption) and industrial uses (e.g. manufacturing, cleaning), introducing important pathways for contaminant movement.

One issue of particular importance is the source of water used for domestic and for irrigation purposes because it could result in direct and important exposure pathways such as ingestion of contaminated drinking water and food.

- Surface-water sources (i.e., Lake Huron) could be affected by runoff or direct discharge of contaminated water into lake sediment.
- Water-supply wells could be drilled into a contaminant plume in the geosphere, or draw in nearby contaminated groundwater.

Further consideration of domestic water use is discussed under *Water source [2.4.05.03]*. Further consideration of irrigation water is discussed under *Rural and agricultural land and water use (incl. fisheries) [2.4.09]* and *Urban and industrial land and water use [2.4.10]*.

Screening Analysis

There is present-day groundwater pumping and use for domestic and agricultural purposes in the area, therefore the use of near-surface aquifers should be considered. Lake Huron could also be used as a source of water, however any impacts are likely to be lower than those from water abstracted from the Shallow Bedrock Groundwater Zone due to greater dilution in the lake.

The presence of Lake Huron and potable groundwater supplies means that dams and reservoirs are considered unlikely. The development of hydroelectric projects is considered unlikely because the regional area around the DGR site has low topographic relief, so that any dams in the area would have low hydraulic head differences (typically less than 20 m).

FEP Screening

Include a well in the shallow geosphere in all scenarios.

1.4.11 Explosions and Crashes

Description

Deliberate or accidental explosions and crashes that might have some impact on a closed repository. Examples include underground nuclear testing, aircraft crash on the site, acts of war or sabotage, accidental equipment or chemical explosions or fires inside or near the repository, and explosion of nuclear or chemical bombs at the repository site.

These events could affect the performance of the repository in a variety of ways, such as changes to the integrity of the host rock and failure of seals. See also *Accidents and unplanned events [1.1.10]*.

Screening Analysis

Events of this type can be excluded because no known non-nuclear explosive device could breach or otherwise seriously affect the rock, groundwater or seals at the depth of the closed DGR. The impacts to exposure groups from the effects of a nuclear bomb exploding near a DGR site or a severe nuclear accident at the Bruce site would likely outweigh any additional impacts arising from the DGR, over both short and long time frames.

An ignition source in the repository is highly unlikely during the postclosure phase. Furthermore, the rapid use of all oxygen following repository closure means that gas explosions in the repository are highly improbable.

FEP Screening

Screened out.

1.4.12 Pollution

Description

Factors related to any type of human activities associated with pollution of the surface environment at or near the repository site that can potentially affect the exposure pathways at or near the repository site after closure.

As used here, pollution refers to the alteration of the chemical composition of the surface environment at or near the repository site, in such a way that the performance of the repository is influenced. Note that this FEP does not refer to pollution caused by the repository, but pollution from another source.

Screening Analysis

Pollution at or near the DGR site could occur in the following forms.

- Soil pollution: Soil pollution is possible from various sources, such as agricultural (e.g. soil fertilisers), industrial (e.g. chemical pollution) and urban development (e.g. pit latrines). These pollution sources may alter the chemical composition of the soil, influencing not only the contaminant migration properties of the soil, but also the vegetation and health of humans in the vicinity of the pollution.
- Groundwater pollution: Groundwater pollution is possible from the same sources as soil pollution, influencing the contaminant migration properties of the underlying aquifer.
- Air pollution: Sources of air pollution may include industries located in the vicinity of the disposal site, resulting in the deposition of contaminants at or near-the facility, which may result in the chemical alteration of the soil, and the chemical composition of the repository environment.
- Acid rain. Processes such as metal refining and fossil-fuel burning are often accompanied by releases into the atmosphere of nitrous oxides, sulphates and various heavy metals. The nitrates and sulphates can combine with atmospheric moisture to form acid rain, which can interfere with the growth, reproduction and survival of organisms. Acid rain can also influence the behaviour and transport of contaminants in the biosphere, particularly in surface water and soil.

The only potential impact of pollution on DGR performance is its ability to influence the mobility of contaminants. However, rocks and soils are naturally variable in their chemical and physical properties and any influence of pollution is likely to be of secondary importance in comparison.

FEP Screening

Screened out.

1.4.13 Remedial Actions

Description

Actions that might be taken following repository closure to remedy problems with the repository, such as not performing to the standards required, disruption by some natural event or process, or inadvertent or deliberate damage by human actions.

The main issue of concern is that the remedial actions may worsen the situation, possibly because it was incorrectly determined that the repository performance was impaired, or because remedial actions are improperly undertaken or unknowingly defeat important barriers. Another possibility is that contaminated materials from remedial activities may not be adequately stored or disposed.

Screening Analysis

The DGR will be operated in a staged manner (see System and its Evolution report, Little et al. 2009), with a period of 9 years of monitoring and closure activity between 2053 and 2062 during which there will be access to the DGR level and any necessary remedial operations can be undertaken with a fair degree of control to ensure that they do not have a detrimental impact on repository safety. Following closure, it is assumed that, even if there were to be remedial actions, their effects on the repository would be assessed at the time of remediation to ensure that they did not detrimentally affect repository safety.

FEP Screening

Screened out.

1.4.14 Technological Developments

Description

Future developments in technology, and changes in capacity and motivation to use these technologies. This factor also includes the loss of capacity to use a technology.

Of interest are those technologies that might change the capacity of humans to intrude deliberately or otherwise into a repository, to cause changes that would affect the movement of contaminants, and to affect exposure to those contaminants or its health implications. A lower level of technology might make it less likely that intrusion could be technically achieved. An improved level of technology might make intrusion more likely but as well might imply increased knowledge of the risks and how to control them. Other possibilities include advances that lead to the prevention or cure of radiation-induced cancers, and advances in food production (recent changes include hydroponics) that could lead to new exposure routes or levels.

Screening Analysis

In the SA study, it is assumed that future humans will largely resemble present-day humans in terms of societal behaviour, capabilities and actions. This means that there is no credit taken for advances in science and technology that might reduce the risk from the repository, e.g. no "cure for cancer" and no simple waste transmutation process.

As noted in the FEP Description, a lower level of technology might make it less likely that intrusion could be technically achieved especially into a repository that is 680 m below the surface. A higher level of technology might make intrusion more likely but as well might imply increased knowledge of the risks and how to control them. For example, factors are not considered that might result in retrieval and better disposal of the wastes.

FEP Screening

Screened out.

1.4.15 Deliberate Human Intrusion

Description

This category considers the possibility of deliberate human intrusion into a repository. It implies that the intruder has some knowledge of the repository and its potentially hazardous contents.

Deliberate intrusion could occur for reasons that include the following:

- performance of remedial activities to correct real or perceived faults in the repository performance, an activity also discussed under *Remedial actions [1.4.13]*;
- authorised retrieval of materials from the repository (see *Retrievability [1.1.11]*);
- unauthorised retrieval of radioactive material for malicious reasons including sabotage and war; and
- archaeological exploration which is driven by the observed or inferred presence of repository structures or contents, although the exact purpose of the repository may have been forgotten (see *Archaeology [1.4.09]*).

The potential effects of deliberate intrusion include removal of contaminants from the repository to the surface environment.

Inadvertent human intrusion involves actions by an intruder who is unaware of the existence of the repository and its contents, or an intruder who may suspect the existence of an underground feature but is unaware of its potentially dangerous contents. Examples of inadvertent human intrusion are discussed under *Drilling activities (human intrusion) [1.4.04]*, *Mining and other underground activities (human intrusion) [1.4.05], Un-intrusive site investigation [1.4.06],* and *Water management (groundwater and surface water) [1.4.10]*.

Screening Analysis

Deliberate human intrusion is excluded consistent with regulatory guide G-320 (CNSC 2006), which states that the consequences of deliberate human intrusion into the repository is the responsibility of those intruding. It is assumed that any society wishing to recover such materials would have the technology to understand and mitigate the short-term and long-term hazards. Malicious acts that might arise from deliberate human intrusion are also beyond the scope of the SA since they are a security rather than a safety issue. Nonetheless, it is noted that the depth of the DGR (680 m) will be a significant deterrent to malicious acts involving deliberate human intrusion.

FEP Screening

Screened out.

1.5 Other External Factors

Description

Any other external scenario-defining factors or events not accommodated in FEP categories [1.1] to [1.4].

There are two subcategories of other external factors, as follows:

1.5.01 Impact of meteorites and human space debris

1.5.02 Evolution of biota

1.5.01 Impact of Meteorites and Human Space Debris

Description

The possibility of a large meteorite or human space debris impact occurring at or close to the repository site.

The impact could cause phenomena such as the creation of a crater, activation, creation and sealing of faults, and physical and chemical changes in rock.

Screening Analysis

Wuschke et al. (1995) provided a generic safety assessment of the probability and consequences of a meteorite impact on a 500 m deep and 4 km^2 repository. For comparison, the DGR is 680 m deep and has a total footprint of about 0.3 km^2, so the risk would be lower.

Wuschke et al. (1995) (see also Goodwin et al. 1994, p.637) estimated the probability of a significant meteorite impact at or near the repository to be 1.4×10^{-11} per year (i.e., less than one chance in 10 billion). Their calculations were based on the assessment that the smallest (and hence most likely) meteorite to have a significant effect on the repository would produce an impact crater that would remove or severely damage the rock to the level of the repository. The New Quebec Crater (1.4 million years old), located on the Ungava peninsula in northern Quebec, is an example of an impact crater of this magnitude. (A large 1-km or more diameter meteor would cause global catastrophe regardless of whether it hit the repository site.)

Wuschke et al. (1995) found the radiological risk from the meteorite impact scenario to be very small, largely because the probability of a meteorite impact of sufficient magnitude to affect the repository was low. At longer times, the cumulative probability of an impact increases but radioactive decay reduces the consequences.

Although Wuschke et al. (1995) used meteorite probability versus size data from the 1980's, results from a more recent survey are very similar (Brown et al. 2002). The impact probability is fairly uniformly distributed over the earth surface.

Wuschke et al. (1995) considered the risk from a large but very unlikely meteorite. Conversely, the consequences of a "likely" meteorite can be considered. Specifically, meteorites with a one-in-a-million per year chance of directly hitting the repository site would be about 0.1-1 m diameter. Although most such bodies would break up on their way through the atmosphere, if a 1-m diameter meteorite did hit the ground intact, it could create a crater up to 4 m deep. This would have no effect on the DGR.

Human space debris falling to earth is also very unlikely to have any impact on the DGR. Most debris is far too small to have any impact. Large structures such as the international space station or shuttle are not very massive (about 300 Mg for the space station), nor very dense, and would impact with generally lower velocities than meteors. For comparison, a nominal 100-m diameter meteor would tend to weigh about 20,000 Mg.

In conclusion, meteorites and human space debris impact do not need to be considered.

FEP Screening

Screened out.

1.5.02 Evolution of Biota

Description
The possibility of biological evolution or genetic manipulation of humans, microbial, animal and plant species, and related consequences.

Over the times scales considered in some safety assessments, natural evolution of plants and animal species is possible. The rate varies between organisms, and can be very rapid in bacteria and microbes. Forced evolution of plant and animal species by selective breeding and genetic manipulation, especially species used for human foods, has occurred over very recent time scales. Humans are also subject to biological evolution, although perhaps to a lesser degree because they tend to modify the environment to suit their needs. Evolution may affect anatomical features and physiological processes.

Screening Analysis
Biological evolution, whether driven by natural random genetic variation and selection or by deliberate future human actions, is not predictable. Consistent with the recommendations of ICRP Publication 81 (ICRP 2000), doses are calculated for “ICRP Reference Man”, which is based on current human physiology.

Similarly, the general characteristics of biota such as plants and animals are assumed to remain similar to current biota.

It is likely that some microbial evolution would occur, but unlikely that it would lead to significant new human exposure or risk pathways since the materials present in the DGR are not unusual (organics, steel, plastics). Human exposure to microbes evolved for efficient anaerobic degradation of these materials would be far more likely due to common surface landfills because of their volume and proximity. First analyses of rock samples from the deep DGR site indicate very little microbial activity (Stroes-Gascoyne and Hamon 2007), likely due to the high salinity and small porosity, which would also inhibit movement of microbes away from the repository.

FEP Screening
Screened out.

2. REPOSITORY SYSTEM FACTORS

Description:

The Repository System Factors include those features, events and processes occurring within the spatial and temporal (postclosure) disposal system domain (i.e. internal factors) whose principal effect is to determine the evolution of the physical, chemical, biological and human conditions of the domain which in turn affect the release and migration of contaminants and the consequent exposure of human beings and the environment.

"Repository System Factors" is divided into four categories as follows:

2.1 Waste, Waste Form & Engineered System

2.2 Geological Environment

2.3 Surface Environment

2.4 Human Behaviour

2.1 Waste, Waste Form & Engineered System

Description

Factors related to the waste, the waste form and engineered components of the DGR.

This category relates to FEPs that are inside the spatial and temporal boundaries of the DGR domain and comprise all the features included in the design and construction of the DGR and its contents, as well as the processes associated with the performance and overall evolution of these features as a function of time.

“Waste, Waste Form and Engineered System" is divided into the following individual FEPs:

2.1.01 Waste inventory
2.1.02 Waste-form characteristics
2.1.03 Waste-packaging characteristics
2.1.04 Emplacement room and access and ring tunnel characteristics
2.1.05 Shaft characteristics
2.1.06 Mechanical processes and conditions (in wastes, emplacement rooms, tunnels and shafts)
2.1.07 Hydraulic/hydrogeological processes and conditions (in wastes, emplacement rooms, tunnels and shafts)
2.1.08 Chemical/geochemical processes and conditions (in wastes, emplacement rooms, tunnels and shafts)
2.1.09 Biological/biochemical processes and conditions (in wastes, emplacement rooms, tunnels and shafts)
2.1.10 Thermal processes and conditions (in wastes, emplacement rooms, tunnels and shafts)
2.1.11 Gas sources (in wastes, emplacement rooms, tunnels and shafts)
2.1.12 Radiation effects (in wastes, emplacement rooms, tunnels and shafts)
2.1.13 Extraneous materials effects
2.1.14 Nuclear criticality

Note that FEPs 2.1.01 to 2.1.05 describe the features of the waste, waste form and engineered aspects of the disposal system, in other words, a description of the components of the system as it is constructed, whereas FEPs 2.1.06 to 2.1.14 describe processes or changes associated with the time-dependent evolution of the waste, waste form and engineered features. Note that FEPs relating to contaminant characteristics are discussed in FEP category 3.1, whilst contaminant release and migration factors are discussed in FEP category 3.2.

2.1.01 Waste Inventory

2.1.01.01 Radionuclide Content

Description

The masses of radioactive isotopes (radionuclides) of all elements in the various waste forms.

Screening Analysis

Estimates of inventories are required for all radionuclides that may give rise to significant impacts. According to the OPG (2008) report on Reference Low and Intermediate Level Waste (L&ILW) Inventory, the total operational and refurbishment L&ILW radionuclide inventory is estimated to be 1.6 x 10^{16} Bq at repository closure (2062), attributed mostly to H-3, C-14, Fe-55, Co-60, Ni-63, Sr-90, Zr-93, Nb-94 and Cs-137.

After emplacement, the change in radionuclide inventories due to radioactive decay and ingrowth is taken into account as described in *Radioactive decay and ingrowth [3.1.01]*.

A large number of radionuclides are present in wastes initially (OPG 2008); however most are short-lived or only present in very small amounts. Screening calculations have been conducted for the L&ILW DGR inventory, to justify the selection of particular radionuclides (33 in total) for consideration in the safety assessment (Walke et al. 2008).

FEP Screening

Include FEP in all scenarios.

2.1.01.02 Chemical Content

Description

The mass of non-radioactive species in the waste forms disposed in the repository.

Screening Analysis

OPG (2008) provides information on the expected chemical inventory in the DGR. In particular, chemical content affects two aspects of the SA:

(i) the potential effects on gas generation, radionuclide mobility and solubility limits (this is discussed in FEP *[2.1.02.02]*); and

(ii) the potential impact of hazardous species in the waste on human and ecological receptors (e.g., from heavy metals).

FEP Screening

Include FEP in all scenarios.

2.1.02 Waste-form Characteristics

2.1.02.01 Metallic Wastes

Description
The physical, chemical and biological characteristics of the metallic wastes and any conditioning material at the time of disposal.

The physical, chemical and biological characteristics of these wastes are important for the definition of:
- contaminant release rates (source term);
- gas generation rate; and
- geochemical conditions in the repository.

Screening Analysis
According to OPG (2008), the waste inventory in the DGR will consist of operational and reactor refurbishment L&ILW. The wastes include the following metals:
- carbon steels (found in the compacted bales and boxes, all non-processible wastes, steam generators, irradiated core components, filters and filter elements, and ion-exchange columns);
- stainless steels (found in certain non-processible wastes, irradiated core components and certain retube wastes);
- copper alloy (found in the heat exchanger piping);
- Inconel 600 (found in the steam generator piping); and
- zirconium (found in certain retube wastes).

A description of the L&ILW waste characteristics is presented in the inventory report (OPG 2008).

For the purposes of the SA, three categories of metallic waste are considered: carbon steel (including copper alloys); stainless steel (including nickel alloys); and zircaloy. The amounts of each of the metals in the LLW and ILW are summarised in Table 2-6 of the System and its Evolution report (Little et al. 2009).

Details of associated conditioning are summarised in Section 3.3 of the Data report (Walke et al. 2009b). Cement is used to condition a small proportion of wastes containing metals. The SA only considers the grouting of steam generators.

FEP Screening
Include FEP in all scenarios.

2.1.02.02 Organic Wastes

Description
The physical, chemical and biological characteristics of the organic wastes and any conditioning material at the time of disposal.

The physical, chemical and biological characteristics of these wastes are important for the definition of:
- contaminant release rates (source term);
- gas generation rate; and
- geochemical conditions in the repository.

Screening Analysis
According to OPG (2008), the waste inventory in the DGR will consist of operational and reactor refurbishment L&ILW, and will include the following organics:
- paper, cotton, rubber and plastics (found in compacted bales and boxes and non-processible wastes);
- wood (found in non-processible wastes); and
- resins (found in certain non-processible wastes, LLW, ALW (Active Liquid Waste) and ILW resins, and ion-exchange columns).

A description of the LLW and ILW waste characteristics is presented in the inventory report (OPG 2008).

For the purposes of the SA, three categories of organic waste are considered: cellulose (paper, cotton, wood and organic absorbents); rubber and plastics (including bitumen); and resins. The amounts of organics in the LLW and ILW are summarised in Table 2-6 of the System and its Evolution report (Little et al. 2009).

Bitumen has been used to condition certain drums containing non-processible wastes. Non-processible wastes can also contain organic absorbents (see Section 3.3 of the Data report, Walke et al. 2009b).

FEP Screening
Include FEP in all scenarios.

2.1.02.03 Non-metallic, Inorganic Wastes

Description
The physical, chemical and biological characteristics of non-metallic, inorganic wastes at the time of disposal.

The physical, chemical and biological characteristics of these waste-forms are important for the definition of:

- contaminant release rates (source term);
- gas generation rate; and
- geochemical conditions in the repository.

Screening Analysis
According to OPG (2008), the waste inventory in the DGR will consist of operational and reactor refurbishment LLW and ILW, including the following non-metallic, inorganic wastes:

- bottom and baghouse ash; and
- concrete found in certain non-processible wastes.

A description of the LLW and ILW waste characteristics is presented in the inventory report (OPG 2008). The amounts of concrete in the LLW and ILW are summarised in Table 2-6 of the System and its Evolution report (Little et al. 2009).

FEP Screening
Include FEP in all scenarios.

2.1.03 Waste-packaging Characteristics

2.1.03.01 Containers

Description

The design-basis characteristics of the containers (including dimensions, material, waste loading, void space and construction method) used for the placement of waste in the repository.

The characteristics of the waste containers will affect the degradation of the waste with time, which in turn can influence the release of contaminants, the generation of gases and the chemical conditions in the repository.

Screening Analysis

A description of the characteristics of the waste packaging is given in the inventory report (OPG 2008). This is summarised from a postclosure safety assessment perspective in Section 2.1.2 and Table 2-3 of the System and its Evolution report (Little et al. 2009) and Section 3.2 of the Data report (Walke et al. 2009b). A range of metal and concrete drums/boxes is used with some metal-covered plastic pallet tanks. Some large irregular objects (e.g., heat exchangers) will be disposed without any packaging.

The waste containers are a source of metals, concrete and plastics that, in the SA, will affect contaminant release, gas generation (from corrosion of metals and degradation of plastics – see *Gas sources [2.1.11]*), and geochemical conditions in the repository (see *Chemical/geochemical processes and conditions [2.1.08]*). The amounts of organics, metals and concrete in the LLW and ILW containers and overpacks are summarised in Table 2-6 of the System and its Evolution report (Little et al. 2009).

FEP Screening

Include FEP in all scenarios.

2.1.03.02 Overpacks

Description

The design-basis characteristics of the overpacks (including dimensions, material, and construction method) used for the placement of waste in the repository.

The characteristics of the waste overpacks will affect the degradation of the waste with time, which in turn can influence the degradation of containers, the release of contaminants, the generation of gases and the chemical conditions in the repository.

Screening Analysis

A description of the characteristics of the waste overpacks is given in the inventory report (OPG 2008). This is summarised from a postclosure safety assessment perspective in Section 2.1.2 and Table 2-3 of the System and its Evolution report (Little et al. 2009) and Section 3.2 of the Data report (Walke et al. 2009b). A range of metal and concrete overpacks is used, although not all waste streams are overpacked.

The overpacks are a source of metals, concrete and plastics that, in the SA, will affect contaminant release, gas generation (from corrosion of metals and degradation of plastics – see *Gas sources [2.1.11]*), and geochemical conditions in the repository (see *Chemical/geochemical processes and conditions [2.1.08]*). The amounts of organics, metals and concrete in the LLW and ILW containers and overpacks are summarised in Table 2-6 of the System and its Evolution report (Little et al. 2009).

<u>FEP Screening</u>
Include FEP in all scenarios.

2.1.04 Emplacement Room and Access and Ring Tunnel Characteristics

Description

The design-basis characteristics of the emplacement rooms, access tunnels and ring tunnels. This aspect is divided into the following parts:

- 2.1.04.01 Roofs and walls
- 2.1.04.02 Floors
- 2.1.04.03 Rock bolts
- 2.1.04.04 Sealing walls
- 2.1.04.05 Backfill

2.1.04.01 Roofs and Walls

Description

The design-basis characteristics of the roofs and walls of emplacement rooms, access tunnels and ring tunnel.

Screening Analysis

A description of the characteristics of the roofs and walls of the rooms and tunnels is given in the conceptual design report (Hatch 2008). This is summarised from a postclosure safety assessment perspective in Section 2.2.1 of the System and its Evolution report (Little et al. 2009) and Section 4.1 of the Data report (Walke et al. 2009b).

The rooms and tunnel will be primarily excavated using roadheaders. The roofs and walls will be covered with shotcrete extending half-way down the walls. Steel wire mesh, held in place by rock bolts, will be used in place of shotcrete in localised areas if rock conditions are favourable.

Considered as a source of metals and concrete in the SA that will affect gas generation (see *Gas sources [2.1.11]*), and geochemical conditions in the repository (see *Chemical/geochemical processes and conditions [2.1.08]*). See Tables 4-8 and 4-9 of Data report (Walke et al. 2009b).

FEP Screening

Include FEP in all scenarios.

2.1.04.02 Floors

Description

The design-basis characteristics of the floors of emplacement rooms, access tunnels and ring tunnel.

Screening Analysis

A description of the characteristics of the floors of the rooms and tunnels is given in the conceptual design report (Hatch 2008). This is summarised from a postclosure safety assessment perspective in Section 2.2.1 of the System and its Evolution report (Little et al. 2009) and Section 4.1 of the Data report (Walke et al. 2009b).

The rooms and tunnels will have concrete floors (typically 0.2 m thick). A railway line will run from the Main Shaft along the access tunnel for the East Panel to allow the movement of large waste packages on rail cars towed by a forklift truck. These large items will require in-room handling using a gantry crane, and rail lines to support it will run the whole length of the three rooms concerned. The concrete floor will be 0.6 m thick along the edges of the access tunnel and emplacement rooms to accommodate embedded rails.

Considered as a source of metals and concrete in the SA that will affect gas generation (see *Gas sources [2.1.11]*), and geochemical conditions in the repository (see *Chemical/geochemical processes and conditions [2.1.08]*). See Tables 4-8 and 4-9 of Data report (Walke et al. 2009b).

FEP Screening
Include FEP in all scenarios.

2.1.04.03 Rock Bolts

Description
The design-basis characteristics of the rock bolts used throughout the emplacement rooms, access tunnels and ring tunnel to support their roofs and walls during the operational phase.

Screening Analysis
A description of the characteristics of the rock bolts is given in Section 7.5.5 of the conceptual design report (Hatch 2008). The rock bolts are Grade 420 steel, 3.6 m long and 25 mm in diameter.

They are considered as a source of metals in the SA that will affect gas generation (from corrosion of metal rails – see *Gas sources [2.1.11]*), and geochemical conditions in the repository (see *Chemical/geochemical processes and conditions [2.1.08]*). See Table 4-9 of Data report (Walke et al. 2009b).

FEP Screening
Include FEP in all scenarios.

2.1.04.04 Sealing Walls

Description
The design-basis characteristics of any walls that are used to seal the emplacement rooms, access tunnels and ring tunnel in the repository.

Screening Analysis
Once an emplacement room has been filled with waste, closure panels will be constructed (see Section 13.4 in the conceptual design report, Hatch (2008), and Section 2.2.3.1 of the System and its Evolution report, Little et al. (2009)). These will be reinforced concrete walls designed to provide a secure, relatively air-tight seal to the room during the operational phase. 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. No details are given in Hatch (2008) as to the nature or location of any seals in the access tunnels or ring tunnel, so it is assumed in the Version 1 SA that there are none present.

The sealing walls are considered as a source of metals and concrete in the SA that will affect gas generation (see *Gas sources [2.1.11]*), and geochemical conditions in the repository (see *Chemical/geochemical processes and conditions [2.1.08]*). See Tables 4-8 and 4-9 of Data report (Walke et al. 2009b).

FEP Screening
Included FEP in all scenarios.

2.1.04.05 Backfill

Description

The design-basis characteristics of any backfill used in the emplacement rooms, access tunnels and ring tunnel in the repository.

Screening Analysis
The conceptual design does not consider any backfill in the rooms and tunnels (Hatch 2008). However, a variant calculation case for the Normal Evolution Scenario consider the backfilling of the ring and access tunnels with concrete to limit the extent of rockfall in the repository (see Appendix A of Postclosure Safety Assessment report, Quintessa et al. 2009).

FEP Screening
FEP included in a Normal Evolution Scenario variant calculation that considers backfilling of tunnels with concrete. FEP excluded in all other Normal Evolution Scenario calculation cases and all other scenarios.

2.1.05 Shaft Characteristics

Description

The design-basis characteristics of the shafts used to access and ventilate the repository. This aspect is divided into the following parts:

- 2.1.05.01 Lining
- 2.1.05.02 Backfill
- 2.1.05.03 Plugs
- 2.1.05.04 Rock bolts

2.1.05.01 Lining

Description

The design-basis characteristics of the shaft lining.

Screening Analysis

The Main and Ventilation shafts will be concrete-lined to limit potential water inflow during construction and operation (see conceptual design report, Hatch 2008). However, 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. Decommissioning of the shafts will involve the removal of the concrete shaft liner from the base of the shaft sumps up to 183 m below ground surface (see Section 14.1.2 of concept design report, Hatch 2008).

FEP Screening

Include FEP in all scenarios for the upper 183 m of the shafts.

2.1.05.02 Backfill

Description

The design-basis characteristics of the shaft backfill.

Screening Analysis

Various materials are used as backfill in the shaft design assessed in the Version 1 SA (see Section 2.2.3.4 and Figure 2-6 of the System and its Evolution Report, Little et al. 2009 and Section 4 of the Data report, Walke et al. 2009b). 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. Backfill between the concrete bulkheads, with the exception of the asphalt waterstops, will not be keyed into the surrounding rock. The role of the backfill is to limit migration of contaminants in groundwater and gas.

FEP Screening

Include FEP in all scenarios, although significantly degraded characteristics are adopted for the Severe Shaft Seal Failure Scenario.

2.1.05.03 Plugs

Description
The design-basis characteristics of the shaft plugs.

Screening Analysis
The shaft design assessed in the Version 1 SA comprises the flowing plugs:

- a concrete monolith that will be placed at the base of each shaft; and
- 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[2].

The characteristics of the monoliths and bulkheads are described in Section 4 of the Data report (Walke et al. 2009b). Their role is to limit migration of contaminants in groundwater and gas.

FEP Screening
Include FEP in all scenarios, although significantly degraded characteristics are adopted for the Severe Shaft Seal Failure Scenario.

2.1.05.04 Rock Bolts

Description
The design-basis characteristics of the rock bolts used in the shafts to support their sides during the operational phase.

Screening Analysis
Rock bolts will be used to secure the shaft walls in the top 291 m of the shafts. The rock bolts will be resin bolts, 3 m long and 25 mm in diameter. Considering the need to minimise the extent of the EDZ in lower parts of the shaft, the use of rockbolts is minimised as their installation can potentially enlarge the EDZ. Instead expandable/yielding steel ribs will be used that can be removed at closure. Details are provided in the conceptual design report (Hatch 2008).

Decommissioning of the shafts will involve the removal of any rock bolts from the base of the shaft sumps up to 183 m below ground surface (see Section 14.1.2 of concept design report, Hatch 2008). It is expected that rock bolts remaining in the upper shaft will not have an impact on postclosure safety and so they are not considered in the SA.

FEP Screening
Screened out.

2 The concrete bulkhead at the surface will not be keyed into the rock (Hatch 2008).

2.1.06 Mechanical Processes and Conditions (in Wastes, Emplacement Rooms, Tunnels and Shafts)

Description

The mechanical processes that affect the wastes, containers, seals and other engineered features, and the overall mechanical evolution of the DGR with time. This includes the effects of hydraulic and mechanical loads imposed on wastes, containers and repository components by the surrounding geology.

This factor is discussed further under:

- 2.1.06.01 Packaging collapse
- 2.1.06.02 Material volume changes
- 2.1.06.03 Emplacement room/tunnel collapse
- 2.1.06.04 Container movement
- 2.1.06.05 Fracture formation
- 2.1.06.06 Stress-corrosion cracking
- 2.1.06.07 Gas explosions
- 2.1.06.08 Influence of climate change

See also related issues under *Mechanical processes and conditions (geosphere) [2.2.05]*.

2.1.06.01 Packaging Collapse

Description

The processes that lead to the collapse of packaging and the compression of waste placed inside in the postclosure period which can promote the release of contaminants from the waste packages. As noted in *Waste-form characteristics [2.1.02]*, there are two main packaging types: steel and concrete. Different processes can cause the collapse of these packages and so this FEP is divided into:

2.1.06.01.A Steel Failure
2.1.06.02.B Concrete Failure

2.1.06.01.A Steel Failure

Description

The processes that lead to the collapse of steel packaging in the postclosure period.

Screening Analysis

Most of the packaging in the DGR comprises carbon and stainless steels. These containers will be subject to corrosion from early in the postclosure period, initially due to water vapour in the humid atmosphere and water in the wastes, and later to groundwater as it slowly infiltrates the emplacement rooms (see *Corrosion [2.1.08.04]*). Ultimately, this process could lead to container collapse.

In addition, rock falls from the roofs and walls of emplacement rooms (see *Emplacement room/ tunnel collapse [2.1.06.03]*) could distort steel containers or, where corrosion has taken hold, cause collapse. Seismic events could also cause collapse in already weakened packages by shaking them.

FEP Screening

Include FEP in all scenarios.

2.1.06.01.B Concrete Failure

Description

The processes that lead to the collapse of concrete packaging in the postclosure period.

Screening Analysis

Concrete containment (in some overpacks) would degrade over time due to various mechanical (e.g., *[2.1.06.02.A]*) and chemical processes (e.g. *[2.1.08.06]*) resulting in its collapse. In addition, rock falls from the roofs and walls of emplacement rooms (see *Emplacement room/ tunnel collapse [2.1.06.03]*) could cause collapse. Seismic events could also cause failure in already weakened concrete packages by shaking them.

FEP Screening

Include FEP in all scenarios.

2.1.06.02 Material Volume Changes

Description
The effects of volume changes in materials used in repositories. The volume changes associated with the main materials used in repositories are discussed in the following three FEPs:

2.1.06.02.A Concrete Shrinkage/Expansion
2.1.06.02.B Bentonite Swelling
2.1.06.02.C Corrosion Products

2.1.06.02.A Concrete Shrinkage/Expansion

Description
Concrete shows volume changes during the curing phase and during ageing.

Screening Analysis
The concretes proposed for use in the DGR will have been emplaced considerably before facility closure. Their curing, with any accompanying volume changes, will therefore have been completed well before the closure of the DGR. Any deleterious effects of the volume changes can therefore be remedied.

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. 1998). These phases are likely to condition coexisting pore fluids to a lower pH and induce some contraction and/or shrinkage of the cement paste. However, 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 ($CaSO_4.2H_2O$). The net solids volume increase is more than 300 %, on the basis that both Al and S are present in the aqueous phase.

FEP Screening
Include FEP in all scenarios.

2.1.06.02.B Backfill Swelling

Description
This FEP is concerned mainly with the use of bentonite clays in a repository. When wet, bentonite swells and becomes highly plastic. It is thus able to function as an efficient sealant, being able to move into crevices and fractures, etc., and can adjust to new features that evolve as the repository ages. Two categories of swelling are generally observed: inner crystalline swelling caused by the hydration of the exchangeable cations in the dry clay; and osmotic swelling, resulting from ion concentration gradients between clay surfaces and water.

The swollen backfill exerts a swelling pressure on the excavated system which is likely to range up to 13 MPa for a well-compacted material (SKB 2006). In practice, the main concern with swollen bentonite is whether it would maintain its swelling pressure, and therefore its performance, in the long term. Chemical modifications (particularly attack by potassium ions in groundwater) could cause significant reductions in swelling pressure, making the material less effective in sealing cracks, etc. (Atkinson et al. 1997).

Screening Assessment
Bentonite is proposed for use as one of the shaft sealants in the DGR. The swelling pressure enables the material to act effectively in this context, and the system would be designed so that the pressure exerted would not have a deleterious effect on the surrounding rock. Mineralisation might lead to embrittlement of bentonite and loss of swelling pressure but the effects are likely to be spatially limited (see Section 4.2.4 of the System and its Evolution report, Little et al. 2009).

FEP Screening
Include FEP in all scenarios.

2.1.06.02.C Corrosion Products

Description
Corrosion of metals in packaging and wastes usually leads to corrosion products that have larger volumes than the original metals.

Screening Assessment
Metallic wastes and packaging will corrode resulting corrosion products that have larger volumes than the original metals. Since the corrosion process is considered in all scenarios, the associated volume changes are considered.

FEP Screening
Include FEP in all scenarios.

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2.1.06.03 Emplacement Room/Tunnel Collapse

Description
The effect of the host geology on the long-term stability of the excavations carried out to construct a deep repository.

Excavation of a deep repository will result in the removal of substantial volumes of host rock. Construction, commissioning and operation of the facility will occupy several decades. Excavation will create stresses across the repository, which may be increased in the postclosure period by seismic events and ice-sheet loading and unloading. The stresses could lead to fracture formation and changes in host rock permeability.

These stresses could lead to rock falls from roofs and tunnels, which might also induce fragmentation of concrete linings and the failure of waste packaging.

Screening Analysis
Failure of the rock will eventually occur as the rooms and tunnels are not backfilled (see *Backfill [2.1.04.05]*). 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 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).

Rockfall, induced by seismic events and/or ice-sheet loading/unloading, will fill the void in the rooms and 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 (see Appendix A in the System and its Evolution report, Little et al. 2009). 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.

Rockfall can cause waste packaging to be breached and the waste placed inside can become compressed (see *Package collapse [2.1.06.01]*) promoting the release of contaminants.

FEP Screening
Include FEP in all scenarios.

2.1.06.04 Container Movement

Description
Effects in and around a repository that could lead to movement of containers.

These effects are essentially as described in *Emplacement room/ tunnel collapse [2.1.06.03].* Thus falls of rocks or fragments of concrete lining on to containers could cause them to move or slump. The causes of this would be relief of the stresses created by excavating the repository, ice-sheet loading/unloading, or seismic events.

Screening Analysis
This type of event could occur in the DGR, particularly as it is proposed not to use a backfill. Slumping of the waste containers in the emplacement rooms will occur as the packages at the bottom of the stacks corrode/degrade 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.

FEP Screening
Include FEP in all scenarios.

2.1.06.05 Fracture Formation

Description
The potential for fracturing in engineered features of the repository (and shafts) in the postclosure period. This would be initiated by the relief of stresses set up in the rock when the facility was excavated, by ice-sheet loading/unloading, or by a seismic event. The resulting falls of rock could lead to fracturing of repository contents, which may already have been weakened by corrosion (of metallic containers and waste) and reaction with groundwater (cementitious walls, roofs, floors and overpacks). Cracks in the repository e.g., due to excavation, may also be enhanced by gas pressure.

Fractures can also develop due to preferential rupturing of various joints in the system, because these are the points of greatest potential weakness. Important types of joint include:
1. the interfaces between concrete linings and the host rock;
2. the interfaces between major concrete features, notably the wall/floor interface; and
3. the interfaces between the concrete plugs and the walls of the shafts.

Screening Analysis
Considered through its time-dependent effect on the physical performance of the concrete bulkhead in the Shallow Bedrock Groundwater Zone and at its interface with the Intermediate Bedrock Groundwater Zone (see Section 2.3.2.1 of the System and its Evolution report, Little et al. 2009). The expected stable geological environment, even under conditions of ice-sheet loading and unloading, is expected to limit fracture formation in the DGR and lower shaft.

