OPG's DEEP GEOLOGIC

REPOSITORY

FOR LOW & INTERMEDIATE LEVEL WASTE

Postclosure Safety Assessment: Features, Events and Processes

March 2011

Prepared by: Quintessa Ltd., SENES Consultants Ltd.
and Geofirma Engineering Ltd.

NWMO DGR-TR-2011-29

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EXECUTIVE SUMMARY

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

The project involves investigation of the site's geological and surface environmental characteristics, conceptual design of the DGR, and safety assessment. The postclosure safety assessment (SA) evaluates the long-term safety of the proposed facility and provides supporting information for the EIS and PSR.

The Postclosure SA requires consideration of a wide range of factors that could potentially affect the behaviour of the repository, contaminants arising from it 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 are 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, therefore, provides a structured and comprehensive list of possible FEPs, and, for each FEP:

- provides a brief explanation of the FEP and its key components;
- discusses its relevance to the DGR and the conceptual models developed for the current Postclosure SA; and
- lists the scenarios (if any) in which the FEP is included in the associated conceptual model(s).

This report provides an initial screening of the FEPs in the scenarios and conceptual models. The final set of FEPs explicitly or implicitly included in the mathematical models is identified in the detailed assessment reports.

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1. INTRODUCTION

Ontario Power Generation (OPG) is proposing to build a Deep Geologic Repository (DGR) for Low and Intermediate Level Waste (L&ILW) near the existing Western Waste Management Facility (WWMF) at the Bruce nuclear site in the Municipality of Kincardine, Ontario (Figure 1.1). The Nuclear Waste Management Organization, on behalf of OPG, is preparing the Environmental Impact Statement (EIS) and Preliminary Safety Report (PSR) for the proposed repository.

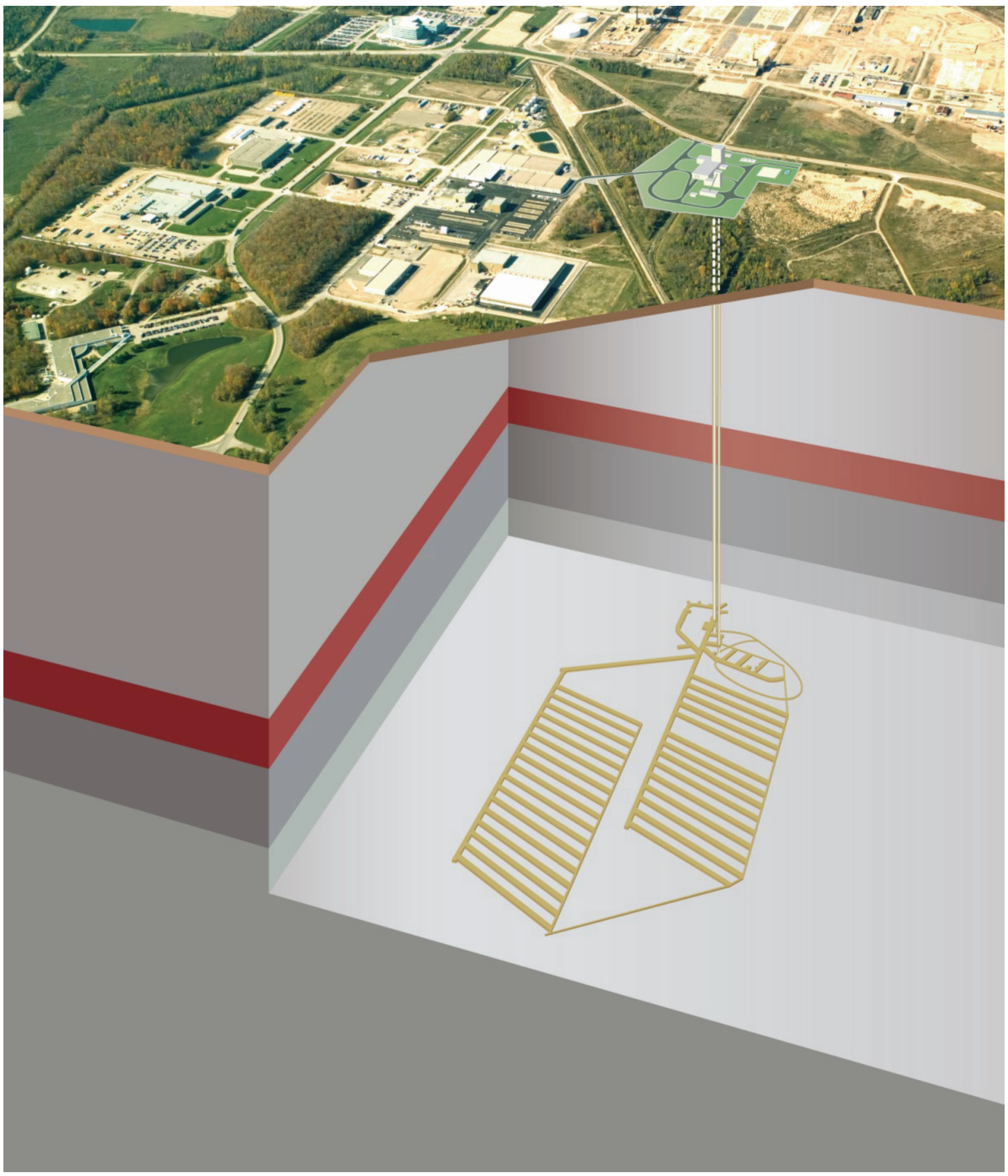

Figure 1.1: The DGR Concept at the Bruce Nuclear Site

The project involves investigation of the site's geological and surface environmental characteristics, preliminary design of the DGR, and safety assessment. The postclosure safety assessment (SA) evaluates the long-term safety of the proposed facility and provides supporting information for the EIS (OPG 2011a) and PSR (OPG 2011b).

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

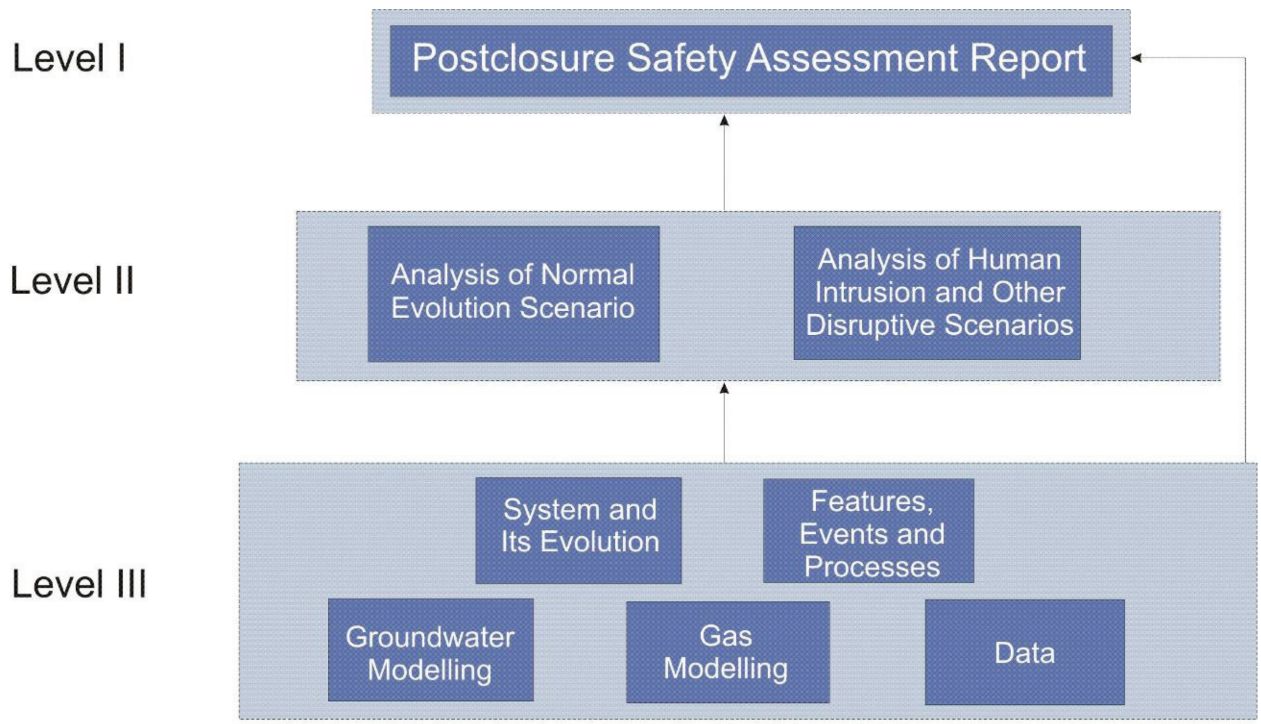

Figure 1.2: Document Structure for the Postclosure Safety Assessment

1.1 PURPOSE AND SCOPE

The Postclosure SA requires consideration of a wide range of factors that could potentially affect the behaviour of the repository, contaminants arising from it 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 are used as input for scenario development and subsequent conceptual model development for the safety assessment. However, not all potential FEPs are necessarily used as input for scenario development and subsequent conceptual model development in a given safety assessment.

The purpose of this report is to describe the features, events and processes (FEPs) that have been considered in the Postclosure SA's scenario and conceptual model development process and the reason(s) for their inclusion/exclusion. 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 current assessment.

The following time periods of interest can be identified.

- From closure of the DGR (assumed to be 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. 2011).
- The subsequent period up to around 100 ka. During this period, most of the initial radioactivity in the repository decays. This period also encompasses a possible glacial maximum, anticipating that following some period of global warming, the glacial cycles will continue as they have in the past million years.
- The subsequent period up to 1 Ma (1 million years), which is the baseline period covered in this safety assessment. During this period, the DGR site is likely to experience several glacial cycles.
- The subsequent period up to 10 Ma that may be considered in the assessment to ensure that peak impacts have been assessed. Such extended timescales are relevant for some very slow processes, including the long half-lives of certain radionuclides, the slow rate of repository saturation once closed, and the long 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 Postclosure SA concerning the waste and waste package (the Inventory Report, OPG 2010), the repository design (Chapter 6, Facility Description, of the Preliminary Safety Report, OPG 2011b), the geological setting (Geosynthesis Report, NWMO 2011), and the surface environment (EIS technical support documents for the DGR, GOLDER 2011a,b,c).

This report provides an initial screening of the FEPs in the scenarios and conceptual models. The final set of FEPs explicitly or implicitly included in the mathematical models is identified in the detailed assessment reports.