FEP Screening
Include FEP in all scenarios for upper shaft, and for all engineered features for the Severe Shaft Seal Failure Scenario.

2.1.06.06 Stress-corrosion Cracking

Description
A potential failure mechanism for metallic containers, involving the uptake of hydrogen gas and formation of metal hydrides.

Stress-corrosion cracking, or hydride embrittlement and cracking, may mechanically weaken the container and promote subsequent failure or other corrosion mechanisms. The process might be accelerated if hydrogen is attracted to and accumulates at a defect or crack site.

Screening Analysis
Stress-corrosion cracking is not considered to be a viable failure mechanism since the various factors (such as oxidants and stress-corrosion agents) necessary for crack initiation and propagation are not expected to be operative simultaneously in the repository environment.

FEP Screening
Screened out.

2.1.06.07 Gas Explosion

Description
A gas fire or explosion can occur if a flammable gas mixture (e.g., H_2/O_2 mixture) forms at sufficient concentration and there is a source of ignition.

Screening Analysis
In the postclosure period, the presence of an explosive gas would only be possible soon after repository closure, if hydrogen generated in oxygen-deficient regions migrated and mixed with any remaining oxygen. The only credible source of ignition in the closed DGR is a rock fall (that produces sparks), which might occur in emplacement rooms and tunnels as no backfill is present.

However, the rapid consumption of all oxygen during the first 10 years following closure due to corrosion and microbial reactions (see the Gas Modelling report, Calder et al. 2009) means that postclosure gas explosions in the repository are highly improbable.

FEP Screening
Screened out.

2.1.06.08 Influence of Climate Change

Description
Influence of climate change on the mechanical processes and conditions in the repository and shafts.

Screening Analysis
After initial anthropogenic warming, it is expected that the cycle of glacial-interglacial cycling experienced during the Quaternary will resume. Consistent with evidence from the site concerning the effects of previous climate change during the Quaternary, the system at depth is expected to be mostly isolated from the effects of future climate change. However, during ice-sheet advance and retreat 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 stress increases of up to 30 MPa. The impact of this on repository stability has not yet been quantitatively evaluated, however it is expected that it will promote rockfalls in the rooms and tunnels (see *Emplacement room/tunnel collapse [2.1.06.03]*) and has been included as a cause of rockfall in the conceptual model (see Appendix A of the System and its Evolution report, Little et al. 2009).

It is recognised that the near-surface environment will be significantly affected by glacial-interglacial cycling and the mechanical impacts of this cycling on the upper shaft (i.e., in the Surficial and Shallow Bedrock Groundwater Zones) are considered to be one of the factors resulting in the degradation of the upper shaft and its properties. For the Severe Shaft Seal Failure Scenario, the degradation and associated mechanical impacts are also assumed to affect the lower shaft (i.e., in the Intermediate and Deep Bedrock Groundwater Zones).

FEP Screening
Include FEP in all scenarios.

2.1.07 Hydraulic / Hydrogeological Processes and Conditions (in Wastes, Emplacement Rooms, Tunnels and Shafts)

Description

The hydrological and hydrogeological processes that affect the wastes, containers, seals and other engineered features, and the overall hydrological evolution of the repository with time. This includes the hydraulic influences on wastes, containers and repository components by the surrounding geology. The movement of contaminants is described in *Water-mediated migration of contaminants [3.2.02]*.

This factor is discussed further under:

- 2.1.07.01 Resaturation/desaturation
- 2.1.07.02 Water flow
- 2.1.07.03 Gas-mediated water flow
- 2.1.07.04 Failure of drainage system
- 2.1.07.05 Fracturing of concrete components due to hydraulic pressure
- 2.1.07.06 Coupled hydraulic processes, including temperature, chemical or electrical gradients
- 2.1.07.07 Influence of climate change

These processes affect each other, and are also affected by other factors, such as the formation of cracks in the backfill (see *Mechanical processes and conditions [2.1.06]*, the *Disturbed zone [2.2.03]*, and *Seismicity [1.2.03]*. See also related issues under *Hydraulic/hydrogeological processes and conditions (geosphere) [2.2.06]*.

2.1.07.01 Resaturation/Desaturation

Description

Repository resaturation processes are important to quantify as mobility of contaminants dissolved in groundwater will only commence after wastes come into contact with water. Water will flow into the repository in a complex process governed by hydraulic gradients, EDZ and geosphere gas and liquid flow parameters, gas pressure in the repository, and relative saturations in the EDZ and geosphere. Most of these processes are described in other FEPs (*2.2.01, 2.2.02, 2.2.06, 2.2.10*). Eventually the repository will completely resaturate.

Screening Analysis

A range of resatuartion/desaturation profiles is considered in the Version 1 SA (see Normal Evolution Scenario Analysis report, Walke et al. 2009a). These include profiles that consider an initial increase in the degree of saturation followed by a decrease (due to the build up of gas pressure) followed by the eventual full resaturation of the DGR. Instantaneous resaturation of the repository is also considered.

FEP Screening

Include FEP in all scenarios.

2.1.07.02 Water Flow

Description
Both during and subsequent to repository resaturation, water will flow within the repository in response to hydraulic gradients and according to hydraulic characteristics of the repository.

Screening Analysis
The repository environment is largely open spaces at a common elevation. No backfilling is currently planned. It is assumed that there is a +140 m pressure head in the Cambrian which will affect the repository and its shafts resulting in the development of water flow and contaminant transport pathways (see Groundwater Modelling report, Avis et al. 2009).

FEP Screening
Include FEP in all scenarios.

2.1.07.03 Gas-mediated Water Flow

Description
Gas generation within the repository may affect water flow within the repository.

Screening Analysis
Degradation of the waste packages will result in the generation of gases, primarily hydrogen, carbon dioxide and methane, over an extended period of time. Initially, the rate of gas generation is assumed to be greater than the rate of gas loss due to the low permeability of the host rock and gas pressure will increase. Thereafter, pressures decrease slowly to the hydrostatic level (see Normal Evolution Scenario Analysis report, Walke et al. 2009a).

The effect of gas generation on water flow in the repository is taken into account in the SA model through the parameterisation of the DGR saturation-desaturation profile (see Normal Evolution Scenario Analysis report, Walke et al. 2009a).

FEP Screening
Include FEP in all scenarios.

2.1.07.04 Failure of Drainage System

Description
Failure of drainage system.

Screening Analysis
It is assumed that the drainage system will be decommissioned during the repository closure process and so no drainage system is operative during the postclosure period.

FEP Screening
Screened out.

2.1.07.05 Fracturing of Repository Components due to Hydraulic Pressure

Description
Forces exerted by flowing groundwater within the repository and shafts that are sufficient to cause fracturing of cementitious components such as overpacks, walls, floors, backfill, linings and plugs

Screening Analysis
The rate of flow of groundwater entering a deep repository is likely to be very slow (otherwise the host geology would not have been selected). The regime of slow flow will continue after the repository has resaturated. Pressure gradients on cementitious components will therefore be very low, minimising the potential for fracturing them by this route.

Although the concrete plugs in the lower shafts might be subject to some pressure gradient, it is considered that the gradient will be insufficient to cause fracturing of the seals.

FEP Screening
Screened out.

2.1.07.06 Coupled Hydraulic Processes including Temperature, Chemical or Electrical Gradients

Description
Fluid flow driven by temperature, chemical or electrical gradients, rather than due to hydraulic pressure gradients. Fluid flow driven by these gradients is referred to as coupled transport, and is called thermal, chemical and electrical osmosis depending on the driving gradient.

Temperature changes in the repository environment will cause expansion (heating) or contraction (cooling) of fluid in the repository. This could induce fluid flows to/from the EDZ/Geosphere.

Screening Analysis
An analysis of the effects of coupled processes and implications for solute transport has been provided in the context of the Swiss Opalinus Clay (spent fuel and ILW disposal), which is under consideration as the possible site of a deep geologic repository (Soler 2001).

Soler (2001) concluded that only thermal osmosis might be important to fluid (and solute) transport. But when mass conservation calculations were undertaken with 2-D and 3-D models, the results showed no significant effect on time scales of 1,000 years or more, in part because temperature gradients would have dropped considerably by then. It was considered possible that coupled processes might be important during the resaturation phase.

However, the LLW and ILW wastes are not expected to cause significant heating of the repository environment (see *Thermal processes and conditions [2.1.10]*), therefore there is no thermal source to drive thermally induced flow. On the basis of these results, coupled processes are considered to be a small effect.

FEP Screening
Screened out.

2.1.07.07 Influence of Climate Change

Description
The influence of climate change on the hydraulic and hydrogeological processes that affect the wastes, containers, seals and other engineered features, and the overall hydrological evolution of the repository with time. This includes the hydraulic influences on wastes, containers and repository components by the surrounding geology. The movement of contaminants is described in *Water-mediated transport of contaminants [3.2.02]*.

Screening Analysis
Global and local climate changes (see *[1.3.01 and 1.3.02]*) may affect the hydraulic properties of the geosphere surrounding the DGR, which could potentially affect wastes, containers and other DGR components. However, due to the low permeability of the host rock and the absence of evidence of the effect of previous ice-sheet advances and retreats at depth, it is expected that there will be no significant hydraulic/hydrogeological effects at the depth of the repository other than the potential for transient changes in heads.

It is recognised that the near-surface environment will be significantly affected by glacial-interglacial cycling and the hydraulic and hydrogeological impacts of this cycling on the upper shaft (i.e. in the Surficial and Shallow Bedrock Groundwater Zones) are considered to be one of the factors resulting in the degradation of the upper shaft and its properties. For the Severe Shaft Seal Failure Scenario, the degradation and resulting hydraulic and hydrogeological impacts are also assumed to affect the lower shaft (i.e., in the Intermediate and Deep Bedrock Groundwater Zones).

FEP Screening
Include FEP in all scenarios for the upper shaft, and also for the lower shaft for the Severe Shaft Seal Failure Scenario.

2.1.08 Chemical / Geochemical Processes and Conditions (in Wastes, Emplacement Rooms, Tunnels and Shafts)

Description

The chemical and longer-term geochemical processes that affect the wastes, containers, engineered features of the repository, and the overall chemical evolution of repository with time. This includes the effects of chemical and geochemical influences on wastes, containers and engineered components by groundwater entering from the surrounding geology.

Under this category, the following FEPs are specifically considered:

2.1.08.01 pH Conditions
2.1.08.02 Eh Conditions
2.1.08.03 Chloride and Sulphate Conditions
2.1.08.04 Corrosion
2.1.08.05 Polymer Degradation
2.1.08.06 Mineralisation
2.1.08.07 Precipitation Reactions
2.1.08.08 Chelating Agent Effects
2.1.08.09 Colloid Formation
2.1.08.10 Osmotic Effects
2.1.08.11 Chemical Concentration Gradients
2.1.08.12 Influence of Climate Change

2.1.08.01 pH Conditions

Description

The pH conditions in water in the repository owing to interactions between the water and the repository materials (wastes, packaging, and engineered features). pH (along with *Eh [2.1.08.02]* and *Chloride and sulphate conditions [2.1.08.03]*) is an important determinant in the chemical behaviour of any repository, which in turn affects the release and transport of contaminants in groundwater and gas.

Screening Analysis

Concretes present in the repository will initially impose an alkaline (or high) pH on the water in the immediate vicinity of the concrete. However, this effect will be limited spatial and temporally, because the reserves of alkalinity in the concrete will be limited and as mildly acidic groundwater enters the concrete from the host rock, reactions will occur that lead to pore blockage, restricting the entry of groundwater (see *Precipitation reactions [2.1.08.07]*). Carbonation of concrete by carbon dioxide during the early postclosure phase of the repository will also consume some of the reservoir of alkalinity and block access to water (see *Carbonation [2.1.08.06.D]*). Furthermore, there will be competing processes from the degradation of the wastes resulting in the formation of hydrogen, carbon dioxide and organic acids that will tend to mitigate against an increase in pH.

Therefore, averaged over the entire DGR, it is expected that pH will be mostly in the pH 6 to 8 range, since the concrete used in the DGR is not considered to be present in sufficient amounts to affect the pH beyond the concrete and adjacent area.

FEP Screening

Include FEP in all scenarios.

2.1.08.02 Redox Conditions

Description

The Eh conditions in water in the repository owing to interactions between the water and the repository materials (wastes, packaging, and engineered features). Eh (along with *pH [2.1.08.01]* and *Chloride and sulphate conditions [2.1.08.03]*) is an important determinant in the chemical behaviour of any repository, which in turn affects the release and transport of contaminants in groundwater and gas.

An oxygen-deficient repository (anaerobic) promotes the formation of lower, and often less soluble, oxidation states of radioelements, promotes relatively slow corrosion and microbial processes, and minimises the rate of gas generation.

Screening Analysis

The redox potential in the emplacement rooms will be positive (aerobic) immediately after repository closure. However, conditions are expected to become anaerobic (negative Eh values) shortly after repository closure, due to the oxygen present in the repository at closure being consumed in a number of processes to create an anaerobic environment for the remainder of the assessment timeframe.

The corrosion of the various steels present is expected to be the most important of these processes (see *Corrosion [2.1.08.04]*). Oxygen could also be consumed in the attack of microbes on cellulosic wastes (see *Microbially/biologically mediated processes [2.1.09.02]*). In addition, radiolysis of the various organic wastes would generate free radicals that would be highly reactive towards oxygen. However, radiolysis will decline rapidly following repository closure and a sizeable proportion of the radiative energy emitted will be absorbed by other types of waste and the containers, so this process will probably not be as significant in controlling Eh as steel corrosion.

FEP Screening

Include FEP in all scenarios.

2.1.08.03 Chloride and Sulphate Conditions

Description
The chloride and sulphate conditions in water in the repository owing to interactions between the water and the repository materials (wastes, packaging, and engineered features). Chloride and sulphate concentrations (along with *pH [2.1.08.01]* and *Eh [2.1.08.02]*) are important in affecting the chemical behaviour of any repository, which in turn affects the release and transport of contaminants in groundwater and gas.

Screening Analysis
Chloride concentrations in the emplacement rooms are expected to increase as high salinity porewater enters the repository (background level of 100 to 260 g l^{-1}) and the initial water in the wastes is consumed by anaerobic steel corrosion (see *Corrosion [2.1.08.04]*). Elsewhere in the repository (including the shafts), salinity is expected to become comparable with background levels (100 to 260 g l^{-1} in the Deep Bedrock Groundwater Zone, 20 to 250 g l^{-1} in the Intermediate Bedrock Groundwater Zone, and 1 to 100 mg l^{-1} in the Shallow Bedrock Groundwater Zone) (see Table 2-7 of the System and its Evolution report, Little et al. 2009).

Sulphate concentrations in the emplacement rooms are expected to fall rapidly due to the consumption of sulphate by microbial reactions with H_2 (see *Microbially/biologically mediated processes [2.1.09.02]*) from the background level of 165 to 1140 mg l^{-1}. Elsewhere in the repository (including the shafts), sulphate concentrations are expected to become comparable with background levels (165 to 1140 mg l^{-1} in the Deep Bedrock Groundwater Zone, 330 to 1500 mg l^{-1} in the Intermediate Bedrock Groundwater Zone, and 70 to 1500 mg l^{-1} in the Shallow Bedrock Groundwater Zone) (see Table 2-7 of the System and its Evolution report, Little et al. 2009).

FEP Screening
Include FEP in all scenarios.

2.1.08.04 Corrosion

Description
The corrosive effect of water on metals in the wastes, packaging, rock bolts, rails and reinforcement in the repository. Three types of corrosion can be identified:

2.1.08.04.A General
2.1.08.04.B Localised
2.1.08.04.C Galvanic

2.1.08.04.A General

Description
If water (be it in liquid or vapour form) can access metals, it can lead to general corrosion of the metals at a rate that varies with time, temperature, redox conditions, pH, salinity and nature of the metal. General corrosion can occur under both the aerobic and anaerobic conditions. The latter is slower than the former, with both rates being slower under high pH conditions (Francis et al. 1997). Rates for carbon steel are faster than for stainless steel and Ni-alloys. The threshold relative humidity for corrosion by water vapour is typically in the range 60-70% (Shreir 1976).

Anaerobic corrosion leads to hydrogen production (though at a low rate), but gas generation does not accompany aerobic corrosion.

Screening Analysis
Water (be it in liquid or vapour form) will contact the various metallic components of the DGR (wastes, packaging, rock bolts, rails and reinforcement) resulting in their general corrosion. Conditions in the DGR become anaerobic soon after closure due to the corrosion of metals using the available oxygen (see *Eh conditions [2.1.08.02]*). Once anaerobic conditions have become established, general corrosion will result in the generation of hydrogen gas (see *Metal waste corrosion [2.1.11.02]* and *Container corrosion [2.1.11.04]*).

The general corrosion of waste packages will result in the release of contaminants into the repository.

FEP Screening
Include FEP in all scenarios.

2.1.08.04.B Localised

Description
The localised formation of cavities in a metal surface caused by non-uniform corrosion. Localised corrosion typically takes the form of either the pitting of free surfaces or crevice corrosion of occluded sites.

Crevice corrosion could occur on the surface of a container under a hydrothermally formed deposit, under an embedded surface defect or particle, under a biofilm or in a closure weld. Pits may initiate at defects on the surface of the containers. These sites may concentrate chloride ions and hydrogen ions and could promote stress-induced cracking of stainless steels (see *Stress-corrosion cracking [2.1.06.06]*).

One issue of concern is that the localised effects may lead to failure long before more uniform corrosion processes. Another possibility is the formation of weaknesses in the container, which then contribute to mechanical failure (see *Mechanical processes and conditions [2.1.06]*).

Screening Analysis
Localised corrosion processes will only occur under aerobic conditions. Of the metals present in the repository, those most susceptible to **localised** corrosion are stainless steel and carbon and galvanised steel in contact with concrete (the so-called "passivated carbon steel" category). Any localised corrosion that initiates under aerobic conditions will cease (or "stifle") as the repository environment becomes anoxic. Because of the high salinity of deep sedimentary deposits, corrosion of the non-susceptible metals, such as unpassivated carbon and galvanised steels and zirconium alloys, will tend to be general in nature (rather than localised), as will that of the susceptible alloys once the repository environment becomes anoxic.

FEP Screening
Screened out.

2.1.08.04.C Galvanic

Description
Metals and alloys can be arranged in a so-called galvanic series in which the corrosion potential gradually becomes more positive. The corrosion rates of metals with more negative corrosion potentials increase when coupled with metals of a more positive corrosion potential. Physical contact between two metals in the presence of water and a dissolved electrolyte will not increase the rate of corrosion of the more electropositive species, but will increase that of the more electronegative species. Gas production rates would increase.

Screening Analysis
Stainless steel (as found in some DGR wastes) is more electropositive than carbon steel (used for containers). Therefore contact between them could result in an increased rate of corrosion of the container. Other metals present in wastes could result in the corrosion of containers for these wastes, depending on their relative electropositivities.

It is not proposed to grout wastes into containers, indicating that physical contact between metal wastes and containers could be maintained as metal is consumed in galvanic corrosion.

This process could occur soon after repository closure if the relevant wastes are wet or condensation results in them becoming so.

FEP Screening
Include FEP in all scenarios.

2.1.08.05 Polymer Degradation

Description
The chemical effect of water in the repository on polymeric materials.

Screening Analysis
The main types of polymeric materials in wastes at the DGR are plastics, ion-exchange resins and cellulosics (paper, wood and cotton). The main relevant characteristic of the water is likely to be its alkalinity.

Plastics such as PVC, polyethylene and polypropylene are expected to be relatively unreactive. Irradiation of PVC before repository closure could make it more susceptible to further degradation by removing HCl. Attack on PVC by concentrated hydroxide solution, oxygen under pressure and high temperature proceeds by the same first step, followed by reactions that produce simple organic acids such as oxalic acid (Rees et al. 2002). Oxygen in the repository would be consumed rapidly after closure, mainly in corrosion, and the amounts of water and alkalinity that could in practice be transferred to the waste plastic may be limited (see *[2.1.08.1.A]*). This situation is likely to persist when significant amounts of groundwater are present in the repository because the extent to which the various concretes present can buffer pH to high values is likely to be limited.

It is unclear whether the styrene/divinylbenzene ion-exchange resins in the DGR wastes would degrade chemically in the postclosure period: However, ions in the alkaline water may be able to displace radionuclides on the resins' sorption sites. Again, limited supplies of pore water and alkalinity suggest that this may not be a significant process.

Cellulose can degrade under alkaline conditions to yield polyfunctional organic acids that can complex a number of long-lived radionuclides (including those of Pu), thereby increasing their solubility and decreasing the degree of sorption (Goldberg et al. 1997). However, the problems noted in this assessment and in *[2.1.08.1.A]* in maintaining high levels of alkalinity indicate that this process is unlikely to be significant.

Degradation of polymers, especially cellulosics, is one of the sources of gas.

FEP Screening
Include FEP in all scenarios.

2.1.08.06 Mineralisation

Description
Long-term chemical changes occurring in repository materials (concrete, bentonite and asphalt) that could affect repository performance. Four associated processes are identified:

2.1.08.06.A Leaching
2.1.08.06.B Chloride attack
2.1.08.06.C Sulphate attack
2.1.08.06.D Carbonation

2.1.08.06.A Leaching

Description
Leaching is the removal by water of minerals from the engineered repository materials (concrete, bentonite and asphalt) that could affect repository performance.

This process is particularly important for concrete and can lead to an initial increase in water pH (see *pH conditions [2.1.08.01]*). Where there are cementitious materials, pH will increase due to leaching of cement through hydrolysis of portlandite (calcium hydroxide) and incongruent dissolution of the C-S-H gel. The pH will decrease 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 rate of leaching of concrete has been shown to be dependent upon the number of pore water flushes (Berner 1990, 1992).

Screening Analysis
Not considered to be an important process for bentonite and asphalt. The long-term decrease in pH resulting from leaching is considered for concrete structures in the upper shaft (i.e., the structures in the Superficial and Shallow Bedrock Groundwater Zones), which are subject to higher groundwater flow rates and hence significantly greater pore water flushes and therefore leaching than concrete in the Intermediate and Deep Bedrock Groundwater Zone (see System and its Evolution Report, Little et al. 2009).

FEP Screening
Include FEP in all scenarios for concrete in upper shaft, and for all concrete for the Severe Shaft Seal Failure Scenario.

2.1.08.06.B Chloride attack

Description
The nature of the chemical processes that may occur between chloride ions in water and the engineered repository materials (concrete, bentonite and asphalt) that could affect repository performance.

The stability of cement pastes in saline solutions and brines has been investigated and Glasser et al. (1998) 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 fluid. 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.

Screening Analysis
Not considered to be an important process for bentonite and asphalt. Considered for concrete structures in the repository (and shaft).

FEP Screening
Include FEP in all scenarios for concrete.

2.1.08.06.C Sulphate Attack

Description
The nature of the chemical processes that may occur between sulphate ions in water and the engineered repository materials (concrete, bentonite and asphalt) that could affect repository performance.

Screening Analysis
Sulphate ions can diffuse into concrete and react with certain phases forming products of larger volume. The resulting internal expansion causes stresses, cracking and exfoliation of the reacted zone at the concrete surface (Francis et al. 1997). Among the products are ettringite and gypsum. The attack depletes the reservoir of alkalinity (calcium hydroxide) in the concrete.

Although the main site of attack by sulphate ions in water is expected to be on the concrete present, swollen bentonite can be susceptible to a reduction in swelling pressure brought about by potassium ions (Atkinson et al. 1997). Its relevance to the current FEP is that potassium might accompany sulphate ions into the repository. Potassium concentrations in the Deep Bedrock Groundwater Zone are estimated to be 120 to 3030 mg l^{-1} and sulphate concentrations are estimated to be between 165 to 1140 mg l^{-1} (System and its Evolution Report, Little et al. 2009).

FEP Screening
Include FEP in all scenarios.

2.1.08.06.D Carbonation

Description
The nature of the chemical processes that may occur between carbonate ions in water and the engineered repository materials (concrete, bentonite and asphalt) that could affect repository performance.

Screening Analysis
The main impact of carbonate ions will be on the concrete present. Carbonation of these features will actually start during the operational phase of the repository by reaction with carbon dioxide in the air. The formation of carbon dioxide during the attack of microbes on cellulosic wastes is a further source of this gas (see *Microbially/biologically mediated processes*

[2.1.09.2]). So carbonation of concrete will start well before this material is contacted by water (Francis et al. 1997).

Francis et al. (1997) note that carbonation:

- reduces the ability of concrete to impose a high pH on repository (and shaft) water by reacting with the main source of alkalinity, calcium hydroxide (see *pH conditions [2.1.08.01]*); and
- heals cracks, sealing them to ingress by water through the production of calcium carbonate which has low solubility. Thus, carbonation will counter the effects of leaching and chloride/sulphate attack (see above).

FEP Screening

Include FEP in all scenarios.

2.1.08.07 Precipitation Reactions

Description

The implications that conditions in the repository (particularly of pH, Eh and concentrations of complexing ions for elements) have for element solubility and the nature of precipitated phases.

Solubility can be defined as the maximum measured aqueous concentration of an element under a given set of conditions in the presence of a limiting solid. This concentration 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).

It is important not to create the impression that solubility limiting reactions defined in this way always impose maximum concentration limits on solutes. In fact, in some cases, metastable solution-solid reactions may give rise to higher aqueous concentrations than would arise by true solubility limitation as defined in the previous paragraph. A good example is where the metastable phase chalcedony causes aqueous silica concentrations to be higher than would be explained by equilibrium between aqueous silica and thermodynamically stable quartz.

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. This effect would occur with a cementitious backfill.

The anaerobic conditions expected to prevail in a repository shortly after closure (negative Eh) drive the most stable oxidation state to a lower level (for elements such as actinides and technetium which have more than one possible oxidation state). 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).

PostSA Screening Analysis

The DGR is likely to operate at around neutral pH. As a result, there will be little control of solubilities through the development of high or low pH conditions. The repository is, however, expected to be anaerobic, and this will be an important control over solubility. Complexants for actinides derived from the decomposition of cellulose may also occur, but alkaline conditions are needed to initiate the degradation. Carbonate ions may be present in groundwater and the concrete features of emplacement rooms.

FEP Screening

Include FEP in all scenarios.

2.1.08.08 Chelating Agents Effects

Description
The effect of chelating agents derived from the pore water on the performance of a repository.

Chelating agents are organic compounds, usually carboxylic acids, which have a number of locations in each molecule that can complex with a single metal atom. The resulting complexes are usually highly stable, a factor that can increase significantly the solubilities of certain elements, such as Pu, with the acidic degradation products of cellulose (Greenfield et al. 1997).

Screening Analysis
Chelating agents are present in certain resins and may be formed as degradation products. However, it is not expected that the chelating agents will be in sufficient concentrations to cause anything but localised impacts on solubility.

FEP Screening
Screened out.

2.1.08.09 Colloid Formation

Description
The existence of colloidal particles in pore water and the effect of these particles on the performance of a repository.

Colloids are dispersions of finely divided particles in a dispersing medium. Particle diameters are typically less than 10 µm. A variety of colloidal substances occur naturally in groundwater, including humic substances, micro-organisms, mineral precipitates and weathering products (Chambers et al. 1995). Colloids could also be generated from materials in a repository, including cementitious materials, bentonite (if used as a backfill) and certain components of the waste and waste containers. They 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.

Colloids are unstable thermodynamically and exist because of the slow kinetics of their agglomeration into solids (called coagulation or flocculation). Colloid stability generally decreases as ionic strength (salinity) increases.

Colloids can be generated in cements and concretes (Chambers et al. 1995). Their movement into a cementitious or bentonite backfill could potentially lead to pore blockage. The permeability to water of cements, concretes and bentonite is very low, at around 10^{-21} m^2. Blockage by concrete-derived colloids of the pores in a backfill may affect a swollen bentonite more than a cementitious backfill. The result would be to decrease further the rate of movement of groundwater and gas in the vicinity of the waste packages.

Screening Analysis
While the formation of colloids is conceivable, colloids are expected to be unstable under the high salinity of the Deep and Intermediate Bedrock Groundwater Zones and so susceptible to agglomeration and dissolution. Furthermore, even if colloids were to form, their migration would be limited – see *Colloid-mediated migration of contaminants [3.2.09].*

FEP Screening
Screened out.

2.1.08.10 Osmotic Effects

Description
Osmosis is the flow of water through a semi-permeable membrane so that the solutions on either side of the membrane become equal in molecular concentrations.

This effect could possibly play a role in equalising water compositions across a repository. Water deposited on the surface of concrete (by condensation or through incoming groundwater) and the pore water would eventually have the same ionic compositions, with osmosis playing a role in achieving this if the pore structure of the concrete acted like a semi-permeable membrane.

Screening Analysis
Ions are able to diffuse into repository materials (especially concrete and bentonite) (Atkinson et al. 1997), indicating that they do not behave as semi-permeable membranes. Therefore osmotic effects are unlikely to be significant.

FEP Screening
Screened out.

2.1.08.11 Chemical Concentration Gradients

Description
The migration of salts and dissolved contaminants *[3.2.02.01]* may be enhanced in the repository because of the existence, or formation, of chemical concentration gradients between the host rock, different wastes and engineered materials.

Chemical concentration gradients will naturally exist between the different materials present in the repository. Such gradients may also be generated, or altered, by temperature changes, radiolysis (changing local redox conditions), different electrochemical potentials between various materials in the repository and ingress of saline groundwater.

Possible effects include altered dissolution rates of the waste matrices and dissolution and precipitation of chemical compounds with subsequent opening or plugging of pores.

Screening Analysis

These driving forces for chemical gradients (e.g., radiolysis, temperature changes) are less significant for low and intermediate level waste than for used fuel. This FEP was assessed to be insignificant in the Third Case Study for used fuel (Garisto et al. 2004b) and is therefore also not significant here.

FEP Screening
Screened out.

2.1.08.12 Influence of Climate Change

Description
The influence of climate change on the chemical/geochemical processes that affect the wastes, containers, seals and other engineered features, and the overall chemical evolution of the repository with time. This includes the chemical/geochemical influences on wastes, containers and repository components by the surrounding geology. The movement of contaminants is described in *Water-mediated transport of contaminants [3.2.02]*.

Screening Analysis
Global and local climate changes (see *[1.3.01 and 1.3.02]*) may affect the chemical/ geochemical properties of the geosphere surrounding the DGR, which could potentially affect wastes, containers and other DGR components. However, due to the low permeability of the host rock and the absence of evidence of the effect of previous ice-sheet advances and retreats at depth (Sykes et al. 2008; Hobbs et al. 2008), it is expected that there will be no significant chemical/geochemical effects at the depth of the repository.

It is recognised that the near-surface environment will be significantly affected by glacial-interglacial cycling and the chemical/geochemical impacts of this cycling on the upper shaft (i.e., in the Surficial and Shallow Bedrock Groundwater Zones) are considered to be one of the factors resulting in the degradation of the upper shaft and its properties. For the Severe Shaft Seal Failure Scenario, the degradation and resulting chemical/geochemical impacts are also assumed to affect the lower shaft (i.e., in the Intermediate and Deep Bedrock Groundwater Zones).

FEP Screening
Include FEP in all scenarios for the upper shaft, and also for the lower shaft for the Severe Shaft Seal Failure Scenario.

2.1.09 Biological / Biochemical Processes and Conditions (in Wastes, Emplacement Rooms, Tunnels and Shafts)

Description

The biological and biochemical processes that affect the wastes, packaging and other engineered features, and the overall biological or biochemical evolution of repository with time. They can result from the activity of microscopic organisms, including archaea, bacteria, protozoans, yeast, viruses and algae (microbes).

A wide range of microbes will inevitably be introduced into the repository during its construction and in the operational phase. Some would be present in the waste packages as delivered to the repository, whereas others would be introduced earlier, as the emplacement rooms were excavated and infrastructure erected. The oxygen in the repository at closure will promote growth of some aerobic microbes, but anaerobic species could also be viable once conditions become anaerobic. Growth also requires the presence of suitable nutrients, which in repositories may include (as appropriate) cellulosic wastes, simple organic molecules and small amounts of putrescible materials.

Only some of the microbes present at repository closure will find the subsequent conditions suitable for their growth. Besides requiring certain types of nutrient, individual microbial populations will only operate under particular conditions of temperature, pH and redox potential and salinity.

Biological and biochemical processes affect the release and transport of contaminants in gas (through the generation of carbon dioxide, methane and hydrogen sulphide) and the groundwater pathway (through microbially-induced corrosion and the formation of biofilms and organic complexation agents).

This category is divided into:

- 2.1.09.01 Microbial growth and poisoning
- 2.1.09.02 Microbially/biologically mediated processes
- 2.1.09.03 Microbial/biological effects on redox (Eh) and acidity/alkalinity (pH)
- 2.1.09.04 Influence of climate change

2.1.09.01 Microbial Growth and Poisoning

Description
Microbes require water and nutrients in order to metabolise and grow. In a repository, organic wastes containing cellulose (paper, cotton and wood) support their growth, as do high levels of humidity. This process leads to the formation of gas, as described in *[2.1.09.02]*. Simple organic molecules containing oxygen, nitrogen or sulphur are also nutrients for microbes. Plastics and most other polymers are relatively inert towards microbes and in general do not support their growth.

Nitrate ions in waste and water can act as a nutrient and participate in cellulose degradation, with the formation of nitrogen. Sulphate is another inorganic nutrient that can participate in cellulose degradation, forming hydrogen sulphide. This gas also forms in the microbially mediated reaction between sulphate ions and hydrogen generated during corrosion of steels. Nitrate and sulphate ions may be present in both water and waste.

Alkaliphilic microbes can grow as biofilms on the surface of cement and might decrease the rate at which water moves.

Microbial growth can lead to the formation of acidic and oxidising species that can participate in corrosion of the metals (mainly steels) forming packaging and in the waste.

Poisoning of microbial processes can occur in a number of ways, including the use of biocides, temperatures in excess of about 70^{o}C, changing the pH to a value at which the microbial population ceases to function, and heavy metals. Although it should be recognised that extremophiles (e.g. various types of archaea) can survive and thrive outside the range at which most microbes flourish.

Screening Assessment
Growth of microbes could occur in the DGR by all the routes described above. Thus microbial growth could have significant implications for the release and transport of contaminants in groundwater and gas.

FEP Screening
Include FEP in all scenarios.

2.1.09.02 Microbially/Biologically Mediated Processes

Description
The main microbially-mediated processes that could occur in repositories are as follows.

1 Degradation of cellulose. Under the aerobic conditions that will prevail immediately following repository closure, this leads to the formation of carbon dioxide. Under anaerobic conditions, a mixture of carbon dioxide and methane is produced. Hydrogen is produced as an intermediate, but it can react with carbon dioxide to produce methane (Nirex 1994). Organic acids are produced as by-products, and, if they drive pH sufficiently low, the relevant microbial populations will be unable to function ('acid souring'), and gas production will cease (Kidby and Rosevear 1997). This pattern of reactions is largely reproduced when simple organic molecules containing oxygen are the substrate. The presence of C-14 in this type of substrate leads to the formation of $^{14}CH_4$ and $^{14}CO_2$.

2 Degradation of nitrate ions. Nitrate ions in waste and groundwater can participate in cellulose degradation, forming nitrogen (Nirex 1994).

3 Degradation of sulphate ions. Hydrogen formed as an intermediate in cellulose degradation and during corrosion can react with sulphate ions in waste and groundwater to yield hydrogen sulphide (Nirex 1994).

4 Biofilm growth. Biofilms could potentially grow on the surfaces of cement/concrete and packaging. In the case of concrete, this could lead to blocking of pores, restricting groundwater movement (Francis et al. 1997). On packaging, the production of acidic and oxidising species could increase the rate of corrosion.

Screening Analysis
All the processes noted above could occur in the DGR. The near-neutral pH of water entering the repository would favour microbial growth.

FEP Screening
Include FEP in all scenarios.

2.1.09.03 Microbial/Biological Effects of Evolution of Redox (Eh) and Acidity/Alkalinity (pH)

Description
Microbial and biological processes can affect both redox potential and pH. A microbial population that changes these features could result in conditions where that population fails to thrive. At this point, a further population may become active.

The microbially mediated production of carbon dioxide from cellulose involves the consumption of oxygen (Nirex 1994). Early in the lifetime of the closed repository, corrosion of steels and decomposition of cellulose would both consume oxygen, leading to the formation of reducing conditions. The sheer quantities of carbon steel in the containers and wastes will probably lead to corrosion dominating.

Organic acids are produced in some of the web of reactions that describe the microbially mediated decomposition of cellulose. In the absence of a material to maintain pH at high values, pH in the repository will tend to decrease. However, due to the presence of concrete on the walls and floors of the tunnels and rooms, it is unlikely to reach a level at which ‘acid souring’ may occur thereby effectively stopping gas production. In ‘acid souring’, the microbial population reach a region of pH in which it could not operate (Kidby and Rosevear 1997).

Sulphur-oxidising bacteria cause the formation of sulphuric acid by the oxidation of sulphur-containing species: this type of bacteria would only survive soon after repository closure, because it requires oxygen in order to thrive. This process could lead to a temporary decrease in pH.

Screening Analysis
The above effects on pH and Eh would be expected to occur at the DGR.

FEP Screening
Include FEP in all scenarios.

2.1.09.04 Influence of Climate Change

Description
The influence of climate change on the biological/biochemical processes that affect the wastes, containers, seals and other engineered features, and the overall biological/biochemical evolution of the repository with time. This includes the biological/biochemical influences on wastes, containers and repository components by the surrounding geology. The movement of contaminants is described in *Water-mediated transport of contaminants [3.2.02]*.

Screening Analysis
Global and local climate changes (see *[1.3.01 and 1.3.02]*) may affect the biological/ biochemical properties of the geosphere surrounding the DGR, which could potentially affect wastes, containers and other DGR components. However, due to the low permeability of the host rock and the absence of evidence of the effect of previous ice-sheet advances and retreats at depth, it is expected that there will be no significant biological/biochemical effects at the depth of the repository.