1.2 REPORT OUTLINE

The report is organized as follows:

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

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

2. APPROACH USED FOR FEP LIST DEVELOPMENT AND SCREENING

There is considerable international precedent for developing a list of potential FEPs appropriate to the system being assessed and using this as a structured basis for assessing factors to consider in the system-specific safety assessment (see for example NAGRA 2002 and SKB 2006).

Following a review of potentially relevant FEP lists, it was decided to develop the DGR FEP list using the following key sources.

- International Atomic Energy Agency (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. (2004a): 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 DGR design, 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. Additional FEPs mentioned in this report, primarily relating to the waste and the repository and their evolution, were evaluated as well.

The FEPs compiled from the above documents were updated to include knowledge gained from other SA studies (such as NAGRA 2002 and ONDRAF/NIRAS 2001) and from international experience (such as FEPCAT, a compilation and categorization of FEPs specific to those relevant to the geosphere in argillaceous host rock, Mazurek et al. 2003). 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 summarized in Chapter 2 of the System and Its Evolution report (QUINTESSA 2011b) and Chapters 3 to 6 of the Data report (QUINTESSA and GEOFIRMA 2011a), and their supporting references. The resulting DGR FEP list was then reviewed by independent members of the Postclosure SA team (i.e., members who had not been involved with the development of the original list) and modifications made. The review process included a check to ensure that all FEPs of potential relevance had been included in the DGR FEP list.

The basic structure of each FEP entry is as follows:

- Description: provides a brief explanation of the FEP and its key components;
- Screening Analysis: discusses its relevance to the DGR and the conceptual models developed for the current Postclosure SA (the conceptual models are documented in Chapter 2 of the Normal Evolution Scenario Analysis report, QUINTESSA 2011a, and Sections 2.2, 3.2, 4.2 and 5.2 of the Human Intrusion and Other Disruptive Scenarios Analysis report, QUINTESSA and SENES 2011); 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 mathematical model that is subsequently developed to represent the conceptual model; for example it might be decided to simplify the mathematical model by excluding the FEP or subsuming it into another FEP.

The screening of FEPs for inclusion in / exclusion from the mathematical models is presented in the reports that document the mathematical models used; i.e., the Normal Evolution Scenario Analysis report (Appendix H.5 of QUINTESSA 2011a) for the AMBER assessment model, the Groundwater Modelling report (Appendix D of GEOFIRMA 2011) for the FRAC3DVS-OPG groundwater model, and the Gas Modelling report (Appendix A of GEOFIRMA and QUINTESSA 2011) for the T2GGM gas model.

Consistent with international practice, 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 be relevant to the Postclosure SA's assessment context given in Chapter 3 of the Postclosure SA main report (QUINTESSA et al. 2011), 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 Postclosure SA are documented in Chapters 7 and 8 of the System and Its Evolution report (QUINTESSA 2011b) and are summarized below.

Normal Evolution Scenario		Expected long-term evolution of the repository and site following closure. Over the 1 Ma assessment timescale, the scenario includes waste and packaging degradation, gas generation and build-up, rockfall, earthquakes and, eventually, glacial cycles.
Disruptive ("What if") Scenarios	Human Intrusion	Inadvertent intrusion into the DGR via an exploration borehole.
	Severe Shaft Seal Failure	Poorly constructed or substantially degraded shaft seal.
	Poorly Sealed Borehole	Poorly sealed or substantially degraded seals in site investigation/monitoring borehole.
	Vertical Fault	Transmissive vertical fault in the vicinity of the DGR.

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 these FEPs are already discussed in the assessment context chapter (Chapter 3) of the Postclosure SA main report (QUINTESSA et al. 2011).

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	Retrieval
	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

Category	FEP	FEP	
	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		
	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	
1.5	Other External Factors		
	1.5.01	Impact of meteorites and human space debris	
	1.5.02	Evolution of biota	
2. INTERNAL FACTORS			
2.1	Waste, Waste Form & Engineered Components		
	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

Category	FEP	FEP	
		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, access tunnel and shaft & services area characteristics	
		2.1.04.01	Roofs and walls
		2.1.04.02	Floors
		2.1.04.03	Rock bolts
		2.1.04.04	Room and closure 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
		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

Category	FEP	FEP	
		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	Redox conditions
		2.1.08.03	Chloride and sulphate concentrations
		2.1.08.04	Corrosion
			A General
			B Localized
			C Galvanic
		2.1.08.05	Polymer degradation
		2.1.08.06	Mineralisation
			A Leaching
			B Chloride attack
			C Sulphate attack
			D Carbonation
			E Illitization
		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).

Category	FEP	FEP	
		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,
			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	Effects of extraneous materials	
	2.1.14	Nuclear criticality	
2.2	Geological Environment		
	2.2.01	Stratigraphy	
	2.2.02	Host rock 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

Category	FEP	FEP	
		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
	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

Category	FEP	FEP	
		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 liquid 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 mineralization	
		3.2.10.01	Dissolution and Precipitation (repository)
		3.2.10.02	Dissolution and Precipitation (geosphere)

Category	FEP	FEP	
		3.2.10.03	Dissolution and Precipitation (biosphere)
		3.2.10.04	Change in mineralization
	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
	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	Inorganic ligands
		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

Category	FEP	FEP	
		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 POSTCLOSURE SAFETY ASSESSMENT

The DGR FEP list has a number of uses in the Postclosure SA, as described below.

1. The Category 1 FEPs (i.e., External Factors) are used in Chapters 3 and 8 of the System and Its Evolution report (QUINTESSA 2011b) to identify potential scenarios for consideration in the assessment. These External FEPs provide the system with both its boundary conditions and with FEPs that might cause change in the system. If these External FEPs 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., Internal Factors) are used in Chapter 8 of the System and Its Evolution report (QUINTESSA 2011b) to identify whether there are any Internal FEPs that might compromise the isolation and containment functions of the DGR system and thereby impact upon the associated long-term safety arguments so resulting in a Disruptive Scenario.

3. The Category 2 FEPs 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 Appendix C of QUINTESSA (2011a), whereas the models and audits for the Disruptive Scenarios are described in Appendix C of QUINTESSA and SENES (2011).

4. The Category 2 and 3 FEPs are also used as a basis of an audit of the AMBER, FRAC3DVS-OPG and T2GGM mathematical models (Appendix H.5 of QUINTESSA 2011a, Appendix D of GEOFIRMA 2011, and Appendix A of GEOFIRMA and QUINTESSA 2011, respectively).

5. FEP DESCRIPTION AND SCREENING ANALYSIS

Each FEP, identified in the list given in Chapter 3, is described and screened in the following pages.

1 EXTERNAL FACTORS

Definition

FEPs with causes or origins 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 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 FEPs 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

1.5 Other External Factors

1.1 Repository Factors

<u>Description</u>

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 Retrieval

1.1.12 Records and Markers

1.1.13 Monitoring

1.1.01 Site Investigations

Description

Investigations carried out to characterize 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 characterization is being used in the assessment (see Sections 2.3 and 2.4 of the System and Its Evolution report, QUINTESSA 2011b and Chapters 5 and 6 of the Data report, QUINTESSA and GEOFIRMA 2011a). Results of future site characterization studies will be used in any future assessments.

For the Poorly Sealed Borehole Scenario, it is assumed that a site investigation borehole is not properly sealed. All other scenarios assume that any site investigation activity undertaken to characterize 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 Postclosure SA is documented in Section 2.2 of the System and Its Evolution report (QUINTESSA 2011b) and Chapter 4 of the Data report (QUINTESSA and GEOFIRMA 2011a) and is based on the design described in Chapter 6 (Facility Description) of the Preliminary Safety Report (OPG 2011b).

Design modifications (e.g., single-ended room and flow-through room designs) 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., around 44 years after it receives its first consignment of waste. The Postclosure SA considers the evolution of the repository, e.g., radioactive decay and gradual resaturation, from 2062 onwards. Account is taken of radioactive decay prior to 2062. No other schedule is considered in the current assessment. See Section 3.8 of the Postclosure SA main report (QUINTESSA et al. 2011).

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 stabilization of these openings, and the installation and assembly of structural elements. It may be necessary to examine the consequences of the failure of quality controls to detect the use of poor construction techniques.

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 (QUINTESSA 2011b) and Section 4.2 of the Data report (QUINTESSA and GEOFIRMA 2011a) under an appropriate quality assurance regime and with appropriate measures being taken to limit the extent and permeability of the disturbed zones around the repository and shafts (see Disturbed zone (in geosphere) [2.2.03]).

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 disturbed zone around the repository and shafts, and seal materials in the shafts, which could result from poor construction.

FEP Screening

Include FEP in all scenarios.

1.1.05 Operation

Description

Factors relating to the operation of the repository including the placing of waste packages in their final positions within the repository and the construction of any walls during the operational period. One potential issue is the 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 repository will be operated consistent with the description given in Chapter 6 (Facility Description) of the Preliminary Safety Report (OPG 2011b). Waste packages are placed in the repository to the design specifications under an appropriate quality assurance regime that prevents their faulty emplacement. Any walls are constructed under the quality assurance regime. Nevertheless a conservative conceptual model is adopted which gives no credit to the waste packaging and walls as chemical or physical barriers (Section 2.3.1 of the Normal Evolution Scenario Analysis report, QUINTESSA 2011a). Thus the effects of unexpected premature failure, which could result from faulty emplacement of waste packages, are incorporated into all calculation cases.

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 placed in the DGR is described in Section 2.2.2 of the System and Its Evolution report (QUINTESSA 2011b) and Section 4.2 in the Data report (QUINTESSA and GEOFIRMA 2011a). The allocation of wastes to emplacement rooms is given in Table 4.2 of the Data report (QUINTESSA and GEOFIRMA 2011a). See also Waste Inventory FEPs [2.1.01].

FEP Screening

Include FEP in all scenarios

1.1.07 Repository Closure

Description

Factors related to the end of waste emplacement 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 that are not detected by the quality control program. 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 Postclosure SA assumes that the repository is closed consistent with the description provided in Section 2.2.3 of the System and Its Evolution report (QUINTESSA 2011b) and Section 4.3 of the Data report (QUINTESSA and GEOFIRMA 2011a). It is assumed that closure of the DGR is undertaken under OPG's quality assurance program.

The Normal Evolution Scenario represents reference assumptions on closure and degradation of shaft seals over time. The Poorly Sealed Borehole Scenario considers the "what if" case in which a site investigation/monitoring borehole is not properly sealed. The Severe 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 construction of engineered features.

Screening Analysis

It is assumed for all scenarios that a quality assurance and control program is implemented to ensure that waste packages are emplaced properly, and room/closure walls and shaft/borehole seals are designed, constructed, filled and emplaced properly. Substantial failure of the quality assurance program is very unlikely and not considered as part of the Normal Evolution Scenario. However, substantial quality assurance program failure is considered as a possible contributor to the Severe Shaft Seal Failure Scenario or the Poorly Sealed Borehole Scenario.

FEP Screening

Include FEP in all scenarios. Assume that the quality control program fails to the extent that it does not detect seal emplacement errors for the Severe Shaft Seal Failure and Poorly Sealed 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 Postclosure 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 SA main report, QUINTESSA et al. 2011).

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]); and
- 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 Retrieval

Description

The retrieval of waste once it has been emplaced in a repository. 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 design options that may hinder subsequent decisions for retrieval. A related issue is discussed under Deliberate human intrusion [1.4.15].

Screening Analysis

The DGR design has features that improve retrievability, notably the absence of backfill in the repository rooms and tunnels, and the extended monitoring period with active ventilation of rooms before their closure. However, it is assumed for the purposes of the current assessment that there is no retrieval of waste after repository closure.

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 or identify 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 sometime 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 one or more robust markers would be included at the site at closure.

The specific details have not been decided, and will likely not be finalized 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 their effectiveness at 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 program will be in place during the operation of the facility (Section 6.11 and 6.12 of the Preliminary Safety Report, OPG 2011b). After closure, there would be a further period of monitoring to confirm that the DGR is performing as expected (Section 13 of OPG 2011b).

The monitoring program 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 Poorly Sealed Borehole Scenario is considered in which it is assumed that a monitoring borehole is not properly sealed, potentially providing a pathway through the host rock.

FEP Screening

Included only in the Poorly Sealed 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 repository 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 activation of faults, 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. The DGR site is located over 1000 km from the nearest plate margin. The Precambrian 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 tectonic stability of the DGR site is confirmed by seismic monitoring data, which show that large earthquakes are highly unlikely (Section 2.2.6.5 of NWMO 2011). At the current spreading rates the North American plate is unlikely to collide with another plate, leading to the development of a new tectonic regime, for many tens of millions of years.

Earthquakes are discussed in Seismicity [1.2.03].

FEP Screening

Screened out.

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 Tectonic movement [1.2.01]) (i.e., beyond the time frame of the assessment - see Section 1.1), and even if orogenic activities occurred at the margins of the North American plate, they would still not affect the situation deep in its interior.

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 seal or backfill materials, shaking and damage to the containers and seals, rockfalls in the repository, modification of the properties of the Excavation Damaged Zone (EDZ) around the repository and shafts, and extension or creation of fractures near the repository and shafts. 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

Southwestern Ontario and the Bruce region lie within the tectonically stable interior of the North American continent, which is characterized by low rates of seismicity. Historical records are available since the late 1800s. Most recorded events have a magnitude of less than M3 (Nutti magnitude), with rare occurrences of larger events up to **M**4.3 within a 150 km radius from the Bruce nuclear site (Section 2.2.6.5 of NWMO 2011). The historical dataset suggests that, in general, the regional study area experiences sparse seismic activity and there is no indication of the existence of major seismogenic features or active faults of concern.

A Probabilistic Seismic Hazard Assessment was performed for the Bruce nuclear site. The frequency of M6 or greater earthquakes within 200 km of the site was estimated at 10^{-4} per annum (Chapter 6 of AMEC GEOMATRIX 2011). This is approximately equivalent to an annual frequency of an M6 or greater event of 10^{-6} within a 20 km radius of the site, assuming roughly uniform probability across the area. The peak ground accelerations obtained from the seismic hazard assessment are 0.18g for events with probability of exceedance of 10^{-5} /a, and 0.6g for events with probability of exceedance of 10^{-6} /a (Chapter 6 of AMEC GEOMATRIX 2011; Section 6.2.2.1 of NWMO 2011).

Dynamic mechanical modelling studies have been used to investigate the impacts of seismic events on cavern stability (Section 6.4 of NWMO 2011). The model results show that seismic shaking does not cause any additional damage or fracturing of the rock mass. That is particularly the case for the seismic events occurring early, before glacial events, when the rock mass is relatively unfractured. The seismic shaking does promote unravelling of already fractured and loose rock mass. The more cycles of glacial loading and unloading the rock has been subject to, the greater the amount of fractured and loose rock, and hence unravelling.

That unravelling can result in additional fracturing of the rock mass as a result of reduction in confinement, but not as a result of seismically induced stress change or inertial forces. Also, model results indicate that events with larger peak ground velocity (i.e., stronger events at greater distance) have more effect than the events with larger peak ground acceleration (i.e., weaker events at shorter distance). Geomechanical modelling has demonstrated that the caverns and pillars will remain stable for seismic events of **M** ≤ 5.0 at 15 km radius and of **M** ≤ 6.5 at 50 km from the site (Section 6.4 of NWMO 2011).

Seismic reactivation of existing faults is a remote possibility as it would require a very large event to occur right at the repository site. Furthermore, since the repository is sited in an area where no faults have been observed, it would require fracturing of previously unfaulted rock.

FEP Screening

Include rockfall effect in all scenarios. Severe seismic event considered as a potential cause for the activation of the fault in the Vertical Fault Scenario and the degradation of the shaft seals in the Severe Shaft Seal Failure Scenario.

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 DGR site is located in the tectonically very stable North American Continental plate.

Volcanic activity is not expected to influence southwestern Ontario for many millions of years. The most recent volcanic activity in Ontario was related to the Great Meteor (or New England) hotspot in the upper mantle. About 130-180 Ma ago, this hotspot was beneath present-day Ontario, where it created the kimberlites found in the James Bay Lowlands and other parts of Ontario. Because of movement of the North American Plate away from the African Plate, this hotspot is currently below the north Atlantic Ocean. No other source of volcanism that might affect southwestern Ontario is known (Section 6.2.2.2 of NWMO 2011).

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 (see FEP [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 composed of 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 heated by volcanic activity or through burial. However, no volcanic activity is expected for the assessment timeframe (see Volcanic and magmatic activity [1.2.04]), nor is burial relevant on the timeframe of the assessment. The Bruce nuclear site will be subject to glacial loading over the assessment timeframe, but this will have insufficient pressure to induce metamorphism.

Therefore, there are neither the temperatures nor pressures needed for metamorphism to occur in the host rock over the time frame of the assessment (Section 1.1).

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 DGR is located in Ordovician sediments in southwestern Ontario. Hydrothermal dolomitization is a potential process in these rocks. However, there are no signs of significant historic hydrothermal dolomitization within the DGR area (Sections 2.2.5 and 2.2.8 of NWMO 2011). Furthermore, the heat flux is low across the Precambrian basement rocks, resulting in a temperature at the proposed repository depth of around 22 ºC (Section 5.1 of the Data report, QUINTESSA and GEOFIRMA 2011a). Therefore, geosphere-driven hydrothermal processes are not of concern over the 1 Ma Postclosure SA time period.

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 localized 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, e.g., on lake bottoms and in till sheets, moraines and eskers. 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

Section 2.2.5.3 of NWMO (2011) indicates that based on the organic maturity of the Paleozoic rocks elsewhere in the Michigan Basin, about 1500 m of material must have been eroded since the end of the Carboniferous era (~300 Ma BP) as the sedimentary layers on the site have been progressively raised due to tectonic activity. This corresponds to about 5 m over the 1 Ma assessment timeframe. This is not significant.

Over shorter time scales, Quaternary glacial cycles have resulted in erosion at the Bruce nuclear site. Section 2.2.7.2 of NWMO (2011) and Hallet (2011) describe the amount of erosion associated with historic glacial cycles, considering global, regional and site-specific evidence for Quaternary ice-sheet erosion, and in particular erosion associated with the Laurentide Ice-sheet. Literature data, field investigations and numerical modelling indicate that over the last 100,000 years, ice-sheet erosion at the Bruce nuclear site has been of the order of metres to a few tens of metres. Deposition of glacial deposits can also occur on similar scales. The net change in surface thickness is, therefore, unlikely to affect the main low-permeability Ordovician rocks over the 1 Ma assessment timeframe, although it will affect the surface environment and shallow geosphere.

FEP Screening

Include erosion in Normal Evolution Scenario.

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 crystallization, 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

No significant physical and chemical changes to the host rock properties are expected over the assessment period given the mineralogy of the rocks, and the associated limited temperatures and pressures 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] is unlikely to occur.

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 root 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. In particular, soils consistent with the climate change assumption.

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 nuclear 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 (Section 2.2.5.4 of NWMO 2011). 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 Evaporite, Salina A2 Evaporite, and Salina A1 Evaporite. These layers are only a few metres thick at the DGR site (Table 5.1 of the Data report, QUINTESSA and GEOFIRMA 2011a). 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 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

As noted in Tectonic movement [1.2.01], Orogeny [1.2.02], Volcanic and magmatic activity [1.2.04], Metamorphism [1.2.05], and Denudation and deposition (large-scale) [1.2.07], there are not anticipated to be any large-scale geological changes over the Postclosure SA timescale, and, therefore, there will not be any commensurate large-scale hydrological/hydrogeological changes. Glaciation is likely to occur; its effects on hydrogeology are considered separately in FEP [1.3.07].

Groundwater and porewater head data from site investigation boreholes at the DGR site show a pattern of over- and under-pressures (see Figure 2.24 of the System and Its Evolution report, QUINTESSA 2011b). The major features of the head-depth profile are significant under-pressures in the Ordovician and significant over-pressures in the Cambrian. Possible sources for the observed pressure profile are analyzed in the Geosynthesis report (Chapter 5, NWMO 2011) and summarized in Section 2.3.6.4 of the System and Its Evolution report (QUINTESSA 2011b).

The observed pattern of over- and under-pressures in the groundwater and porewater hydraulic head data represents a state of disequilibrium due to previous geological events and related processes. The evidence presented by NWMO (2011) indicates that whereas the Cambrian over-pressures are likely to be maintained over geological timescales, the Ordovician under-pressures may slowly evolve over the postclosure SA timescale towards equilibrium conditions and this effect should be considered in the postclosure SA.

Seismicity [1.2.03] is unlikely to occur at a level that would have notable effects on groundwater. However, a severe seismic event is considered as a potential cause for the activation of the fault in the Vertical Fault Scenario. This would affect the geosphere heads and flows.

Muir Wood (1994) has identified the potential for the expulsion of some groundwater at the surface. However, this requires the fault to be connected to the surface and there is no evidence of such faulting in the vicinity of the Bruce nuclear site (Armstrong and Carter 2010).

FEP Screening

Include transient evolution of disequilibrium heads in all scenarios. A severe seismic event is considered as a potential cause for the activation of the fault in the Vertical Fault Scenario.