It is recognised that the near-surface environment will be significantly affected by glacial-interglacial cycling and this could impact the biological and biochemical processes and conditions in the Superficial and Shallow Bedrock Groundwater Zones. However, changes in these processes and conditions are not expected to impact the evolution of the upper shaft (i.e., in the Surficial and Shallow Bedrock Groundwater Zones) significantly. It is expected that the impact of glacial-interglacial cycling on mechanical *[2.1.06.08]*, hydraulic/hydrogeological *[2.1.07.07]*, chemical/geochemical *[2.1.08.12]* and thermal *[2.1.10.05]* processes and conditions will have a greater impact on the evolution of the upper shaft.

FEP Screening
Screened out.

2.1.10 Thermal Processes and Conditions (in Wastes, Emplacement Rooms, Tunnels and Shafts)

Description

The thermal processes that affect the wastes, packaging and engineering features in the repository, and the overall evolution of the repository thermal conditions with time.

This includes the effects of changes in thermal conditions caused by radioactive decay heat, microbiological processes and corrosion. Given that the concrete used in floors, walls and for some packages will have been prepared a considerable period before repository closure, it is expected that the heat output from the associated curing process will have been completed and removed by ventilation by the point of closure. Thermal processes may affect the waste packages, the emplacement rooms and the immediately surrounding rock. They may also affect repository chemistry, e.g. radionuclide solubilities and sorption. Thermal processes have the potential to affect the release and transport of contaminants in groundwater and gas.

This category is divided into:

- 2.1.10.01 Radiogenic, chemical and biological heat production from the waste packages
- 2.1.10.02 Heat production from engineered features
- 2.1.10.03 Temperature evolution
- 2.1.10.04 Temperature dependence of processes
- 2.1.10.05 Influence of climate change

2.1.10.01 Radiogenic, Chemical and Biological Heat Production from the Waste Packages

Description
The heating effect produced by radioactive decay, chemical reactions (such as corrosion) and microbiological processes affecting the waste packages.

At repository closure, relatively short-lived radionuclides such as Co-60 and Cs-137 will dominate radiogenic heat production. Retube wastes will contribute most to heat generation and could result in a rise of a few degrees centigrade. However, the temperature of the wastes will fall continuously over a period of some decades. Radiogenic heating will continue at a lower level for more than 10,000 years due to the decay of long-lived isotopes such as Pu-240 (Goldberg et al. 1997).

Corrosion of waste metals will be in progress at the time of repository closure, resulting in a further slight rise in temperature. The heat output from corrosion should fall as consumption of oxygen causes slower anaerobic processes to replace the aerobic ones that dominate at the point of closure.

Other chemical processes (possibly including the decomposition of cellulose) will be less prevalent than corrosion, and will contribute significantly less to temperature rise.

Microbial processes may be well-established in certain organic wastes at the time of closure, and will emit some heat. However, the rates of these processes are self limiting in that they decrease sharply as the temperature rises.

Screening Analysis
All the above processes could initially occur in the DGR. Because the emplacement rooms will not be backfilled, the immediately surrounding geology may have an important role to play in acting as a heat sink. 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). In addition, much of the heat will be generated in the operating period when it will be removed by ventilation.

FEP Screening
Screened out.

2.1.10.02 Heat Production from Engineered Features

Description
Concrete hydration, which is part of the chemical process of cement curing, has a significant heat of reaction that could potentially lead to temperature increases in a closed repository. The period of heat generation is of the order of a few months.

In addition, the use of asphalt in the shaft seal will result in the heating of the surrounding materials and rocks as the asphalt cools.

Screening Analysis
Concrete will be used to provide floors and walls in the emplacement rooms and also to line excavations in the DGR. These will be put in place well before closure of the repository. A backfill will not be employed. The position and size of concrete seals in shafts to the surface are unlikely to affect emplacement rooms during the curing phase.

Concrete hydration will therefore have ended, and the associated heat dissipated, well before the point of facility closure.

There is a need to undertake analysis of the effects of the heating of surrounding materials and rocks as the asphalt cools. For the purpose of the current assessment, it is assumed that it does not have a significant impact. This assumption will be reviewed in future iterations.

FEP Screening
Screened out.

2.1.10.03 Temperature Evolution

Description
A range of processes could potentially give off significant amounts of heat in a closed repository, including concrete hydration of engineered features – see *[2.1.10.01]* and *[2.1.10.02]*. All of these processes could contribute to the evolution of temperature in the repository.

Screening Analysis
Given that heat generation processes are not considered to cause a significant rise in temperature, a significant temperature evolution in repository is not expected.

Temperature effects associated with glacial and interglacial cycling are addressed in *[2.1.10.05]*.

FEP Screening
Screened out.

2.1.10.04 Temperature Dependence of Processes

Description
As described in *[2.1.10.01]* and *[2.1.10.02]*, a number of processes could lead to temperature increases in a closed repository on a temporary basis. This could lead to changes in the rates of a number of processes in the repository, including:
2.1.10.04.A Mechanical
2.1.10.04.B Hydraulic
2.1.10.04.C Chemical
2.1.10.04.D Biological

2.1.10.04.A Mechanical

Definition
The increase in temperature in a repository following closure would extend into the surrounding host rock. The resulting temperature gradients in the rock could induce stresses that could lead to increases in the widths of apertures in the host rock immediately surrounding the emplacement rooms, and possibly create new ones. The effect might well be permanent due to a lack of elasticity in the host rock, unlike the temperature excursion that led to it. This in turn might lead to groundwater flowing into the repository that might otherwise have passed round it, thus shortening the resaturation period. Contaminated groundwater might be able to migrate more easily.

Screening Analysis
The surrounding host rock is expected to act as a heat sink during the temporary increase in temperature following facility closure. The mechanical impact on the surrounding rock is expected to be insignificant.

FEP Screening
Screened out.

2.1.10.04.B Hydraulic

Description
A temporary rise in temperature in a repository following final closure will lead to changes in a number of parameters that affect fluid flow. The densities and viscosities of fluids could fall somewhat, whereas the pressure they exert in the repository could potentially increase.

Screening Analysis
The hydraulic impact on the surrounding rock is expected to be insignificant since the temperature increase is small.

FEP Screening
Screened out.

2.1.10.04.C Chemical

Description
A temporary elevation of temperature above the ambient exerted by the host rock is expected to accompany repository closure. The majority of chemical processes are likely to be affected on a correspondingly temporary basis. The main one that may lead to permanent change is mineralisation, particularly of cements and concretes present as structural materials, packaging and backfill.

Mineralisation converts cements and concretes to thermodynamically more stable forms that may exhibit changed sorption behaviour towards radionuclides (Atkinson et al. 1997). The highly alkaline pH they induce in repository waters could be decreased, which may change the limiting repository solubilities of certain contaminants.

Screening Analysis
Given that the DGR will not be backfilled, and that the chemistry of the groundwater is unlikely to be dominated by the concrete present in the emplacement rooms, the significance of permanent chemical changes in concrete due to the temporary temperature rise following repository closure is likely to be insignificant.

FEP Screening
Screened out.

2.1.10.04.D Biological

Description
Microbes are likely to attack cellulose-containing wastes such as paper, wood and cotton, initially yielding carbon dioxide while there is still oxygen in the closed repository, and carbon dioxide and methane under anaerobic conditions.

Microbes usually thrive at temperatures of 30-50^{o}C in the presence of suitable substrates, but at significantly higher temperatures (70^{o}C), they die (Goldberg et al. 1997). When the repository temperature subsequently falls, microbial populations are likely to become re-established, and gas production from cellulose will resume.

Screening Analysis
Given that temperatures in the DGR are unlikely to rise significantly above the ambient temperature of around 20^{o}C, the above effect is not considered relevant to the DGR.

FEP Screening
Screened out.

2.1.10.05 Influence of Climate Change

Description
The influence of climate change on the temperature in the repository and the shafts.

Screening Analysis
Global and local climate changes (see *[1.3.01 and 1.3.02]*) may affect the temperature of the geosphere surrounding the DGR. 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. The general picture that emerges from the results is that the permafrost thickness rarely exceeded 60 m and annual average, earth-surface temperatures at the site ranged between -4 °C and +10 °C. Generally, permafrost is not continuous unless the depth of permafrost exceeds 60 to 90 m (Brown and Pewe 1973).

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 about 21°C. However, it is expected that cooling at the surface would lead to diffusion of lower temperatures to depth on the timescale of thousands to tens of thousands of years. Calculations have not yet been undertaken to determine the impact of surface temperature changes on repository temperatures and the timescales over which temperature changes might occur.

For the purposes of the current assessment, it is assumed that climate change does not have a significant impact on the temperature in the repository. This assumption will be reviewed in future iterations. In contrast, it is recognised that the shaft in the near-surface environment (i.e., the Superficial and Shallow Bedrock Groundwater Zones) will be significantly affected by temperature changes with the formation of discontinuous permafrost down to 60 m (see System and its Evolution report, Little et al. 2009). The associated freeze-thaw cycling could be one of the factors resulting in the degradation of the upper shaft and its properties considered in the Version 1 SA.

FEP Screening
Include FEP in all scenarios.

2.1.11 Gas Sources (in Wastes, Emplacement Rooms, Tunnels and Shafts)

Description

Factors within and around the wastes, packaging and engineered features resulting in the generation of gases and their subsequent effects on the repository system. Six sources are considered:

2.1.11.01 Radioactive decay

2.1.11.02 Metal corrosion

2.1.11.03 Organic waste degradation

2.1.11.04 Cement degradation

2.1.11.05 Asphalt degradation

2.1.11.01 Radioactive Decay

Description

The production of gaseous isotopes in radioactive decay processes.

There are two main sources of gas in a repository by this route:

- the production of helium as α–particles; and
- the generation of isotopes of radon in the decay of uranium, thorium and radium in wastes and in minerals in the host rock. The main isotopes considered in assessments are Rn-220 (half-life 55.6 seconds) and Rn-222 (the longest-lived isotope at 3.82 days). Gas from both sources might be carried from the repository to the surface in bulk gas migrating to the surface.

Screening Analysis

Helium will constitute only a very small proportion of the total gas formed in a repository, such as the one proposed for the Bruce site, and could be carried away from it in dissolved form (Biddle et al. 1988).

Radon generated in the repository decays away before reaching the surface for all scenarios other than the Human Intrusion Scenario (which effectively by-passes the geosphere). The potential impact of radon generated in the repository will therefore be considered in the SA only for the Human Intrusion Scenario.

FEP Screening

Include FEP in Human Intrusion Scenario only.

2.1.11.02 Metal Corrosion

Description
The metal (wastes, packaging, rock bolts, rails and re-enforcement) present in the repository will degrade, resulting in hydrogen gas generation if the conditions are aerobic.

Screening Analysis
The degradation reactions of these metals are discussed in detail in the System and its Evolution report (Little et al. 2009).

The proposed DGR will be aerobic for a short period following facility closure, the oxygen being consumed in the general corrosion of carbon steels present in wastes and packaging. Anaerobic conditions will then be rapidly established *[2.1.08.02]*. Anaerobic corrosion of steels then involves the reduction of water, which generates hydrogen. Considerable volumes of gas could form because of the substantial inventories of carbon steels in wastes and as packaging.

The corrosion of metals is likely to be an important process generating gas in the deep repository.

FEP Screening
Include FEP in all scenarios.

2.1.11.03 Organic Waste Degradation

Description
The organic wastes present in the DGR include cellulose-based materials such as cloth, wood and paper, and plastic-type materials such as ion-exchange resins. These materials will degrade with time, and may affect contaminant release and gas generation.

Screening Analysis
The organics present in the various DGR waste forms can be broadly classified as belonging to one of two groups:

1. cellulosic waste (generally comprising paper and other similar material); and

2. recalcitrant waste (comprising less-biodegradable organics, such as plastics and resins).

In the presence of microbes, organic material is hydrolysed to glucose with the rate of hydrolysis of cellulosic material being one to two orders of magnitude faster than that for the recalcitrant organic wastes. Glucose, in turn, can be microbially decomposed into CH_4 and CO_2. This is a key process as it results in the liberation of large volumes of gas into the repository.

In the presence of H_2 generated from corrosion of metals, CO_2 can be reduced to CH_4. This process is important as it results in the conversion of five moles of gas to one mole, and can result in a decrease (or at least restrain the increase) in the gas pressure during system evolution.

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; Husain and Jain 2003; 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 ^{60}Co) 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.

The process of organic waste 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).

<u>FEP Screening</u>
Include FEP in all scenarios.

2.1.11.04 Cement Degradation

<u>Description</u>
The action of radiation on concrete components of the repository that are sufficiently close to the source of the radiation (that is the waste) to be affected by it. Such components include the concrete containers that will be used to package certain ILW streams and any concrete overpacks. Other concrete components, notably seals and the floors and walls of emplacement rooms, are likely to be too distant to be significantly affected.

The action of radiation on concrete is to produce hydrogen gas from the radiolysis of free water in the cement pores. The extent of gas formation by this route decreases rapidly following repository closure as the radionuclides decay.

<u>Screening Analysis</u>
The rapid decrease in radioactivity in the postclosure period indicates that the amount of gas likely to be generated by this route is substantially less than from corrosion.

<u>FEP Screening</u>
Screened out.

2.1.11.05 Asphalt Degradation

Description
Gas generated from the degradation of asphalt.

Screening Analysis
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, asphaltenes are more or less unaffected by micro-organisms (Pettersson and Elert 2001) and the degradation of resins is expected to be very slow *[2.1.11.03]*. 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. Any degradation would be extremely slow, with only small volumes of CO_2 and CH_4 being produced.

FEP Screening
Screened out.

2.1.12 Radiation Effects (in Wastes, Emplacement Rooms, Tunnels and Shafts)

Description
The scope for the degradation of repository materials (polymers, concrete and metals) by radioactive decay in the wastes.

Radioactive decay also generates heat - the effects of radiogenic heat production are considered in *Radiogenic, chemical and biological heat production from wastes [2.1.10.01]*.

Screening Analysis
The rapid fall in radiation levels after facility closure indicates that this is unlikely to have significant effects.

FEP Screening
Screened out.

2.1.13 Extraneous Materials

Definition
The effect of extraneous materials introduced into a repository with waste packages and during repository construction and operation.

Waste packages will inevitably contain microbes that could initiate microbiological processes in the repository during the postclosure period. This is discussed in *Biological/biochemical processes and conditions [2.1.09]*.

Repository construction and operation will also introduce microbes, and possibly putrescible materials such as discarded food and small animals. These would provide sites for rapid growth of microbes in the postclosure period.

Screening Analysis
The presence of a range of microbial populations in the repository at the point of closure is dealt with elsewhere in the FEP analysis *[2.1.09]*. It is expected that the amounts of putrescible materials present underground will be minimised through the application of the appropriate managerial controls. Even though their presence would bring forward the initiation of microbial processes, these would occur in any event. The extent to which initiation was brought forward would be small compared with the timeframe for the assessment of repository safety.

FEP Screening
Screened out.

2.1.14 Nuclear Criticality

Description

Factors related to possibility and effects of spontaneous nuclear chain reactions within the DGR.

A chain reaction is the self-sustaining process of nuclear fission in which each neutron released from a fission triggers, on average, at least one other nuclear fission. Nuclear criticality requires a sufficient concentration and localised mass (critical mass) of fissile isotopes (e.g. U-235, Pu-239) and also presence of neutron moderating materials in a suitable geometry; a chain reaction will be damped by the presence of neutron absorbing isotopes (e.g. Pu-240).

Screening Analysis

The DGR will not accept used fuel, nor waste with significant fuel fragments. Furthermore, the OPG CANDU reactors do not use enriched fuel. The only source of actinides in the repository is those collected from losses in the primary heat transport system, typically either sorbed on resins or onto piping and heat-exchanger surfaces. The concentrations are therefore substantially lower than could result in a criticality. In addition, the safety report for the Western Waste Management Facility (OPG 2004) has shown that there are no criticality issues associated with the used fuel wastes currently stored in the facility. Given that low and intermediate level wastes have substantially less fissile materials than used fuels, criticality safety is not expected to be an issue for the waste disposed in the DGR.

There is no possibility of a criticality accident, based on the mass of fissile nuclides (i.e., U-235, U-233, Pu-239) in the DGR. Knief (1985) provides screening values of 0.78 kg for U-235, 0.55 kg for U-233 and 0.48 kg for Pu-239. The total mass of U-235, U-233 and Pu-239 given in the combined LLW and ILW inventory (as disposed) is 0.06 kg, 0.0006 kg, and 0.23 kg, respectively (derived from the inventory given in the Data report, Walke et al. 2009b). Although some ingrowth of U-235 and U-233 will occur, it is considered that it will not result in a critical mass being reached. Furthermore, this mass is likely to be dispersed in different emplacement rooms rather than being in a single location.

FEP Screening

Screened out.

2.2 Geological Environment

Description

Features and processes of the geological environment surrounding the repository including, for example, the hydrogeological, geomechanical and geochemical features and processes, both in pre-emplacement state and as modified by the presence of the repository and other long-term changes.

The "Geological Environment" category of FEPs is inside the spatial and temporal boundaries of the disposal system domain and includes all the geological features and processes that may lead to changes in the geological environment.

"Geological Environment" is divided into individual FEPs as follows:

2.2.01 Stratigraphy
2.2.02 Host lithology
2.2.03 Disturbed zone (in geosphere)
2.2.04 Large-scale discontinuities (in geosphere)
2.2.05 Mechanical processes and conditions (in geosphere)
2.2.06 Hydraulic/hydrogeological processes and conditions (in geosphere)
2.2.07 Chemical/geochemical processes and conditions (in geosphere)
2.2.08 Biological/biochemical processes and conditions (in geosphere)
2.2.09 Thermal processes and conditions (in geosphere)
2.2.10 Gas sources and effects (in geosphere)
2.2.11 Geological resources (in geosphere)
2.2.12 Undetected features (in geosphere)

Note that FEPs 2.2.01, 2.2.02, 2.2.03, 2.2.04, 2.2.11 and 2.2.12 describe the geological environment features, whereas FEPs 2.2.05 to 2.2.10 describe the processes or the changes that can occur in this environment.

2.2.01 Stratigraphy

Description

Stratigraphy describes the succession of different rock types that form the geosphere, and hence the characteristics of rocks (other than the host rock which is considered under *Host lithology [2.2.02]*), as they may evolve with time. Geological formations and units are separate rock structures and types that make up the region in which the repository is located. This does not include overburdens, soils and sediments overlying the bedrock, which are discussed in *Soil and sediment [2.3.02*].

These various geological units help to isolate the repository from the surface environment. They may play an important role in determining where surface water infiltrates into the geological system, and where deep groundwaters eventually discharge.

Relevant properties include the extent of the other geological units, thermal and hydraulic conductivity, fracture frequency and connectivity, compressive and shear strength, porosity, tortuosity, thickness, structure, groundwater composition and salinity, mineral composition and pore water pressure. The inhomogeneity and uncertainty of these properties is also part of their characterisation. These properties could change with time and temperature.

Screening Analysis

The DGR will be located at ~675 metres depth in Ordovician age sediments with markedly different rock properties from the overlying Silurian and underlying Cambrian age sediments. The thickness of the Ordovician sediments is expected to provide significant geologic isolation. The overlying Silurian sediments are also expected to provide significant geological isolation.

Heterogeneity within each stratigraphic formation / unit is expected to be small compared with the heterogeneities between formations / units on the basis of regional information. Therefore it is currently assumed that each stratigraphic formation / unit is homogeneous. Information to determine heterogeneity within each stratigraphic formation / unit at the DGR site will not be available until Phase 2 of the site-characterisation project.

FEP Screening

Include FEP in all scenarios.

2.2.02 Host lithology

Description

The characteristics of the rock matrix in which the repository is sited, including its evolution in time. This does not include the *Disturbed zone [2.2.03]*.

The host rock serves to isolate the repository from the surface environment and is determined by the repository location and depth. Relevant properties include its extent, thermal and hydraulic conductivity (or permeability), fracture frequency and connectivity, compressive and shear strength, porosity, tortuosity, structure, groundwater composition and salinity, mineral composition and pore water pressure. The inhomogeneity of these properties is also part of their characterisation.

Uncertainty in these properties is an important issue. For instance, rock properties measured in the laboratory may be significantly different from *in situ* values due to stress relief cracking after drilling. More generally, the rock characterisation around a repository may be incomplete or inaccurate. Finally, some underlying assumptions may be unsupported or not transferable from one rock domain to another. For instance, observations of near-surface rock may suggest that highly fractured rock will be relatively permeable, which may be incorrect when applied to other fractured rock that has experienced extensive fracture infilling. Another example might involve the presumption that permeabilities tend to decrease uniformly with rock depth, a generalisation that requires site-specific support.

Properties of the host rock could change with time, starting from an initial state that may be somewhat unsaturated, as a result of dewatering of the DGR during the operational phase, and include atmospheric air and may contain contaminants introduced into the repository. The properties may change with temperature.

Screening Analysis

The DGR will be located in a sedimentary sequence. Properties of individual formations / units are important to the safety analyses and will be incorporated in the models. Rock properties are expected to be time invariant over the duration of the assessment period.

Isothermal conditions are expected to apply for the most part. The exception to this statement is the Normal Evolution Scenario with climate change, in which glaciation-related changes to rock properties (specifically permafrost) may occur in the upper sequences.

FEP Screening

Include FEP in all scenarios.

2.2.03 Disturbed zone (in Geosphere)

Description

The characteristics of the zone of rock immediately surrounding emplacement rooms, tunnels, shafts and other underground openings that may be mechanically disturbed during excavation, including their evolution. This zone of rock is known as the excavation damaged zone or EDZ.

The EDZ is formed as a consequence of the repository excavation, and its extent and properties depend on factors such as the nature of the host rock, the excavation method, and the location and effectiveness of seals and grouts around the rooms and tunnels. Although it is not a physically separate entity from the host rock, the EDZ could comprise a layer of rock with properties that are significantly different from those of the surrounding host rock. Relevant properties are permeability, porosity, mechanical strength, fracture frequency and fracture connectivity.

This category is divided into:

2.2.03.01 Emplacement rooms and tunnels

2.2.03.02 Shafts

2.2.03.01 Emplacement rooms and tunnels

Screening Analysis

The EDZ around the repository is unlikely to have any significant impact due to the open repository design. However, the EDZ around the emplacement rooms and tunnels may form a preferential pathway from the emplacement rooms to the shaft EDZ (*Shafts [2.2.03.02]*), bypassing tunnel seals. The physical extent of the EDZ is important to determine the cross-sectional area of the pathway and thus the volumetric flux of dissolved radionuclides through the EDZ.

FEP Screening

Include FEP in all scenarios.

2.2.03.02 Shafts

Screening Analysis

The EDZ around each shaft may form a preferential pathway, with increased hydraulic conductivity, to the Shallow Bedrock Groundwater Zone (SBGZ). Since hydraulic conductivities in the SBGZ are many orders of magnitude higher than in the Deep and Intermediate Groundwater Zones, the EDZ is less significant in the SBGZ.

The EDZ around the each shaft may connect with the EDZ around the tunnels and emplacement rooms, bypassing the tunnel seals. The shaft-sealing design assumes that, if possible, the most extensively damaged zone which forms the walls of the shafts and other excavations (i.e., the inner EDZ) will be removed at key points along the shafts, and the potentially continuous EDZ pathway blocked using concrete bulkheads. In addition, swelling bentonite clays and asphalt used in the shaft-sealing design will tend to penetrate and block the EDZ pathway.

FEP Screening

Include FEP in all scenarios.

2.2.04 Large-scale discontinuities (in Geosphere)

Description

Discontinuities in the host rock and other geological units, including faults and fractures, joints, shear zones, and intrusive dykes as well as the linear surface features (lineaments) corresponding to these discontinuities.

Some of these features might form preferential groundwater and contaminant transport pathways, reducing the effectiveness of some portion of the geosphere (as a barrier) or focussing contaminant releases into the biosphere at particular discharge locations. However, some large-scale discontinuities can also result in reduced conductivity and transport. Other features (such as intrusive dykes) might provide information on the potential for future magmatic or seismic activity.

The (smaller-scale) discontinuities may also evolve over time because of the construction and continuing existence of the repository.

This category is divided into:

2.2.04.01 Faults and shear zones

2.2.04.02 Fractures and joints

2.2.04.03 Dykes

2.2.04.01 Faults and shear zones

Screening Analysis

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. 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).

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 Paleozoic rocks in the study area, an assessment supported by the low level of seismicity in the Bruce Megablock (Gartner Lee 2008b).

The Phase 1 DGR site characterisation activities included a 2-D seismic reflection survey. The results have identified two seismic features that are to be investigated by inclined boreholes. The results will be available for the Version 2 safety assessment. Potentially these could be local fractures, although there is no evidence from DGR-1 and DGR-2 data that they are open.

This is consistent with expectation that any faults and shear zones should be sealed under current stress regime.

FEP Screening
Include FEP in Extreme Earthquake Scenarios only. It is cautiously assumed that a vertical fault, located several hundred metres from the DGR, is reactivated by an extreme earthquake at closure (Penfold and Little 2009).

2.2.04.02 Fractures and joints

Screening Analysis
Cores taken from the DGR1 and 2 boreholes have shown that only small-scale fractures are present in the Deep and Intermediate Bedrock Groundwater Zones. These small-scale fractures are very sparsely spaced. Hydrogeological and geochemical evidence indicates that these small-scale fractures are closed and / or poorly connected. It is expected that these small-scale fractures will be closed under the current stress regime.

Small-scale fractures and joints are more likely to be present in the Shallow Bedrock Groundwater Zone. The scale of these features is such that, at the scale of the contaminant transport pathways, their impacts are subsumed within the measured hydraulic conductivities.

FEP Screening
Screened out.

2.2.04.03 Dykes

Screening Analysis
There is no evidence of dykes at the DGR site. Although the Phase 1 DGR site characterisation 2-D seismic survey identified two features to be investigated by inclined boreholes during the Phase 2 site characterisation, the seismic profiles are not consistent with these features being dykes. At the regional scale, dykes have only been identified in the Pre-Cambrian basement (Hobbs et al. 2008).

FEP Screening
Screened out.

2.2.05 Mechanical Processes and Conditions (in Geosphere)

Description

The mechanical processes that affect the host rock and other rock units, and their evolution with time. This includes the effects of changes due to the excavation and long-term presence of the repository.

This category is divided into:

2.2.05.01 Geomechanical properties

2.2.05.02 Current stress regime

2.2.05.03 Future stress regime

2.2.05.01 Geomechanical properties

Screening Analysis

The current repository design does not include backfilling of the tunnels and emplacement rooms after waste emplacement.

The geomechanical properties of the rock will affect the extent and properties of the EDZ, the engineering required to maintain stable openings during the operational phase and the potential for rockfall postclosure. Uniaxial compressive strength tests on host rock core samples from the DGR2 borehole, and existing underground structures in the Ordovician formations at shallow depths elsewhere in the region, indicate that stable excavations can successfully be created (Gartner Lee 2008b).

FEP Screening

Include FEP in all scenarios.

2.2.05.02 Current stress regime

Screening Analysis

The current stress regime will affect the extent and properties of the EDZ. Long-term modelling of cavern stability under the current stress regime indicates that the EDZ will grow with time and rockfall will occur (Damjanac 2008).

FEP Screening

Include FEP in all scenarios.

2.2.05.03 Future stress regime

Screening Analysis

The current stress regime may be perturbed in the future by earthquakes and glacial loading and unloading. Earthquakes in particular may result in rockfall and removal of the EDZ. The EDZ will then reform through continued stress relief until the next rockfall event. Eventually the void space in the repository will be filled by rockfall material and the system will stabilise.

FEP Screening

Include FEP in all scenarios.

2.2.06 Hydraulic / Hydrogeological Processes and Conditions (in Geosphere)

Description

The hydraulic and hydrogeological processes and conditions that affect the migration of fluids through the host rock and other rock units, and the evolution of conditions with time. This includes the impacts of construction and operational dewatering of the repository and the effects of the long- term presence of the repository.

This category is divided into:
2.2.06.01 Hydraulic properties
2.2.06.02 Current hydraulic potentials and gradients
2.2.06.03 Future hydraulic potentials and gradients

2.2.06.01 Hydraulic properties

Screening Analysis

These are the properties of the host rock and other rock units that affect the migration of fluids, for example the hydraulic conductivity in the context of flow through a porous medium, plus the presence of open fractures, capillary suction and the gas-entry pressure.

FEP Screening

Include FEP in all scenarios.

2.2.06.02 Current hydraulic potentials and gradients

Screening Analysis

The hydraulic gradients drive fluid flow through the host rock and other rock units. The near-surface hydraulic gradients are topographically controlled and are in equilibrium with the current surface conditions. Heads in the Salina A0 formation and deeper are out of equilibrium with the current surface conditions (Sykes et al. 2008).

FEP Screening

Include FEP in all scenarios.

2.2.06.03 Future hydraulic potentials and gradients

Screening Analysis

Hydraulic gradients will evolve with time due to evolving surface boundary conditions. For example due to changes in climate and landform, but more significantly due to glacial cycles. Geochemical evidence (Hobbs et al. 2008) and palaeoclimate groundwater simulations (Sykes et al. 2008) indicate that fresh glacial meltwaters were injected to the depth of the Salina F formation at the DGR site during the last glacial cycle.

Heads in the deeper formations (Salina A0 and deeper) are out of equilibrium with the present-day surface boundary conditions. They are evolving towards a state of equilibrium. This evolution may be perturbed by future glacial cycles.

FEP Screening

FEP included in a Normal Evolution Scenario variant calculation that considers transient head conditions (Avis et al. 2009). FEP excluded in all other Normal Evolution Scenario calculation cases and all other scenarios.

2.2.07 Chemical / Geochemical Processes and Conditions (in Geosphere)

Description

The chemical processes that affect the geochemical environment in the host rock and other rock units, and the evolution of geochemical conditions with time. This includes the effects of changes in conditions associated with the excavation and long-term presence of the repository, e.g. Eh, pH and the dissolution and precipitation of minerals. The chemical conditions affect the mobility of contaminants. The main chemical processes included are contaminant sorption and solubility.

This category is divided into:

2.2.07.01 Mineralogical properties

2.2.07.02 Geochemical properties

2.2.07.03 Effects of engineered barriers

2.2.07.04 Effects of climate change

2.2.07.01 Mineralogical properties

Screening Analysis

The host rock and other rock mineralogy will affect the buffering of geochemical conditions in response to perturbation by the repository materials and wastes, and provide a substrate for sorption of contaminants. Used to inform the selection of distribution coefficients that describe contaminant mobility.

FEP Screening

Include FEP in all scenarios.

2.2.07.02 Geochemical properties

Screening Analysis

The geochemical properties will affect the migration of contaminants. The main geochemical conditions that affect groundwater transport of contaminants are pH and Eh. The geochemical conditions are assumed to be time-independent for the period of interest. Although the chemical conditions in the near-surface will likely change, for example due to injection of glacial meltwaters, there is geochemical evidence that deep groundwaters in the Ordovician sediments are ancient and therefore only slowly changing (Hobbs et al. 2008). Geochemical properties are used to inform the selection of distribution coefficients that describe contaminant mobility.

FEP Screening

Include FEP in all scenarios.

2.2.07.03 Effects of engineered barriers

Screening Analysis

The engineering materials in the repository could perturb the natural geochemical conditions in the geosphere. There could be a chemical plume from the repository into the geosphere that could affect geochemical conditions in the geosphere and cause mineralogical alteration. Plumes of different chemistries may originate from the different areas of the repository. For example the ILW wastes may give rise to an alkaline plume due to the concrete used for operational shielding, whereas the LLW may give rise to a more acidic plume due to degradation of organic materials.

The spatial extent of the plumes and of the associated mineralogical alteration of the geosphere is anticipated to be small due to the limited chemical potential of the majority of the wastes and repository materials at the scale of the geosphere, and the low solute fluxes from the repository to the geosphere.

FEP Screening

Screened out.

2.2.07.04 Effects of climate change

Screening Analysis

Climate change is expected to alter the geochemical conditions in the Shallow Bedrock Groundwater Zone, for example due to injection of glacial meltwaters (Hobbs et al. 2008). However, for the Version 1 SA, these changes are assumed to have limited effect on the assessment calculations and a stylised approach using constant climate conditions is adopted (Walke et al. 2009a; Penfold and Little 2009). Geochemical evidence indicates that the waters below the Shallow Bedrock Groundwater Zone are ancient and will not be perturbed by climate change (Hobbs et al. 2008).

FEP Screening

Screened out.

2.2.08 Biological / Biochemical Processes and Conditions (in Geosphere)

Description

The biological and biochemical processes that affect the host rock and other rock units, and their evolution with time. This includes the effects of changes in conditions, e.g., microbe populations, due to the excavation and long-term presence of the repository.

Screening Analysis

Microbial processes are considered in the repository (see FEP *[2.1.09]*). In comparison, it is considered that the role of microbes in the geosphere will have no significant impact on the migration of contaminants through the geosphere and furthermore that the microbes present will not change significantly with time.

FEP Screening

Screened out.

2.2.09 Thermal Processes and Conditions (in Geosphere)

Description
The thermal processes that affect the host rock and other rock units, and the overall evolution of conditions with time. This includes the effects of changes in conditions, e.g., temperature, caused by the excavation and long-term presence of the repository.

This category is divided into:
2.2.09.01 Thermal properties
2.2.09.02 Effects of waste and repository minerals
2.2.09.03 Effects of climate change

2.2.09.01 Thermal properties

Screening Analysis
The thermal properties of the host rock and other rock units affect the migration of heat from / to the repository. These properties include the heat capacity, thermal conductance and hydraulic properties (*Hydraulic / hydrogeological processes and conditions [2.2.06]*) in the context of heat transport by convection.

The temperature at the repository horizon is approximately 21°C with a gradient of approximately 1.75°C per 100 m depth (Walke et al. 2009b).

The background thermal gradient is not considered to have any significant impact on the migration of contaminants through the geosphere. Furthermore, the thermal perturbation from the wastes in the repository is small and so will also have no significant impact *[2.1.10]*.

FEP Screening
Screened out.

2.2.09.02 Effects of waste and repository minerals

Screening Analysis
Heat may be generated in the repository due to radioactive decay, setting / curing of concretes and shaft seal materials, and biogeochemical reactions including corrosion. The heat generated is considered to be insignificant and isothermal conditions are expected to prevail.

The impact of repository-derived heat on the geosphere is assumed to be insignificant due to expected limited temperature increase in repository (see *Thermal processes and conditions (in wastes, emplacement rooms, tunnels and shafts) [2.1.10]*) and the geosphere being a large heat sink.

FEP Screening
Screened out.

2.2.09.03 Effects of climate change

Screening Analysis

Climate change, in particular glacial cycles, will affect the temperature of the geosphere. Global cooling and the onset of glaciation may lead to a reduction in geosphere temperatures ultimately leading to permafrost. However, as a glacier develops over the permafrost the insulating effect will lead to melting of the permafrost and an increase in geosphere temperatures. Geosphere temperatures are not likely to be significantly perturbed at repository depth. It is recognised that the surface and near-surface environment will be significantly affected with the formation of discontinuous permafrost down to 60 m (see System and its Evolution report, Little et al. 2009). This is considered in the Version 1 SA through the development of a variant calculation case for the Normal Evolution Scenario that considers a tundra environment with discontinuous permafrost (see Normal Evolution Scenario Analysis report, Walke et al. 2009a).

FEP Screening

FEP included in a Normal Evolution Scenario variant calculation that considers releases to a tundra environment with discontinuous permafrost. FEP excluded in all other Normal Evolution Scenario calculation cases and all other scenarios.

2.2.10 Gas Processes and Effects (in Geosphere)

Description

The natural sources of gases within the geosphere, the migration of gas (including gas generated in the repository) within the geosphere, and the behaviour and effects of gas on the geosphere.

Gases found in the geosphere include methane, hydrogen, nitrogen, carbon dioxide, helium and trace amounts of other noble gases. Oxygen is generally not found as it rapidly combines with rock minerals, organics, etc. Radon and helium are produced by natural radiogenic sources (i.e. radioactive decay of uranium and thorium in the rock). The same types of gases can be generated in the repository.

This category is divided into:

2.2.10.01 Gas sources (excluding waste and repository materials)

2.2.10.02 Gas migration

2.2.10.03 Gas dissolution

2.2.10.04 Gas-induced fractures

2.2.10.01 Gas sources (excluding waste and repository materials)

Screening Analysis

There is no significant generation of gas in the deep geosphere in the area of the DGR. For example pressurised gas at depth was not encountered during the drilling of boreholes DGR1 and 2. Methane gas is found in the regional oil / gas fields and its generation is a direct consequence of the thermal history of the sedimentary basin and resultant evolution of organic materials originally deposited with the sediments (Hobbs et al. 2008). Methane generation has also been observed in shallow groundwaters in the wider region associated with the injection of glacial meltwaters (Hobbs et al. 2008).

Some of the rock formations at the DGR site may contain some gas, which could be significant with respect to future contaminant transport from the repository because of its influence on the migration of gas and groundwater. Initial site-characterisation information suggests 5 to 15% of the porosity in the Ordovician might be gas-filled. This will be further investigated as part of the Phase 2 site characterisation work. Sykes et al. (2008) have suggested that an alternative explanation for the underpressures observed in the Ordovician formations is a non-wetting gas phase, as opposed to sediment erosion on geological timescales or glacial events prior to the last (Laurentian) glacial cycle.

FEP Screening

FEP included in a Normal Evolution Scenario variant calculation that considers residual gas saturation in the Ordovician (Calder et al. 2009). FEP excluded in all other Normal Evolution Scenario calculation cases and all other scenarios.