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, and 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 flat, and would be expected to be relatively stable over the assessment period due to the absence of geological drivers. All but three of the geological FEPs (FEP [1.2.01] to FEP [1.2.10]) have been screened out, and of the three that have been included (Seismicity [1.2.03], Denudation and deposition [1.2.07] and Pedogenesis [1.2.09]), only Denudation and deposition is expected to have a significant effect on the geomorphology. The most significant denudation and deposition process will be denudation in response to glacial cycles, i.e., climate change, and is, therefore, captured under Geomorphic response to climate change [1.3.10].

FEP Screening

Screened out.

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]). Geomechanical modelling indicates that the in-situ rock stresses are not likely to lead to significant damage directly. However, in combination with seismic loads and loading from glaciation, failure of roof and pillars would occur in the unsupported rooms and tunnels, until the spaces eventually fill with rubble and stabilize (Section 6.4 of NWMO 2011).

Seismic reactivation of existing faults is discussed in Seismicity [1.2.03].

FEP Screening

Include FEP (rockfall) 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 characterized 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 characterized by glacial/interglacial cycling, which more recently has had a periodicity of about 100,000 years. Some key factors supporting glacial cycles are still present (continental plate arrangements and solar insolation variability), and would support future ice ages.

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 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 FEP [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, it is prudent to assume for the Postclosure SA that cycling will resume. This is because such cycling has the potential to adversely affect the repository.

FEP Screening

Include FEP in Normal Evolution Scenario.

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 characterized 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 nuclear site, it is expected that this will involve extended periods when the site is under periglacial conditions- see FEP [1.3.04] and also when the site is covered by an ice-sheet- see FEP [1.3.05].

FEP Screening

Include FEP in Normal Evolution Scenario.

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 movement of the land mass associated with ice-sheet loading or unloading (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. The surface of the DGR site is more than 150 m above present sea level and the site is far from the nearest ocean.

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 lower boundary 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, characterized 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 nuclear site, the results of modelling using the University of Toronto Glacial System Model (Peltier 2011) 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 its depth 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 limited because they will not become frozen, and because their salinity and low permeability will isolate them from changes in the Shallow Bedrock Groundwater Zone. Regional data indicates a maximum depth of glacial meltwater about 100 m below ground surface. Data from the DGR boreholes (Section 4.5 of NWMO 2011) indicate that, consistent with regional data, ice-sheet meltwater has generally not penetrated deep, except in the thin aquifer in the Silurian A1 carbonate unit at around 330 m depth.

The periglacial effects on the ecosystem (e.g., permafrost formation) will be potentially significant in terms of receptor characteristics and exposure pathways.

FEP Screening

Include FEP in Normal Evolution Scenario.

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 FEP [1.3.02], during future glacial cycles, the repository site is expected to be covered periodically by ice-sheets. Peltier (2011) 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, when head gradients are largest. The process could alter groundwater compositions in the Shallow Bedrock Groundwater Zone, notably concentrations of oxygen or other electrochemical oxidants. This particular process is not expected in the Deep Bedrock Groundwater Zone due to the low permeability of the rocks, and the high salinity (and hence density) of the porewaters. Geochemical data from the site indicate that porewaters in the Deep Bedrock Groundwater Zone have not mixed with, or been displaced by surface waters, including meltwaters from ice-sheets that could be under very high injection pressures. Coupled hydro-mechanical paleoclimatic groundwater flow models (Section 5.4.6 of NWMO 2011) support this geochemical interpretation.

Peltier (2011) 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. Assessment of the geomechanical response to ice-sheet loading has identified its potential to cause rockfall in the repository excavations, however, the performance of the shaft seals will be unaffected (Section 6.4.3 of NWMO 2011).

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 whereas 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]) and surface topography (see Geomorphologic response to climate changes [1.3.10]).

FEP Screening

Include FEP in Normal Evolution Scenario.

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 for erosion. The high temperatures and humidity associated with tropical climates result in rapid biological degradation.

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 nuclear 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 a temperature rise sufficiently extreme to induce tropical or desert conditions. Therefore, warm climate effects are not included in the Postclosure 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 run-off, 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 repository 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

Significant changes will occur in the Shallow Bedrock Groundwater Zone at the DGR site due to climate change, and in particular to glacial cycles. As the climate cools, the recharge to the shallow groundwater decreases due to reduced precipitation and an increased proportion of precipitation becoming surface run-off due to spring snowmelt. As the climate cools further and arctic conditions become established, permafrost is expected to develop down to several tens of metres (Peltier 2011).

While the site is covered by an ice sheet, 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. 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 and the development of proglacial lakes.

Data from the DGR boreholes (Section 4.5 of NWMO 2011) indicate that the maximum depth of glacial meltwater penetration is to the permeable Salina A1 Upper Carbonate within the Intermediate Bedrock Groundwater Zone (330 m). However, saline groundwater in the slightly deeper, permeable, Guelph formation has not been displaced.

Consistent with the observed impacts of historical glacial cycles, it is considered that flow conditions in the Deep and Intermediate Bedrock Groundwater Zones at the DGR site will not be significantly altered by future glacial/interglacial cycling (see FEP [1.2.11]).

FEP Screening

Include FEP in Normal Evolution Scenario.

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. The current ecosystem in the vicinity of the Bruce nuclear site can be expected to evolve as a result of global warming in the next millennium. There could be significant changes on specific biota, but the overall nature of the ecosystem is expected to remain similar to the present temperate climate mixed forest, based on the likely range of changes expected for this region.

However, in the longer term, glacial cycling would result in significant changes to the ecosystem found at the site. As the temperature cools, the ecosystem will evolve into a tundra system, which would then in turn be removed by the ice sheet. Following glacial retreat and during interglacial periods, it is assumed that tundra-based and temperate-climate-based ecosystems would eventually be re-established. These could have different receptors and different important exposure pathways.

Therefore, consideration of a temperate-climate and a tundra ecosystem in the Normal Evolution Scenario would provide a measure of the potential importance of the ecological response to climate change.

FEP Screening

Include temperate-climate and tundra ecosystems in the Normal Evolution Scenario.

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 critical groups will change as a result of climate changes. Global warming in the next millennium can be expected to have some 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 would become re-established, and communities would be re-established in the area. The different human behaviours could lead to changes in the importance of various exposure pathways.

Consideration of temperate-climate and tundra-based human lifestyles would provide a measure of the potential importance of the human response to climate change.

FEP Screening

Include temperate-climate and tundra lifestyle in Normal Evolution Scenario.

1.3.10 Geomorphologic Response to Climate Change

Description

Factors related to surface landform changes on a regional and local scale caused by the climate changes listed in FEP [1.3.01] to FEP [1.3.06].

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 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 External FEP is closely associated with Local glacial and ice-sheet effects [1.3.05]. It is recognized that the glacial/interglacial cycling that 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 of the System and Its Evolution report, QUINTESSA 2011b).

FEP Screening

Include FEP in Normal Evolution Scenario.

1.4 Future Human Actions

Description

Factors related to human actions and regional practices associated with the postclosure period (future) that 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 that generally originate from outside the temporal and spatial boundaries of the repository 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" 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

In the near-term, human-induced global warming may cause temperature and precipitation changes whose impacts 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. On a local scale, changes in regional land-use are considered to have a less significant impact on climate.

In the longer term, the key effect is glaciation. Peltier (2011) notes that the initiation of a glacial episode in the next 60,000 years would be inhibited by current levels of greenhouse gases. Furthermore, work on long-term climate modelling using Earth Models of Intermediate Complexity 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 concentrations will return to historic levels and glacial-interglacial cycling will be re-established (BIOCLIM 2004).

FEP Screening

Include FEP in all scenarios. Specifically, consider effects of near-term global warming and of delayed glaciation within the Normal Evolution Scenario.

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 Postclosure 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 SA main report, QUINTESSA et al. 2011). 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 nuclear site (i.e., predominantly agriculture, recreation and forestry) (see Section 2.4.7 of the System and Its Evolution report, QUINTESSA 2011b). It is also assumed that social and institutional developments can be impacted by climate change (see Section 6.3 of the System and Its Evolution report, QUINTESSA 2011b).

FEP Screening

Include FEP in all scenarios. In particular, consider that institutional control is maintained for 300 years, and that the site use becomes consistent with current land use in the area.

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 repository performance. Examples of these actions are presented in FEPs [1.4.04] to [1.4.10]. 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 not discovered, 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 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 pumping 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 from those otherwise considered; 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 80 m at the site since the water is not potable at greater depths (see FEP [2.4.05.03]).

Exploration boreholes could be drilled down into the DGR. However, the drilling of such deep boreholes at the site is very unlikely. The depth (about 680 m), small footprint of the DGR's emplacement rooms (about 0.065 km^2) (Table 4.3 of the Data report, QUINTESSA and GEOFIRMA 2011a), and lack of commercially viable natural resources (Section 2.3.5 of the System and Its Evolution report, QUINTESSA 2011b) in the area mean that the annual probability of such a borehole intruding into the DGR would be very low. Furthermore, over a million year time frame, drilling would also be limited by the presence of ice-sheets.

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. Deep drilling is screened out from all scenarios other than the Human Intrusion Scenario. 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 commercial interest (Section 2.3.5 of the System and Its Evolution report, QUINTESSA 2011b). Other underground activities are unlikely at the site, because the geology is uniform across a large area and so there is nothing unique at the site (Section 2.3 of the System and Its Evolution report, QUINTESSA 2011b).

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 commercial interest.

Finally, any deep underground activities would likely start with exploratory borehole drilling, and so would be likely to discover the existence of the repository as already discussed under Drilling activities [1.4.04].

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 External FEP 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, unconsolidated sediments, or bedrock and change groundwater recharge and discharge locations or affect groundwater flow regimes).

Screening Analysis

The depth of the repository (about 680 m) means that there is no direct impact of surface excavations on it. Excavation might occur into surficial deposits, which in turn might contain repository-derived contaminants (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 (considered in all scenarios) and less than the impacts of intruding directly into the DGR via an exploration borehole (considered in the Human Intrusion Scenario).

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.
- Changes in land use, for example reclamation/extension, agricultural activity, urbanization, 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) – see Section 6.3.2.3 of the System and Its Evolution report (QUINTESSA 2011b). 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 Postclosure SA.

FEP Screening

Include FEP in all scenarios. In particular, consider potential future receptors at site based on eventual site development consistent with larger regional land use in area.

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 nuclear site. However, given the depth of the repository (about 680 m), 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 contain repository derived contaminants but in very low concentrations. 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 (considered in all scenarios), and less than the impacts of intruding directly into the DGR via an exploration borehole (considered in the Human Intrusion Scenario).

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, unconsolidated sediments 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 run-off 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 (Section 2.4.4 of the System and Its Evolution report, QUINTESSA 2011b); 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 pumped from the Shallow Bedrock Groundwater Zone due to greater dilution in the lake. A variant case considers the drinking of lake water rather than well water.

Dams and reservoirs for control of water supplies are unlikely due to the existing water bodies (Lake Huron) and shallow groundwater aquifers. Hydroelectric dams are 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 (about 680 m). The impacts to critical groups from the effects of a nuclear bomb exploding near a DGR site or a severe nuclear accident at the Bruce nuclear site would 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 not credible.

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 from agriculture (e.g., fertilizers), industry (e.g., chemical pollution) and urban development (e.g., pit latrines).
- Groundwater pollution from the same sources as soil pollution, influencing the contaminant migration properties of the underlying aquifer.
- Air pollution, resulting in the deposition of contaminants at or near-the facility.
- Acid rain.

These pollution sources may alter the chemical composition of the soil, influencing the contaminant migration properties of the soil, and also affecting the type and health of biota and humans in the vicinity of the pollution. However, the large thickness of low-permeability rock above the repository isolates it from any chemical changes in the near surface due to pollution, so there is no impact on DGR performance.

Any contaminants that reach the near-surface region must be relatively mobile, so pollution is unlikely to make them more mobile.

A highly polluted surface region could change the nature of human activities at surface, and change the relative importance of different exposure pathways. However, the effect of any pollution would be to reduce occupancy and local resource use compared with the maximum reasonable occupancy/use assumed in the assessment (Section 7.1 of the Data report, QUINTESSA and GEOFIRMA 2011a).

FEP Screening

Screened out.

1.4.13 Remedial Actions

Description

Actions that might be taken following repository closure to remedy problems with the repository arising from its sub-standard performance, 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 Section 2.2 of the System and Its Evolution report, QUINTESSA 2011b), with a period of monitoring and closure activity after operations have ended, 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 altered levels of exposure.

Screening Analysis

Although changes in human society and technology are likely, they are unpredictable over the time period of interest. In the Postclosure SA, consistent with the recommendations of the International Commission on Radiological Protection (ICRP) (2000) and Section 7.5.4 of the Canadian Nuclear Safety Commission (CNSC) regulatory guide G-320 (CNSC 2006), it is assumed that future humans will largely resemble present-day humans in terms of habits and characteristics. This avoids open-ended speculation and 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 about 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 (e.g., during exploratory drilling).

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:

- Undertaking of remedial activities to correct real or perceived faults in the repository performance, an activity also discussed under Remedial actions [1.4.13];
- Authorized retrieval of materials from the repository (see Retrieval [1.1.11]);
- Unauthorized retrieval of radioactive material for malicious reasons including sabotage and war; and
- Archaeological exploration that is driven by the observed or inferred presence of repository structures or contents (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 since 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 Postclosure SA since they are a security rather than a safety issue. Nonetheless, it is noted that the depth and degree of isolation the DGR (about 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

The following analysis considers a range of potential impacts.

1. 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 used fuel repository. Wuschke et al. (1995) (see also Goodwin et al. 1994, p.637) estimated the probability of a significant meteorite impact on this used fuel repository to be 1.4 x 10^{-11} per year. Their calculations were based on the assessment that the smallest (and hence most likely) meteorite to have a significant effect would produce an impact crater that would remove or redistribute the rock to the level of the repository. The Pingualuit Crater (1.4 million years old), in northern Quebec, is an example of an impact crater of this magnitude; the impact created a crater 270 m deep, and it is estimated that another 250 m of shattered rock underlies the crater floor. Although Wuschke et al. (1995) used meteorite probability versus size data from the 1980s, results from a more recent survey are very similar (Brown et al. 2002).

   Wuschke et al. (1995) further found the radiological risk from this meteorite impact scenario on a used fuel repository 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.

   For comparison, the DGR is about 680 m deep and has a waste panel footprint of ~0.25 km^2, so the probability of an impact crater reaching DGR would be more than an order of magnitude lower than that assessed by Wuschke et al. (1995), on the order of 10^{-12} /a. And since the DGR only contains L&ILW, the consequences would also be less.

2. An additional case can be considered in which a meteor impact fractures the overlying rock to repository depth but does not expose the waste. This case is about five times more likely than a meteorite that exposes the waste (Wuschke et al. 1995). For the DGR, the risk would be on the order of 10^{-11} /a. However, while more likely, the consequences would be smaller. Waste materials are not brought directly to surface, but radionuclides must migrate through the fractured rock to surface. Such transport is dependent upon hydraulic gradients in the geosphere, and its effects will be limited by sorption in the rocks and mixing with uncontaminated water in the surface. Again, at long times the cumulative probability of an impact increases, but the consequences decrease due to radioactive decay. For the DGR, there is a significant decrease in radioactivity by around 60 ka due to decay of C-14. The likelihood of such an impact on the DGR during the next 100 ka is about one in a million.

3. 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.

4. 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 10 m diameter meteor would be about 200 Mg.

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

<u>FEP Screening</u>

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. Changes could increase or decrease sensitivity to radionuclides.

Consistent with the recommendations of ICRP Publication 81 (ICRP 2000), human doses are calculated for "ICRP Reference Man", whose characteristics are 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 adaptation would occur, but unlikely that it would lead to significant new species since the materials present in the DGR are not unusual (organics, steel, plastics). Rock samples from the deep DGR site indicate very little microbial activity, likely due to the high salinity and small porosity, which would inhibit microbes' activity and movement.

FEP Screening

Screened out.

2 INTERNAL FACTORS

Description:

Internal Factors include those features, events and processes occurring within the spatial and temporal (postclosure) repository system domain whose principal effect is to determine the evolution of the physical, chemical, biological and human conditions of the domain that, in turn, affect the release and migration of contaminants and the consequent exposure of human beings and the environment.

"Internal Factors" is divided into four categories as follows:

2.1 Waste, Waste Form & Engineered Components

2.2 Geological Environment

2.3 Surface Environment

2.4 Human Behaviour

2.1 Waste, Waste Form & Engineered Components

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 those features as a function of time.

“Waste, Waste Form and Engineered Components" 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, Access Tunnel, and Shaft & Services Area 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 Effects of Extraneous Materials

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 repository, 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 components. Note that FEPs relating to contaminant characteristics are discussed in FEP category 3.1, whereas 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. The Inventory Report (OPG 2010) estimates the total operational and refurbishment L&ILW radionuclide inventory 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 (e.g., Appendix B of the Inventory Report, OPG 2010); 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 (37 in total) for consideration in the safety assessment (see Appendix A of the Data report, QUINTESSA and GEOFIRMA 2011a).

FEP Screening

Include FEP in all scenarios.

2.1.01.02 Chemical Content

Description

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

Screening Analysis

The Inventory Report (OPG 2010) provides information on the expected chemical inventory in the DGR. In particular, chemical content affects two aspects of the Postclosure SA:

- gas generation, radionuclide mobility and solubility limits (this is discussed in FEP [2.1.02.02]); and
- the potential impact of hazardous species in the waste on human and ecological receptors (e.g., from heavy metals) considered in FEP [3.3.07].

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 emplacement.

The physical, chemical and biological characteristics of these wastes are important for the definition of:

- Contaminant release rates (source term);
- Gas generation rates; and
- Geochemical conditions in the repository.

Screening Analysis

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 Chapters 2 and 3 of the Inventory Report (OPG 2010).

For the purposes of the Postclosure SA, three categories of metallic waste are considered: carbon steel; stainless steel; and Zircaloy. The amounts of each of the metals in the LLW and ILW are summarized in Table 2.7 of the System and Its Evolution report (QUINTESSA 2011b).

Details of associated conditioning are summarized in Section 3.3 of the Data report (QUINTESSA and GEOFIRMA 2011a). Cement is used to condition a small proportion of wastes containing metals.

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 emplacement.

The physical, chemical and biological characteristics of these wastes are important for the definition of:

- Contaminant release rates (source term);
- Gas generation rates; and
- Geochemical conditions in the repository.

Screening Analysis

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, Active Liquid Waste, and ILW resins, and ion-exchange columns).

A description of the LLW and ILW waste characteristics is presented in Chapters 2 and 3 of the Inventory Report (OPG 2010).

For the purposes of the Postclosure SA, three categories of organic waste are considered: cellulose (paper, cotton, wood and organic absorbents); rubber and plastics; and resins. The amounts of organics in the LLW and ILW are summarized in Table 2.7 of the System and Its Evolution report (QUINTESSA 2011b).

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, QUINTESSA and GEOFIRMA 2011a).

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 emplacement.

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

- Contaminant release rates (source term);
- Gas generation rates; and
- Geochemical conditions in the repository.

Screening Analysis

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 Chapters 2 and 3 of the Inventory Report (OPG 2010). The amounts of concrete in the LLW and ILW are summarized in Table 2.7 of the System and Its Evolution report (QUINTESSA 2011b).

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 containers is given in Appendix E of the Inventory Report (OPG 2010). This is summarized from a postclosure safety assessment perspective in Section 2.1.2 and Table 2.3 of the System and Its Evolution report (QUINTESSA 2011b) and Section 3.2 of the Data report (QUINTESSA and GEOFIRMA 2011a). A range of metal and concrete drums/boxes is used with some metal-framed plastic pallet tanks. Some large irregular objects (e.g., heat exchangers) will be emplaced without any packaging.

The waste containers are a source of metals, concrete and plastics that, in the Postclosure 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 summarized in Table 2.7 of the System and Its Evolution report (QUINTESSA 2011b).

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 Appendix E of the Inventory Report (OPG 2010). This is summarized from a postclosure safety assessment perspective in Section 2.1.2 and Table 2.3 of the System and Its Evolution report (QUINTESSA 2011b) and Section 3.2 of the Data report (QUINTESSA and GEOFIRMA 2011a).

The overpacks are a source of metals, concrete and plastics that, in the Postclosure 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 summarized in Table 2.7 of the System and Its Evolution report (QUINTESSA 2011b).

FEP Screening

Include FEP in all scenarios.

2.1.04 Emplacement Room, Access Tunnel and Shaft & Services Area Characteristics

Description

The design-basis characteristics of the emplacement rooms, access tunnels, and shaft & services area. 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 Room and Closure 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 shaft & services area.

Screening Analysis

A description of the characteristics of the roofs and walls of the rooms and tunnels is summarized from a postclosure safety assessment perspective in Section 2.2.1 of the System and Its Evolution report (QUINTESSA 2011b) and Section 4.2 of the Data report (QUINTESSA and GEOFIRMA 2011a).

It is expected that the rooms and tunnel will be primarily excavated using drill and blast techniques, although the use of roadheaders is being considered as an alternative.