2.2.10.02 Gas migration

<u>Screening Analysis</u>
Gas can migrate in the geosphere either in the gas phase (bulk gas) or through dissolution and subsequent transport in groundwater (dissolved gas). Gaseous radionuclides can be transported within the bulk gas phase or as dissolved gas. Gas can dissolve or come out of solution depending on changes in pressure (depth), temperature and concentration (due to dilution, dispersion, and biogeochemical reactions). Viscous fingering can potentially occur at the interface between gas and water saturated areas of the geosphere. The effect of fingering would be to reduce the volume of water with which the gas would come into contact (Metcalfe et al. 2008). However, the extent of gas-water interaction is influenced by many other factors such as the presence and connectivity any fractures and spatial variation in the capillary pressure behaviour. The impacts of fingering are anticipated to be within the range of gas permeability, capillary pressure curve, etc. parameter uncertainty. Transport of bulk and dissolved gasses, dissolution and exsolution are considered as two–phase-flow processes.

<u>FEP Screening</u>
Include FEP in all scenarios.

2.2.10.03 Gas dissolution

<u>Screening Analysis</u>
Gas can dissolve in groundwater and exsolve from solution. Dissolution / exsolution are controlled by changes in pressure (depth), temperature and concentration (due to dilution, dispersion, and biogeochemical reactions). Biogeochemical reactions can influence the gas pressure, for example microbial reduction of carbon dioxide with hydrogen to form water and methane. Carbonate equilibria will be an important geochemical control on the generation of carbon dioxide (dissolution of carbonates) and removal carbon dioxide (precipitation of carbonates). The stable equilibrium may change between calcareous and non-calcareous lithologies.

Transport of bulk gas within the shaft EDZ and subsequent dissolution within the Shallow Bedrock Groundwater Zone is recognised as a potentially significant transport path for C-14. Carbonate equilibria reactions are considered to be significant in the repository / repository EDZ and shaft / shaft EDZ, but not elsewhere in the geosphere (*Effects of engineered barriers [2.2.07.03]*).

<u>FEP Screening</u>
Include FEP in all scenarios.

2.2.10.04 Gas-induced fractures

Description

Fracturing of host rock due to gas pressure exceeding lithostatic pressure.

Screening Analysis

High gas pressures could lead to dilation or fracturing of rock, particularly along horizontal bedding planes since these are mechanically weaker and since, at the DGR horizon, the vertical stresses are likely much lower than the horizontal stresses.

Under natural conditions, gas reservoirs are typically around the environmental head. Engineered underground gas storage systems typically allow gas pressures to be somewhat higher, but less than the lithostatic pressure.

Modelling for the DGR indicates that the gas pressures are likely to be on the order of the environmental head of 7.5 MPa at the DGR horizon, and much less than the lithostatic pressure of about 17 MPa.

Therefore formation of gas-induced fractures at the DGR site is not expected.

FEP Screening

Screened out.

2.2.11 Geological Resources (in Geosphere)

Description

Natural resources within the geosphere, particularly those that might encourage investigation or excavation at or near the repository site.

Potential deep geologic resources include oil and gas, solid minerals, water and geothermal energy. Near-surface resources include deposits such as sand, gravel and clay. See also *Deliberate human intrusion [1.4.02], Drilling activities (human intrusion) [1.4.04]* and *Mining and other underground activities (human intrusion) [1.4.05]*.

Screening Analysis

Gas exploration wells have been drilled in the vicinity of the Bruce site. Commercially useful petrochemical resources were not found. There is no indication that mineral resources are available in the Pre-Cambrian basement rocks. Although significant deposits of salt and anhydrite are present to the south of the region, there are no significant deposits at the DGR.

Surface use of the area for gravel or aggregates is common at present; however, this should have no impact on the performance of the DGR.

However, the groundwater aquifer down to around 100 m is used for municipal and domestic water in the region (see Section 2.3 of the System and its Evolution report, Little et al. 2009).

FEP Screening

Include FEP in all scenarios.

2.2.12 Undetected Features (in Geosphere)

Description

Natural or man-made features within the geosphere that are not detected during the site investigation, or even during excavation and operation of the repository. Examples of possible features are faults, fracture zones, induced fractures caused by excavation, inhomogeneities, unexpected splays or branching of known fractures, brine pockets and old boreholes and mine workings. These features could play a significant role in the transport of groundwater to and from the disposal repository.

Screening Analysis

Mazurek (2004) discusses the possible occurrence of large Dolomitised fault zones in Ordovician sediments in Southern Ontario that may form high permeability pathways from the repository formations. These fault zones formed the pathways for hydrocarbon migration into ‘traps’ within the Silurian (Hobbs et al. 2008). However, such features are not present at the DGR site and are unlikely to remain undetected.

Vertical faults and fractures may be present in the repository formations. However, the compressive stress regime expected in the Ordovician sediments would likely seal any vertical faults and thus these would not represent higher permeability pathways (see *Large-scale discontinuities [2.2.04]*).

The Phase 1 site investigation 2D seismic survey has identified two potential fracture zones that are to be investigated by included boreholes as part of the Phase 2 site characterisation work. This builds confidence that significant features are unlikely to remain undetected.

It is unlikely that any faults in the vicinity of the DGR would remain undetected due to the lateral continuity and predictability of the geological formations / units. Any significant fault offset would easily be recognised from the site investigation borehole geological logs. There is no hydrological or geochemical evidence from the Phase 1 site characterisation for the presence of open fractures / faults in the Deep and Intermediate Bedrock Groundwater Zones.

FEP Screening

Include FEP in the Human Intrusion and Extreme Earthquake Scenarios only.

2.3 Surface Environment

Description

These are the factors related to the features and processes within the surface environment of the disposal system.

The "Surface Environment" category of FEPs are inside the spatial and temporal boundaries of the disposal system domain and include all the features at or near the surface - including near-surface aquifers and unconsolidated sediments – and the processes that may lead to changes in the surface environment, but exclude human activities and their behaviour in this environment (see Category 1.4 and Category 2.4).

"Surface Environment" is divided into individual FEPs as follows:

- 2.3.01 Topography and morphology
- 2.3.02 Biomes
- 2.3.03 Soil and sediment
- 2.3.04 Near-surface aquifers and water-bearing features
- 2.3.05 Terrestrial surface-water bodies
- 2.3.06 Coastal features
- 2.3.07 Marine features
- 2.3.08 Atmosphere
- 2.3.09 Vegetation
- 2.3.10 Animal populations
- 2.3.11 Climate and weather
- 2.3.12 Hydrological regime and water balance (near-surface)
- 2.3.13 Erosion and deposition
- 2.3.14 Ecological/biological/microbial systems
- 2.3.15 Biotic intrusion

2.3.01 Topography and morphology

Description

The relief or shape of the (land and water) surface, and its evolution with time. Surface types include plains, hills, valleys, outcrops, channels and canyons. Changes covered within this category are limited to short-term processes, such as river erosion, that could occur over a few centuries.

Topography is important because it defines surface-water flows, the location of groundwater recharge and discharge locations, and the magnitude of hydraulic heads that drive local and regional groundwater flows. Features such as slope or depression affect the amounts of moisture and soil that are retained locally, which in turn influences plant and animal communities.

Changes to the topography and morphology with time could also be important. The current topography is part of an ongoing process of evolution of the Earth's surface. Regional and local changes can occur from processes such as lake infilling, rivercourse meander, river erosion, wind erosion, soil subsidence, landscape subsidence (possibly caused by the repository excavation), uplift (e.g. from previous ice ages), and construction of dams (both by beaver and human activities). Some such changes can affect temperature and local climate. Changes resulting from processes acting on a geologic time scale, such as mountain building, are described under *Geological processes and effects [1.2*]. Other changes resulting from evolution of the climate and human actions are discussed under *Climatic processes and effects [1.3]* and *Future human actions (active) [1.4]*.

Changes to topography can also affect the location and activities of the critical group. For instance, changes affecting the depth of local water tables could alter irrigation practices.

Screening Analysis

The topography provides a surface boundary condition for hydraulic heads that in turn affect the groundwater flow. The surface topography can therefore be considered as an input to the geosphere groundwater flow model, on regional (5700 km^2 scale), subregional (84 km^2) and site (2 km^2) scales.

The topography and morphology also defines the surface-water bodies and groundwater discharge zones. These are used to define reference locations for critical groups, and for the reference characteristics of the local water supplies.

The topography and morphology also contribute to the definition of the surface ecology and land use.

As noted in *Tectonic movement and orogeny [1.2.01]*, there is no mountain building occurring in the region, only slow erosion. In addition, the Normal Evolution Scenario with climate change considers glaciation.

FEP Screening

Include FEP in all scenarios.

2.3.02 Biomes

Description

Factors related to the characteristics of biomes found on earth, and their evolution.

A biome can be defined as a mixed community of plants and animals (a biotic community) occupying a major geographical area on a continental scale. Usually applied to terrestrial environments, each biome is characterised by similarity of vegetation structure or physiognomy rather than by similarity of species composition, and is usually related to climate. Within a particular biome, the plants and animals are regarded as being well adapted to each other and to broadly similar environmental conditions, especially climate.

The most important factors influencing biome classification (if unaffected by human activity) include temperature, precipitation, latitude and altitude. However, anthropogenic activities may also influence the classification.

Screening Analysis

The climate of the watershed is best described as temperate-boreal because of location in the mid-latitudes. The extremes of the climate are moderated by the presence of Lake Huron. Under these conditions, the natural biome of the region is that of a forest.

However, the site of the DGR and much of the surrounding area has been affected by anthropogenic activities, which influences the biotic community. This has meant that the forest has been cleared from some of the terrestrial area and the land turned to agriculture.

Note that within the major regional biome, smaller and somewhat different ecosystems also exist. Within the context of the DGR, this is especially true given its location close to the edge of Lake Huron and the resulting marsh and wetland areas associated with the watercourses and lake margins.

FEP Screening

Include FEP in all scenarios.

2.3.03 Soil and sediment

Description
The soils and sediments that overlie the rock of the geosphere, including their evolution in time.

Further discussion of soils and sediments is provided under three categories:
- 2.3.03.01 Surface soils
- 2.3.03.02 Overburden
- 2.3.03.03 Aquatic sediments

The first two categories involve terrestrial soils found on the surface and near-surface. The third category involves aquatic sediments found at the bottom of surface-water bodies such as lakes, rivers, and streams.

2.3.03.01 Surface soils

Description
The soils and sediments that are at or near the terrestrial surface.

Surface soils are considered to be those within a few meters of the surface. Typically the top 0.3 m is the active surface soil region which contains the bulk of the plant roots, as well as being the region most directly affected by agricultural practices such as ploughing.

The soil type, such as loam, sand, clay or organic, can be roughly characterised by parameters such as particle-size distribution and organic matter content. These various soil types will have different physical and chemical properties associated with them (e.g. erosion rates, water percolation rates, pH, organic content), different land management practices (e.g. irrigation and fertilisation needs, crop yields) and different contaminant transport properties (e.g. sorption). Microbial populations (or their absence) are an important component of soils and sediments.

In the vicinity of the DGR site, there is generally a layer of topsoil, typically about 0.3 m, overlying silt till with occasional regions of peat-like material. Soil and subsoil is generally firm to stiff and dense. Moisture varies, but the soil is generally moist and often wet or even saturated.

Contaminant mobility and transport in soils and their pore waters is dependent on various soil properties, and contaminant redistribution can lead to a number of different exposure pathways (see further discussion under *Contaminant release and migration factors [3.2]*).

The properties (including existence) of soils will evolve because of natural weathering processes that include hydration and dehydration, freeze-thaw cycles, dissolution and leaching, oxidation, acid hydrolysis and complexation. For instance, a podzolic soil is formed in temperate areas with high rainfall and granite parent material; this soil type tends to be acidic with iron and aluminium oxides, clays, alkalis and alkaline earth metals leached from surface to deeper horizons. Soils also evolve because of erosion that could be driven by water and wind, and initiated by land-management practices such as deforestation and row cropping on sloping terrain. Important impacts of interest are how these changes might then affect local ecosystems and the net consequence to groundwater and contaminant movement. These processes may also affect how the critical group uses the soils.

Screening Analysis

Surface soils are the natural substrate for terrestrial plants, including those grown for human and animal consumption, trees for timber used in building and heating (woodlot). Organic soils are also used directly as peat for fuel.

Surface soils may become contaminated if contaminants migrate from the DGR, for example, through the use of contaminated irrigation water. People and biota may be directly exposed to the soils by external irradiation, ingestion and inhalation, or indirectly through the use of food or materials grown/reared on the contaminated soils.

The soil type at the site may change over time. Natural evolution of soil types is slow. However, human intervention, such as through drainage or application of additives (manure, lime etc.), can speed the process up.

FEP Screening

Include FEP in all scenarios.

2.3.03.02 Overburden

Description

The unconsolidated rock, clay, sand and soils that overly the rock of the geosphere, but not including the surface soils. This category includes similar material that may be found under surface-water bodies, but not sediments formed by the deposition of particulates from surface water (see *Aquatic sediments [2.3.03.03]*). It may serve as a pathway for contaminated groundwater flows from the geosphere and as a source of diluting contaminant-free water. Overburden with a high clay content can be relatively impermeable, and groundwater flow might be restricted or confined to channels and fractures. A localised discharge from the geosphere might be dispersed over a larger area by the effects of this overburden, resulting in more widespread sorption and possibly more numerous discharges (and smaller contaminant concentrations) into the surface environment.

Surface soils in Canada are typically a few meters deep, but in some areas there may be tens of meters or more between surface soils and underlying bedrock. This intermediate zone, called the overburden, is typically comprised of an unconsolidated mixture of rock and mineral particulates. The transition from soil to overburden and from overburden to bedrock may not be abrupt. Similarly, a layer of unconsolidated rock mineral material may exist between sediments deposited at the bottom of a surface-water body and the underlying bedrock. Depending on the depositional history, overburden may include alternating layers with greater organic matter than found in the surface layers.

At this site, unconsolidated ('overburden') sediments are comprised of a comparatively complex sequence of surface sands and gravels from former beach deposits 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 on the eastern margin of the Bruce Site.

The overburden will change in time. These changes will be driven by natural weathering processes in the same way that soils evolve. Human activities such as dredging and excavation can affect the overburden.

Screening Analysis

Overlying sediments or overburden may become contaminated if contaminants migrate from the DGR. The properties of the sediments will influence the mobility of contaminants migrating through the material and influencing discharges into the biosphere.

FEP Screening

Include FEP in all scenarios.

2.3.03.03 Aquatic sediments

Description

Sediments formed by the deposition of particulates from surface water. 'Mixed sediments' refers to relatively recent, and often quite shallow, deposits that are susceptible to resuspension. 'Compacted sediments' refers to the underlying older and usually thicker deposits that are compacted to some degree.

Aquatic sediments are found at the bottom of surface-water bodies. They are generally composed of fine-grained sand, clays and organic material. Aquatic sediments are subject to wave action and currents and can be eroded and reformed relatively easily. Mixed and compact sediments may eventually form surface soil and overburden sediments when, for instance, a river changes its course or a lake dries up. They are often dredged for use as soil conditioners.

Aquatic sediments can play an important role in contaminant transport through sorption processes (see *Sorption and desorption [3.2.12]* and *Colloid-mediated migration of contaminants [3.2.09]*). Contaminant sorption onto sediments can remove contaminants from the aqueous environment, but in the process contribute to exposure routes involving contaminated sediments such as through emergent plants like wild rice, or the transformation of lake beds to agricultural land (see, for instance, *Surface excavations, human activities [1.4.07]*).

Screening Analysis

The Bruce site is situated on the shores of Lake Huron. Lake Huron is a cold, deep oligotrophic lake with low nutrient levels. The lake includes four main zones of depositional sediments, underlying the deeper waters of Georgian Bay, and the southern, western and central basins. 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 North Channel are likely similar to sediments in Georgian Bay.

In addition, there are sediments associated with other surface water courses such as the local railway ditch and nearby wetland (east of the WWMF) and local streams such as stream C (see System and its Evolution report, Little et al. 2009).

Although the precise characteristics of such water course will vary of the timescales of the assessment, it is expected that similar water bodies will be present at the site during inter-glacial periods. Thus, should contaminants from the DGR reach the surface environment then they may become sorbed onto aquatic sediments and subsequently taken up by aquatic plants, get moved with the sediments or re-enter the water column.

FEP Screening

Include FEP in all scenarios.

2.3.04 Near-surface aquifers and water-bearing features

Description

The characteristics of aquifers and water-bearing features within a few metres of the land surface, and their evolution in time. The term aquifer is used to denote a specific groundwater source, and not the geological formation in which the source occur. All subsurface water, including aquifers, forms part of the hydrological cycle or water cycle on earth.

Screening Analysis

Groundwater flows westward through overburden sediments to discharge into Lake Huron. Layers of sand and gravel constitute local aquifers, whereas the till layers comprise aquitards (i.e., they restrict groundwater flow).

The aquifers in the area of the DGR are used for water abstraction and can provide the source for natural discharge to the surface.

FEP Screening

Include FEP in all scenarios.

2.3.05 Terrestrial surface-water bodies

Description

The characteristics of surface-water bodies such as rivers, lakes, wetlands and springs, and their evolution in time. Particulates that deposit from surface-water bodies are discussed under *Aquatic sediments [2.3.03.03]*.

The sources of rivers and streams often indicate the watershed boundaries, while lakes and wetlands are often found within the watershed area at topographic low points. Discharge points for deep groundwaters are often found at the margin or base of surface-water bodies. Springs are also discharge points where the water table intersects the surface and groundwater flows out into the surface environment.

The following sub-categories are considered:

- 2.3.05.01 Wetlands
- 2.3.05.02 Lakes and rivers
- 2.3.05.03 Springs and discharge zones.

2.3.05.01 Wetlands

Description

Land areas where the water table is at or near the surface. They may be flooded during wet seasons with water that is generally sufficiently shallow to enable the growth of bottom-rooted plants.

Wetlands (including marshes, fens and peat bogs) may be underlain by, or lead to formation of, thick deposits of organic material (e.g. peat). Wetlands may be discharge areas for deep groundwaters, and salt licks are possible.

One particular interest with respect to a repository is the behaviour of wetlands in removing contaminants from water. For instance, the passage of water through multiple layers of organic material may serve as a biochemical filter to concentrate heavy metals such as uranium and halides such as iodine. Other issues involve the possible future uses of wetlands. For instance, wetlands might also be drained to provide agricultural land (see *Surface excavations, human activities [1.4.07]*) and mined for peat which is then used as a fuel or soil supplement.

Screening Analysis

Wetlands are present in the regional area. Drainage from the site reaches Baie du Doré which is a provincially significant wetland with an area of about 9.5×10^5 m^2. There is also a small wetland (4 ha), located east of the WWMF boundary, which is not a provincially significant wetland. The wetland has experienced yearly fluctuations in water levels and occasionally has small areas of open water.

Contaminants can be sorbed onto the wetland soil, and can be leached out of the wetland soil by the water flowing through the soil block (e.g., with runoff water). Wetland soils (e.g., peat) can be used as fuel for heating (see *Other contaminated materials [3.3.03]*).

FEP Screening

Include FEP in all scenarios.

2.3.05.02 Lakes and rivers

<u>Description</u>

The properties and evolution in time of bodies of surface water that are large enough to persist for many years.

Properties of surface-water bodies include physical, chemical and biological attributes such as size, productivity and supported ecosystems. Other important properties are the following.

- Flushing refers to the net rate of water flow and generally has seasonal variations.
- Mixing refers to the dispersal of contaminants through the water body. Contaminants may enter a lake at a localised site. Mixing will be promoted by natural processes such as currents, wind and the annual disintegration of the thermocline, and by artificial processes such water extraction. Conversely, discharges to the bottom of a lake may not be well mixed because of density effects where a warm surface layer (epilimnion) floats on a cold bottom layer (hypolimnion), especially for deep lakes and during cold seasons. Mixing processes could also stir up contaminated sediments.
- Rate of sedimentation. Rivers and streams often carry large quantities of particulate material produced by erosion of river banks. These particulates can sediment, or be deposited, in areas where water currents are slow, such as at river deltas and in lake bottoms. See also *Aquatic sediments [2.3.03.3]*.

Surface-water bodies will evolve through a number of processes. For example, lakes may gradually fill in and be transformed into wetlands and eventually dry land with rich soils suitable for agriculture. Lakes may also be drained to use their sediments for farming, or sediments might be dredged to enrich poor soils. Lakes can also undergo eutrophication and other geochemical changes (e.g. acidification), significantly affecting their ecology. Rivers can change their beds, especially after a glaciation episode, exposing sediments for farming or changing land-use options. Streams can be dammed by beavers, and then be transformed into wetlands. Climate changes can also bring about evolution of surface-water bodies, such as flooding of land to create a lake or a new river bed.

Surface-water bodies and springs can involve a variety of contaminant transport mechanisms and exposure pathways, such as transfer to fish, ingestion of drinking water by humans and other organisms, and water immersion. These issues are discussed further under *Contaminant release and migration factors [3.2]* and *Exposure factors [3.3]*.

<u>Screening Analysis</u>

The Bruce site is situated on the shores of Lake Huron. Lake Huron is a cold, deep oligotrophic lake with low nutrient levels. For safety assessment modelling purposes, Lake Huron is divided into six sections or “components”- North Channel, Georgian Bay, Mackinac Basin, Central Basin, South Basin, and Saginaw Bay.

There are no major rivers or lakes in the vicinity of the site other than Lake Huron. The WWMF and the immediate surrounding area discharge into the Railway Ditch (originally excavated parallel to the abandoned rail line) and a wetland immediately east of the site (see Section 6.1 of the Data report, Walke et al. 2009b). The Railway Ditch drains into Stream “C” which flows slowly into the Baie du Doré. Under most prevailing current conditions, there is little circulation in the Baie du Doré bay, which appears to be more heavily influenced by wind and wave action than by broad circulation patterns in the lake.

FEP Screening

Include FEP in all scenarios.

2.3.05.03 Springs and Discharge Zones

Description

Places where the water table intersects the surface, allowing groundwaters to flow out onto the surface as springs, seepage lines, streams, wetlands or lakes. Discharge zones are often low-lying areas such as at the margin or bottoms of lakes and wetlands (bogs and marshes). Springs may also be found at various elevations depending on factors such as the lithology and stratigraphy of the geosphere and the location of outcropping geological units.

Discharge zones could be local or regional, with regional discharges likely resulting in greater dispersion and longer travel times. Discharge zones can be affected by changes in the water table caused by local climate changes (e.g. seasonal rainy periods, climate swings with extremes in precipitation), human activities (e.g. diversion of surface water, pumping of groundwater from wells), or changes in topography (e.g. lakes formed by a beaver dam, erosion of a new river channel). Discharge locations for deep groundwater can also show measurable release rates of geosphere gases such as radon and helium.

Springs and other discharge zones can be associated with salt licks, which refer to localised areas where the discharge of saline groundwater, followed by evaporation, leads to the accumulation of salts that become diet supplements for wild and domesticated animals. One important concern is that the deep groundwaters may be contaminated by the presence of the repository, leading to contamination of animals using the salt licks.

Springs can run dry, possibly a seasonal occurrence. Climate changes can also bring about evolution of surface-water bodies and springs, such as flooding of land to create a lake or a new river bed.

Screening Analysis

Springs and discharge zones represent a Geosphere Biosphere Interface (GBI), where potentially contaminated discharges from the geosphere enter the biosphere. It is considered that under present-day conditions, any contamination will discharge directly into Lake Huron. It is recognised that under future conditions, terrestrial discharge might be possible, for example due to significantly lower water levels in Lake Huron.

FEP Screening

Include FEP in all scenarios.

2.3.06 Coastal Features

Description

The coastal zone is the warm, nutrient rich, shallow water that extends from the high-tide mark on land to the gentle sloping, shallow edge of the continental shelf (the submerged part of the continents). This zone, which are characterised by a number of features, has numerous interactions with the land and thus is easily affected by human activities. Coastal features include headlands, bays, beaches, spits, cliffs and estuaries.

The processes operating on these features, e.g. along-shore transport, may represent a significant mechanism for dilution or accumulation of materials (including radionuclides) entering the system. Of particular interest in safety assessments are elevated levels of stable isotopes of some elements; for instance, elevated concentrations of stable isotopes of iodine and chlorine would lead to reduced impacts arising from radioactive iodine-129 and chlorine-36, due to homeostatic control of these elements.

Screening Analysis

Coastal features are not included in the SA since the DGR is located inland.

FEP Screening

Screened out.

2.3.07 Marine Features

Description

The characteristics of seas and oceans, including the sea bed, and their evolution. Marine features include oceans, ocean trenches, shallow seas, and inland seas.

Processes operating on these features such as erosion, deposition, thermal stratification and salinity gradients, may represent a significant mechanism for dilution or accumulation of materials (including radionuclides) entering the system.

Screening Analysis

Marine features are not included in the SA. The location of the DGR is inland. Therefore, there is no need to include marine features in the SA.

FEP Screening

Screened out.

2.3.08 Atmosphere

Description

The characteristics of the atmosphere and its evolution. Relevant processes include physical transport of gases, aerosols and dust in the atmosphere and chemical and photochemical reactions.

There are a variety of pathways through which contaminants released from a repository could become suspended as particulates or gases in the atmosphere.

- Direct release of contaminated gases to the atmosphere after migration from the DGR.
- Processes affecting soils include degassing, wind erosion, ploughing, irrigation and saltation. Saltation refers to the process by which detached soil particles bounce along the soil surface.
- Processes affecting surface waters include degassing, bubble bursting and wind suspension or aerosol formation.
- Processes involving vegetation include fires, which are routinely used to clear land for agricultural use, to reduce peat, to kill weeds and to remove stubble. Natural forest and grass fires are important features and can occur frequently and regularly. Related fires include burning of peat, wood and other fuels for household heating purposes. Forest and other fires can become potent agents for atmospheric contamination, if the material is contaminated. Concomitant effects can also occur from the smoke and entrained carcinogens.

These processes can increase concentrations of contaminants in air, either as gases or particulates. Atmospheric suspension thus could lead to exposure pathways such as inhalation and air immersion (skyshine).

Once in the air, contaminants could become dispersed and deposit to underlying surfaces such as land used to produce agricultural products. Airborne contaminants, apart from gaseous species, will settle on the surface by gravity. Wet deposition, also called washout, refers to the influence of precipitation which can accelerate the delivery of contaminants to the surface. Atmospheric deposition can lead to contamination of surfaces that are remote from the original source. It may be an important mechanism in some exposure routes, such as ingestion (by humans and animals) of plants that have taken up contaminants deposited on their leaves or other surfaces.

Gases generated in the repository might discharge to the surface. Some gases, including hydrogen, methane and hydrogen sulphide, are flammable when mixed with oxygen in the atmosphere. If large gas volumes discharge, there might be a sustained fire at a discharge location that could disperse contaminants into the atmosphere. Some combinations of flammable gases and oxygen can form explosive mixtures with a greater potential for dispersing contaminants as particulates or aerosols.

The atmosphere also has huge dilution potential. For instance, wind is a major environmental force in the transport of contaminants through the atmosphere, by processes of advection, dispersion and diffusion. Wind could also have indirect effects on the behaviour and transport of contaminants through processes such as evapotranspiration, fires, and deposition onto soil and vegetation. The wind attributes are discussed under *Climate and weather [2.3.11]*.

Screening Analysis

Atmospheric processes that are potentially important include: advection/dispersion, precipitation (e.g., rainfall), wet and dry deposition (to soil and plants), and contaminant transport as gases or as particulates (dust or aerosols). Gas and particulate sources include soil, surface waters, and fires (land clearing or forest fires, agricultural fires, and energy fires).

Note that both indoor and outdoor atmospheric conditions need to be considered.

FEP Screening

Include FEP in all scenarios.

2.3.09 Vegetation

Description

The characteristics of terrestrial and aquatic vegetation, including algae and fungi, and their evolution.

Vascular plants and trees can take up contaminants in soil via their roots or from airborne deposition onto their exposed surfaces. Surface vegetation, with large surface areas such as mosses and lichens, may be particularly sensitive to deposition. The degree of uptake varies depending on factors that include the contaminant, soil, plant and the stage of the plant's growth cycle.

The effects of the repository on vegetation need to be considered with respect to possible changes to local conditions such as moisture levels, groundwater flow, salinity and temperature. Potential impacts need to consider any local endangered or valued species.

Vegetation will change with time, with consequent changes to its properties and its effects on contaminant transport and exposure routes. Local ecosystems will respond, often very quickly, to changes such as denudation caused by lumbering, the infilling of a lake, and fluctuations in water tables in response to local climate variation. Some changes, such as the formation of mature forests, can take hundreds of years.

Once in plants, contaminants can be passed into various food webs and lead to different exposure routes affecting humans and other biota. One direct exposure route involves ingestion of contaminated plants. Inhalation and external exposures could result from using vegetation for fuel and as building materials. Contaminant accumulation in aquatic vegetation will affect biota, and contaminant movement in surface waters.

Screening Analysis

The biosphere within the DGR system includes areas of farmed land and semi-natural land (wetland). Farmland accounts for around 60% of the land use in the Bruce county, with many cattle farmers, as wells as farmers of pigs, sheep, goats and poultry, and crops such as oats, barley, canola and hay (see Section 6.4 of the Data report, Walke et al. 2009b).

Contaminants can be taken up by vegetation from soil and from atmospheric deposition (including interception of irrigation water). The following types of vegetation are considered important as potential exposure pathways to humans:

- Large-scale agricultural crops (e.g. oats, barley, canola, wheat and corn);
- Small-scale subsistence crops (e.g. potatoes, onions, carrots, cabbage and beans);
- Forage crops (principally pasture); and,
- Foodstuffs potentially gathered from semi-natural habitats (e.g. berries, mushrooms and nuts).

FEP Screening

Include FEP in all scenarios.

2.3.10 Animal Populations

Description

The characteristics of terrestrial and aquatic animals (including microbes), and their evolution.

A large range of characteristics is possible and many could affect contaminant transport and exposure routes. One of the more important group of animals is those (both domestic and wild) that might serve as a source of food for local people.

- Habitat can effect exposure routes. For instance burrowing animals may live extensively in contaminated soil.
- Diet varies considerably between different species.
- Contaminant levels can increase when moving up the food chain (biomagnification), although for most radionuclides concentrations decrease (bioexclusion).
- Miscellaneous characteristics could be important. Examples include animal grooming and fighting that may lead to external contamination.

The effects of the repository on animals need to be considered with respect to possible changes to local conditions such as moisture levels, groundwater flows, salinity and temperature. Potential impacts need to consider any local species that are endangered or valued. For instance, a repository sited in an environmentally sensitive area might have relatively minor impacts overall, but at the same time could have serious impacts on a local endangered species.

Screening Analysis

Domesticated food animals (beef and dairy cows, pig, sheep, goats, poultry) and fish are present in the area and represent potential pathways for human exposure to radionuclide contamination (see Section 6.5 of the Data report, Walke et al. 2009b).

The most common habitat in the vicinity of the site is fresh-moist white cedar coniferous forest, dry-fresh sugar maple deciduous forest, and mineral cultural meadow. The Bruce site and surrounding area provides habitat for a variety of wildlife, including reptiles and amphibians such as frog, peeper, salamander and turtle, birds such as wild turkey, American crow and blue jay, and mammals such as deer, porcupine, racoon, groundhog, squirrel, muskrat, and beaver.

Animals can become exposed to radionuclides through the following pathways: air inhalation, soil ingestion, plant ingestion, ingestion of prey, water ingestion and external radiation exposure from, for example, ground and water contamination.

FEP Screening

Include FEP in all scenarios.

2.3.11 Climate and weather

Description

The characteristics of climate and weather, and their evolution.

Climate and weather are characterised by precipitation, temperature, pressure and wind speed and direction. These factors can influence contaminant movement through the biosphere. For instance, rain, snow and other forms of precipitation may remove airborne contaminants and deposit them on various ground surfaces, including plants, and have a major influence on the behaviour and transport of contaminants in the environment through recharging of surface-water bodies and leaching of soils.

Daily and seasonal variations can have a wide influence. For example, these variations affect irrigation requirements for agricultural crops, habitat for animal populations, the source of drinking water and the accumulation and release of contaminants under snow and ice cover. The variability in the weather should be included so that extremes such as drought, flooding, storms and duration of snow melt are identified and their potential effects are taken into consideration. For instance, severe drought could markedly concentrate contaminants in the surface environment or promote wind erosion. Another example is severe flooding, which might be responsible for the majority of topographical changes caused by water erosion.

Screening Analysis

The annual mean temperature for the site is 8.9 °C, with mean monthly values varying from -7 °C in January and February to 15 to 19 °C during June to August (see Sections 6.1 and 6.3 of the Data report, Walke et al. 2009b). The annual rate of precipitation is in the range of 800 to 1000 mm/y with slightly more than 20% falling as snow. The average wind speeds in the area are between 12 and 15 km/h (about 3.5 m/s) with generally stronger winds in the winter season. The prevailing winds are from the south and southwest.

The climate and weather affects the types of ecosystems and land use that are present in the area. Rainfall affects the surface-water system.

FEP Screening

Include FEP in all scenarios.

2.3.12 Hydrological Regime and Water Balance (Near-Surface)

Description

The near-surface hydrology at a watershed scale, including soil water balance, and its evolution with time.

The hydrological regime is a description of the movement of water through the surface and near- surface environment. A key component is runoff, which refers to precipitation water that runs off laterally, at or below the surface, to drain into a water body. It is important in determining the flushing rate of surface-water bodies. Runoff may also carry contaminants, scavenged from the atmosphere or leached from soil and plants, to water bodies. Moreover, runoff is an important component in the water balance which, together with precipitation and evapotranspiration, determines irrigation water needs.

Extremes such as drought, flooding, storms and snow melt may be relevant. For instance, flooding can:

- alter the landscape, and destroy or create agricultural land and wetlands;
- destroy existing vegetation such as mature forests;
- enhance the mobility of contaminants by leaching them from exposed soil and rock; and
- promote mixing of contaminants throughout otherwise unsaturated soil zones, giving seasonally homogeneous soil contaminant profiles.

Changes to the hydrological regime could also induce changes in the behaviour of the critical group. For instance, a severe drought might lead people to stop agricultural practices, or to change water supply to a well or a more distant surface-water body.

Screening Analysis

The hydrological regime of the area is dominated by the presence of Lake Huron. The area around the site is drained by ditches and streams into wetlands, which ultimately discharge into the lake.

Advection in water provides a potentially important migration route for contaminants, should they reach the surface environment.

FEP Screening

Include FEP in all scenarios.

2.3.13 Erosion and Deposition

Description

The processes of removal and formation of soils and sediments that operate in the surface environment.

Relevant processes may include fluvial and glacial erosion and deposition, denudation, eolian erosion, and deposition and silting of river deltas and harbours. These processes will be controlled by factors such as the climate, vegetation, topography and geomorphology. Small-scale effects include downward movement and packing of soil particles during the formation and evolution of soils. Erosion of soil, overburden and bedrock by wind, water and ice may move contaminants laterally away from a discharge area, or it may bring uncontaminated soil and overburden into the area, and thereby reduce local contamination concentrations. Alternatively, erosion may deposit contaminated material into a previously uncontaminated and more crucial area, such as a field used for crops. Erosion and deposition processes can redistribute contaminants between terrestrial and aquatic areas.

Screening Analysis

Erosion of soils and sediments can be important over the long timescales considered in the assessment. Surface soils erode into water courses and are replaced by input of new organic material and by erosion and weathering of subsurface materials.

Deposition and suspension can be important for moving contaminants sorbed onto sediments around the surface environment.

Sediment deposition and accumulation in wetland areas can ultimately lead to the succession of wetland areas into areas suitable for farming.

A related but much larger scale, disruptive process is discussed under *Denudation and deposition (large-scale) [1.2.07]*.

FEP Screening

Include FEP in all scenarios.

2.3.14 Ecological / Biological / Microbial Systems

Description

The relations between populations of animals, plants and microbes, and their evolution. Characteristics of the ecological system include the ecosystem type, such as boreal and tundra, and natural cycles such as seasonal variations and random events such as forest fires.

There is a complex interrelationship between various components of the ecosystem. Important processes include:

- biotransformation or metabolism which involves alteration of substances by an organism to provide energy or raw materials, often categorised as catabolism (breaking down of more complex molecules) and anabolism (building up of life molecules from simpler materials);
- cometabolism or the biodegradation of synthetic or hazardous waste materials as a concurrent process with normal metabolic processes;
- bioconcentration, which refers to the ability of an organism to concentrate nutrients and chemicals from its environment, usually from water or soil;
- bioaccumulation, which refers to the tendency of an organism to continue to bioconcentrate throughout its lifetime;
- biomagnification, which refers to the occurrence of nutrients and chemicals at successively higher concentrations with increasing trophic level in the food web;
- biological interim storage, which refers to temporary holdback of nutrients and contaminants;
- recycling, which refers to the reuse of organic material and nutrients;
- biological feedback, which includes a number of effects including destruction of biota when contaminant concentrations reach toxic levels and promotion of growth of a species caused by the elimination or growth of another;
- adaptation and internal behavioural responses that could in turn affect processes such as bioaccumulation; and
- species association, species composition and age class structure in different ecosystem types.

Another important consideration is the evolution of ecosystems, describing changes in time in the interrelationships between populations of animals, plants and microbes. Ecosystems are in a continuous process of adaptation and evolution, and considerable change could occur over long time frames. Various important biological and ecological processes affect the development of forests, grasslands and marshes and an entire system will respond and evolve in concert to an applied external stress or change. For instance, entire ecosystems can change after natural disturbances such as flood or extreme temperature changes or as a result of human activities (see also *Future human actions [1.4]* and *Human behaviour [2.4]*). The main issue is whether and how these changes might influence contaminant transport and exposure routes.

Finally, the effects of the DGR on ecosystems needs to be considered with respect to possible changes to local conditions such as moisture levels, groundwater flows, salinity and temperature.

Screening Analysis

The ecosystems of the surface environment provide the background within which contaminant migration may occur, should such contaminants be released to the biosphere. These include natural (forest, wetland, aquatic) and man-made (agricultural) ecosystems.

Contaminants may migrate through these systems, e.g., via root uptake into vegetation and subsequent movement through the food chain.

The ecosystems therefore provide a potential exposure route for humans, but also provide the systems within which exposure of non-human biota may occur.