The roofs and walls will be covered with shotcrete extending down to within 1.5 m of the floor. Steel wire mesh, held in place by rock bolts, will be used in place of shotcrete in localized areas if rock conditions are favourable. These materials are considered as a source of metals and concrete in the Postclosure 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 the Data report (QUINTESSA and GEOFIRMA 2011a).

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 shaft and services area.

Screening Analysis

A description of the characteristics of the floors of the rooms and tunnels is summarized from a postclosure SA perspective in Section 2.2.1 of the System and Its Evolution report (QUINTESSA 2011b) and Section 4.2 of the Data report (QUINTESSA and GEOFIRMA 2011a).

The rooms and tunnels will have concrete floors (typically 0.2 m thick) and certain tunnels and rooms with have rails in their floors to allow the movement of large waste packages by self-powered rail carts. The floors are considered as a source of metals and concrete in the Postclosure 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 the Data report (QUINTESSA and GEOFIRMA 2011a).

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 shaft & services area to support their roofs and walls during the operational phase.

Screening Analysis

The rock bolts are steel and are taken to be 3.6 m long and 25 mm in diameter (NWMO 2010). They are considered as a source of metals in the Postclosure SA that will affect gas generation (from corrosion – 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 the Data report (QUINTESSA and GEOFIRMA 2011a).

FEP Screening

Include FEP in all scenarios.

2.1.04.04 Room and Closure Walls

Description

The design-basis characteristics of any walls that are used to close the emplacement rooms, access tunnels and shaft & services area in the repository.

Screening Analysis

Once an emplacement room has been filled with waste, a room end wall will be constructed (see Section 2.2.3.1 of the System and Its Evolution report, QUINTESSA 2011b). These room walls may be constructed of reinforced concrete blocks, and the wall will likely extend above the waste package height within the room, but not to the roof and so will not seal the emplacement room.

After a group of emplacement rooms have been filled with waste packages, concrete closure walls will be constructed in the access tunnel and ventilation drift to isolate this group of rooms (Section 6.13 of the Preliminary Safety Report, OPG 2011b). It is expected that there may be six closure walls in place at the end of repository operations.

The room and closure walls are a source of concrete (and, to a lesser extent, steel from the reinforcement) that will affect postclosure 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 the Data report (QUINTESSA and GEOFIRMA 2011a).

However, they are neglected as a transport barrier for preventing radionuclide movement and mixing across the repository panels.

FEP Screening

Include 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 shaft & services area in the repository.

Screening Analysis

The design does not consider any backfill in the rooms and tunnels (see Section 4.2.3.1 of the Postclosure SA main report, QUINTESSA et al. 2011).

However, a variant calculation case for the Normal Evolution Scenario considers the effect of backfilling of the DGR to limit the extent of rockfall in the repository (see Section 6.3 of Postclosure SA main report, QUINTESSA et al. 2011).

FEP Screening

FEP included in a Normal Evolution Scenario variant calculation that considers backfilling of DGR with gravel.

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 Sections 6.3.1.2 and 6.3.2.2 of the Preliminary Safety Report, OPG 2011b). Decommissioning of the shafts will involve the removal of the concrete shaft liner from the repository shaft station level up to about 180 m below ground surface (see Section 13.6.3 of the Preliminary Safety Report, OPG 2011b).

The liner will be left in place for the shaft bottoms and the upper 180 m of the shafts. The concrete liner will, in general, have different hydraulic properties from those of the surrounding rock.

FEP Screening

Include FEP in all scenarios.

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 Postclosure SA (see Section 2.2.3.4 and Figure 2.8 of the System and Its Evolution report, QUINTESSA 2011b and Section 4.3.2 of the Data report, QUINTESSA and GEOFIRMA 2011a). A 70:30 bentonite/sand mix will be used as the main backfill. An asphalt mastic mix will also be used in a thick section in the lower shaft to provide an alternative low-permeability barrier. The backfill in the upper shaft will be compacted engineered fill such as sand. Backfill 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 Postclosure SA comprises the following plugs:

- A concrete monolith that will be placed at the base of each shaft;
- Three concrete bulkheads in the shaft that will be keyed into the rock surrounding the shaft for mechanical support; and
- A thick concrete cap at the top of each shaft.

The characteristics of the monoliths and bulkheads are described in Section 4.3.2 of the Data report (QUINTESSA and GEOFIRMA 2011a). Their role is to provide structural support to the shaft backfill and, to a lesser extent, 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 and decommissioning phases.

Screening Analysis

Rock bolts will be used to provide support for the shaft walls from 20 m downwards. These might not be removed during shaft decommissioning. However, it is expected that any impacts arising from rock bolts remaining in the shaft will be spatially limited and so will not have an impact on postclosure safety. Therefore, the rock bolts do not need to be considered in the Postclosure SA.

FEP Screening

Screened out.

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 leading to the collapse of packaging and the compression of waste placed inside the repository 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

2.1.06.01.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 due to pore water from the geosphere 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. Conservatively the Postclosure SA takes no account of the barrier function of the packaging and assumes packaging collapse from the start of the assessment (see Section 2.3.1 of the Normal Evolution Scenario Analysis report, QUINTESSA 2011a).

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 containers and overpacks would degrade over time due to various mechanical (e.g., FEP [2.1.06.02.A]) and chemical processes (e.g., FEP [2.1.08.06]) resulting in their 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 of already weakened concrete containers and overpacks by shaking them.

Conservatively the Postclosure SA takes no account of the barrier function of the packaging and assumes packaging collapse from the start of the assessment (see Section 2.3.1 of the Normal Evolution Scenario Analysis report, QUINTESSA 2011a).

FEP Screening

Include FEP in all scenarios.

2.1.06.02 Material Volume Changes

Description

The effects of volume changes in materials used in the repository. 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 crystallization 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 higher 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. Reaction of cement minerals with CO_2 generated from microbial degradation of organic wastes can result in precipitation of calcite and ‘armouring’ of concrete surfaces, which will protect them from further alteration.

It is considered that the net effect of the various concrete altering reactions is that the low initial permeability of the concrete will increase with time. This change in permeability is considered for the concrete shaft seals and monolith, although alteration may take tens of thousands of years in the Deep and Intermediate Bedrock Groundwater Zones where transport is diffusion dominated (Section 4.5.3 of the System and Its Evolution report, QUINTESSA 2011b). Conservatively, safety assessment calculations for the Normal Evolution Scenario assume that concrete is degraded at the start of the assessment (Section 2.3.2 of the Normal Evolution Scenario Analysis report, QUINTESSA 2011a).

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 that 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. Cation exchange with groundwater species could result in some reduction in swelling. Chemical modifications (particularly attack by potassium ions in groundwater or reaction with alkaline plumes from concrete) could cause significant reductions in swelling pressure, making the material less effective in sealing cracks (see Illitization [2.1.08.06E]).

Screening Analysis

Bentonite-sand is proposed for use as one of the shaft sealants in the DGR. For the proposed reference material bentonite density and considering the geosphere porewater composition, the swelling pressure is anticipated to be approximately 0.4 MPa (see Section 4.5.4 and Figure 4.4 of the System and Its Evolution report, QUINTESSA 2011b). This swelling pressure and the lithostatic pressure will both act to seal the interface with the shaft wall rock.

Mineralization might also lead to embrittlement of bentonite and loss of swelling pressure but this effect is likely to be limited due to the low temperatures and the low permeability of the surrounding rock. Although there is no direct data on bentonite stability under the highly saline Na-Ca-Cl site groundwater conditions at the DGR site, there are some natural analogs, notably some Spanish bentonites, that have been exposed to saline Na-Cl (sea) water over millions of years, and show no significant mineral alteration (Laine and Karttunen 2010; Savage 2005). Localized alteration is most likely to occur where the bentonite-sand is in contact with the concrete seals (see Section 4.5.4 of the System and Its Evolution report, QUINTESSA 2011b).

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 Analysis

Metallic wastes and packaging will corrode and result in the generation of H_2 under anaerobic conditions (Section 4.3 of QUINTESSA and GEOFIRMA 2011b).

The corrosion products could serve as a medium that helps fill voids and restrains radionuclide transport by sorption and physical infill; however this aspect is conservatively ignored. They may also form colloids (see Colloid formation [2.1.08.09]).

Due to the large amount of iron metal in the repository, and the large amount of CO_2 that can potentially be generated from microbial degradation of organic wastes, the formation of the specific corrosion product siderite is explicitly considered as a potential CO_2 sink.

FEP Screening

Include FEP in all scenarios.

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 that 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 failures of waste packaging.

Screening Analysis

The repository is designed to provide very good structural stability, taking into account the good strength properties of the host rock, the alignment of the rooms with the principal stresses, and the thick rock pillar between rooms.

However, rockfall into the repository will eventually occur as the rooms and tunnels are not backfilled (see Backfill [2.1.04.05]). Seismic events will induce rockfall from the roof, whereas cycles of ice-sheet loading and unloading will induce collapse (rockfall) from the pillars. Rockfall will eventually 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 becomes self-supporting. Based on geomechanical modelling, a self-supporting collapse zone is expected to develop eventually due to the combined effects of rockfall from roof and pillar collapse, with the zone contained within the Cobourg formation, approximately 10 m into the roof (Section 6.4 of NWMO 2011).

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. In safety assessment calculations, rockfall is conservatively assumed to occur soon after repository closure.

FEP Screening

Include FEP in all scenarios.

2.1.06.04 Container Movement

Description

Movement of containers in the repository that could lead to, or be coincident with, container failure.

The possible causes are essentially as described in Emplacement room/ tunnel collapse [2.1.06.03] – notably seismic shaking and rockfall. Also package corrosion could cause container collapse.

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 lose 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.

The key issue of relevance to the Postclosure SA is container collapse, thereby removing any barrier to waste-water contact, and increasing the potential for waste-water contact in a partially saturated repository as waste collapses into the void space between containers. In the Postclosure SA, all containers are assumed to fail quickly, without linking this to any specific cause.

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 (such as the interfaces between the concrete plugs and the walls of the shafts), because these are the points of greatest potential weakness.

Screening Analysis

Fractures may develop in the shaft monolith and bulkheads due to physico-chemical degradation (Table 4.2 of the System and Its Evolution report, QUINTESSA 2011b). Fractures may also develop in response to ice-sheet loading and unloading or seismic events, with the shallowest bulkhead being most vulnerable and the deepest bulkhead being the least vulnerable. The main effect is an increase in the permeability of these concrete components.

The bentonite-sand and asphalt components have swelling and creep capacity and are not expected to fracture, or will self-seal.

FEP Screening

Include FEP in all scenarios for the shaft monolith and bulkheads.