FEP Screening

Include FEP in all scenarios.

2.3.15 Biotic Intrusion

Description:

Burrowing animals, which burrow in the ground for shelter, nesting, storage, and foraging. Burrows for shelter can extend to depths greater than 1.0 m, and extend to even greater depths for foraging activities. Rodents dig underground tunnels, bring the soil up to the ground surface, and deposit it around burrow openings. Gopher tunnels can range from 0.5 to 60 m. Gophers can excavate 800 to 16,000 kg soil ha^{-1} y^{-1}.

Depending on the vegetation type in the vicinity of the repository and the safety concept adopted for the disposal of radioactive waste, roots may intrude into the facility leading to the disruption of system behaviour.

Screening Analysis

Biotic intrusion is important for near-surface facilities. As the project is for a deep geological repository, consideration of intrusion by animals and plants is not necessary.

FEP Screening

Screened out.

2.4 Human Behaviour

Description

Factors related to habits and characteristics of the individuals or populations to whom potential exposures from the disposal of radioactive waste in a DGR are calculated. Note that it is assumed that the potential impact of human behaviour on the environment is considered to have been addressed elsewhere (see FEP *[1.4.01]*).

The "Human Behaviour" category of FEPs refers to "potential exposure groups", and therefore is inside the spatial and temporal boundaries of the disposal system domain. Note, however, that it excludes intrusive or intrusive-related activities, i.e., those activities that will have a direct impact on the performance of the DGR.

"Human Behaviour" is divided into individual FEPs as follows:

2.4.01 Human characteristics (physiology, metabolism)
2.4.02 Age, gender and ethnicity
2.4.03 Diet and fluid intake
2.4.04 Habits (non-diet related behaviour)
2.4.05 Community characteristics
2.4.06 Food preparation and water processing
2.4.07 Dwellings
2.4.08 Natural/semi-natural land and water use
2.4.09 Rural and agricultural land and water use
2.4.10 Urban and industrial land and water use
2.4.11 Leisure and other uses of environment

2.4.01 Human Characteristics (Physiology, Metabolism)

Description

The characteristics (e.g. physiology, metabolism) of individual humans. Physiology refers to body and organ form and function. Metabolism refers to the chemical and biochemical reactions that occur within an organism in connection with the production and use of energy.

These characteristics can affect the impacts on humans from internal and external exposure to contaminants. For instance, iodine taken into the human body tends to concentrate and metabolise in the thyroid gland which would then be most affected by radioactive iodine-129, whereas carbon and hydrogen are distributed throughout soft tissues which would be most affected by radioactive carbon-14 and tritium. Chemical toxics may also concentrate and metabolise in specific organs; for instance mercury tends to accumulate and disrupt metabolic processes in the brain.

People vary in their physiology and metabolism. In addition to the variation in individual humans, different groups, such as aboriginal groups, might have a genetic tendency towards certain features that may affect their susceptibility to contaminants. Variability is discussed under *Age, gender and ethnicity [2.4.02]*.

Screening Analysis

Characteristics related to the internal workings of the human body (e.g., physiology and metabolism) are implicitly included through the selected values of, for example, the radiation dose coefficients, which are derived based on a knowledge of human physiology and metabolism, human energy requirements (and corresponding food ingestion rates), human water ingestion rates, and human breathing rates.

Note that specific-activity models that may be used in the SA (e.g., for H-3, Cl-36, C-14, and I-129) require specific physiological information on the H, Cl and C content of the human body, and the iodine content of the human thyroid and other tissues.

According to the CNSC Regulatory Guide G-320 (CNSC 2006): "The use of human receptors in a scenario may be based on the International Commission on Radiological Protection (ICRP) concept of a critical group for radiological protection of persons. The critical group is a group of people representative of those individuals in the population that are expected to receive the highest annual radiological dose. Such a group would be small enough to be relatively homogeneous with respect to age, diet and those aspects of behaviour that affect the annual doses received.

The habits and characteristics that are assumed for the critical group should be chosen based on reasonably conservative and plausible assumptions that consider current lifestyles and available site-specific or region-specific information. To define a critical group and biosphere, either a site-specific approach based on current available site or regional information or a stylised approach based on more general habits and conditions could be used."

Several hypothetical potential exposure groups (critical groups) are considered in the SA. These are identified as part of the process of developing scenarios and conceptual models for the SA. The characteristics of these exposure groups (e.g., lifestyle and location) are cautiously selected so as to maximise calculated dose rates.

FEP Screening

Include FEP in all scenarios.

2.4.02 Age, Gender and Ethnicity

Description

Susceptibility to radioactive and chemically toxic materials varies with age, sex and reproductive status. Children and infants, although similar to adults, often have characteristic differences (e.g. respiratory rates, food types, ingestion of soil) that may lead to different exposure characteristics.

Screening Analysis

Dose rates to children or infants may be more limiting than dose rates to adults, in some particular circumstances. Therefore, for scenarios in which children or infants may receive exposure, the SA may assess all three age groups. Note that it may be appropriate to assume that human intrusion is by adults alone.

Differences in dose rate due to gender are discussed in the OPG (2005c) report on alternative exposure groups for the DGR SA, and the Whillans (2006) report on gender effects in radiation dose and risk assessment for DGR disposal. According to OPG (2005c), in most cases, the variation within a population of males is at least as great as that between males and females, and the variability in most dose calculations. Furthermore, according to Whillans (2006), "differences in dose and risk estimation due to gender are in most cases small in comparison to other sources of uncertainty in these estimates, less than a factor of two, and are often not detectable." Both reports recommend the use of gender-independent or gender-averaged risk coefficients. Therefore, it is not considered necessary for the SA to differentiate between doses to male and female receptors.

FEP Screening

Include FEP in all scenarios.

2.4.03 Diet and Fluid Intake

Description

The intake of food and water by individual humans, and the composition and origin of intake.

The diet of humans can vary greatly, both qualitatively and quantitatively. Potential food types include grains, legumes, cultivated and wild fruit and berries, juices from wild and cultivated fruits, domestic animals, products of domestic animals (such as milk, yoghurt, cheese and eggs), wild game, fish and fish roe, mushrooms, nuts, tree sap (maple syrup), offal, fungi, aquatic crustaceans, terrestrial invertebrates, honey, normal crop plants, native non-berry plants, medicinal plants and water. Humans may inadvertently ingest soil with food or from their hands, or they may have an unnatural (possibly pathological) craving for soil ingestion due to mineral deficiency. (Soil ingestion can be particularly important for contaminants that have low biomobility.) Human diet may also include a variety of drugs that might be produced where they could become contaminated.

The total amount of food consumed can also vary with factors such as age and degree of physical activity. For instance, people performing hard physical labour will generally have a larger energy and food intake than people performing more sedentary tasks, and the very young typically have greater intake of milk and dairy products than the elderly. Consideration could also be given to vegetarian and other special diets, and to changes in diet that come about in response to external factors such as evolution of the climate, and human factors such as growth in the population and population density.

This category is divided into individual FEPs as follows:

- 2.4.3.01 Farming diet
- 2.4.3.02 Hunter/gatherer diet
- 2.4.3.03 Other diets

2.4.03.01 Farming diet

Description

The food and water intake characteristics of persons living a farming lifestyle. For instance, the community's food intake may have a high proportion of plant food grown on local soil, as well as domesticated animals and fish. Water would come from wells or from Lake Huron.

The type of farming household can vary from self-sufficient to an "industrial" or monoculture operation.

Screening Analysis

Of the various plausible critical group lifestyles, it is expected that doses to a self-sufficient farming group would be the highest because such a group is assumed to reside and grow its food in areas where contaminant concentrations are expected to be highest, particularly if it uses a well and irrigates its crops (Zach et al. 1996, Garisto et al. 2005).

Farming is also currently a major activity in the area around the Bruce site.

Therefore, the SA includes a self-sufficient farming household as the primary critical group (the Local Exposure Group). The diet and fluid intakes of the farming household as well as the source of these foodstuffs is explicitly included in the SA (see Section 2.3.3 of the Normal Evolution Report, Walke et al. 2009a, and Section 7.1 of the Data report, Walke et al. 2009b).

FEP Screening

Include FEP in all scenarios.

2.4.03.02 Hunter/gatherer diet

Description

The food and water ingested by persons living a hunter/gatherer lifestyle in the vicinity of the site. Typically, the community's food intake would have a high proportion of fish and wild game, with little agriculture, water would come from springs or the lake, and a high percentage of time may be spent outdoors.

Screening Analysis

Of the various plausible critical group lifestyles, it is expected that doses to a self-sufficient farming group would be the highest, and therefore, as noted in [*2.4.03.01*], this diet and lifestyle is included in all scenarios.

The current diet of people living in the area include a variety of non-cultivated foods, notably fish, but also a small percentage of other local wild foods such as deer, rabbit, berries and mushrooms. These are included in the diet habits of the Local Exposure Group noted in [*2.4.03.01*] (see Section 7.1 of the Data report, Walke et al. 2009a). Therefore some elements of a hunter diet are already included in the Local Exposure Group.

However, given the long timeframes being considered, including the possible presence of permafrost as part of future climate changes, alternative diets based primarily on hunter/gatherer diets are relevant. Also, a traditional first nations diet would include a strong hunter/gatherer diet, specifically with a large fish component. A diet with a significant fish update would be an alternative of interest to current communities more distant from the DGR in terms of possible impact. Therefore it would be useful to demonstrate the implications of these alternative diets at least within the Normal Evolution Scenario.

FEP Screening

Indirectly included in all scenarios since some elements of a hunter diet are included in the Local Exposure Group's diet. A fisher diet is also explicitly considered in a variant calculation case for the Normal Evolution Scenario.

2.4.03.03 Other diets

Description

Other diets that are not represented by a farming or hunter/gatherer diet.

Screening Analysis

Garisto et al. (2005) describes several alternative exposure groups with differing diets. However, since self-sufficient farming diet usually gives a reasonable or conservative estimate of dose, and since the fisher diet is included as outlined in [*2.4.03.02*], it is not considered necessary to include any other diets.

FEP Screening

Screened out.

2.4.04 Habits (non-diet related behaviour)

Description

The behaviour (excluding diet) of individual humans, including time spent in various environments, pursuit of activities and uses of materials.

Habits (and diet) will be influenced by agricultural practices and human factors such as culture, religion, economics and technology. Examples of behaviour that might give rise to particular modes of exposure to environmental contaminants include:

- outdoor activities such as fishing, logging and swimming that could increase external exposure;
- keeping of pets that could become externally contaminated through a variety of pathways and increase external exposure when handled by humans;
- agricultural practices, such as ploughing, cultivation and harvesting, which can create dust and lead to inhalation and external exposure;
- dwelling location, such as underground or partially buried, or on bodies of water; and
- use of physical resources such as peat, wood, stone and water.

Other examples are discussed in the FEPs for *Community characteristics [2.4.05],* and *Leisure and other uses of environment [2.4.11]*.

Screening Analysis

Particular habits of interest in the SA include (see Section 2.3.3 of the Normal Evolution Scenario report, Walke et al. 2009a, and Section 7.1 of the Data report, Walke et al. 2009b):

- time spent indoors;
- time spent outdoors;
- time spent immersed in water (bathing or swimming);
- water source (well or lake), see also under *[2.4.05.03]*; and
- agricultural practices, if any (irrigation, ploughing).

FEP Screening

Include FEP in all scenarios.

2.4.05 Community Characteristics

Description

The characteristics, behaviour and lifestyle of groups of humans that might be affected by the DGR.

Some of the more important characteristics are discussed separately under:

2.4.5.01 Community type
2.4.5.02 Community location
2.4.5.03 Water source of the critical group.

2.4.05.01 Community type

Description

The general nature and size of the community, and in particular its degree of self-sufficiency.

Communities found at present in the DGR area range from rural farm households to larger towns that support heavy industries. A relevant classification scheme can be based on the degree of self-sufficiency of members of the community, such as the following.

- A hunter-gather community might best describe a subsistence lifestyle employed by nomadic or semi-nomadic groups who roam relatively large areas of land, hunting wild game and fish, and gathering native fruits, berries, roots and nuts (representing hypothetical future conditions).
- A self-sufficient rural community describes a lifestyle that relies mostly on local resources for food, water, house heating fuels, clothing, etc.
- Other rural communities with specialised industry, such as centres for mining or railroads, might have unique lifestyles and exposure routes.
- An agricultural community that may practise intensive farming (including factory farms, fish farms, monoculture intensive crops, greenhouses and hydroponics), but may also use external resources for some of its food, water, etc.
- An urban community that may rely mostly on resources imported from beyond the local area.

Some characteristics may have the potential for unique exposure pathways; for instance ploughing of contaminated agricultural land may be an important inhalation and external exposure pathway.

Screening Analysis

The general nature of the potentially exposed communities and their degree of self-sufficiency is an important consideration for the SA. For example, self-sufficiency is used to derive a cautious estimate of exposure, whereas partial subsistence may be used to represent site-specific present-day or other more realistic conditions.

FEP Screening

Include FEP in all scenarios.

2.4.05.02 Community location

Description

The location of the community relative to areas that might be contaminated by the effects of the DGR.

A community most at risk might be situated on the discharge area of groundwaters that may have become contaminated by the DGR. All exposure pathways could be affected.

Alternatively, the largest impacts might be experienced by a community situated at a downstream location, where contaminants from multiple groundwater discharge areas converge and contaminants accumulate.

Screening Analysis

In the SA, it is assumed that the potentially exposed communities reside close to the DGR. The well, home and fields are cautiously located where potential radionuclide concentrations and, hence, calculated dose rates would be highest.

Dose rates to communities living "downstream" should be lower than for groups living near the DGR due to dilution in the surface environment (see *Hydrological regime and water balance [2.3.12]*) and are also explicitly addressed.

FEP Screening

Include FEP in all scenarios.

2.4.05.03 Water source

Description

The origin of water used by the critical group for domestic purposes, including drinking, and to meet irrigation demands.

Humans require water for domestic use, including drinking, cooking, washing and bathing. They may also require water to irrigate gardens and large agricultural fields used for crops and forage, to provide drinking water for livestock and to serve other purposes such as supply and maintenance of water for fish hatcheries or process water for industry. Potential water sources on the Michigan Basin include lakes, rivers, streams, springs and wells although bottled spring water might be imported principally for drinking purposes. Note that different sources might be used for different purposes; for instance, water used for domestic purposes might derive from a dedicated water-supply well whereas water for irrigation may be taken from a nearby lake or from a different water-supply well. In addition, the volume of water required, and hence the type of water source, will be affected by the size, lifestyle and occupations of the community, and additional volumes and sources might be required for a growing community.

These sources could be contaminated to different degrees, with factors such as volume of diluting water, sedimentation and sorption affecting contaminant concentrations in the water. Moreover, the ingestion of contaminated drinking water could involve a relatively direct exposure route, with few delay and dilution processes. Consequently, radiological and chemical toxicity impacts on the critical group could depend strongly on its source of water.

Finally, there is a need to consider the potential impacts of waste water processing, which may affect exposures to other critical groups and biota.

See also the related discussions under:

- FEP for *Water management (groundwater and surface water) [1.4.10]* which includes more considerations on water-supply wells;
- FEPs for *Near-surface aquifers [2.3.04]* and *Surface-water bodies [2.3.05]* which are further concerned with water sources; and
- other uses of water (and land) discussed under FEPs *[2.4.09]* and *[2.4.10]*.

Screening Analysis

Given that aquifers and surface-water features may become contaminated, the water source for the potentially exposed groups is an important consideration in the SA. The SA assumes that potential exposures may arise from taking drinking, domestic and irrigation water from a well (about 80 m depth) that intersects a contaminant plume from the DGR. The well is taken to be 80 m deep, based on consideration of the local aquifer depth, the depth of potable water and typical practice for wells in the area. The groundwater becomes increasingly brackish at greater depths (see System and its Evolution report, Little et al. 2009).

FEP Screening

Include FEP in all scenarios.

2.4.06 Food preparation and water processing

Description

The treatment of foodstuffs and water between raw origin and consumption.

Once a crop is harvested or an animal is slaughtered, it may be subject to a variety of storage, processing and preparation activities prior to human or livestock consumption, and these could change the contaminant distribution and content in the product. For example, any delay between harvesting and ingestion will result in losses caused by radioactive decay. Other examples include:

- stored crops could become contaminated (or decontaminated) by seepage or flooding with contaminated (or uncontaminated) water;
- water supplies might be subjected to chemical treatment and filtration, removing harmful contaminants, prior to human or livestock consumption;
- food preparation, such as peeling, boiling and frying, can enhance or decrease contaminant concentrations in food. Depending on the circumstances, contaminants in cooking utensils or fuel could be transferred to the food; and
- greenhouse production of tomatoes and cucumbers, hydroponics (raising of crops without soil) and related practices, followed by cleaning and preservation, might involve the use of more or less contaminated soil and water.

Screening Analysis

The effect of food and water processing and preparation can be excluded. This is justified because contaminants in water and foods are usually lost as a result of processing and preparation, therefore its exclusion is a cautious assumption.

The SA neglects the effect of radioactive decay between the time food is harvested and the time it is consumed. Since these holdup times are generally short compared with the long travel time through the geosphere, the effects of such decay can be neglected.

FEP Screening

Screened out.

2.4.07 Dwellings

Description

The characteristics of the houses or other structures or shelters in which humans spend time.

Factors that may affect their occupants' exposure modes and levels include:

- the dwelling location which may be particularly important for impacts from radon (see *Radon and radon daughter exposure [3.3.08]*);
- materials used in construction such as wood, stone and ashes, especially for those materials that tend to accumulate contaminants (FEP *[3.3.03]*);
- design elements for improved energy efficiency and air tightness and size which could have a strong influence on air exchange rates and indoor concentrations of contaminants;
- heating source, such as wood, peat and biogas (generated from plant materials, faeces and refuse, or from trapping methane from garbage disposal sites, bogs and sediments), which may be contaminated by different sources and to varying degrees and affect indoor and outdoor concentrations of contaminants (FEP *[3.3.03]*);
- the likelihood of infiltration of water or gases into basements or flooding of basements from surface or groundwater sources, which could introduce contaminants into a household (see *Radon and radon daughter exposure [3.3.08]*);
- creation of household dust and fumes from indoor and outdoor sources and activities, which could affect contaminant concentrations inside the household; and
- the introduction into the dwelling of contaminated furnishings, household plants, etc.

Many of these factors are important because they could affect contaminant concentrations in air, affecting exposures from inhalation. External exposure pathways, and ingestion exposure, could also be influenced.

Screening Analysis

The following characteristics of the house/shelter are considered in the SA:

- the location, particularly in relation to the main and ventilation shafts, with the associated potential for gas release into the building;
- the building size, as specified by building height and width;
- the building air infiltration rate, i.e., the number of air exchanges per hour; and
- the number of people residing in the house.

FEP Screening

Include FEP in all scenarios.

2.4.08 Natural/Semi-Natural Land and Water Use

Description
The use of natural or semi-natural tracts of land and water such as forest, bush and lakes.

Special foodstuffs and resources may be gathered from natural land and water which may lead to significant modes of exposure. Examples include picking of wild blueberries in season as a supplement to normal diet (see also *Diet and fluid intake [2.4.03],* and *Habits (excluding diet) [2.4.04]*) and gathering of peat and wood for household heating (see also *Dwellings [2.4.07]*).

Other examples of wild and natural land and water use are discussed elsewhere, such as under *Community characteristics [2.4.05]* and *Water management (groundwater and surface water) [1.4.10]*.

Screening Analysis
The region around the site of the DGR includes areas of natural and semi-natural land that may become contaminated should radionuclides and/or chemical species from the waste reach the surface environment. These areas include biota of interest in the assessment. Potentially exposed groups may also use these areas, for example, for recreation, hunting and gathering food.

Note that the use of this land by potentially exposed groups depends on the characteristics of such groups.

FEP Screening
Include FEP in all scenarios.

2.4.09 Rural and Agricultural Land and Water Use

Description
The use of land and water for agriculture, fisheries, game ranching and similar practices.

An important set of processes are those related to agricultural practices which can affect the land form, hydrology and natural ecology, and which can also have direct effects on key elements of local food chains. Examples of such agricultural practices include:
- irrigation of gardens and fields, whether from a well or nearby surface-water source;
- supply of water and local feed for domestic animals;
- draining of wetlands for farming use;
- growth of a range of crops or intensive monoculture crops; and
- use of intensive farming practices such as greenhouses or hydroponics.

Other agricultural practices, possibly having lesser impact, include:
- the use of crop fertilisers (chemicals, manure, fish meal, minerals, ashes and sewage sludge), soil conditioners (peat moss, leaf litter or lake sediments);
- the use of herbicides, pesticides, fungicides and related products;
- recycling, particularly of organic materials in, for example, soil conditioners; and
- outdoor spraying of water to cool buildings and control dust.

Fish hatcheries and fish farming could expose fish to contaminated water, sediments and feed. Game ranching of indigenous (bison, elk) and imported (ostrich, llama) animals could affect dose impacts because many wild animals have much leaner meat or use different foods than domestic animals; also game animals tend to be older when slaughtered. In addition, there are markets for products such as antlers and gall bladders that could represent new exposure pathways.

In considering rural and agricultural use of land and water, the duration of the use may need to be considered, since the land (or water) may not be able to sustain the use indefinitely. For example, long-term irrigation of soils with groundwater tends to lead to the accumulation of salts in the topsoil, and agricultural practices such as tilling and grazing may lead to accelerated erosion rates. In practice, these may be compensated by crop rotation, or otherwise leaving the land fallow for an extended period.

Screening Analysis
The region around the site of the DGR includes areas of rural and agricultural land that may become contaminated should radionuclides and/or chemical species from the waste reach the surface environment. Potentially exposed groups are likely to use these areas, particularly for agriculture.

The extent of such land and water use depends on the characteristics of the critical group.

The rural and agricultural land and water practices followed by potentially exposed groups include the following:

- raising poultry, pigs, sheep, goats, beef cattle and milk cows on local land;
- growing all food needed by the household and its animals;
- irrigating crops and gardens with well water; and
- taking fish from a local lake.

FEP Screening

Include FEP in all scenarios.

2.4.10 Urban and Industrial Land and Water Use

Description

The use of land and water for urban or industrial purposes, and the effect on hydrology and potential contaminant pathways.

Water has a variety of industrial uses in mining, the pulp and paper industry, food preparation, and electricity generation. The establishment of large water-use systems could influence the behaviour and transport of contaminants in the environment. For example, water resources may be diverted over considerable distances to serve industrial requirements or to serve the needs of an urban community. This action could result in changes to existing hydrology and introduce remote sources of contaminants to a large community. It could also lead to exposure pathways in which the most exposed individual is an industrial worker.

Another exposure route could involve ‘hobby’ gardens located on urban lands. The produce from these gardens might be more contaminated than agricultural crops because the amateur gardener might over-irrigate, over-fertilise, etc.

Finally, the characteristics of large urban communities might have more subtle effects. For example, sewage effluent can be concentrated and released at single points of discharge.

Other examples of urban and industrial land and water use are discussed under *Community characteristics [2.4.05]* and *Water management (groundwater and surface water) [1.4.10]*.

Screening Analysis

In the case of urban or industrial use, it is likely that the population would be less exposed to radionuclides discharged from the DGR because the food and water they consume would likely come from wider geographical sources, and so any contamination of which would be subject to significant dilution (i.e., a supermarket and municipal water supply, respectively).

FEP Screening

Screened out.

2.4.11 Leisure and Other Uses of Environment

Description

Leisure activities, their effects on the surface environment, and implications for contaminant exposure pathways.

Significant areas of land, water, and coastal areas may be devoted to leisure activities, e.g. water bodies for recreational uses, wilderness areas for hiking, cross-country skiing and camping activities. Other leisure activities, such as hockey, curling, baseball and golf, might use local resources, while reading, watching television and resting might occur mostly in the residence of the critical group. Many of these activities might influence which exposure pathways have significant impacts, such as the likelihood and magnitude of external exposure to contaminated ground or inhalation exposure to contaminated air. The ratio of time spent indoors and outdoors, and hence the importance of different exposure routes, will depend on climate, and the characteristics and interests of the critical group.

Screening Analysis

In the SA, consideration will be given to potentially exposed groups that are most exposed to radionuclides released from the DGR.

Leisure activities in the area around the DGR include use of land that may become contaminated by releases, including hunting and foraging in natural and semi-natural areas, fishing and swimming. The affect of potential leisure activities on the habits and behaviour of potentially exposed groups is therefore addressed.

FEP Screening

Include FEP in all scenarios.

3. CONTAMINANT FACTORS

Description:

The “Contaminant Factors” FEPs include those processes that directly affect the release and migration of contaminants in the disposal system environment, as well as those processes that directly affect the impact on human beings and the environment following exposure to contaminants in environmental media.

The aim of a safety assessment is to determine how *contaminant materials* may be *released* from the repository and along which paths they can *migrate* and what effect they will ultimately have on human beings and the environment if *exposed* to the contaminant materials. To reach a defensible decision about regulatory compliance, some measures of *impact* on human health and the environment are thus required as end products of the safety assessment process.

"Contaminant Factors" is divided into three categories:

3.01 Contaminant Characteristics

3.02 Contaminant Release and Migration Factors

3.03 Exposure Factors

3.1 Contaminant Characteristics

Definition:

The “Contaminant Characteristics” category of FEPs is related to the physical, chemical (organic and inorganic) and radiological properties of the contaminant(s) contained in the waste.

“Contaminant Characteristics” is divided into individual FEPs.

3.1.01 Radioactive decay and in-growth

3.1.02 Organics and potential organic forms

3.1.03 Chemical/organic toxin stability

3.1.04 Inorganic solids/solutes

3.1.05 Volatiles and potential for volatility

3.1.06 Noble gases

3.1.01 Radioactive Decay and In-Growth

Description

Radioactive decay is the spontaneous disintegration or de-excitation of an atomic nucleus, resulting in the emission of sub-atomic particles and energy and the formation of a new progeny (or "daughter") nucleus. Ingrowth is the increase in the number of such progeny as a result of the decay of the parent nuclide. A decay chain is a set of radioactive nuclides (or radionuclides) that decay sequentially from the first to the last member of the set. It is the particles and energy emitted during radioactive decay that leads to potential dose and damage to living organisms.

Screening Analysis

Radioactive decay and ingrowth is explicitly accounted for in the SA throughout the modelled system, including the repository, geosphere and biosphere. A large number of radionuclides are present in wastes, however only a subset of all radionuclides present have a combination of sufficient half-life and typical activity to mean that they need to be considered in safety assessment calculations. The list of radionuclides of interest is based on those included in OPG's waste inventory, with a number of radionuclides with short half-life and relatively low activity being excluded. The list has been supplemented with radionuclides that are not present at disposal, but will ingrow through radioactive decay. OPG (2008) provides an inventory of the LLW and ILW. Section 3.5 of the Data report (Walke et al. 2009b) provides a list of radionuclides to be included in the SA along with the half-lives and the decay schemes.

FEP Screening

Include FEP in all scenarios.

3.1.02 Organics and Potential for Organic Forms

Description

The characteristics of radionuclides or chemical contaminants that can be incorporated into organic species under repository or surface-environment conditions. This incorporation is likely to be mediated by biological processes.

Organic compounds may include C-14 and stable organic complexes which may form compounds with other contaminants (usually metals). The resulting organic forms may be more or less mobile or toxic than the original form. For example, the action of anaerobic bacteria in sediments can produce high concentrations of mercury as methyl-mercury compounds in water, which are much more mobile than most inorganic mercury compounds and are more likely to contaminate aquatic biota. See also *Biological/biochemical processes and conditions (in wastes, emplacement rooms, tunnels and shafts) [2.1.09], Biological/biochemical processes and conditions (in geosphere) [2.2.08]* and *Ecological/biological/microbial systems [2.3.14]*.

Screening Analysis

The chemical speciation of radionuclides in groundwater, including formation of organic forms, is not explicitly modelled in the SA because of the lack of reliable data. However, the effect of chemical speciation is implicitly accounted for in the selection of associated parameter values, e.g., solubilities, sorption coefficients, etc. with uncertainty bands. See also discussion under *[2.1.09.02]*.

FEP Screening

Include FEP in all scenarios.

3.1.03 Chemical/Organic Toxin Stability

Description

The ability of a toxic chemical element or compound, including toxic organic compounds, to resist changes that result in formation of another compound or organic species with different properties.

Chemical and organic substances decompose by processes that are primarily driven by chemical and biological reactions, at rates that are dependent on temperature and other factors. When this decomposition occurs, it can change the ability of the substance to move, or change the toxicity of the material.

Screening Analysis

The inventories of non-radionuclides of potential concern are described in *Waste inventory [2.1.01]*. Specific information on organic constituents in wastes is provided in OPG (2008).

In addition, the concentration of EDTA, citrate and oxalate has been recorded (although these are not sources of risk, per se, these substances are important from the perspective of mobilising radionuclides).

The kinetics of degradation of organic toxins is neglected for the groundwater pathway (i.e. dioxin levels are assumed to remain constant). Degradation of organics is considered for the gas pathway.

FEP Screening

Include FEP in all scenarios.

3.1.04 Inorganic Solids/Solutes

Description

The characteristics of other contaminant or constituent inorganic solids and solutes that may be of concern.

The identified radionuclide contaminants are mostly isotopes of metallic elements, and thus can be classified as inorganic. Their chemical and physical properties are then determined by the element to which they belong; for instance, Tc-99 will have the sorption and precipitation characteristics of technetium. Also, most minerals in the geosphere and substances introduced into the repository are inorganic compounds.

The contaminant inventories are identified in the Inventory report (OPG 2008). The inventories of substances of potential concern are described in *Waste inventory [2.1.01]*.

Screening Analysis

The transport of inorganic contaminants is included in the modelling of the repository, geosphere and biosphere.

FEP Screening

Include FEP in all scenarios.

3.1.05 Volatiles and Potential for Volatility

Description

The characteristics of radionuclides and chemical contaminants that are volatile or have the potential for volatility in the repository or the surface environment.

Some radionuclides may be isotopes of noble gases (see *[3.1.06]*) or may form volatile compounds, such as C-14 incorporated into carbon dioxide or methane, I-129 forming iodine gas, and tritium (H-3) incorporated into hydrogen gas or water vapour. Similar comments apply to the stable isotopes of these and other elements.

Screening Analysis

In the Version 1 SA gas modelling report (Calder et al. 2009), gas is considered to migrate from the repository via two paths: directly from the emplacement rooms into the surrounding host rock; and up through the shaft and its associated EDZ. Gaseous and volatile species might also be transported as dissolved species in groundwater but subsequently released as gases upon discharge into the near-surface geosphere and biosphere. For instance, carbon dioxide is highly soluble in groundwater, and often appears as bubbles near a discharge area. See also *Gas sources and effects [2.1.11 and 2.2.10]*.

The potential for certain radionuclides to volatilise, specifically C-14, I-129, Rn-222 and the noble gases, is taken into account in the assessment model. Formation of a gas phase in the DGR, due to for example production of H_2 by steel corrosion, is considered as discussed under *Gas sources and effects (repository) [2.1.11] and Gas sources and effects (geosphere) [2.2.10]*. The approach used to model volatilisation is given in Section 2.3 and Appendix D of the Normal Evolution Analysis report (Walke et al. 2009a).

FEP Screening

Include FEP in all scenarios.

3.1.06 Noble Gases

Description

The characteristics of the noble gases: helium, neon, argon, krypton, xenon and radon (He, Ne, Ar, Kr, Xe and Rn).

Since these elements are chemically inert, they are largely unaffected by sorption, will not precipitate, and will thus move with little delay through various transport media. One isotope of special concern is Rn-222 (radon-222), the decay product of Ra-226 (radium-226). This isotope of radon has a half-life of about 3.8 days and decays through a series of very short-lived radionuclides (with half lives of 27 minutes or less) to a lead isotope (Pb-210) whose half life is 22.3 years. The behaviour of Rn-222 and its daughters is unique and can lead to different modes of exposure to humans, described under *Radon and radon daughter exposure [3.3.08]*.

Screening Analysis

The characteristics of the radionuclides of the noble gas Rn are explicitly accounted for in the SA. The radionuclides of the other noble gases (with the exception of Kr and Ar) are relatively short lived (with no long-lived parents or daughters) and are, therefore, neglected since they do not contribute to the calculated postclosure dose rates. Kr and Ar have been screened out by screening calculations (Walke et al. 2008).

FEP Screening

Include FEP in all scenarios.

3.2 Contaminant Release and Migration Factors

Description:

The Contaminant Release and Migration category of FEPs is related to the physical, chemical and radiological processes that directly affect the release and migration of materials that will result in contaminant concentrations in environmental media.

For contaminants contained in waste material to pose a risk to human beings and the environment, those contaminants first have to be released from their physical state at disposal. Contaminant releases from a waste repository can occur through numerous pathways during the natural evolution of the facility, dependent on the location of the disposal cells and the characteristics of the waste forms, waste packaging, and the engineered barriers.

Once released from their initial state at disposal, contaminants migrate from the disposal system domain and concentrate in environmental media, where they can pose a risk to human health and the environment.

“Contaminant Release and Migration Factors " is divided into individual FEPs as follows:

3.2.01 Contaminant release pathways

3.2.02 Water-mediated migration of contaminants

3.2.03 Solid-mediated migration of contaminants

3.2.04 Gas-mediated migration of contaminants

3.2.05 Atmospheric migration of contaminants

3.2.06 Microbially/biologically-mediated processes, effects on contaminant release and migration

3.2.07 Animal-, plant- and microbe-mediated migration of contaminants

3.2.08 Human-action-mediated migration of contaminants

3.2.09 Colloid-mediated migration of contaminants

3.2.10 Dissolution, precipitation and crystallisation

3.2.11 Speciation and solubility (contaminant)

3.2.12 Sorption and desorption (contaminant)

3.2.13 Complexing agent effects (contaminant)

3.2.14 Foodchains and uptake of contaminants

3.2.01 Contaminant Release Pathways

Definition:

Factors related to the pathways as well as the associated processes and conditions for the release of radiotoxic and chemotoxic species from their physical state at disposal in the repository.

The release of contaminants from their physical state at disposal into the environment is generally associated with three pathways: (i) water release, (ii) gas phase release and (iii) solid phase release.

- Water-mediated release of contaminants: Generally, following three main processes drive the water-mediated release of contaminants.
  - Water flow through the repository due to repository resaturation.
  - Breaching (i.e., degradation) of waste, waste form and engineered barrier system (e.g., general, pitting or crevice corrosion, sulphate or chloride attack). Breaching will be influenced by the hydrological (e.g., moisture content) and chemical (e.g., pH and redox) conditions.
  - Leaching of contaminants in solution from the repository into the environment. Both hydrological (e.g., moisture content and flow rate) and chemical (e.g., solubility limits) factors will influence the leaching of contaminants.

  Once released, migration of contaminants through the geosphere will begin.

- Gas-mediated release of contaminants: Gas phase release of radionuclides may occur if the waste contains gasses and/or contaminants that might be converted to a gaseous state due to processes occurring in the repository (See FEP *[2.1.11]* for gas sources and effects in the waste, waste form and engineered features).
  - Processes: Generally, the processes of advection, dispersion, diffusion, decay and sorption will control the movement of the gas in the repository.
  - Biosphere entry points: Biosphere entry points for gas released from the repository include the ground surface above the repository, basements (in particular for radon gas) wells, springs, rivers, lakes.
  - Dissolution of gas: Dissolution of gas released from the waste, waste form and engineered features in groundwater.

- Solid-mediated release of contaminants: In contrast to water- and gas-mediated releases of contaminants that are associated with the normal evolution of a repository, solid-mediated releases of contaminants are associated with alternative evolutions of the system. Mechanisms for the release of contaminants in the solid phase can be divided into the following three categories.
  - Human action: Human actions that result in direct disruption of the waste, waste form and engineered barrier integrity and the subsequent release of contaminants, can be categorised as human intrusion events (e.g. drilling, excavation).
  - Natural disruption events and processes: Distinction can be made between events occurring over a short period of time (e.g. seismic activity) and processes occurring

over a longer period of time (e.g. erosion), leading to the disruption of the waste, waste form and engineered barrier integrity and the subsequent release of contaminants.

– Animal action: Animal actions that result in direct disruption of the waste, waste form and engineered barrier integrity and the subsequent release of contaminants, can be categorised as animal intrusion events. Animals burrow in the ground for shelter, nesting, storage, and foraging (see FEP *[2.3.15]* for a discussion of potential burrowing animals).

When considering these mechanisms, it is important to recognise the effect of sorption and radioactive decay in modifying the concentrations of radionuclides in the solid phase.

Screening Analysis

The rate of release of contaminants from the waste forms following packaging degradation depends on the characteristics of the waste form. For example, the release of contaminants embedded in the Zircaloy tubes would occur gradually and be controlled by the slow corrosion rate of the Zircaloy which in turn may be controlled by the solubility of the oxide layer. The release of contaminants from ion-exchange resins may be more rapid and may be controlled by ion exchange upon ingress of saline water.

Consideration of the three pathways of release has been incorporated into the modelling for the SA as well as in the development of appropriate scenarios. The following FEPs discuss the pathways in more detail:

- Water-release pathway – FEP *[3.2.02]*
- Gas-phase release pathway – FEP *[3.2.04]*
- Solid-phase release pathway – FEP *[3.2.03]*

FEP Screening

Include FEP in all scenarios.

3.2.02 Water–mediated Migration of Contaminants

Description

Transport of radionuclides and chemical contaminants in groundwater and surface water.

Water-mediated transport processes include:

- advection or movement with the bulk movement of the fluid;
- percolation or convection, where the movement of the fluid is driven by gravity and heat, respectively;
- dispersion, or the spread in the spatial distribution of contaminants with time because of differential rates of advective or convective transport;
- molecular diffusion, or the random movement of individual atoms or molecules within the fluid;
- matrix diffusion or diffusion into stagnant pores; and
- multiphase transport processes including unsaturated flow.

Water-mediated effects in the repository, geosphere and biosphere are discussed under FEPs 3.2.02.01, 3.2.02.02 and 3.2.02.03 respectively. Multiphase transport processes are discussed under FEP *[3.2.02.04]*.

3.2.02.01 Water-mediated effects (repository)

Transport of radionuclides and chemical contaminants in groundwater within the repository and the associated shafts. The FEP is divided into the following sub-FEPs:
3.2.02.01.A Advection
3.2.02.01.B Molecular diffusion
3.2.02.01.C Dispersion

3.2.02.01.A Advection

Description
Processes involving groundwater movement through the repository (and shafts) under the influence of a pressure or thermal gradient. Contaminants may be transported in moving groundwater as dissolved species, particulates and colloids.

Screening Analysis
Resaturation of the repository and shafts will gradually occur. Their resaturation is described in Section 2.3 of the Normal Evolution Scenario analysis report (see Walke et al. 2009a).

FEP Screening
Include FEP in all scenarios.

3.2.02.01.B Molecular diffusion

Description
The migration of contaminants in the repository caused by molecular motion (i.e. diffusion) only.

Molecular diffusion can occur in moving or stagnant groundwater. Although water molecules themselves can diffuse, the diffusion of dissolved species and particulates (including contaminants) is of most concern here. Diffusive transport is driven by thermal, concentration or chemical potential gradients and can be in any direction relative to advective flow of groundwater. Diffusion can be the most important transport mechanism in situations where groundwater flow is very slow.

Screening Analysis
In the SA it is assumed that the water within each emplacement room is well-mixed. The transport of contaminants from the waste forms to the surrounding water is controlled by diffusion for some waste forms (e.g., due to the presence of a concrete overpack). This diffusion barrier is accounted for in the SA. In addition, the diffusion of contaminants across the block walls separating the rooms is accounted for in the SA.

FEP Screening
Include FEP in all scenarios.

3.2.02.01.C Dispersion

Description

Variations in groundwater velocity and pathways cause dispersion, i.e., the spatial spreading of contaminants during advective transport.

Screening Analysis

Dispersion will occur associated with the advective flow.

FEP Screening

Include FEP in all scenarios.

3.2.02.02 Water-mediated effects (geosphere)

Description

Transport of radionuclides and chemical contaminants in groundwater within the geosphere.

The characteristics of the geosphere vary from low-permeable virtually fracture free rock to highly porous and permeable unconsolidated recent sediments. The types of groundwater flow regimes active in the different regions are described elsewhere; see, for example, *Hydrological processes and conditions (repository and geosphere) [2.1.08 and 2.2.06*] and *Near-surface aquifers [2.3.04]*. Consequently, all transport processes could be important in different parts of the geosphere. The FEP is divided into the following sub-FEPs:

3.2.02.02.A Advection
3.2.02.02.B Molecular diffusion
3.2.02.02.C Dispersion
3.2.02.02.D Matrix diffusion

Other factors to consider, including evolution of the geosphere, are discussed under *Geological environment [2.2]*.

3.2.02.02.A Advection

Description

Processes involving groundwater movement through rock under the influence of a pressure or thermal gradient.

Groundwater in the geosphere can move because of the effects of thermal buoyancy, hydraulic heads (gravity) and density differences. The groundwater can move through the pore spaces between sediment grains (porous / matrix flow) or through fractures in the rock (fracture flow). Groundwater flow velocities in fractured rock are significantly higher than in porous rock of the same hydraulic conductivity.

Contaminants may be transported in moving groundwater as dissolved species, particulates and colloids. Variations in groundwater velocity and pathways through the pore/fracture network cause dispersion, i.e., the spatial spreading of contaminants during advective transport. These variations occur at the millimetre and smaller scale for porous flow and at larger scales for fracture flow. For fracture flow the description of fracture spreading by dispersion is dependent on the scale of the fracture network compared with the scale of the overall transport pathlength.

Screening Analysis

The sedimentary rocks of the Deep and Intermediate Bedrock Groundwater Zones are have very low hydraulic conductivity (Walke et al. 2009b), resulting in diffusion-dominated transport and mostly negligible advection and hydrodynamic dispersion. However, advection may be significant in the repository and shaft EDZs in which hydraulic conductivities are increased compared with the host rock and other formations.

The hydraulic conductivity of the overlying Shallow Bedrock Groundwater Zone is sufficiently high to allow significant advective flow (Walke et al. 2009b).

FEP Screening

Include FEP in all scenarios.

3.2.02.02.B Molecular diffusion

Description
The migration of contaminants in the geosphere caused by molecular motion (i.e., diffusion) only.

Molecular diffusion can occur in moving or stagnant groundwater. Although water molecules themselves can diffuse, the diffusion of dissolved species and particulates (including contaminants) is of most concern here. Diffusive transport is driven by thermal, concentration or chemical potential gradients and can be in any direction relative to advective flow of groundwater. Diffusion can be the most important transport mechanism in situations where groundwater flow is very slow.

Screening Analysis
Diffusion is expected to be the most important transport mechanism in the undisturbed low-permeability rocks of the Deep and Intermediate Bedrock Groundwater Zones.

FEP Screening
Include FEP in all scenarios.

3.2.02.02.C Dispersion

Description

Variations in groundwater velocity and pathways cause dispersion, i.e., the spatial spreading of contaminants during advective transport.

Screening Analysis
Dispersion will occur associated with the advective flow in the Shallow Bedrock Groundwater Zone. Dispersion is not expected to be significant in the Deep and Intermediate Bedrock Zones where contaminant transport is diffusion dominated (Sykes et al. 2008).

FEP Screening
Include FEP in all scenarios.

3.2.02.02.D Matrix diffusion

Description

The migration of contaminants, by molecular diffusion, into and out of stagnant water in the geosphere.

Of particular interest is the diffusion of dissolved contaminants and particulates between a conductive fracture (or other relatively conductive zone) and the stagnant water in the matrix of the adjacent rock mass. Stagnant water can be present, for example, in the pore spaces or in the non-conducting small-scale fractures of the host rock. Matrix diffusion is sometimes referred to as a dual-porosity or dual-continuum process, because part of the total pore space of the rock supports groundwater flow whereas the water in the remaining pore space is stagnant. Contaminants that diffuse from a fracture into the adjacent rock can diffuse back from the rock once concentrations in the fracture decrease. This results in a two-component contaminant breakthrough curve.

Screening Analysis

Matrix diffusion is usually only considered in systems dominated by fracture rather than porous flow, where separate fracture and matrix continua exist, and transport is dominated by advection in the fractures. Site characterisation data show that fractures are very sparsely spaced in the Deep and Intermediate Bedrock Groundwater Zone. Hydrological and geochemical data indicate that these small fractures are closed, consistent with expectations given the current stress regime (see *Fractures and Joints [2.2.04.02]*).

Small-scale fractures and joints are more likely to be present in the Shallow Bedrock Groundwater Zone. The scale of these features is such that, at the scale of the contaminant transport pathways, their impacts are subsumed within the measured hydraulic conductivities, and groundwater flow can be treated as an equivalent porous medium. Contaminant transport can also be treated as transport within an equivalent porous medium, although this will tend to underestimate retardation due to matrix diffusion. Ignoring matrix diffusion means that not only will peak contaminant concentrations be overestimated, but also contaminant concentrations will be predicted to fall more rapidly from the peak than would be the case if matrix diffusion was considered.

FEP Screening

Screened out.

3.2.02.03 Water-mediated effects (biosphere)

Description

Transport of radionuclides and chemical contaminants in the waters of the accessible environment.

Contaminants released from a repository would likely enter the biosphere through discharge of deep groundwater into a lake or river or abstraction via a well, and their fate and environmental and human impact would be largely affected by subsequent transport processes. Included FEPs are:

3.2.02.03.A Groundwater discharge to biosphere
3.2.02.03.B Infiltration
3.2.02.03.C Capillary rise
3.2.02.03.D Transport by surface run-off
3.2.02.03.E Transport by interflow
3.2.02.03.F Transport in surface-water bodies

3.2.02.03.A Groundwater discharge to biosphere

Description

Contaminants may discharge from the geosphere directly into surface-water bodies and soils.

Screening Analysis

Groundwater transport of contaminants to Lake Huron is considered for all scenarios (see Section 2.3.3 of the Normal Evolution Scenario report, Walke et al. 2009a) consistent with the results from modelling of current groundwater discharge from the Shallow Bedrock Groundwater Zone (see groundwater modelling report, Avis et al. 2009). For the Normal Evolution Scenario with climate change, consideration is given to the potential future discharge of contaminants to a river since it is assumed that the lake level has dropped (see Section 4.3.1 of the Normal Evolution Scenario report, Walke et al. 2009a).

FEP Screening

Include FEP in all scenarios.

3.2.02.03.B Infiltration

Description

The ingress of rain and snow melt water into the ground. Infiltration of precipitation is a mechanism of groundwater recharge and potential contamination if the precipitation is contaminated.

Screening Analysis

Infiltration is considered in the SA biosphere. For example, once contaminants potentially reach the soil, they accumulate due to ongoing discharge processes but also leach out due to infiltration (see Section 2.3.3 of the Normal Evolution Scenario report, Walke et al. 2009a). However, infiltration is not considered to return infiltrating contaminants to the SA geosphere model because the precipitation is relatively uncontaminated.

FEP Screening

Include FEP in all scenarios.

3.2.02.03.C Capillary rise

Description
Capillary rise is the rise in a liquid above the level of zero pressure due to a net upward force produced by the attraction of the water molecules to a solid surface. In the DGR context capillary rise is a possible mechanism for moving contaminated groundwater closer to ground surface and the biosphere. It will occur in the near-surface groundwater regime only.

Screening Analysis
Groundwater contamination within the near-surface system is assumed to directly impact the biosphere without using this mechanism (i.e., release to soils occurs via irrigation).

FEP Screening
Screened out.

3.2.02.03.D Transport by surface run-off

Description
Transport of soil contaminants into receiving water bodies by run-off over the surface of the soil.

Screening Analysis
The SA includes run-off in the water balance (see Section 6.1.2 of the Data report, Walke et al. 2009b). However, it is not considered as a transport process for contaminants in the liquid phase since it is assumed that the run-off water is not contaminated. Rather than flow over the soil surface, potentially contaminated irrigation water is taken to infiltrate into the soil and then migrate from the soil via interflow *[3.2.02.03.E]* or infiltration *[3.2.02.03.B]*. Transport of contaminant in the solid phase via runoff is taken into account through the consideration of soil erosion *[3.2.03]* (see Section 2.3.3 of the Normal Evolution Scenario report, Walke et al. 2009a).

FEP Screening
Include FEP in all scenarios through subsuming it into *Solid-mediated Migration of Contaminants [3.2.03]*.

3.2.02.03.E Transport by interflow

Description
The lateral movement of water through the soil into surface-water courses can occur during or following significant precipitation events when the rate of infiltration of water at the top of the soil profile exceeds the exfiltration rate from the base of the soil profile.

Screening Analysis
Interflow will result in advective transport of contaminants in solution. As interflow is only of relevance for the overburden sediments, it is represented in terms of transport through a porous medium (see Section 2.3.3 of the Normal Evolution Scenario report, Walke et al. 2009a).

FEP Screening
Include FEP in all scenarios.

3.2.02.03.F Transport in surface-water bodies

Description

Transport of contaminants either in aqueous state or as particulates in lakes, rivers and/or streams.

Screening Analysis

In order to assess the environmental impact of contaminants, it is important to consider their transport in the various surface waters in the vicinity of the Bruce site (see FEP *[2.3.05]* and Section 6.1.2 of the Data report, Walke et al. 2009b).

FEP Screening

Include FEP in all scenarios.

3.2.02.04 Multiphase transport processes

Description

Pore water will flow into the repository and gas out of the repository in a complex process governed by hydraulic gradients, EDZ characteristics and geosphere gas and liquid flow parameters, gas pressure in the repository, and relative saturations in the EDZ and geosphere. Most of these processes are described in other FEPs (*2.2.01, 2.2.02, 2.2.06, 2.2.10*).

Screening Analysis

Two-phase flow and transport is represented using the T2GGM code. The modelling and its results are presented in the Gas modelling report (Calder et al. 2009). These results are used to inform the assessment modelling work that considers multiphase transport of contaminants from the DGR into the geosphere and eventually into the biosphere. Details of the assessment modelling are presented in the Normal Evolution Scenario Analysis report (Walke et al. 2009a) (see for example Sections 2.3.1.3 and 2.3.2.2) and the Human Intrusion and Other Disruptive Scenarios Analysis report (Penfold and Little 2009) (see for example Section 2.2.2).

FEP Screening

Include FEP in all scenarios.

3.2.03 Solid–mediated migration of contaminants

Description

The transport of radionuclides and chemical contaminants in large-scale solid phase movement.

The processes of most interest are large-scale erosion processes that are described throughout *External factors [1],* such as *Denudation and deposition [1.2.07], Volcanic and magmatic activity [1.2.04],* and *Periglacial effects [1.3.04]*. However, smaller-scale processes can also occur such as the downward movement of soil particles in time as soil formation proceeds. Evidence of this is found in column studies where the density of lower horizons can increase due to particle migration following disturbance in the surface soil layers. In the aquatic environment, a similar process occurs in the horizontal and can result in the silting of lakes.

Transport of small particles suspended in water and air is discussed under *Water-mediated and Gas-mediated transport of contaminants [3.2.02 and 3.2.04]*. Transport of solids by human activities is included in *Human-action-mediated transport of contaminants [3.2.08]*.

Screening Analysis

The SA considers the transport of contaminants (in the biosphere) due to water erosion/ deposition and atmospheric resuspension/deposition (see Appendix B.2.2 of the Normal Evolution Scenario Analysis report, Walke et al. 2009a).

FEP Screening

Include FEP in all scenarios.

3.2.04 Gas–mediated migration of contaminants

Description

The transport of radionuclides and chemical contaminants in gas or vapour phase, or as fine particulate or aerosols suspended in gas or vapour, but excludes *Atmospheric migration of contaminants [3.2.05]*.

Radioactive and chemically toxic gases may be generated from the wastes, e.g. C-14 as carbon dioxide or methane, and transported in the gas phase through the DGR and geosphere. Radioactive and chemically toxic gases, aerosols or particulates may also be transported along with other non-toxic gases. Alternatively, gas pressures could be sufficiently high to form an unsaturated phase where two-phase flow is important, or to expel contaminants dissolved in groundwater from parts of the DGR and geosphere.

Issues such as dwelling location, which could affect seepage of gases such as radon into basements, and heating source, which could involve biogas production, are discussed under *Dwellings [2.4.07]*. See also *Gas sources and effects [2.1.11], Volatiles and potential for volatility [3.1.05]* and *Noble gases [3.1.06]*.

Screening Analysis

The SA considers the potential for gas generation and the resulting gas transport. T2GGM is used to model the migration of gases from the repository through the geosphere as discussed in the Gas Modelling report (Calder et al. 2009). These results are used to inform the assessment modelling of gas migration from the DGR into the geosphere and eventually into the biosphere. Details of the assessment modelling are presented in the Normal Evolution Scenario Analysis report (Walke et al. 2009a) (see for example Sections 2.3.1.3 and 2.3.2.2) and the Human Intrusion and Other Disruptive Scenarios Analysis report (Penfold and Little 2009) (see for example Section 2.2.2).

FEP Screening

Include FEP in all scenarios.

3.2.05 Atmospheric Migration of Contaminants

Description

The transport of radionuclides and chemical contaminants in the atmosphere as gas, vapour, or suspended fine particulate or aerosol.

Contaminants may enter the atmosphere as a result of processes such as evaporation of volatile species or degassing from soils or water (particularly during irrigation or outdoor spraying of water), transpiration from plants, suspension of dusts due to wind erosion, ploughing or fires (forest, agricultural and from house heating). Contaminants may also enter the indoor atmosphere from: use of contaminated water in showers and air humidifiers; suspension of soils/sediment brought in on clothing or footwear; or from infiltration of contaminated water and gases into basements.

The atmosphere may provide a significant mechanism to transport and dilute these contaminants. For example, advection and dispersion by wind can move contaminants from local to very large areas. The atmosphere could also effectively remove contaminants from the accessible environment by transport to sinks such as the deep ocean.

This category also provides for specific human and animal exposure pathways different from those related to groundwater, notably inhalation and immersion in contaminated air.

Screening Analysis

Atmospheric transport (advection and dispersion) of contaminants are explicitly modelled in the SA. This includes the volatilisation of contaminants from soil and surface-water bodies, formation and transport of water aerosols, formation and transport of dust particles, infiltration of Rn-222 into buildings, and atmospheric deposition of contaminants onto soil and plants. In this way, the critical group is exposed to radionuclides via the air inhalation and air immersion pathways. See Section 2.3.3.2 of the Normal Evolution Scenario Analysis report (Walke et al. 2009a) for the Version 1 SA conceptual model for atmospheric migration of contaminants for the Normal Evolution Scenario (and for all other scenarios, other than the Human Intrusion Scenario). The conceptual model for the Human Intrusion Scenario is presented in Section 2.2.2 of the Human Intrusion and Other Disruptive Scenarios Analysis report (Penfold and Little 2009).

FEP Screening

Include FEP in all scenarios.

3.2.06 Microbially/biologically–mediated processes, effects on contaminant release and migration

Description

The biological processes that can affect the form (chemical species) or related properties of contaminants. Transport-related processes are discussed under *Animal-, plant- and microbe-mediated transport of contaminants [3.2.07]*.

Biological-mediated processes occurring in the DGR and geosphere are likely to be limited by the availability of nutrients and energy. Possible processes that could affect contaminant properties include the following.

- The formation of biofilms could cover the container interior, exterior and defect surfaces, and on the repository walls and in fractures, biofilms could cover existing mineral surfaces. The effect might be to increase or decrease contaminant sorption.
- The action of anaerobic bacteria could modify groundwater composition, affecting the pH and Eh and subsequently increasing or decreasing contaminant sorption and solubility. Changes to Eh would be most important for redox-sensitive elements such as technetium and plutonium.
- Micro-organisms might metabolise or serve directly as organic complexing agents that can change solubilities and sorption properties for many elements, including iodine and many heavy metals (see *Complexing agent effects (contaminant) [3.2.13]*).

These last two processes could also occur in the accessible environment, where the potential for biological activity is likely to be less restricted. Other processes occurring in the accessible environment include the following examples.

- Bacteria and microbes may chemically transform contaminants and thereby change their sorption and solubility properties. Properties that lead to increased mobility would promote transport while the reverse effect could cause zones of accumulation and could increase or decrease plant uptake depending on the species and complexes formed and the timeframe.
- Microbes or plants could actively accumulate contaminants and incorporate them into their structure, where they would be held until the organism died and decomposed or the structural component was sloughed off. See also *Food chains and uptake of contaminants [3.2.14]*.

Screening Analysis

Biologically mediated processes (excluding transport) are considered in the Version 1 SA.

Their impact on corrosion, degradation and gas generation rates and associated gas and aqueous release rates are accounted for in the conceptual model of evolving repository conditions (see Section 2.3.1.1 of the Normal Evolution Scenario Analysis report, Walke et al. 2009a) and the gas generation and transport model implemented in T2GGM (see the Gas Modelling report, Calder et al. 2009).

The effects of such processes in the biosphere are included by using parameter values from field experiments under natural conditions (e.g. soil to plant concentration factors and animal transfer factors) that relate the concentration in the soil/water to that in the animal/plant.

With respect to the possibility of periodic accumulation and sloughing of biofilms at wells, it is noted that the dose estimates of interest are over long time scales, which would tend to average out short-term decreases or spikes in dose rates.

FEP Screening

Include FEP in all scenarios.

3.2.07 Animal-, plant- and microbe-mediated migration of contaminants

Description

The transport of radionuclides and chemical contaminants as a result of animal, plant and microbial activity. Other biological effects on contaminant properties are discussed under *Microbially/biologically-mediated processes [3.2.06]*.

Animals can have a direct or indirect influence on contaminant transport. For instance, wild animals can ingest contaminated water and food from remote areas, and move to the location of the critical group. Another process is bioturbation of soil and sediment, whereby burrowing animals (such as worms) and trees can physically displace large amounts of soil, promoting the redistribution and uniform mixing of contaminants in soil and sediment. Subsequent transport in soils and soil pores can then result in a variety of exposure pathways, notably where plants take up contaminants in soil via their roots. Plants can also take up contaminants deposited on their leaves. The extent of root and leaf uptake depends on soil and plant types, the chemical nature of the contaminant, and seasonal effects such as in early spring and summer when plants are actively growing.

Microbes affect contaminant transport indirectly by changing transport-related properties (see the discussion under *Microbially/biologically-mediated processes [3.2.06]*). More direct effects include:

- formation of biofilms that restrict or plug groundwater flow and contaminant transport; and
- decomposition reactions of bacteria and microbes to leach or otherwise release contaminants that have been taken up by soils, plants and animals.

This latter effect is part of the larger process of natural recycling. Micro-organisms have a strong influence on environmental 'cycles of matter', affecting the movement and transport of elements such as carbon, nitrogen and oxygen (and radioactive or chemically toxic contaminants) through the biosphere, geosphere, hydrosphere, atmosphere and anthrosphere.

Some transport-related effects of plants and animals are discussed under *Surface environment [2.3]*, and the effects of microbes under *Wastes and engineered systems, Geological environment* and *Surface environment [2.1, 2.2 and 2.3]*. See also factors such as bioconcentration, bioaccumulation and biomagnification, under *Ecological/biological/microbial systems [2.3.14]*.

Screening Analysis

Given the depth of the DGR (680 m), consideration of the transport of radionuclides and chemical contaminants as a result of animal, plant and microbial activity is limited to transport in the biosphere.

Some biologically mediated contaminant transport processes are explicitly modelled in the SA, including (see Section 2.3.3 of the Normal Evolution Scenario report, Walke et al. 2009a):

(1) uptake of radionuclides and non-radionuclides from soils by plants;

(2) uptake of radionuclides and non-radionuclides from soil, water, and plants by animals; and

(3) uptake of radionuclides and non-radionuclides from soil, water, and plant and animal foodstuffs by humans.

Some biologically-mediated transport processes are only implicitly modelled, including:

(1) bioturbation in soils;

(2) recycling of contaminants in animal droppings; and

(3) recycling of contaminants in falling leaves.

These latter processes are implicitly treated by use of cautious models. For example, contaminants are taken not to be depleted from soils by plant uptake, implicitly accounting for recycling of contaminants back to the soil in animal droppings and falling leaves.

Other biologically-mediated transport processes, such as the spreading of contaminants by animals, are not modelled but their neglect is expected to be cautious, e.g., by not modelling the spread of contaminants by animals, contaminants remain in the local environment, thereby increasing the contaminant concentrations to which the critical group is exposed.

FEP Screening

Include FEP in all scenarios.

3.2.08 Human–action-mediated migration of contaminants

Description

The transport of radionuclides and chemical contaminants as a direct result of human actions.

Human-action-mediated transport of contaminants includes processes such as drilling into or excavation of contaminated areas such as the repository or contaminated overburden or sediments from lakes, rivers and estuaries. These actions result in the transport of contaminated rock, soil or water to the accessible environment. Large-scale activities, such as dam construction, may result in the movement of large volumes of contaminated solid material from one part of the biosphere to another, and to the diversion of groundwater-flow regimes that affect discharge locations of contaminated water. Smaller-scale and often seasonal activities, such as ploughing, which result in the mixing of the top layers of agricultural soil, and irrigation, which could involve contaminated water, could affect contaminant transport.

These processes can act to dilute and disperse contaminants in the environment through mixing processes. However, they can also act to enhance contaminant concentrations or pathways in the environment. For instance, contaminants can be accumulated in compost piles or animal and human waste and then used as soil conditioners.

More discussion on human actions that could affect contaminant transport is provided under *Future human actions (active) [1.4]* and *Human behaviour [2.4]*.

Screening Analysis

Transport of contaminants by human action is represented in the SA.

In the Human Intrusion Scenario, the consequences of moving waste to the surface as a result of drilling is evaluated (see Section 2.2.2 of the Human Intrusion and Other Disruptive Scenarios Analysis report, Penfold and Little 2009). In other scenarios, transport of contaminants with the irrigation water taken from a well is represented (see Figure 2-17 of the Normal Evolution Scenario Analysis report, Walke et al. 2009a). These have been shown to be important exposure pathways in other assessments (Goodwin et al. 1994; Goodwin et al. 1996; Wuschke 1996).

Some human-mediated transport processes are only implicitly modelled. For example, the assumption of a well-mixed upper soil layer implies that the land is regularly ploughed. The assumption that contaminants are not depleted from the soil by plant uptake could imply that the humans recycle their waste to the soil (i.e., use compost piles).

However, contaminant transport by large-scale human activities (e.g., dam construction) is not modelled because of the large inherent uncertainties involved and the likelihood that such projects would spread contaminants over large areas, reducing the contaminant concentrations to which the critical group is exposed.

FEP Screening

Include FEP in all scenarios.

3.2.09 Colloid-mediated migration of contaminants

Description

The transport of colloids, and their interaction with radionuclides and chemical contaminants in repository or environmental conditions. Colloids consist of small organic or inorganic particles in the nanometre to micrometre size range, small enough to form long-lasting suspensions in a liquid phase.

Colloids could potentially represent a route for increasing the rate of movement of radionuclides away from the repository, because their high specific surface areas might encourage sorption. To be mobile over considerable distances, a colloidal particle must not be susceptible to aggregation with other, similar particles, nor can it be filtered out in the repository or geosphere.

Colloids may influence contaminant transport by serving as a mobile carrier of highly-sorbing (and therefore potentially immobile) contaminants. In some situations, colloids might serve to concentrate contaminants. Colloid transport may be affected by anion exclusion which may prevent their movement through small pores or enhance their movement down the centre of larger pores. Colloids may 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.

Screening Analysis

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

- Their formation is expected to be limited due to the highly saline conditions in the DGR and Deep Bedrock Groundwater Zone – see *Colloid formation [2.1.08.09]*.
- The small pore size and low permeability of shaft seals are expected to limit migration of colloids by filtering.
- Consistent with the findings of Stumm (1992), 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.

FEP Screening

Screened out.

3.2.10 Dissolution, Precipitation and Crystallisation

Description

The dissolution, precipitation and crystallisation of radionuclides and chemical contaminants under repository or environmental conditions, and their evolution with time. Dissolution is the process by which molecules of a solid dissolve into solution. Precipitation and crystallisation are processes by which solids are formed from molecules in solutions.

Water is an excellent solvent; its dipolar nature allows it to dissolve most metals and metalloids that are in the form of ionic compounds, and its ability to hydrogen bond means it can dissolve many organic compounds. The maximum or saturated concentration for each solute is primarily determined by the properties of the solute and solvent, and influenced by other factors such as temperature, presence of other solutes including (for ionic species) common ions, pressure and ionic strength. This maximum concentration is also known as the solubility limit (see *Speciation and solubility [3.2.11]*).

Formation of some precipitates can be kinetically hindered. In some cases, the solutions may become temporarily oversaturated, and it is generally not possible to predict when precipitation might start. Moreover, an intermediate solid phase might form. For instance, the first precipitated solid phase may have an amorphous structure which later transforms into the more stable crystalline structure at a rate that depends on the temperature and other factors. An example is iron in oxidising solutions, which may initially precipitate as an amorphous ferric hydroxide, $Fe(OH)_3$, and later transform to crystalline goethite (FeOOH).

Co-precipitation is a variant of precipitation in which a forming precipitant incorporates a subsidiary compound which would not precipitate in isolation. For example, precipitation of barium sulphate can induce precipitation of radium sulphate even if the latter is undersaturated. Thus, an element may precipitate even though it is soluble in isolation.

The various domains of a repository system will have different local conditions of temperature and groundwater composition so that precipitation and dissolution of the same species may occur simultaneously, but at different locations.

Dissolution, precipitation and crystallisation can be important processes because they change the proportion of dissolved and solid species. Dissolved species are more mobile than solid species (but see also *Colloid-mediated migration of contaminants [3.2.09]*). Dissolution may open pores and transport pathways; conversely, the formation of precipitates can act to plug pores and constrict water movement and contaminant transport.

This category is divided into:

3.2.10.01 Dissolution and precipitation (repository)
3.2.10.02 Dissolution and precipitation (geosphere)
3.2.10.03 Dissolution and precipitation (biosphere)
3.2.10.04 Change in mineralisation

3.2.10.01 Dissolution and precipitation (repository)

Description
Dissolution and precipitation processes, including their evolution in time, occurring in the repository.

Most contaminants are released from the waste form when they dissolve into the groundwater that has entered the container. The largest concentration of most contaminants is likely to occur inside the container, and many contaminants could re-precipitate as different compounds. The mass of these precipitates could increase until dissolution of the waste form ceases, after which the mass would decrease as the precipitate itself dissolves. Precipitation could also occur in the shaft or elsewhere in the repository if there is an abrupt change in the chemical environment (including groundwater composition and pH) or if ingrowth from radioactive decay produces a local increase in concentration.

Screening Analysis
The dissolution of contaminants (including radionuclides) from the waste forms and the potential precipitation of the contaminants in the waste package is explicitly modelled in the SA.

Precipitation of contaminants elsewhere in the repository and in the shaft is not modelled, because concentrations outside the waste package are expected to be less than radionuclide solubilities given that contaminant concentrations will decrease as they diffuse outwards from the package and no abrupt changes in chemical conditions are expected.

FEP Screening
Include FEP in all scenarios.

3.2.10.02 Dissolution and precipitation (geosphere)

Description
This FEP refers to the process by which solids dissolve in and/or are precipitated from solutions. The occurrence and extent of these reactions may affect and be affected by the pH and redox potential of the water-rock system. Dissolution/precipitation in the context of this FEP refers to pure phases.

Screening Analysis
Dissolution and precipitation reactions may occur in the geosphere, and particularly the EDZ during the operational phase when the rock is exposed to an oxic atmosphere, and during the post-closure phase where engineering materials, such as the shaft seals are in contact with the EDZ. Dissolution and precipitation reactions may also occur in the EDZ and host rock close to the GDF due to a chemical plume from the GDF (see *Chemical / Geochemical Processes and Conditions [2.2.07]*).

The impacts of these potential interactions are considered by Little et al. (2009) and are screened out for the Normal Evolution Scenario. Any unanticipated reactions between the shaft engineering materials and the shaft EDZ are bounded by the Severe Shaft Seal Failure Scenario (Penfold and Little 2009).

FEP Screening
Screened out.

3.2.10.03 Dissolution and precipitation (biosphere)

Description

Dissolution and precipitation processes, including their evolution in time, occurring in the surface and near-surface environment accessed by animals and plants.

Contaminants entering the biosphere from the geosphere will likely encounter quite different chemical and physical conditions, such as atmospheric concentrations of oxygen and carbon dioxide in water. These conditions may lead to precipitation at the biosphere-geosphere interface. Contaminants moving through the biosphere could be subjected to precipitation or dissolution as a result of different local conditions, or by active microbial processes. These reactions can take place in surface water and pore water in saturated and unsaturated soil. Fixation of radioactive C-14 can be especially important if calcite or related carbonate minerals are stable solids in the biosphere.

An important determinant in the transfer of contaminants in the environment is mobility. Highly mobile contaminants tend to reach humans and other organisms, and increase radiation or chemical exposure. Chemical precipitation in surface water, wetlands and soil tends to reduce mobility and thereby doses. Chemical precipitation in the soil rooting zone is usually negatively correlated with uptake by plant roots (i.e. larger solubilities correspond to greater uptake). However, precipitation in the rooting zone also immobilises contaminants leaving them in place where they could eventually be accessed by plants, and thus may result in larger transfers over time. Furthermore, precipitation could give rise to higher concentrations for external exposure. See also the related discussion under *Speciation and solubility (biosphere)* and *Sorption/desorption (biosphere) [3.2.11.03 and 3.2.12.03]*.

These processes can change in response to processes such as daily and seasonal changes in meteoric precipitation, climate change, and land use change.

Screening Analysis

Precipitation (and redissolution) of contaminants in the biosphere is not explicitly modelled in the SA.

Many of the biosphere contaminant parameter values used in the SA (e.g., plant concentration factors, soil K_d values, etc.) are based on field or laboratory experiments. These biosphere parameter values could, in theory, be affected by dissolution and precipitation processes. Thus, such processes, if important, would be implicitly included, although it would not be possible to ascertain the importance of such processes on the calculated impacts.

FEP Screening

Screened out.

3.2.10.04 Change in mineralisation

Description
Changes to the mineral composition of the rocks and engineered repository materials that might affect the migration of contaminants.

A potential change in mineralisation in the geosphere might be caused by the invasion of fluids hot relative to the present *in-situ* temperature of the Cobourg formation, or fluids of different salinity. Because the Cobourg formation is very saline already, the potential for the later form of fluid invasion is limited. Also, the likelihood of geothermal fluids invading southwestern Ontario in the next few million years is remote; the last invasion appears to have been during the Palaeozoic Era (248-545 Ma) according to Mazurek (2004) and references therein. It should be noted that flow of cold fluids might cause changes in mineralogical composition. Introduction of high-pressure cold water, for example beneath an ice-sheet, could cause some changes in mineralisation.

Mineralisation can also affect the engineered repository materials (such as concrete and bentonite) (see *Mineralisation [2.1.08.06]*) and the migration of contaminants through the materials.

Screening Assessment
Any changes to host rock mineralisation are likely to be limited and are unlikely to have any impact on transport characteristics. However, mineralisation changes to concrete need to be considered (see *[2.1.08.06]*).

FEP Screening
Include FEP in all scenarios.

3.2.11 Speciation and Solubility (Contaminant)

<u>Description</u>
The chemical form or species of an element dissolved in groundwater, and its solubility. The solubility of an element is the maximum (or saturated) concentration that can exist in the groundwater and is dependent on the species, temperature, pressure, presence of other solutes, and the ionic strength. An element may also be present in groundwater as particulates; see *Colloid-mediated migration of contaminants [3.2.09]*. If a metastable phase controls the aqueous concentration then the aqueous concentration could be far higher than would be produced by true solubility equilibrium with a thermodynamically stable phase. An example is where aqueous silica concentrations are controlled by a metastable equilibrium with chalcedony, rather than by thermodynamically stable quartz.

Several dissolved species may co-exist. The nature of the dominant species may be important. For instance, clay and most rock minerals sorb cations more strongly than anions.

An important parameter that could influence the chemical speciation and solubility of some elements is the electrochemical potential or Eh of the water.

An element will precipitate when its concentration (given by the mass of all species of that element in a unit volume of water) exceeds the elemental solubility limit. Chemical kinetics might affect the nature of the solid phase that forms. From a practical viewpoint, if a solid phase is slow to form and the time frame short, then the effective solubility of an element might be relatively large, perhaps equal to the solubility limit of an amorphous solid.

FEPs in this category include:

3.2.11.01 Speciation and solubility (solubility limitation, repository)
3.2.11.02 Speciation and solubility (solubility limitation, geosphere)
3.2.11.03 Speciation and solubility (solubility limitation, biosphere)
3.2.11.04 Solubility changes caused by chemical interaction between waste and pore water
3.2.11.05 Solubility changes caused by change in temperature
3.2.11.06 Species equilibrium change caused by change in temperature

3.2.11.01 Speciation and solubility (solubility limitation, repository)

Description
Speciation and solubility processes, including their evolution in time, occurring in the repository that affect the dissolution/precipitation of contaminants.

Chemical speciation could have important effects in the repository, where contaminant concentrations are likely largest. Small concentrations of complexing agents could form stable dissolved species, enhancing the dissolution of contaminants from the waste form and increasing their solubility. Conversely, solubility limits will be smaller when complexing agents have low concentrations or where the chemical environment decreases the stability of dissolved species or enhances the stability of a solid phase. Complexing agents are discussed further in *Complexing agent effects (contaminants) [3.2.13]*.

If the concentration of the contaminant in the repository exceeds its solubility limit, then the contaminant precipitates. See also *Dissolution, precipitation and mineralisation (repository) [3.2.10.01]*.

Solubility limits, and thus formation or dissolution of precipitates, could be different at different positions in the repository because of differences in temperature, groundwater composition (complexing agents) and other factors. The evolution of the chemical environment will affect the solubility of different species, and hence will also affect where precipitates form or dissolve. Solubility limits can also be affected by increased pressures. Chemical kinetics could also have large effects on effective solubility limits.

Screening Analysis
The solubility of contaminants in the repository has been considered for a number of radionuclides that have been shown by preliminary calculations to be potentially important radionuclides for the long-term safety of the DGR: C-14, Cl-36, Ni-59, Zr-93, Nb-94, U-233 and Np-237. The solubility of these contaminants is based on the expected water chemistry in the repository. For all other contaminants, it is cautiously assumed that there is no solubility limitation.

The likely solubilities of the key elements are presented in Table 3-22 of the Data report (Walke et al. 2009b). Of the elements considered ((C, Zr, Np, Ni, U, Nb and Cl), it is cautiously concluded that only carbon and uranium are likely to be influenced by solubility limitation. Solubility limits for C and U are only considered inside the container, since the concentration of the contaminants will be highest there. Neglecting precipitation elsewhere in the repository is cautious for estimating transport out of the repository.

FEP Screening
Include FEP in all scenarios (C and U solubility limit in repository).

3.2.11.02 Speciation and solubility (solubility limitation, geosphere)

Description
Speciation and solubility processes, including their evolution in time, occurring in the geosphere that affect the dissolution/precipitation of contaminants.

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 location in the geosphere. In addition, these effects will change with time in response to evolution of the groundwater and temperature.

Screening Analysis
In the SA, the speciation and solubility of contaminants in the geosphere is not modelled. Neglect of solubility limits in the geosphere is considered reasonable because of the lower contaminant concentrations in the geosphere due to dispersion and dilution, and since ignoring precipitation is usually cautious, i.e., precipitation would reduce contaminant concentrations and fluxes. See also *Dissolution, precipitation and migration (geosphere) [3.2.10.02]*.

However, chemical speciation in the geosphere is implicitly accounted for in the selection of the associated parameter values and their uncertainty ranges (e.g., geosphere sorption coefficients). That is, these parameter values are derived from experimental data based on tests that include groundwater, minerals and relevant pH/Eh conditions, and which are therefore influenced by chemical speciation.