2.1.06.06 Stress-corrosion Cracking

Description

A potential failure mechanism for metallic containers resulting from the attack by various chemical agents such as chloride and hydrogen.

Stress-corrosion cracking, including hydride embrittlement and cracking may mechanically weaken the container and promote subsequent failure or other corrosion mechanisms. These processes may be accelerated if a chemical agent (such as hydrogen and chloride) 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 as 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.

Further, the containers are assumed to fail quickly in the Postclosure SA, so potential failure mechanisms are not relevant.

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. To generate an explosive gas, methane from the rock, or methane or hydrogen generated from waste and container degradation in an oxygen-deficient region of the DGR, would have to migrate and mix with any remaining oxygen elsewhere in the DGR. 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 Section 5.1.1 of the Gas Modelling report, GEOFIRMA and QUINTESSA 2011), as well as the mechanical stability of the rooms, 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

Due to the DGR's depth and the low-permeability rock and shaft seals, expected climate changes over the next ten to one hundred thousand years will in general have no effect on conditions in the repository and shafts. However, at longer times, it is likely that the glacial-interglacial cycling experienced during the Quaternary will resume, which will have effects on mechanical conditions.

Permafrost associated with this cycling is not expected to be deep or continuous at the site, and will not reach repository depth. 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 (2011) has estimated normal stress increases of up to 30 MPa. Mechanical models (Section 6.4 of NWMO 2011) indicate that cycles of ice-sheet loading and unloading will cause rockfall from the walls of the emplacement rooms (i.e., the pillars). The system will stabilize after three to four cycles of loading and unloading (see Emplacement room/tunnel collapse [2.1.06.03]) and this has been included as a cause of rockfall in the conceptual model (see Section 4.4.1 of the System and Its Evolution report, QUINTESSA 2011b).

It is recognized that the near-surface environment will be significantly affected by glacial-interglacial cycling, including the upper shaft (i.e., in the Surficial and Shallow Bedrock Groundwater Zones). However, this part of the shaft seal is not relied upon for long-term performance and is simply backfilled with a relatively permeable fill. Any concrete components here (shaft liner, surface concrete plug) are assumed to degrade to properties similar to the surrounding relatively permeable rock.

The consequences of unexpected effects on the lower shaft seal (i.e., in the Intermediate and Deep Bedrock Groundwater Zones) are tested in the Severe Shaft Seal Failure scenario.

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 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

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 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). Eventually the repository will completely resaturate.

Screening Analysis

A range of resaturation/desaturation profiles is considered in the Postclosure SA (see Chapter 8 of the Gas Modelling report, GEOFIRMA and QUINTESSA 2011. Instantaneous resaturation of the repository is also considered (see Chapter 3 of the Groundwater Modelling report, GEOFIRMA 2011).

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 and shafts in response to hydraulic gradients and according to hydraulic characteristics of the repository and shafts.

Screening Analysis

The repository environment is largely open spaces at a common elevation. No backfilling is planned. Therefore, there will not be any appreciable hydraulic gradient within the DGR.

There are no significant horizontal hydraulic gradients around the repository horizon. Therefore, once the repository has resaturated, there is no natural flow that would be reflected in the repository. If there is an advective water flow pathway via the shaft, then there will be (small) flows within the tunnels to the shaft.

There is a vertical hydraulic gradient around the repository due to the excess pressure head in the Cambrian rocks below the DGR This may support some vertical water flow through the repository, possibly with some focussing of flow up the shaft given that it has a slightly higher permeability than the surrounding rock. The flow velocity is expected to be small due to the low permeability of the shaft and even smaller rock permeability. However, as this flow could support contaminant transport, it is included in the Postclosure SA.

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 over an extended period of time. Initially, the rate of gas generation is expected to be greater than the rate of gas migration (loss) due to the low permeability of the host rock, and gas pressure will increase. As the gas pressure increases, the rate of water flow into the repository will decrease. If the gas pressure rises above the geosphere environmental water pressure, water can be expelled from the repository, back into the host rock or into the shaft.

These gas effects on water flow are taken into account in the Postclosure SA model (see the Normal Evolution Scenario Analysis report, QUINTESSA 2011a).

FEP Screening

Include FEP in all scenarios.

2.1.07.04 Failure of Drainage System

Description

Failure of drainage system in repository.

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 groundwater or gas within the repository and shafts that are sufficient to cause fracturing of repository components such as overpacks, walls, floors, backfill and plugs.

Screening Analysis

The generation of pressure in the repository due to inflow of water (and potentially gas) from the geosphere, and generation of gas in-situ, will be slow, so there is time for pressures to equilibrate across components within the repository. Differential pressures are unlikely to develop across the room end walls and closure plugs, but in any case these are not assumed to be a barrier in the Postclosure SA.

The shaft will likely resaturate faster than the repository, and there may be differential saturations/capillary pressures in the shaft materials during resaturation. The shaft bulkheads and the massive monolith at the base of the shaft will resist these forces and maintain stability 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 or 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

Large disequilibrium hydraulic pressures have been measured in the deep geosphere at the Bruce nuclear site (see Hydrological/hydrogeological response to geological changes [1.2.11]). The low Total Dissolved Solids (TDS) gradient in this region (see Sections 4.4 and 5.2 of NWMO 2011) indicates that these disequilibrium pressures are not due to chemical osmosis. There are no local sources of electrical gradients. Therefore, fluid flow driven by chemical or electrical osmosis is not important at the DGR.

Radioactive decay may cause some heating within emplacement rooms and the adjacent host rock for ILW retube wastes. However the effect will only last a few years and will not cause significant temperature gradients. There are no other significant sources of heat in the DGR. Geosphere temperatures will respond to changes in surface temperatures due to glacial cycles, such that significant disequilibrium temperature gradients will not develop in the geosphere (Section 4.2 of the System and Its Evolution Report, QUINTESSA 2011b). Therefore, fluid flow will not occur in response to thermal gradients.

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 FEPs [1.3.01 and 1.3.02]) may affect the hydraulic properties of the geosphere surrounding the DGR, which could potentially affect repository components. In particular, glaciation will impose changes to the hydraulic heads across the site. However, due to the low permeability of the host rock and the absence of evidence of the effects of previous ice-sheet advances and retreats at depth, it is expected that there will be no significant hydraulic effects at the depth of the repository (Sections 4.5 and 5.4.6 of the Geosynthesis report, NWMO 2011).

It is recognized that the near-surface environment will be significantly affected by glacial-interglacial cycling, including the upper shaft (i.e., in the Surficial and Shallow Bedrock Groundwater Zones). However this part of the shaft seal is not relied upon for long-term performance and is simply backfilled with a relatively permeable fill. Any concrete components here (shaft liner, surface concrete plug) are assumed to degrade to properties similar to the surrounding relatively permeable rock.

The consequences of unexpected effects on the lower shaft seal (i.e., in the Intermediate and Deep Bedrock Groundwater Zones) are tested in the Severe Shaft Seal Failure scenario.

FEP Screening

Include FEP in all scenarios.

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 influences on wastes, containers and engineered components by groundwater entering from the surrounding rocks.

Under this category, the following FEPs are specifically considered:

2.1.08.01 pH Conditions

2.1.08.02 Redox Conditions

2.1.08.03 Chloride and Sulphate Concentrations

2.1.08.04 Corrosion

2.1.08.05 Polymer Degradation

2.1.08.06 Mineralization

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 conditions (along with Eh conditions [2.1.08.02] and Chloride and sulphate concentrations [2.1.08.03]) is an important determinant of 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 spatially and temporally, because the reserves of alkalinity in the concrete will be limited and as pore water enters the concrete slowly 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 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 (Table 4.1 of the System and Its Evolution report, QUINTESSA 2011b). This range of pH is used in the consideration of solubility, sorption, corrosion rates and general mineral and seal material stability.

FEP Screening

Include FEP in all scenarios.

2.1.08.02 Redox Conditions

Description

The redox conditions of water in the repository owing to interactions between the water and the repository materials (wastes, packaging, and engineered features). The redox state, which is typically represented by the redox potential, Eh (along with pH conditions [2.1.08.01] and Chloride and sulphate concentrations [2.1.08.03]) is an important determinant of 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 minimizes 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]). Radiolysis of the various organic wastes could generate free radicals that would be highly reactive towards oxygen, but the radioactivity in the DGR is too low for this process to be as significant in controlling Eh as steel corrosion.

Natural Eh in the porewaters of the geosphere has not been determined directly, because the act of sampling these waters inevitably disturbs their redox state. Therefore, the in-situ redox state must be estimated indirectly, based on lithological and mineralogical observations. Reduced-S minerals (principally pyrite) and reduced Fe-minerals (pyrite and ferroan carbonate minerals) are present in the host rock and surrounding rock in small quantities. Oxidized sulphate minerals (gypsum and anhydrite) and oxidized Fe-minerals (principally hematite) are also present. These minerals are the most likely redox buffers and their coexistence is consistent with in-situ conditions being anoxic and reducing, with Eh around -120 mV at pH 6. Under these circumstances reduced sulphur species (H_2S and HS-) are expected to be present in very low concentrations. Redox buffering by reduced organic species, including CH_4, would be expected to produce even more reducing conditions, but these species are likely to be present at very low concentrations and are unlikely to be in thermodynamic equilibrium.

FEP Screening

Include FEP in all scenarios.

2.1.08.03 Chloride and Sulphate Concentrations

Description

The chloride and sulphate concentrations in water in the repository owing to the concentrations of these solutes in inflowing natural porewater and interactions between the water and the repository materials (wastes, packaging, and engineered features). Chloride and sulphate concentrations (along with pH conditions [2.1.08.01] and Eh conditions [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 water are expected to increase as high salinity natural porewater enters the repository (background level of 100 to 260 g/L) 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 in the Deep Bedrock Groundwater Zone, 20 to 250 g/L in the Intermediate Bedrock Groundwater Zone, and 1 to 100 mg/L in the Shallow Bedrock Groundwater Zone) (Section 4.4 of NWMO 2011).

Sulphate concentrations in the emplacement room water are expected to fall rapidly due to the consumption of sulphate by microbial reactions also involving H_2 (see Microbially/biologically mediated processes [2.1.09.02]) from the background level of 1450 mg/L (Table 5.4 of the Data report, QUINTESSA and GEOFIRMA 2011a).

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 Localized

2.1.08.04.C Galvanic

2.1.08.04.A General

Description

If water (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 aerobic and anaerobic conditions. The latter is slower than the former, with both rates being slower under high pH conditions (Francis et al. 1997). Corrosion 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 (in liquid or vapour form) will contact the various metallic components of the DGR (wastes, packaging, rock bolts, rails and rebar) 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. The Postclosure SA assumes that all packages fail quickly.