Mazurek et al. (2003), in the FEPCAT report on mudrocks and clays, pointed out that mineral phases “that could limit radioelement concentrations are not generally observed in site studies.” Rather, their presence is inferred from geochemical modelling based upon a complete geochemical analysis of pore waters, groundwaters and mineralogy.

FEP Screening
Screened out.

3.2.11.03 Speciation and solubility (solubility limitation, biosphere)

Description
Speciation and solubility processes, including their evolution in time, occurring in the accessible environment that effect the dissolution/precipitation of contaminants.

Speciation of contaminants in near-surface and surface waters of the biosphere could be important because of:

- the relatively large concentrations of oxygen and carbon dioxide that are dissolved in rain water and that exist in the soil pore water;
- organic complexes leached from decomposition products of vegetation and other organic matter (including pesticides and herbicides);
- the high concentrations of humates and fulvates normally found in soils (see *Complexing agent effects (contaminant) [3.2.13]*); and
- organic compounds and detritus produced by microbial processes.

There could be a rapid change in composition in depth caused, for instance, when the relatively fresh surface water containing aggressive carbonic acid undergoes chemical reactions as the water moves down through the soil profile.

The composition of waters in the biosphere, including their dependence on location (and depth) and their evolution with time, will affect the formation of contaminant species and hence the solubility of contaminants. For instance, the presence of high concentrations of carbonate could decrease the solubility of calcium but enhance the solubility of uranium, or C-14 could exchange with C-12 in the carbonates and become mineralised. Likewise the presence of oxygen and organic complexes could decrease or increase solubility limits of different elements. Large solubility limits increase the mobility of contaminants, but low solubility limits may lead to larger exposures over time if precipitation occurs in an undesirable location, such as in the surface soil of a vegetable garden or a terrestrial discharge area (see *Sorption and desorption (biosphere) [3.2.12.03]*). See also the discussion under *Dissolution, precipitation and mineralisation (biosphere) [3.2.10.03]*.

Screening Analysis
Contaminant speciation and solubility in the biosphere is not explicitly modelled in the SA.

Neglect of solubility limits in the biosphere should be reasonable because of the likely lower contaminant concentrations in the biosphere due to dispersion and dilution; see also *Dissolution, precipitation and mineralisation (biosphere) [3.2.10.03]*.

Since the biosphere contaminant parameter values (e.g. soil Kd, plant/soil concentration ratios, volatility) are based on field or laboratory experiments, chemical speciation and solubility effects would have influenced the measured experimental data. Thus, such effects are likely implicitly included in the SA.

FEP Screening
Screened out.

3.2.11.04 Solubility changes caused by chemical interaction between waste and pore water

Description
The high salinity of the pore waters of the Ordovician rocks will most probably cause an increase in the solubility of the radionuclides attached to waste forms, particularly ion-exchange columns, once the containers have become corroded. Thus, release of the radionuclides by desorption into the invading pore waters is unlikely to be constrained by the solubilities of the various radionuclides that are typically considered in safety assessments.

Screening Analysis
The radioactive wastes present in the repository at closure comprise a complex geochemical suite of components that are available for diffusive transport through the host rock once desorbed from the waste forms that the repository is to store. Desorption from ion-exchange columns, the principal source of radioactivity in ILW in the proposed repository will proceed readily in the highly saline pore waters that are present within the Cobourg formation. The desorption of these radionuclides will not be limited by their typical solubilities in fresh-water environments. Highly saline waters, perhaps of brine strength, will permit considerable ionic complexing, e.g., $^{137}CsCl°$ or $^{90}SrCO_3°$, that raises the individual ionic solubilities and will therefore promote desorption from the ion-exchange columns.

FEP Screening
Include FEP in all scenarios.

3.2.11.05 Solubility changes caused by change in temperature

Description
Solubility changes associated with temperature include those due to temperature-dependent complex-ion formation constants, aqueous dissolution of gases and solubility products of minerals. The most likely cause of temperature change appears to be associated with glaciation and its effects.

Screening Analysis
Solubility limitation is only considered in the repository (see FEP *[3.2.11.01]*). It expected that there will not be any significant changes in repository temperature (see FEP *[2.1.10]*).

FEP Screening
Screened out.

3.2.11.06 Species equilibrium change caused by change in temperature

Description
Complexation and association/dissociation of ions to form species are affected by temperature variations through changes in the entropy of the reaction. The simplest example is that of the ionisation of water, i.e., thus the definition of neutral pH is a function of temperature varying from pK=14 at 25°C to pK~15 at 0°C.

Screening Analysis

It is not expected that the Deep and Intermediate Bedrock Groundwater Zones will be significantly affected by temperature changes – see *Thermal processes and conditions (in geosphere)*. However, the potential for the Shallow Bedrock Groundwater Zone to be affected by reduced temperatures resulting in the formation of permafrost indicates that there might be a need to consider how radioelement species will behave under conditions of decreased temperature. Note that permafrost formation may be accompanied by marked salinity increases, owing to dissolved solutes partitioning into the residual aqueous phase that forms when freezing occurs. This effect will influence species equilibrium and will be superimposed on any temperature effect.

For the purposes of the Version 1 SA, it is assumed that temperature changes in the Shallow Bedrock Groundwater Zone will not have a significant effect on speciation and the associated mobility of contaminants. Note that the Version 1 SA already adopts the cautious assumption that most contaminants are not retarded in the Shallow Bedrock Groundwater Zone and, for those that are retarded, a minimum credible value is adopted. So it is expected that any temperature changes in the Shallow Bedrock Groundwater Zone that might affect contaminant speciation and mobility are unlikely to significantly increase contaminant mobility in comparison to the base case conditions.

FEP Screening
Screened out.

3.2.12 Sorption and Desorption (Contaminant)

Description

The sorption and desorption of radionuclides and chemical contaminants in the repository system. Sorption describes the physicochemical interactions of a dissolved species with a solid phase to remove the species from solution. Desorption is the opposite process.

Most cases of interest will involve solutions containing trace concentrations of contaminants. These solutions are usually discussed in terms of two sorption-desorption mechanisms.

- Ion-exchange processes involve an electrostatic or ionic attraction between charged dissolved species and oppositely charged surfaces.
- Chemisorption involves the formation of a chemical bond.

Neutral species and (usually) anions are generally not strongly sorbed.

Sorption and desorption are often described by a simple partition coefficient (Kd), also called the distribution constant. This parameter is defined as the ratio of the amount of a contaminant sorbed onto the solid relative to that in solution. A related parameter, called the capacity factor or storage capacity, is often used to describe sorption on backfill, and is given by the equation (capacity factor) = (porosity) + K_d x (dry bulk density), where porosity and density refer to the properties of the solid sorbing medium.

Sorption models employing distribution coefficients or storage capacities are linear models which assume the processes are reversible, rapid and have no limits. However, non-linear effects can be significant, such as chemical kinetic effects which favour desorption over sorption, a limited availability of sorption sites or exposed surface area , concentration-dependent interactions which may decrease sorption at higher contaminant concentrations, and removal of sorption sites because of competition by other ions in groundwater (particularly saline groundwater). These effects could reduce the degree of sorption.

Sorption processes are important because they can slow down the migration of contaminants, and contribute to the spread of their releases as a function of time (and in space if dispersive effects are important). Thus sorption will attenuate peak concentrations, and the delay times would have to allow for additional decay or decomposition.

This category is divided into the following FEPs:

3.2.12.01	Sorption and desorption (repository)
3.2.12.02	Sorption and desorption (geosphere)
3.2.12.03	Sorption and desorption (biosphere)
3.2.12.04	Chemical reactions caused by adsorption or desorption
3.2.12.05	Anion exclusion effects
3.2.12.06	Sorption change caused by change in temperature

3.2.12.01 Sorption and desorption (repository)

Description

See *[3.2.12]* above.

Screening Analysis

In the SA, sorption in the repository (including the shaft and EDZ) has been considered for a number of radionuclides that have been shown by preliminary calculations to be potentially important radionuclides for the long-term safety of the DGR: C-14, Cl-36, Ni-59, Zr-93, Nb-94, U-233 and Np-237. For all other contaminants, in the absence of site-specific data, sorption is presently conservatively neglected.

The sorption coefficients of these key elements are presented in Tables 3-23, 4-19 and 5-10 of the Data report (Walke et al. 2009b). The sorption and desorption of these contaminants in the shaft and EDZ are modelled assuming a linear sorption isotherm.

Irreversible sorption is not modelled. Sorption on the iron oxides that would likely form in the interior of a failed container is also not included. These are cautious assumptions. Sorption properties are considered as constant in time.

FEP Screening

Include FEP in all scenarios.

3.2.12.02 Sorption and desorption (geosphere)

Description

See *[3.2.12]* above.

Screening Analysis

Affects attenuation of contaminants in geosphere. Sorption in geosphere has been considered for C-14, Cl-36, Ni-59, Zr-93, Nb-94, U-233 and Np-237 – see Table 5-10 of the Data report (Walke et al. 2009b). For all other contaminants, it is assumed that there is no sorption in the geosphere other than in the Quaternary sands, gravels and tills. Irreversible sorption is not modelled and sorption properties are considered as constant in time.

FEP Screening

Include FEP in all scenarios.

3.2.12.03 Sorption and desorption (biosphere)

Description

Sorption and desorption processes, and their evolution with time, occurring in the accessible environment, including weathered overburden and subsoil and sediments under surface water bodies.

Sorption and desorption are important processes in soil and sediments. Plant/soil concentration ratios are often negatively correlated with soil sorption. Factors affecting soil sorption include primarily soil texture and mineralogy, pH, and Eh.

In surface waters, contaminants may adhere to particulates suspended in the water column and settle to the bottom. Contaminants can enter sediments from the water column or from below with discharging groundwater from the geosphere. Factors affecting sediment sorption include sediment properties (such as organic matter content), surface-water pH, temperature and water flushing rates.

Evolution of sorption and desorption processes could be important in the biosphere which is subject to a wide range of natural and human-induced changes. For instance, contaminant retention or mobility could change in response to seasonal variations in precipitation, or more slowly in response to climate variations and modification of land use.

Screening Analysis

In the SA, sorption and desorption of contaminants in sediments and soils is modelled explicitly assuming a linear sorption isotherm characterised by Kd - see Table 6-5 of the Data report (Walke et al. 2009b). Sorption properties are assumed to be constant in time.

Irreversible sorption is not modelled. This could be a non-cautious approximation since irreversible sorption would prevent leaching of contaminants out of the soil layer, thereby increasing the calculated soil concentrations. However, it is not expected to be a significant process.

Colloid-mediated migration of contaminants [3.2.09] and *Complexing agent effects [3.2.13]* may be important in the biosphere, but are assumed to be taken into account in the measured values for Kd which typically come from experiments with relevant soils.

FEP Screening

Include FEP in all scenarios.

3.2.12.04 Chemical reactions caused by adsorption or desorption

Description
It is conceivable that certain chemical or geochemical reactions may occur as a result of adsorption and/or desorption that affect other chemical reactions in the pore water or in the minerals that comprise the rock. Such reactions may be of importance to radionuclide migration studies.

Screening Analysis
This postulates that sorption reactions may cause other chemical reactions that would not otherwise be considered in SA. It is considered that there is no need to identify this issue as a separate FEP. Rather, the FEP can be considered within the context of the overall geochemical modelling of the pore water-rock interaction processes – see *Chemical/geochemical processes and conditions (in geosphere) [2.2.07]*.

FEP Screening
Screened out.

3.2.12.05 Anion exclusion effects

Description
Anion exclusion refers to the overlapping of electrical double layers within a pore and the subsequent exclusion (full or partial) of anions from the pore. In order to retain electrical neutrality within the pore, cations are also excluded. Neutral species and water itself may migrate through such a pore unimpeded.

Electrical (or diffuse) double layers (EDL) project into aqueous solution around charged surfaces such as clay minerals and hydrous metal oxides (see Stumm 1992; Appelo and Postma 2005). The concentration of cations and anions held within the EDL decreases with distance from the surface and the EDL itself contracts with the salinity of the pore water.

Anion exclusion occurs whenever pores become so small that double layers from opposite sides of the pore overlap and electrostatically repulse anions because of their negative potential. This leaves a very small part of the pore space that is available to anions and results in cases in which anions migrate more rapidly than other solutes displaying early breakthrough from the pore space.

Screening Analysis
Diffusion experiments undertaken using core samples from the DGR-1 and DGR-2 boreholes drilled at the Bruce site with iodide and tritiated water tracers have shown that ion exclusion effects occur (see discussion in Walke et al. 2009b). As expected, the effects are greater in the shales than in the limestones / dolostones.

FEP Screening
Screened in.

3.2.12.06 Sorption change caused by change in temperature

Description

Temperature-dependent changes in sorption may be brought about by the infiltration of glacial meltwater or by permafrost penetration into the rocks beneath the Bruce site. These would affect the partitioning of radionuclides between dissolved and sorbed states. Note that salinity might increase during permafrost formation, owing to solutes partitioning into the aqueous phase. This effect may influence sorption.

Screening Analysis

Significant changes in temperature in the Deep and Intermediate Bedrock Groundwater Zones are not expected – see *[2.1.10 and 2.2.09]*. The impact of temperature changes in the Shallow Bedrock Groundwater Zone and biosphere system are not expected to be as significant as other changes (e.g., sediment/soil characteristics).

FEP Screening

Screened out.

3.2.13 Complexing Agent Effects (Contaminant)

Description

The modification of speciation or transport of radionuclides and chemical contaminants in the disposal system because of the effects of chemical complexing agents.

This category is divided into:

- 3.2.13.01 Organics
- 3.2.13.02 Chelating agents
- 3.2.13.03 Microbes

3.2.13.01 Organics

Description

Chemical complexing agents include simple inorganic ions such as the chloride, fluoride and sulphate anions, small organic species such as the methyl radical, and larger organic-based species such as humic and fulvic acids which occur naturally in soils and in the geosphere. Humic acids and humates are weathering-resistant organic polymers with a gram molecular weight of about 150 000 and are relatively insoluble in water. Fulvic acids and fulvates are weathering-resistant organic polymers with a gram molecular weight of about 1000 and are somewhat soluble in water. These and other complexing agents might be introduced into the repository, for example as naturally occurring contaminants found in bentonite clay and surface water, or via degradation of organic wastes.

Screening Analysis

The organic carbon content of the host rocks may be sufficient to complex a small percentage of the radionuclides that might become mobile, however the FEPCAT study (Mazurek et al. 2003, FEP A2.2.2) found that “the effect of natural organics on the performance of a multi-barrier system was found to be small and limited to migration of trivalent actinides”.

The repository, however, will contain a significant amount of various organic materials. As they degrade, there will likely be organic materials formed that will include species that tend to complex and therefore could increase the solubility of some radionuclide elements. However, contaminant transport out of the repository would not be much affected by complexation with organics because such complexed radionuclides would be large and would diffuse very slowly into the host rock.

The SA conservatively neglects solubility limits within the repository for all species but C and U (see *[3.2.11.01]),* and also assumes that radionuclides diffuse based on the diffusivity appropriate for small species.

FEP Screening

Screened out by use of conservative parameters.

3.2.13.02 Chelating agents

Description
Chelating agents are organic macromolecules that bind metal ions to form soluble species. The concern with chelates is that they may promote the solubility and migration of radionuclides with which they bind.

The chief concern is that these complexing agents can chemically bond with a radionuclide or other contaminant to form another stable species. These reactions might even involve non-sorbed species such as iodide including I-129. Some chelating agents might form chemical bonds with metallic elements to yield stable species. The formation of new species can:

- increase (or decrease) the solubility of the complexed element; and
- modify transport properties, for instance, by forming a neutral or anionic complex that is less likely to sorb, or a cationic complex with multiple charge sites.

Inorganic complexing in highly saline waters, (see *[3.2.11.04]*), perhaps of brine strength, will permit considerable complex formation, e.g., $^{137}CsCl°$ or $^{90}SrCO_3°$, however this is not strictly a chelation process.

Screening Analysis
Small quantities of complexing agents are present in the waste, notably EDTA in the CANDECON resins. However, the quantities are not large relative to the overall repository amounts, and these large molecules would be inhibited from diffusing through the surrounding host rock.

The SA conservatively neglects solubility limits within the repository for all species but C and U (see *[3.2.11.01]),* and also assumes that radionuclides diffuse based on the diffusivity appropriate for small species.

FEP Screening
Screened out by use of conservative parameters.

3.2.13.03 Microbes

Description
Micro-organisms may produce subtle effects on radionuclide transport by sorbing radionuclides or by acting as colloids.

Screening Analysis
The SA conservatively neglects sorption onto biological substrates including biofilms.

Diffusion experiments undertaken using core samples from the DGR-1 and DGR-2 boreholes drilled at the Bruce site with iodide and tritiated water tracers have shown that ion exclusion effects occur (Walke et al. 2009b). This indicates that the sizes of the connected pores are very small. This is also consistent with the very low measured porosity and permeability. It is therefore unlikely that colloidal populations of micro-organisms will act to enhance contaminant transport. This is consistent with the conclusions drawn regarding the impacts of chelating agents (see *[3.2.13.02]*).

FEP Screening
Screened out by use of conservative parameters.

3.2.14 Food chains and uptake of contaminants

Description

The incorporation of radionuclides and chemical contaminants into plant or animal species that are part of the human food chain.

Important general processes, also discussed under *Ecological/biological/microbial systems [2.3.14]*, include:

- biotransformation or metabolism which involves catabolism (breaking down of more complex molecules), anabolism (building up of life molecules from simpler materials) and cometabolism (biodegradation of synthetic or hazardous waste materials concurrently with catabolism);
- bioconcentration, which refers to the ability of an organism to concentrate contaminants from its environment, usually from water or soil;
- bioaccumulation, which refers to the tendency of an organism to continue to bioconcentrate contaminants throughout its lifetime;
- biomagnification, which refers to the occurrence of contaminants at successively higher concentrations with increasing trophic level in the food web;
- biological interim storage, which refers to temporary holdback of contaminants;
- recycling, which refers to the reuse of contaminants; and
- biological feedback, which includes a number of effects such as destruction of biota when contaminant concentrations reach toxic levels.

Contaminants can enter the human food chain through many different routes.

- Plants may become directly contaminated as a result of deposition of contaminants onto their surfaces and uptake of contaminated water by their roots, and indirectly contaminated through exposure to soil and soil conditioners that are contaminated.
- Animals may become contaminated as a result of inhalation of contaminated air, from external deposition of contaminants onto their bodies, and from ingestion of contaminated food, soil and water.

Microorganisms also form part of the human food chain, directly with foods such as yoghurt and indirectly through processes such as fermentation.

The complexity of possible routes is due, in part, to the fact that both domestic and wild plants and animals might serve as sources of food for the critical group. Factors such as habitat of plants and diet and habits of animals are clearly important. Each of these factors can show a large range of variability. For instance, animal diet:

- varies considerably between different species and between domestic and wild animals of the same species;
- may include plants, fruits, water and other animals (by scavengers and predators);
- may include food supplements, man-made and natural salt licks and medication; and

- for terrestrial animals, may include soil ingestion, either routinely and inadvertently with contaminated plants or sometimes purposefully to meet nutritional needs, and, for aquatic biota, may include ingestion of sediment.

Screening Analysis

The following food chains are considered to be of relevance to the assessment, should contaminants reach the surface environment (see Section 2.3.3 of the Normal Evolution Scenario report, Walke et al. 2009a):

- Soil to plants to humans.
- Soil to plants to animals to humans.
- Soil to animals to humans.
- Water to plants to humans.
- Water to soil to plants to humans.
- Water to animals to humans.
- Air to plants to humans.
- Air to animals to humans.
- Air to plants to animals to humans.

Different types of food chain are also of relevance, including agricultural, wild foods and recreational (e.g. recreational fishing) (see Section 7.1 of the Data report, Walke et al. 2009b).

Food chains are also of relevance for assessment of exposure of non-human biota. These are represented in non-human biota exposure assessments, e.g., in the determination of No Effect Concentrations, see Garisto et al. (2008).

FEP Screening

Include FEP in all scenarios.

3.3 Exposure Factors

Description:

The Exposure Factor category of FEPs is related to processes and conditions that directly affect the health or give rise to other impacts on human beings and the environment, from given contaminant concentrations in environmental media.

Human beings and other living organisms exposed to a contaminant concentration in environmental media will be subject to a possible impact. Various modes of exposure ranging from external exposure to inhalation and ingestion are possible. The level of impact is a function of the properties of the contaminant, the contaminant concentration in the environmental media and various human and other organism behavioural and physiological characteristics related to the mode of exposure.

“Exposure Factors" is divided into individual FEPs:

- 3.3.01 Contaminant concentrations in drinking water, foodstuffs and drugs
- 3.3.02 Contaminant concentrations in non-food products
- 3.3.03 Contaminant concentrations in environmental media
- 3.3.04 Exposure modes
- 3.3.05 Dosimetry and biokinetics
- 3.3.06 Radiological toxicity/effects
- 3.3.07 Chemical toxicity/effects
- 3.3.08 Radon and radon daughter exposure

3.3.01 Contaminant concentrations in drinking water, foodstuffs and drugs

Description

The presence of radionuclides and chemical contaminants in drinking water, foodstuffs or drugs that may be consumed by humans or animals.

Contaminants may be incorporated into the food chain through contaminated soil, water and air. Water used for drinking is particularly important because it can provide a direct pathway of contaminant ingestion, with few delays. However, factors such as bioconcentration, bioaccumulation and biomagnification can increase concentrations of some contaminants in foodstuffs and may result in significant exposure to particular contaminants.

See also the related discussion under *Food chains and uptake of contaminants [3.2.14]* and throughout *Human behaviour [2.4],* particularly under *Diet and fluid intake [2.4.03]* and *Water source [2.4.05.03]*.

Screening Analysis

Potential exposure to contaminated drinking water and foodstuffs is represented in the SA, which requires calculation of the associated contaminant concentrations (see Section D.2.5 of the Normal Evolution Scenario report, Walke et al. 2009a). Potential foodstuffs include fish, plants, and animal products. Related exposure factors include the drinking water ingestion rate and ingestion rates for the different foodstuffs (see Section 7.1 of the Data report, Walke et al. 2009b).

Exposure from contaminated drugs is not considered since exposure is assumed to be dominated by the exposure pathways associated with drinking water and foodstuffs.

FEP Screening

Include FEP in all scenarios.

3.3.02 Contaminant concentrations in non-food products

Description

The presence of radionuclides and chemical contaminants in human manufactured materials or in environmental materials that have special uses.

Common examples of other materials that could be contaminated include:

- wood and rock used as building material and household furnishings;
- natural fibres and animal skins used in clothing; and
- peat, charcoal and biogas (from plant materials, faeces and refuse, or from trapping methane from garbage disposal sites, bogs and sediments) for use in house heating.

Other possibilities might be locally important, such as the use of charcoal as a filtering agent or the use of tree sap in the production of resins and tars.

Screening Analysis

It is noted that in the Third Case Study exposure to the following "other contaminated materials" was explicitly modelled from the following routes (Garisto et al. 2004c):

- building materials made from wood and soil; and
- heating fuels such peat and wood.

The results indicated that exposure to building materials and heating fuels is insignificant in comparison with other exposure pathways.

It is therefore assumed that contaminant concentrations in non-food products can be ignored.

FEP Screening

Screened out.

3.2.03 Contaminant concentrations in environmental media

Description

The presence of radionuclides and chemical contaminants in environmental media including soil, water, sediment and air.

These concentrations will be important in assessing the impact on biota, and also on assessing the external exposure and inhalation routes for humans. Concentrations in environmental media are also usually required to determine the contaminant concentrations in food. The comparison of calculated contaminant concentrations in environmental media with naturally occurring concentrations of similar species may provide additional information for safety assessment that is less dependent on assumptions as to human behaviour.

Contaminant concentrations in environmental media could be affected by many considerations; for instance, concentrations in indoor air could be affected by house location and concentrations in outdoor air by forest and grass fires. The discussions under *Surface environment [2.3]* describe features and processes that could contribute to contamination of environmental media and the discussions under *Contaminant release and migration factors [3.2]* provide more specific detail on how contaminants from the DGR could move through and enter different components of the accessible environment. The accessible environment of concern is discussed under *Human behaviour [2.4] and Exposure modes [3.3.04]* for humans and other biota.

Some media might attain higher concentrations than their surroundings because of natural processes such as bioaccumulation or evaporation of water. The presence of colloids might correspond to high local concentrations of contaminants (see *Colloid-mediated migration of contaminants [3.2.09]*). Moreover, human practices such as excessive watering of gardens might lead to higher concentrations or accumulation of contaminants (see *Human action mediated transport of contaminants [3.2.08]*).

Screening Analysis

Contaminant concentrations in environmental media provide an intermediate end-point in considering potential exposures to humans and non-human biota. The concentrations are also of interest in their own right, for example, for comparison against background concentrations.

FEP Screening

Include FEP in all scenarios.

3.3.04 Exposure modes

Description
The exposure of humans and biota to radionuclides and chemical contaminants.

Exposure modes can be broadly categorised as internal and external with respect to the human body or other affected biota. Internal exposure means the contaminant enters and may temporarily or permanently reside in the affected organism. External exposure means the contaminant is outside the organism at all times, although radiation and energy might be transferred into the organism.

Radiotoxic and chemotoxic species differ in their ability to affect organisms.

- Radiotoxic materials can lead to impacts through internal or external exposure.
- Chemotoxic species are only of concern from internal exposure, although there may be apparent exceptions. For instance, chemicals may be sorbed through skin or surfaces of other biota, but subsequent impacts are actually from internal exposure.

This exposure is considered under:

3.3.04.01 Exposure of humans

3.3.04.02 Exposure of biota other than humans.

3.3.04.01 Exposure of humans

Description

Exposure modes affecting humans.

Potentially important internal and external exposure modes affecting humans are:

- ingestion (internal) exposure from ingesting contaminated water, food, soil, dust and drugs (including injection of drugs);
- absorption (internal) exposure by uptake through the skin, for example from the use of contaminated health and beauty products such as toothpaste, shaving cream, soap and moisturisers, and the injection of contaminated drugs (in the specific case of tritiated water vapour, skin sorption could be more important than inhalation);
- inhalation (internal) exposure from inhaling gaseous and particulate contaminants; and
- external exposure from irradiation by radionuclides deposited on, or present on, the ground (groundshine), buildings, vegetation, animals, rocks and other objects, and as a result of immersion in contaminated water bodies and air.

Screening Analysis

Internal exposure from ingestion of soil, water and foodstuffs, and inhalation of dust and gases are relevant exposure modes to be considered. External exposure to contaminated media outside the body, including air immersion, ground exposure and water immersion also merit consideration (see Section 2.3.3 of the Normal Evolution Scenario report, Walke et al. 2009a).

Note that the following exposure modes are considered to be relatively insignificant in comparison and are therefore excluded:

- Exposure via dermal absorption, including injection of drugs, is considered to be relatively unimportant. Tritium, for which dermal absorption can merit consideration, has a relatively short half life (12.35 a). The geological isolation and institutional control period mean that radioactive decay will reduce the amount of tritium to which exposure might occur to a relatively small quantity; therefore the exposure pathway is screened out.

- External irradiation from buildings, vegetation and animals. External irradiation from building materials was considered in the Third Case Study and shown to be relatively unimportant (Garisto et al. 2004c). External irradiation from soil and sediment is considered to dominate over external irradiation from vegetation and animals.

FEP Screening

Include FEP in all scenarios.

3.3.04.02 Exposure of biota other than humans

Description

Exposure modes affecting biota (plants and animals) other than humans.

Biota can be divided into two broad groups:

- domesticated and cultivated species, which may have relatively well-known properties including information on diet and contaminant-transfer processes; and
- wild and indigenous species, whose characteristics may be less well understood.

Due to the site of the DGR both groups of biota are important. The DGR is located in an area where there is agriculture as well as natural areas. The area in the vicinity of the DGR includes wetlands and surroundings that constitute a meadow and deciduous and coniferous trees which provide a habitat for a variety of wildlife (see FEP *[2.3.10]*). The properties of wildlife may be quite different from domesticated and cultivated biota, especially in terms of factors that influence contaminant uptake, accumulation and transfer, such as their ecological niche, diet, life cycle, and seasonal effects. For instance, amphibians and benthic fish may experience relatively unique impacts involving external exposure to contaminated lake sediment.

The exposure pathway would be similar to those for humans - inhalation, ingestion, external contamination or irradiation. However the relative importance of these pathways would likely be quite different from humans and also between species. For example,

- Burrowing animals are more directly exposed externally and internally to contaminated soils and sediments;
- Aquatic plants may take up contaminants from the water column and the atmosphere (emergent plants), or from the water as well as the sediments (submergent plants).

Another factor that can be considered is the home range of the non-human biota. Some animals have a limited home range and may reside in a small area, whereas others may have a home range that encompasses an area much larger than that influenced by the DGR.

Screening Analysis

Doses to non-human biota are an end-point of interest for the SA.

- Animals can become exposed to radionuclides through the following pathways: air inhalation, soil ingestion, plant ingestion, water ingestion and external radiation exposure from, for example, ground and water contamination.
- Plants can be exposed internally, through root uptake, absorption through stomata and absorption across above-ground surfaces. Plants are also subject to external irradiation from the ground (terrestrial plants) and water and sediment (aquatic plants).

The degree to which these processes may need to be represented is a modelling decision. However it is noted that non-human biota assessments traditionally adopt simplified exposure models for both radionuclides (equilibrium transfer factors) and for non-radiological species which form the basis of No Effect Concentrations and/or Environmental Quality Standards against which the assessment is made (see Section 7.3 of the Data report, Walke et al. 2009b).

FEP Screening

Include FEP in all scenarios.

3.3.05 Dosimetry

Description

Dosimetry describes the dependence between radiation or chemical toxicity effect and the amount of radiation or chemical agent in the organs, tissues or the whole body.

Doses depend on factors that include:

- the form of exposure, e.g. internal or external exposure;
- the metabolism of the radioelement or chemical and physicochemical form if inhaled or ingested and its residence time in tissues or organs;
- the energy and type of radioactive emissions of the radionuclide; and
- the age at exposure and the lifetime commitment to the exposure.

Different species will have different dosimetry. Thus, dosimetry is separated into two FEPs:

3.3.05.01 Dosimetry for humans

3.3.05.02 Dosimetry for non-human biota

3.3.05.01 Dosimetry for humans

Description

The approach to dosimetry for humans can be adopted from standard international protocols. One special consideration that pertains to radioactive material is the decay of a parent radionuclide (or precursor) to its daughter radionuclide (or progeny), because:

- the precursor and progeny can have substantially different chemical and physical properties - these differences can effect the movement of contaminants through an organism; and
- the precursor and progeny can have quite different toxicity properties.

One important example of these effects is discussed in *Radon and radon progeny exposure [3.3.08]*. The estimated dose is compared to an acceptable level as discussed in FEP *[3.3.06.01]*.

Similar comments apply to chemotoxic effects, except that chemical and biochemical disruption of cell functions, not radioactive emissions, affects the tissues of the body. Chemical toxics can have a wide variation of effects on biota and Toxicological Reference Values (TRVs) reported as intake levels are used to determine the potential for inducing effects. The chemical form of a compound plays an important role in determining whether and how the toxic component interacts with cells and tissues. A very large number of chemical compounds exist and suitable quantitative dosimetry data may be sparse.

Screening Analysis

In the SA, the potential impact of radioactive and non-radioactive contaminants is of interest, as discussed in Section 3.6 of the Postclosure SA report (Quintessa et al. 2009).

Radiation dosimetry is included in the SA due to its central role in determining radiation exposure for comparison against relevant regulatory criteria. It is noted that whole body effective internal and external dose coefficients are based on the 1990 and 2007 recommendations of the ICRP (ICRP 1991 and 2007).

Whole body effective dose coefficients are calculated taking into account, for example, the radiation energies and types emitted by the radionuclide, the half-life of the radionuclide, the residence time of the radionuclide in the body, the organs that accumulate the radionuclide, tissue weighting factors, radiation weighting factors, etc. The calculated dose rates include the effects of decay chains, either by explicitly modelling the chains or by including the contribution from the progeny in the dose coefficient for the parent (see Section 7.2 of the Data report, Walke et al. 2009b).

The internal dose coefficients (ingestion and air inhalation) are taken from ICRP 72 (ICRP 1996). The external air immersion, water immersion and ground exposure dose coefficients are based on Eckerman and Leggett (1996).

The potential effects of chemicals are generally assessed through comparison to benchmarks that are based on intake rates (FEP *[3.3.07]*). Therefore detailed dosimetry is not required for this class of contaminant.

FEP Screening

Include FEP in all scenarios.

3.3.05.02 Dosimetry for non-human biota

Description

The dosimetry for non-human biota accounts for the same exposure routes, internal and external exposure, considered for humans, although some simplifying assumptions are generally made to allow the doses to different types and classes of biota to be estimated.

For non-radiological contaminants, the Toxicological Reference Values (TRVs) can be reported as intake levels such as the No Observed Adverse Effect Level (NOAEL) or a concentration which would have effects on a certain percent of the population (e.g. EC20, a concentration where 20% of the population is affected). The chemical form of a compound plays an important role in determining whether and how the toxic component interacts with cells and tissues. A very large number of chemical compounds exist and suitable quantitative dosimetry data may be sparse.

Screening Analysis

In the SA, the potential impact of radioactive and non-radioactive contaminants will be of interest, as discussed in Section 3.6 of the Postclosure SA report (Quintessa et al. 2009).

It is noted that if the modelled biosphere concentrations are very low, it may be sufficient to show that they are less than conservative screening levels for non-human biota, such as generic No-Effect Concentrations (NECs) derived for radionuclides (Garisto et al. 2008)

If the results indicate a need for more detailed assessment for non-human biota, then the dosimetry might adopt the steady-state methods recommended by IAEA (1992) and UNSCEAR (1996). Internal and external screening-level Dose Conversion Factors (DCFs) may be obtained using the ERICA tool (Copplestone and Allott 2006).

The potential effects of chemicals are generally assessed through comparison to benchmarks that are based on intake rates or media concentration (FEP *[3.3.07]*). Therefore detailed dosimetry is not required for this class of contaminant.

FEP Screening

Include FEP in all scenarios.

3.3.06 Radiological Toxicity / Effects

Description
The effects of radiation on man and other organisms.

Radiation effects can be classified in several different ways:

- somatic or genetic, occurring in the exposed individual or in the offspring of the exposed individual, respectively; and
- stochastic or nonstochastic, where the probability of the effect is a function of dose received) or the severity of the effect is a function of dose received and no effect may be observed below some threshold, respectively.

Toxicity and Effects are examined in two FEPs:

3.3.06.01 Radiological toxicity/effects for humans
3.3.06.02 Radiological toxicity/effects for non-human biota

3.3.06.01 Radiological toxicity/effects for humans

Description
At high exposure levels, radiation can kill a substantial fraction of cells and this can lead to acute radiation sickness and death. Such exposure levels are considered unlikely in the prudent management of radioactive nuclear waste. At low exposure levels, cancer induction (carcinogenesis) and genetic effects are of main concerns, possibly because of mutations that may lead to cancer or, if the reproductive cells are affected, hereditary effects that may be detrimental and transmitted to future generations. Radionuclides could also be teratogenic, that is, cause developmental disturbances in humans and other organisms. High exposures can cause serious malformations, but the situation is less clear at lower doses, especially those at or below background radiation levels where the most likely effect in humans might relate to adverse effects on brain development and mental capacity for those exposed in utero.

Another possible concern, synergistic impacts, is discussed under *Chemical toxicity/effects for humans [3.3.07.01]*.

Screening Analysis
In the SA, radiological doses to humans are of interest, as discussed in Section 3.4 of the Postclosure SA report (Quintessa et al. 2009).

Radiological toxicity effects are therefore considered within the SA. Specifically, the dose rates to potentially exposed groups of humans are assessed. These dose rates can be translated into risks of cancer and hereditary disease using the liner no-threshold model (ICRP 1991, 2007).

FEP Screening
Include FEP in all scenarios.

3.3.06.02 Radiological toxicity/effects for non-human biota

Description

For non-human biota the goal is to evaluate potential effects at a population or community level. Thus the endpoint of concern is generally reproductive impairment. If the effects are widespread throughout a population of some biota, there could also be consequential effects, such as disruption of food webs or ecosystems.

If the effects are widespread throughout a population of some biota, there could also be consequential effects, such as disruption of food webs or ecosystems. Another possible concern, synergistic impacts, is discussed under *Chemical toxicity/effects for biota other than humans [3.3.07.02]*.

Screening Analysis

In the SA, radiation doses to non-human biota are assessed, as discussed in Section 3.4.3 of the Postclosure SA report (Quintessa et al. 2009).

Note that if the modelled biosphere concentrations are very low, it may be sufficient to show that they are less than conservative screening levels for non-human biota, such as generic No-Effect Concentrations (NECs) derived for radionuclides (Garisto et al. 2008)

Should more detailed calculations be required for non-human biota, then calculated doses may be compared to dose benchmarks available from recognised agencies such as UNSCEAR, Environment Canada, and Health Canada, CNSC and IAEA.

FEP Screening

Include FEP in all scenarios.

3.3.07 Chemical Toxicity / Effects

Description

The effects of chemically toxic species on man and other organisms.

Some elements in nuclear fuel waste can be chemically toxic to humans and other organisms, including plants. The waste will include a wide range of radiologically stable, but potentially toxic species, including heavy metals and persistent organic species.

Chemical toxicity concerns includes elements of radionuclides; for instance:

- naturally occurring uranium is a heavy metal and as such is chemically toxic;
- technetium-99 may be more chemically toxic than radiotoxic (Coffey et al. 1984, Gerber et al. 1989); and
- iodine-129 may be more chemically toxic than radiotoxic to non-human biota.

There is currently no developed methodology for calculation of interaction effects between exposures, either between individual chemical contaminants or between chemical and radiation effects. These effects may be synergistic or antagonistic. The SA approach follows current practice in addressing each contaminant individually. This approach would have to be considered further if it was determined that several chemical contaminants had high toxicity quotients.

Toxicity and Effects are examined in two FEPs:

3.3.07.01 Chemical toxicity/effects for humans

3.3.07.02 Chemical toxicity/effects for non-human biota

3.3.07.01 Chemical toxicity/effects for humans

Description

Chemical toxicity can involve a wide range of effects, including teratogenic effects (developmental disturbances), mutagenic effects (mutations that may lead to cancer or hereditary changes transmitted to future generations) and carcinogenic (cancer inducing) effects and thus interfere with reproduction, growth and survival, with subsequent disruption of food chains that may affect other biota. Detrimental impacts can be found for most elements, but health and environmental impacts from arsenic, cadmium, chromium, lead, mercury and selenium are among those that have received the greatest attention. See also *Radiological toxicity/effects for humans [3.3.06.01]*.

Another issue of concern is synergistic effects (and its opposite, antagonistic effects) or the combined effects of two or more radiotoxic or chemotoxic species on man and other organisms. Two or more toxic substances may interact with each other, or interact jointly with an organism, to produce biological effects that can be different in extent and kind than from either substance separately. That is, even if the two substances affect he same physiologic function, their effects may be more than additive, or two substances affecting different physiologic functions may have more serious cumulative effects on an organism. In addition, an inactive substance may enhance the action of an active substance (potentiation) or an active substance may decrease the effect of another active substance (antagonism). Some effects, such as hormesis, may be beneficial.

Screening Analysis

The potential effects of chemicals on humans are an endpoint of interest in the SA, see Section 3.4.4 of the Postclosure SA report (Quintessa et al. 2009).

A tiered approach is adopted whereby calculated concentrations are compared against Environmental Quality Standards designed to protect human health and the environment (see Section 7.3.2 of the Data report, Walke et al. 2009b).

Should more detailed calculations be required, then Toxicological Reference Values (TRVs) may be compiled from peer-reviewed standard databases. For effects on humans, the following sources may be considered:

- the U.S. EPA IRIS database;
- Health Canada TRVs for PQRA (Health Canada 2004); and
- World Health Organisation.

FEP Screening

Include FEP in all scenarios.

3.3.07.02 Chemical toxicity/effects for non-human biota

Description

For non-human biota the goal is to evaluate potential effects at a population or community level. This involves assessing the potential risks of unacceptable mortality, decreased growth, or reproductive impairment for populations exposed to contaminants.

Chemical toxics can have a wide variation of effects on biota, and the dose response of an organism is often reported as intake levels such as the No Observed Adverse Effect Level (NOAEL) or the concentration that would have effects to a certain portion of the population (e.g. EC20, a concentration at which 20% of the population is affected). The chemical form of a compound plays an important role in determining whether and how the toxic component interacts with cells and tissues.

Note that protection of non-human biota from chemical toxicity is traditionally achieved through the establishment of Environmental Quality Standards (EQSs) by the appropriate national regulatory authority. EQSs are usually set taking factors such as NOAELs and EC20 into account.

Screening Analysis

The potential effects of chemicals on non-human biota are an endpoint of interest in the SA, see Section 3.4.4 of the Postclosure SA report (Quintessa et al. 2009).

A tiered approach is adopted whereby calculated concentrations are compared against Environmental Quality Standards designed to protect human health and the environment (see Section 7.3.2 of the Data report, Walke et al. 2009b).

Should more detailed calculations be required, then the U.S. EPA EcoTox database may also be used. Where appropriate TRVs can be selected that are consistent with those used for ERAs conducted for other OPG sites, such as the Pickering site and the WWMF.

FEP Screening

Include FEP in all scenarios.

3.3.08 Radon and radon progeny exposure

Description

Radon and radon progeny exposure is considered separately from exposure to other radionuclides because the behaviour of radon and its progeny, and their modes of exposure, are somewhat different.

Radon-222 is mobile (see *Noble gases [3.1.06]*) and can readily enter different components of the biosphere. It has a short half-life (about 3.8 days), as do its immediate progeny, Po-218, Pb-214, Bi-214 and Po-214 (the next decay product, Pb-210 has a half-life of 22.3 years). The consequence is that exposure to Rn-222 almost always implies exposure to its short-lived progeny which are relatively immobile and relatively reactive. One exposure route involves external exposure from immersion in contaminated air. However, the principal mode of exposure to humans and animals is inhalation of radon progeny attached to dust particles, which then deposit in the respiratory system. This particular exposure mode is a large (and in some cases the largest) component of dose to humans received from natural background sources of radiation, and arises primarily from infiltration of Rn-222 into human dwellings.

Screening Analysis

The Am-242m decay chain, which includes U-238 and Pu-238, is included in the SA (see Section 3.5.2 of the Data report, Walke et al. 2009b), therefore Rn-222 may arise and is assessed.

The dose rate from exposure to Rn-222 calculated in the SA includes doses from radon progeny. This is achieved by using a Rn-222 air inhalation dose coefficient based on the most up-to-date dosimetric information for radon and radon progeny radionuclides (ICRP 1993).

FEP Screening

Include FEP in all scenarios.

REFERENCES

Appelo, C.A.J. and D. Postma. 2005. Geochemistry, Groundwater and Pollution, 2nd Edition, Balkema Publishers, New York, USA.

Atkinson, A., A.W. Harris and J.A. Hearne. 1997. Comparison of Materials for the Backfilling of Repositories. Nirex Report NSS/R306. Harwell, UK.

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

BEAK. 2002. Guidance for Calculation of Derived Release Limits for Radionuclides in Airborne and Liquid Effluents from Ontario Power Generation Nuclear Facilities. Ontario Power Generation Report N-REP-03482-10000-R00. Toronto, Canada.

Benovich, I. 2003. Derived Release Limits for the Western Waste Management Facility. Ontario Power Generation Report OPG 0125-REP-03482-00002-R00. Toronto, Canada.

Berner, U. R. 1990. A Thermodynamic Description of the Evolution of Porewater Chemistry and Uranium Speciation during the Degradation of Cement. Nagra Technical Report, NTB 90-12. Wettingen, Switzerland.

Berner, U. R. 1992. Evolution of Porewater Chemistry during Degradation of Cement in a Radioactive Waste Repository Environment. Waste Management 12. 201-219.

Biddle, P., A.A. Davies, D.J. McGahan, J.H. Rees and P.E. Rushbrook. 1988. The Evolution of Minor Active and Toxic Gases in Repositories. Nirex Report NSS/R118. Harwell, UK.

BIOCLIM. 2004. Development and Application of a Methodology for taking Climate-driven Environmental Change into account in Performance Assessments. BIOCLIM Deliverable D10-12, April 2004. Available from ANDRA, http://www.andra.fr/bioclim/.

Bowerman, B. S., J.H. Clinton and S.R. Cowdery. 1988. Biodegradation of Ion Exchange Media. NUREG/CR-5221, BNL-NUREG-52163, Brookhaven National Laboratory, New York, USA.

Bracke, G., W. Muller and K. Kugel. 2004. Derivation of Gas Generation Rates for the Morsleben Radioactive Waste Repository (ERAM). Proceeding of the DisTec Conference, April 26-28, Berlin.

Brodersen, K., K. Berghman, F. Glasser, N. Longomazino, J.C. Nomine and J. Wang. 1991. Chemical and Thermal Stability of Waste Products. In: L. Cecille (Editor), Radioactive Waste Management and Disposal. Elsevier Science Publishers Ltd, London, UK.

Brown, P., R.E. Spalding, D.O. ReVelle, E. Tagliaferri and S.P. Worden. 2002. The Flux of Small Near-Earth Objects Colliding with the Earth. Nature 420, 294-296.

Brown, R.J.E. and T.L. Pewe. 1973. Distribution of Permafrost in North America and its Relationship to the Environment: A Review, 1963-1973. In: Permafrost: North American Contribution to the 2nd International Conference, 13th-28th July 1973, Yakutsk. National Academy of Sciences, Washington D.C., USA.

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

Canadian Nuclear Safety Commission (CNSC). 2006. Regulatory Guide G-320, Assessing the Long Term Safety of Radioactive Waste Management. Ottawa, Canada.

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

Chambers, A. V., S.J. Williams and S.J. Wisbey. 1995. Nirex Near Field Research: Report on Current Status in 1994. Nirex Report S/95/011. Harwell, UK.

Coffey, J.L., R.L. Hayes, J.J. Rafter, E.E. Watson and J.E. Carlton. 1984. Radiation Dosimetry and Chemical Toxicity Considerations for ^{99}Tc. Health Physics 46, 422-428.

Copplestone, D. and R. Allott. 2006. Framework for Protection of Wildlife and the Environment Agency Approach. Environment Agency of England and Wales NDAWG Paper 9-03. Bristol, UK.

Damjanac, B. 2008. OPG's Deep Geologic Repository for Low and Intermediate Level Waste. Phase 1 Long-term Cavern Stability. Ontario Power Generation Report OPG 00216-REP-01300-00005-R00. Toronto, Canada.

Davis, P.A., R. Zach, M.E. Stephens, B.D. Amiro, G.A. Bird, J.A.K. Reid, M.I. Sheppard, S.C. Sheppard and M. Stephenson. 1993. The Disposal of Canada's Nuclear Fuel Waste: The Biosphere Model, BIOTRAC, for Postclosure Assessment. AECL Research Report AECL-10720, COG-93-10. Chalk River, Canada.

Eckerman, K.F. and R.W. Leggett. 1996. DCFPAK: Dose Coefficients Data File Package for Sandia National Laboratory. Oak Ridge National Laboratory report ORNL/TM-13347. Oak Ridge, USA. (http://homer.hsr.ornl.gov/vlab/VLcodeDF.html).

Evans, D. W. 2000. IX Resin Waste Management: An Evaluation of Current Status and Technology. Ontario Power Generation Report OPG 06819-REP-03469-10007-R00. Toronto, Canada.

Francis, A. J., R. Cather, R. and I.G. Crossland. 1997. Development of the Nirex Reference Vault Backfill: Report on Current Status in 1994. Nirex Report S/97/014. Harwell, UK.

Garisto, F., P. Gierszewski, T. Melnyk and A. D'Andrea. 2004a. Third Case Study - Reference Data and Codes. Ontario Power Generation, Nuclear Waste Management Division report 06819-REP-01200-10107-R00. Toronto, Canada.

Garisto F., P. Gierszewski and K. Wei. 2004b. Third Case Study – Features, Events and Processes. Ontario Power Generation Report No: 06819-REP-01200-10125-R00. Toronto, Canada.

Garisto, F., J. Avis, N. Calder, A. D'Andreas, P. Gierszewski, C. Kitson, T. Melnyk, K. Wei and L. Wojciechowski. 2004c. Third Case Study Defective Container Scenario. Ontario Power Generation Report OPG 06819-REP-01200-10126-R00.

Garisto, N.C, Z. Eslami and F. Bhesania. 2005. Alternative Exposure Groups, Characteristics and Data for the Post-Closure Safety Assessment of a Deep Geological Repository. Ontario Power Generation Report OPG 06819-REP-01200-10150- R00. Toronto, Canada.

Garisto N.C., F. Cooper and S.L. Fernandes. 2008. No-Effect Concentrations for Screening Assessment of Radiological Impacts on Non-Human Biota. SENES Consultants Limited report for the Nuclear Waste Management Organization (NWMO). NWMO Report TR-2008-02. Toronto, Canada.

Gartner Lee Limited. 2008a. OPG's Deep Geologic Repository for Low and Intermediate Level Waste. Phase 1 Regional Geology, Southern Ontario. Ontario Power Generation Report OPG 00216-REP-01300-00007-R00. Toronto, Canada.

Gartner Lee Limited. 2008b. OPG's Deep Geologic Repository for Low and Intermediate Level Waste. Phase 1 Regional Geomechanics, Southern Ontario. Ontario Power Generation Report OPG 00216-REP-01300-00008-R00. Toronto, Canada.

Gartner Lee Limited. 2008c. OPG's Deep Geologic Repository for Low and Intermediate Level Waste. Phase 1 Regional Geomechanics, Southern Ontario. Ontario Power Generation Report OPG 00216-REP-01300-00008-R00. Toronto, Canada.

Gerber, G.B., M. Hegela, J. Vankerkom, R. Kirchmann, J.R. Maisin and M. Lambiet-Collier. 1989. Toxicity of ^{99}Tc: Can it represent a Risk to Man? Health Physics 57, 345-350.

Gierszewski P., J. Avis, N. Calder, A. D'Andrea, F. Garisto, C. Kitson, T. Melnyk, K. Wei and L. Wojciechowski. 2004. Third Case Study – Postclosure Safety Assessment. Ontario Power Generation Report OPG 06819-REP-01200-10109-R00, Toronto, Canada.

Glasser, F.P., J. Pedersen, K. Goldthorpe, M. Atkins, M. Tyrer, D.G. Bennett, D. Ross, K. Quillin and S. Duerden 1998. The Chemistry of Blended Cements and Backfills intended for use in Radioactive Waste Disposal. R&D Technical Report P98, Environment Agency of England and Wales. Bristol, UK.

Goldberg, J. E., L.J. Gould, T.G. Heath, G.J. Holtom, S.W. Swanton and C.J. Tweed. 1997. Effects of Elevated Temperatures in the Near Field of a Cementitious Repository for Radioactive Waste. Nirex Report S/97/013. Harwell, UK.

Goodwin, B.W., D.B. McConnell, T.H. Andres, W.C. Hajas, D.M. LeNeveu, T.W. Melnyk, G.R. Sherman, M.E. Stephens, J.G. Szekely, P.C. Bera, C.M. Cosgrove, K.D. Dougan, S.B. Keeling, C.I. Kitson, B.C. Kummen, S.E. Oliver, K. Witzke, L. Wojciechowski and A.G. Wikjord. 1994. The Disposal of Canada's Nuclear Fuel Waste: Postclosure Assessment of a Reference System. Atomic Energy of Canada Limited report AECL-10717, COG-93-7. Pinawa, Canada.

Goodwin, B.W., T.H. Andres, W.C. Hajas, D.M. LeNeveu, T.W. Melnyk, J.G. Szekely, A.G. Wikjord, D.C. Donahue, S.B. Keeling, C.I. Kitson, S.E. Oliver, K. Witzke and L. Wojciechowski. 1996. The Disposal of Canada's Nuclear Fuel Waste: A Study of Postclosure Safety of In-room Emplacement of Used CANDU Fuel in Copper Containers in Permeable Plutonic Rock. Volume 5: Radiological Assessment. Atomic Energy of Canada Limited report AECL-11494-5, COG-95-552-5. Pinawa, Canada.

Greenfield, B.F., M.W. Spindler and D.R. Woodwark. 1997. Summary of Effects of Organic Degradation Products on Near–field Radioelement Chemistry. Nirex Report NSS/R298. Harwell, UK.

Hatch. 2008. OPG's Deep Geological Repository for Low and Intermediate Level Waste. Conceptual Design Report. Hatch 323874DGR-RPT-CDR200-Rev01. Ontario Power Generation Report OPG 00216-REP-03902-00004-R01. Toronto, Canada.

Health Canada. 2004. Federal Contaminated Site Risk Assessment in Canada. Part II: Health Canada Toxicological Reference Values (TRVs). Ottawa, Canada.

Hobbs, M.Y., S.K. Frape, O. Shouakar-Stash and L.R. Kennell. 2008. OPG's Deep Geologic Repository for Low and Intermediate Level Waste. Phase 1 Regional Hydrochemistry, Southern Ontario. Ontario Power Generation Report OPG 00216-REP-01300-00007-R00. Toronto, Canada

Husain, A. and D. Jain. 2003. Chemical Radiochemical and Microbiological Characterisation of the Contents of Resin Liners Sampled at the Western Waste Management Facility in 2002. Kinectrics Report:9820-090-RA-0001-R00. Toronto, Canada.

Intera Engineering Limited. 2006. Geoscientific Site Characterization Plan for OPG's Deep Geologic Repository for Low & Intermediate Level Waste. Ontario Power Generation Report OPG 00216-REP-03902-00002-R00. Toronto, Canada.

Intera Engineering Limited. 2008. Phase 2 Geoscientific Site Characterisation Plan Repository Bruce Nuclear Site. Ontario Power Generation Report OPG 002160-REP-03902-00006-R00. Toronto, Canada.

International Atomic Energy Agency (IAEA). 1992. Effects of Ionizing Radiation on Plants and Animals at Levels Implied by Current Radiation Protection Standards. International Atomic Energy Agency Technical Report Series No. 332. Austria, Vienna.

International Atomic Energy Agency (IAEA). 2004. Improvement of Safety Assessment Methodologies for Near Surface Disposal Facilities. Volume I: Review and Enhancement of Safety Assessment Approaches and Tools. IAEA-ISAM-1. Vienna, Austria.

International Commission on Radiation Protection (ICRP). 1991. 1990 recommendations of the International Commission on Radiological Protection. ICRP Publication 60, Pergamon Press, Oxford, UK.

International Commission on Radiation Protection (ICRP). 1993. Protection against Radon-222 at Home and Work. ICRP Publication 65, Pergamon Press, Oxford, UK.

International Commission on Radiation Protection (ICRP). 1996. Age-dependent doses to members of the public from intake of radionuclides: Part 5, Compilation of ingestion and inhalation dose coefficients. ICRP Publication 72, Pergamon Press, Oxford, UK.

International Commission on Radiation Protection (ICRP). 2000. Radiation protection recommendations as applied to the disposal of long-lived solid radioactive waste. ICRP Publication 81, Pergamon Press, Oxford, UK.

International Commission on Radiation Protection (ICRP). 2007. The 2007 Recommendations of the International Commission on Radiological Protection. ICRP Publication 103, Pergamon Press, Oxford, UK.

Jaupart, C., J.C. Mareschal, L. Guillou-Frottier and A. Davaille. 1998. Heat Flow and Thickness of the Lithosphere in the Canadian Shield. J. Geophys. Res. 103, 15269-15286.

Kidby, D. W. and A. Rosevear. 1997. The Microbiological Basis of the Gas Generation Program GAMMON. Nirex Report NSS/R369. Harwell, UK.

Knief, R.N. 1985. Nuclear Criticality Safety: Theory and Practice. American Nuclear Society, LaGrange Park, USA.

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

Mazurek, M. 2004. Long-term Used Nuclear Fuel Waste Management – Geoscientific Review of the Sedimentary Sequence in Southern Ontario. University of Bern Technical Report TR 04-01. Bern, Switzerland.

Mazurek, M., F. J. Pearson, G. Volckaert and H. Bock. 2003. Features, Events and Processes Evaluation Catalogue for Argillaceous Media. NEA Report 4437, OECD/NEA, Paris. France.

Metcalfe, R., S.P. Watson, J.H. Rees, P. Humphreys and F. King. (2008). NDA Work on Gas Generation and Migration from a Deep Geological Repository. A Review undertaken on behalf of the Nuclear Waste Assessment Team. Environment Agency Report GEHO1108BOZN-E-E, Environment Agency of England and Wales. Bristol, UK.

Müller, R.D., J.-Y. Royer and L.A. Lawver. 1993. Revised Plate Motions Relative to the Hotspots from Combined Atlantic and Indian Ocean Hotspot Tracks. Geology 21, 275-278.

Nirex. 1994. Postclosure Performance Assessment: Gas Generation and Migration. Nirex Report S/94/003. Harwell, UK.

Nuclear Energy Agency (NEA). 1999. Safety Assessment of Radioactive Waste Repositories – Systematic Approaches to Scenario Development – An International Database of Features, Events and Processes. A report of the NEA Working Group on Development of a Database of Features, Events and Processes Relevant to the Assessment of the Postclosure Safety of Radioactive Waste Repositories, OECD/NEA, Paris, France.

Nuclear Waste Management Organization (NWMO). 2009. L&ILW Deep Geologic Repository – Preliminary Waste Acceptance Criteria. Nuclear Waste Management Organization Document 00216N-PR-03461-0001-R000. Toronto, Canada.

Ontario Power Generation (OPG). 2004. Western Waste Management Facility Safety Report. Ontario Power Generation Report W-SR-01320-00001 R00. Toronto, Canada.

Ontario Power Generation (OPG). 2005a. WWMF Refurbishment Waste Storage Facility Environmental Assessment. Ontario Power Generation Report OPG 01098-REP-07701-00002 R00. Toronto, Canada.

Ontario Power Generation (OPG). 2005b. Project Description. Deep Geologic Repository for Low and Intermediate Level Radioactive Waste. Ontario Power Generation Report OPG 00216-REP-07722.07-00001. Toronto, Canada.

Ontario Power Generation (OPG). 2005c. Alternative Exposure Groups, Characteristics and Data for the Postclosure Safety Assessment of a Deep Geological Repository. Prepared by SENES Consultants Limited. Ontario Power Generation Report OPG 06819-REP-01200-10150-R00. Toronto, Canada.

Ontario Power Generation (OPG). 2008. Reference Low and Intermediate Level Waste Inventory for the Deep Geologic Repository. Ontario Power Generation Report OPG 00216-REP-03902-00003-R01. Toronto, Canada.

Penfold, J. and R. Little. 2009. Postclosure Safety Assessment (V1): Analysis of Human Intrusion and Other Disruptive Scenarios. Nuclear Waste Management Organization (NWMO) Report DGR-TR-2009-03-R0. Toronto, Canada.

Penfold, J.S.S., R.H. Little, R.A. Bowden and M.J. Egan. 2003. Preliminary Safety Assessment of Concepts for a Permanent Waste Repository at the Western Waste Management Facility Bruce Site. Quintessa Report QRS-1027B-1 v1.0. Henley-on-Thames, United Kingdom.

Peltier W. R. 2008. OPG's Deep Geologic Repository for Low and Intermediate Level Waste. Phase 1 Long Term Climate Change Study. Ontario Power Generation Report OPG 00216-REP-01300-00004-R00. Toronto, Canada.

Penfold, J.S.S., R.H. Little, P.C. Robinson, and D. Savage. 2002. Improved Safety Assessment Modelling of Immobilised LLW Packages for Disposal. Ontario Power Generation Report OPG 05386-REP-03469.3-10002-R00. Toronto, Canada.

Pettersson, M. and M. Elert. 2001. Characterisation of Bitumenised Waste in SFR1. SKB Report R-01-26. Stockholm, Sweden.

Quintessa, Intera and SENES. 2009. Postclosure Safety Assessment (V1) Report. Nuclear Waste Management Organization (NWMO) Report DGR-TR-2009-01-R0. Toronto, Canada.

Rees, J.H., L.J. Gould, M. Kelly and N.J. Pilkington. 2002. The Impact of Non-aqueous Phase Liquids on Repository Performance. Nirex Report AEAT/ERRA-0405. Harwell, UK.

Sanford, B.V., F.J. Thompson and G.H. McFall. 1985. Plate tectonics- a possible controlling mechanism in the development of hydrocarbon traps in Southwestern Ontario. Bull. Canadian Petrol. Geol. 33, 52-71.

Shreir, L.L. 1976. Corrosion. 2nd edition, Newnes-Butterworths, London, UK.

SKB. 2006. Long-term safety for KBS-3 Repositories at Forsmark and Laxemar – A First Evaluation. Main Report of the SR-Can Project. SKB Report TR-06-09. Stockholm, Sweden

Soler, J.M. 2001. The Effect of Coupled Transport Phenomena in the Opalinus Clay and Implications for Radionuclide Transport. Jrnl. of Contaminant Hydrology 53, 63-84.

Stroes-Gascoyne, S. and C.J. Hamon. 2007. Preliminary Results from the Microbial Analysis of an Ordovician Limestone Core Sample. Nuclear Waste Management Organization Technical Memorandum, Toronto, Canada.

Stumm, W. 1992. Chemistry of the Solid-Water Interface. Wiley-Interscience, New York, USA.

Sykes, J.F., E.A. Sykes, S.D. Normani, Y. Yin and Y.-J. Park. 2008. OPG's Deep Geologic Repository for Low and Intermediate Level Waste: Phase I Hydrogeological Modelling. Ontario Power Generation Report OPG 00216-REP-01300-00009-R00. Toronto, Canada.

Torstenfelt, B. 1989. Chemical Degradation of Ion Exchange Resins in a Cement Matrix – A Review. ABB Atom Report RVC 89-160. Zurich, Switzerland

United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). 1996. Sources and Effects of Ionising Radiation. United Nations Scientific Committee on the Effects of Atomic Radiation 1996 Report to the General Assembly, Fifty-first Session, Supplement No. 46 (A/51/46), Annex: Effects of Radiation on the Environment, United Nations Sales No. E96.IX.3. New York, USA.

Walke, R.C., L. Limer, A. Paulley and J. Rees. 2008. Selection of Radionuclides and Chemical Species for the Version 1 Postclosure Safety Assessment of the Deep Geologic Repository Project. Quintessa Technical Memorandum for Ontario Power Generation QRS-1335A-TM6. Henley-on-Thames, UK.

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

Walke, R., A. Bath, A. Bond, N. Calder, P. Humphreys, F. King, R. Little, R. Metcalfe, J. Penfold, J. Rees, D. Savage, G. Towler and R. Walsh. 2009b. Postclosure Safety Assessment (V1): Data. Nuclear Waste Management Organization (NWMO) Report DGR-TR-2009-08-R0. Toronto, Canada.

Whillans, D.W. 2006. Gender Effects in Radiation Dose and Risk Assessment for Geological Disposal of Radioactive Waste. Ontario Power Generation Report OPG 06819-REP-01200-10159-R00. Toronto, Canada.

Wood, A.W. and J. Kienle. 1990. Volcanoes of North America: United States and Canada. Cambridge Univ. Press. Cambridge, UK.

Wuschke, D.M., S.H. Whitaker, B.W. Goodwin and L.R. Rasmussen. 1995. Assessment of the Long-Term Risk of a Meteorite Impact on a Hypothetical Canadian Nuclear Fuel Waste Disposal Vault Deep in Plutonic Rock. Atomic Energy of Canada Limited report AECL-11014, COG-93-470. Pinawa, Canada.

Wuschke, D.M. 1996. Assessment of the Long-Term Risks of Inadvertent Human Intrusion into a Proposed Canadian Nuclear Fuel Waste Disposal Vault in Deep Plutonic Rock - Revision 1. Atomic Energy of Canada Limited Report AECL-10279 Rev. 1, COG-92-151 Rev. 1. Pinawa, Canada.

Zach, R., J.G. Szekely, G.A. Bird, W.C. Hajas, C.R. Macdonald and S.C. Sheppard. 1996. Alternative Human Characteristics and Lifestyles in the BIOTRAC Biosphere Model for Assessing Canada's Nuclear Fuel Waste Disposal Concept. Atomic Energy of Canada Limited Technical Record TR-719, COG-95-542. Pinawa, Canada.

APPENDIX A

REVIEW OF ASSESSMENT-SPECIFIC LISTS AND SCREENING PROCEDURES FOR FEPs

A.1 INTRODUCTION

The review examines major repository postclosure safety assessments from a number of countries. From the review, recommendations are made for the screening of FEPs for the proposed L&ILW DGR at the Bruce site.

A.2 REVIEW OF ASSESSMENTS

A.2.1 Belgium (SAFIR 2 Assessment)

This assessment covers the disposal of vitrified HLW, spent fuel, hull endpieces and grids from spent fuel assemblies to Boom clay (ONDRAF/NIRAS 2001). The NEA list of FEPs was employed (NEA 1999), to which were added additional FEPs relevant to disposal in clay. Screening was conducted against the following criteria:

- probability of occurrence below 10^{-8} /year.
- negligible impact.
- irrelevant to the host geology at Mol-Dessel.
- irrelevant for the wastes under consideration or the design of the repository.
- same effect as another FEP.

The screening was carried out using judgements reached by experts.

A.2.2 Finland (TILA-99 Assessment)

This assessment examines the deep disposal of spent fuel at four candidate sites (Vieno and Nordman 1999). The treatment of FEPs in two earlier Finnish assessments of spent fuel disposal – TVO-92 and TILA-96 – was audited against the NEA list as shown in NEA (1999). Screening decisions were taken on the basis of results from these earlier studies. This provided the FEP list for the TILA-99 assessment, which in practice did not differ materially from the earlier lists.

A.2.3 Japan (H-12 Assessment)

This was a generic assessment of HLW disposal. In this assessment, the initial list of FEPs was compiled from the NEA list, Nagra FEP list and expert opinion. FEPs were screened out using the following criteria (JNC 2000):

- unlikely to affect safety if a suitable site is selected;
- can be avoided by suitable design and construction of the repository and by appropriate engineering controls;
- extremely low probability of occurrence; and
- insignificant consequences.

A.2.4 Sweden (SAFE Assessment)

This assessment was for the Forsmark SFR repository for L&ILW. The initial list of FEPs was compiled from NEA (1999) and earlier SKB assessments. The FEPs were screened against the following criteria (SKB 2001):

- relevance to the type of geology and geographic setting;
- relevance to the waste types involved;
- relevant to the first 10,000 years of the postclosure period, in line with timeframe of assessment; and
- negligible effect on repository safety.

The FEPs screened in were divided between those that were included in the system description and EFEPs (External) that were scenario-initiating events and conditions. The EFEPs were relevant to the reference and variant scenarios, as appropriate. Examples included climate change, human activities and initial defects in the technical barriers.

Extensive use was made of expert judgement in reaching decisions.

A.2.5 Switzerland (Project Opalinus Clay)

This was an assessment of a deep repository for vitrified HLW, spent fuel and long-lived ILW. Nagra has compiled a database of FEPs specific to disposals in Opalinus clay, based on the Kristillin-I FEP list and ancillary compilations from Nagra staff and consultants. This was then audited against two NEA compilations, one broad and the other relevant to disposal in clay formations (Nagra 2002). The augmented list was then screened, based on criteria very similar to those used in the Belgian, Japanese and Swedish assessments noted above.

Two novel categories of FEP are defined.

- Reserve FEPs: these are omitted from assessments because suitable models, codes or databases are not available. Their exclusion leads to a conservative treatment of safety. Examples include sorption of radionuclides on container corrosion products and the long resaturation time of the repository.
- Super FEPs: these are agglomerations of relevant individual FEPs. Their use simplified the definition of scenarios. Examples include corrosion of cladding, breaching of cladding, dissolution of the fuel matrix, migration of gas and criticality.

A.2.6 UK (Drigg Assessment)

BNFL discusses the screening of FEPs in the 2002 postclosure safety case for the shallow site near Drigg for the disposal of LLW (BNFL 2002a). The Safety Case was underpinned by a description of the system provided through two levels of analysis. These included definition of the process system itself (i.e. the repository and its surroundings) and related system-specific FEPs, and definition of the external system environment, through ‘external’ FEPs (EFEPs). These EFEPs served to provide context and boundary conditions to the assessment of process system FEPs, and considered factors such as climate and landscape change and potential future human actions.

The list of EFEPs was derived from a systematic assessment of the system and its environs, and was audited against internationally available FEP lists. In order to focus upon the key external issues for the site, a screening process was then undertaken for the EFEPs. The screening arguments employed were as follows.

- An EFEP should not be physically implausible given the timescale of the assessment.
- It should not be physically implausible given the site context.
- The EFEP should not have a probability of occurrence (or rate of change of external influence on the site) that is low compared with other EFEPs.
- It should not be only associated with global disaster.
- It should not be included if it can be considered to be subsumed directly within the treatment of other, more directly relevant EFEP(s).
- An EFEP should not be considered if in contradiction to regulatory guidance.
- It should not be considered if effectively excluded by the definition of the safety assessment context.

The nature of the EFEPs meant that quantitative screening calculations could not be undertaken as this would have required a full assessment of the site in advance. However it is anticipated that the outputs of the 2002 assessment will be utilised to screen EFEPs for further assessments. 28 EFEPs were identified, and these were utilised to inform boundary conditions and other ‘external’ factors within the safety assessment.

The process system FEPs, which were numerous, were derived through a systematic analysis of the potential interactions between the various components of the process system, and was also audited against internationally available FEP lists. The FEPs were categorised and screened through the use of a systematic approach underpinned by a ‘Clearing House’ process. According to BNFL (2002b), “A structured procedure was applied in which the Clearing House teams systematically considered each FEP in turn, by discussing and responding to a set of standard questions, presented in the form of a decision tree. This began with the key question: ‘Do we know the importance of this FEP to the assessment?”

As the assessment undertaken in 2002 was essentially the first full iteration of assessment of the site, notwithstanding earlier less detailed assessments, it was considered that there were limited quantitative arguments available to support the screening out of FEPs at this stage. Therefore, a large majority of the FEPs were taken forward for analysis. However, many FEPs were assessed through the use of ‘logical arguments’, i.e. qualitatively, and a number of others were ‘subsumed’ within the assessment of other FEPs and related uncertainty and sensitivity calculations. In total, 147 of the 1405 FEPs were ‘explicitly’ treated through modelling exercises in the safety assessment, with the remainder being subsumed within the treatment of the main ‘modelled’ FEPs, or through ‘side calculations’ or logical arguments. This led to only 71 being directly screened out. BNFL (2002b) suggests that the 2002 assessment results will enable many more FEPs to be screened out in future iterations.

A.2.7 UK (Generic Deep Repository Assessment)

This assessment was concerned with the disposal of ILW and LLW containing relatively high levels of α–nuclides to a range of conceptualised geologies (Nirex 2003). The vast majority of FEPs were identified using expert elicitation, with about 1700 being identified in total (Bailey and Billington 1998). The resulting FEP database was compared with an NEA (1999) compilation, and no omissions or deficiencies were identified.

FEPs screening was delayed to a much later stage in scenario and conceptual model development than in the other assessments reviewed here. A base scenario and variant scenario were developed, and the corresponding conceptual models identified without screening taking place. At this point individual FEPs and conceptual models (represented by groups of FEPs) were screened for their impact on the assessment. The screening was performed by considering the influence that these FEPs and models had on others. A low influence led to that FEP or conceptual model (and its attendant FEPs) being screened out.

This lack of influence could either be specified in regulatory guidance or be due to a lack of impact on the system (Bailey and Billington 1998). The latter was assessed either by expert judgement or by scoping calculations. These screening criteria are also found in other assessments reviewed here, but with the screening being carried out at an earlier stage.

The Nirex assessment draws a distinction between system FEPs, which define the natural or expected evolution of the repository, and probabilistic FEPs, which may not exist or occur for significant periods of the assessment. The latter were used to define the variant scenarios (which included nuclear criticality).

A.3 CONCLUSIONS

The main conclusions of this review of FEPs and screening procedures used in mature international safety assessments are as follows:

1. There is not standard detailed FEP list; rather each organisation develops a FEP list appropriate to its specific repository and site.

2. The FEP list is usually based on an international compilation, notably NEA (1999), and augmented by site-specific information as well as other relevant site studies.

3. The following criteria for the subsequent screening have been identified:
   - the FEP should be relevant to the types of wastes;
   - the FEP should be relevant to the design of the repository;
   - the FEP should be relevant to the geological/geographic setting;
   - the FEP should not have the same effect as another whose overall definition may be more appropriate; and
   - the FEP should be relevant to assessment context, in particular to the prevailing regulatory guidance (for instance, the time frame that needs to be assessed).

4. Some assessments use a low probability of occurrence associated with a negligible impact as a criterion for screening out FEPs. The screening here should be conservative, e.g., the SAFIR 2 assessment used a probability threshold of 10^{-8}/year.

5. Some beneficial FEPs where definitive models or data do not exist may be excluded from the assessment, but explicitly acknowledged as “Reserve FEPs”. The existence of these Reserve FEPs can then be used to provide additional qualitative support to the safety case and to demonstrate a conservative approach to safety (Nagra 2002).

6. Screening commonly makes extensive use of expert judgement. These judgements typically build on extensive international knowledge of the process and on accumulated

knowledge of a given repository and site, such as through prior assessments.

7. Quantitative screening tends to be reserved for complex topics, such as criticality, human intrusion, temperature rise following repository closure, and stresses in the host rock. Because of this complexity, and the associated lack of confidence in simple calculations, such areas may in practice be taken into the scenarios that are assessed in detail, for example, Nirex considers criticality as a variant scenario and JNC does likewise with human intrusion.

REFERENCES FOR APPENDIX A

Bailey, L. E. F. and Billington, D. E. 1998. Overview of the FEP Analysis Approach to Model Development. Nirex Report S/98/009. Harwell, UK.

BNFL. 2002a. The 2002 Drigg Postclosure Safety Case. BNFL Report. UK.

BNFL. 2002b. Drigg Postclosure Safety Case: PCRSA Process System Analysis. BNFL Report. UK.

JNC. 2000. H12: Project to Establish the Scientific and Technical Basis for HLW Disposal in Japan, Supporting Report 3, Safety Assessment of the Geological Disposal System. Japan Nuclear Cycle Report JNC TN1410 2000-004. Tokai, Japan.

NAGRA. 2002. FEP Management for the Opalinus Clay Safety Assessment. Nagra Technical Report 02-23. Wettingen, Switzerland.

NEA. 1999. Safety Assessment of Radioactive Waste Repositories – Systematic Approaches to Scenario Development – An International Database of Features, Events and Processes. A report of the NEA working group on development of a Database of Features, Events and Processes Relevant to the Assessment of the Postclosure Safety of Radioactive Waste Repositories. OECD/NEA report. Paris, France.

Nirex. 2003. Generic Repository Studies: Generic Postclosure Performance Assessment. Nirex Report N/080. Harwell, UK.

ONDRAF/NIRAS. 2001. SAFIR 2: Safety Assessment and Feasibility Interim Report 2. ONDRAF/NIRAS Report NIROND 2001-06E. Brussels, Belgium.

SKB. 2001. Project SAFE: Scenario and System Analysis. SKB Report R-01-013. Stockholm, Sweden.

Vieno, T. and Nordman, H. 1999. Safety Assessment of Spent Fuel Disposal in Hästholmen, Kivetty, Olkiluoto and Romuvaara. Posiva Report 99-07. Helsinki, Finland.