FEP Screening

Include FEP in all scenarios.

2.1.08.04.B Localized

Description

The localized formation of cavities in a metal surface caused by non-uniform corrosion. Localized 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 localized 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

Localized corrosion processes will only occur under aerobic conditions. Of the metals present in the repository, those most susceptible to localized corrosion are stainless steel and carbon and galvanized steel in contact with concrete (the so-called “passivated carbon steel” category). Any localized corrosion that initiates under aerobic conditions will cease (or “stifle”) as the repository environment becomes anoxic. Because of the high salinity of porewater in the deep sedimentary rocks, corrosion of the non-susceptible metals, such as unpassivated carbon and galvanized steels and zirconium alloys, will tend to be general in nature (rather than localized), as will that of the susceptible alloys once the repository environment becomes anoxic. However, waste packages are assumed in the Postclosure SA to fail quickly anyway, so the exact mechanism is not important.

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 (e.g., as found in some DGR wastes) is more electropositive than carbon steel (e.g., as used for some 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 once conditions become sufficiently humid to support corrosion.

Galvanic corrosion will only occur where there is contact between different metals. The total contact area is difficult to quantify, but will be small compared with the total area of metals undergoing general corrosion. The additional contribution of galvanic corrosion to gas generation will, therefore, be small and bounded by the conservatively high corrosion rates used in the gas generation model (Section 3.6.5 of the Data report, QUINTESSA and GEOFIRMA 2011a).

FEP Screening

Screened out.

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). These organic materials can be microbially degraded, although the rates of degradation are expected to be slow in the DGR environment, especially for plastics and ion-exchange resins. Water is required to support microbial degradation of these materials, resulting in the generation of biomass and gas (see Appendix F of the Data report, QUINTESSA and GEOFIRMA 2011a).

FEP Screening

Include FEP in all scenarios.

2.1.08.06 Mineralization

<u>Description</u>

Long-term chemical changes occurring in repository materials (concrete, bentonite and asphalt) that could affect repository performance. Five 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.E Illitization

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 - see Sections 4.5.4 and 4.5.5 of the System and Its Evolution report (QUINTESSA 2011b).

The shaft concrete bulkheads and monolith are formed from Low Heat High Performance Cement (LHHPC), which is of lower pH than concrete formed from Ordinary Portland Cement (OPC). The monolith is located in very low permeability rock. Therefore, there is not anticipated to be significant leaching, and reaction with the host rock porewater will be limited by the rate of diffusion of reagents. Although the deeper bulkheads are in contact with relatively more permeable geological formations than the monolith, the head gradients are low such that leaching is anticipated to be relatively limited.

Leaching is likely to be more significant for the shallowest bulkhead, which is overlain by permeable engineered fill within the permeable Shallow Bedrock Groundwater Zone. There is anticipated to be significant leaching from the concrete shaft lining that is present in the Shallow Bedrock Groundwater Zone and this is expected to degrade relatively quickly. However, this shallow shaft liner does not have any postclosure safety function. See Section 4.5.3 of the System and Its Evolution Report for further details (QUINTESSA 2011b).

FEP Screening

Include FEP in all scenarios for concrete.

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 leaching of portlandite is increased in the presence of chloride, thereby increasing concrete porosity. Concrete strength can be reduced and swelling may occur (Hewlett 2003, and references therein). The reaction of concrete with chloride can result in the formation of complex salts, such as Friedel's Salt: $Ca_4Al_2(Cl)_{1.95}(OH)_{12.5}\cdot 4H_2O$ or Kuzel's Salt: $Ca_4Al_2(Cl)(SO_4)_{0.5}(OH)_{12}\cdot 6H_2O$ (Balonis et al. 2010; and references therein).

In addition, portlandite solubility increases with increasing NaCl content (Glasser et al. 1998) and the presence of Mg in brine may 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.

Screening Analysis

Considered as one of the degradation mechanisms for concrete structures in the repository (and shaft) (see Section 4.5.3 of the System and Its Evolution Report, QUINTESSA 2011b).

Not considered to be an important process for bentonite and asphalt. Savage (2005) cites natural analogue evidence that shows no sign of mineral alteration as a result of intrusion of sea water into bentonite deposits.

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.

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.

Screening Analysis

Simple scoping calculations presented in Appendix E.5.3 of the System and Its Evolution report (QUINTESSA 2011b) suggest that thousands to tens of thousands of years are required for sufficient sulphate ingress for major cement alteration and that the availability of Al might limit the formation of phases such as ettringite that can result in cracking.

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.

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; 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).

Screening Analysis

The main impact of carbonate ions will be on the concrete present – see discussion in Section 4.5.3 of the System and Its Evolution report (QUINTESSA 2011b). 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).

Calculations in Appendix E.5.2 of the System and Its Evolution report (QUINTESSA 2011b) show that carbonation is likely to be slow and mainly confined to the interfaces with the geosphere, given the capacity for calcite growth to result in pore blocking and the armouring of surfaces.

In the Postclosure SA, carbonation is not represented explicitly, but is assumed to be one of a number of processes that lead to degradation of concrete. Conservatively, the monolith and shaft bulkheads are assumed to be degraded at the start of the assessment.

FEP Screening

Screened out

2.1.08.06.E Illitization

Description

The process of illitization (commonly associated with burial diagenesis of sediments) involves smectite being converted to illite with a 2:1 layer charge increase as Al is substituted for Si in tetrahedral sheets, uptake of K into interlayer regions and the release of silica. The reaction is strongly dependent upon time, temperature and availability of K^+. Significant illitization of bentonite would result in loss of swelling capacity. See also Backfill swelling [2.1.06.02B].

Screening Analysis

Bentonite can be susceptible to a reduction in swelling pressure brought about by potassium ions (Atkinson et al. 1997). Potassium concentrations in the Deep Bedrock Groundwater Zone are estimated to be about 17.3 g/L and sulphate concentrations are estimated to about 1.4 g/L (Table 5.4 of the Data report, QUINTESSA and GEOFIRMA 2011a). However, the application of a kinetic model to the Bruce nuclear site suggests that this process (illitization) will be negligible (see Appendix E.3 of the System and Its Evolution report, QUINTESSA 2011b).

FEP Screening

Screened out.

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 elemental 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 solid may be the most thermodynamically stable solid phase that can form under the prevailing conditions, but alternatively it may be a metastable phase. The solubility-limited 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 (Appelo and Postma 2005).

It is important not to create the impression that solubility limiting reactions defined in this way always impose maximum concentration limits on solutes. In some cases, metastable solution-solid reactions may give rise to higher aqueous concentrations than would arise by true solubility limitation by the most thermodynamically stable phase. 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.

Supersaturation is often required in order for the chemical potential to become high enough to initiate precipitation. Similarly, the presence of complexing ions can increase solubility, and cause elements to remain in solution under conditions when they would otherwise be expected to precipitate.

Screening Analysis

The DGR is likely to operate at around neutral pH, with the pH of water in the DGR buffered by the limestone host rock. There will be local deviations in pH: for example there may be lower pH value within organic wastes due to waste degradation and generation of organic acids; and higher pH within concrete overpacks.

The repository is expected to be anaerobic, and this will be an important control over solubility. Anaerobic conditions are expected due to the natural chemistry of the geosphere porewaters (Section 4.4.5 of NWMO 2011), and the chemical oxygen demand of the organic and metal wastes and metal containers.

The geosphere porewater is highly saline and saturated with many major ions. This will limit the potential for dissolution of materials in the DGR. Complexants may be derived from the decomposition of cellulose, but alkaline conditions are needed to initiate the degradation. With the exception of the ion-exchange resins, which are only expected to degrade very slowly (if at all - see Organic waste degradation [2.1.11.3]), the organic wastes are not within concrete overpacks. Any organic complexants generated from the resins may be microbially degraded before they migrate from the repository with complexed elements.

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 that 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.

Screening Analysis

Chelating agents (EDTA) are present in CANDECON resins, and others may be formed as degradation products. However, it is not expected that the chelating agents will be in sufficient concentrations to cause anything but localized impacts on solubility. Therefore, chelating agents are not considered to be significant in terms of the bulk chemical evolution of the DGR.

Note that chelating agents are considered to be potentially important in the context of radionuclide mobility, e.g., Pu solubility can be significantly increased by chelation with the acidic degradation products of cellulose (Greenfield et al. 1997). However, it is conservatively assumed that there is no solubility limitation for any radionuclide, except C-14, in the repository (see Section 3.6.3.2 of the Data report, QUINTESSA and GEOFIRMA 2011a) – see FEP [3.2.13.01].

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 (e.g., Nilsson and Degueldre 2007 and references therein). 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. For example, SKB is concerned about the potential for erosion of the bentonite buffer, leading to formation of colloidal and particulate material, if freshwater were to reach their repository.

Colloids may also form in the repository during degradation of the wastes or engineered barrier materials. For example, colloid formation may be promoted by steep chemical gradients within the repository system, such as at an interface where the Eh or pH changes abruptly because of chemical or biological activity.

The thermodynamic stability of colloids depends upon varied factors, such as the chemistry and surface charge of the colloid and the chemistry of the dispersion medium. Even certain colloids that are thermodynamically unstable may be treated as being stable owing to the slow rates at which they agglomerate into solids (called coagulation or flocculation). Colloid stability generally decreases as ionic strength (salinity) increases. Colloids can act to increase elemental solubilities, and they can lead to pore blockage if they are filtered out as the dispersing medium (i.e., water) flows through materials with small pore diameters, e.g., concrete or bentonite backfill.

Screening Analysis

Geologic evidence indicates that the Intermediate and Deep Bedrock Groundwater Zones have been saline for millions of years and not affected by fresh waters from glaciation or recharge (see Section 4.5 of NWMO 2011). Colloids are expected to be unstable under the high salinity of the Intermediate and Deep Bedrock Groundwater Zones and so susceptible to agglomeration and dissolution. Even if colloids are generated in the DGR, they are not considered to be significant in terms of the bulk chemical evolution of the DGR.

Note that the effect of colloids on contaminants is discussed in 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 driven by the unequal chemical potentials of the solutions on either side of the membrane. This effect could possibly play a role in equalising water compositions across a repository.

Screening Analysis

In the Postclosure SA, waste packages are assumed to fail and not provide a barrier for water movement. Also, the repository as a whole is relatively open and porous and is not a barrier to water transport. 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 water/solid reactions (including precipitation and dissolution reactions), 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 consequent opening or plugging of pores.

This FEP does not consider contaminant gradients which are considered under Contaminant release and migration factors [3.2].

Screening Analysis

Chemical concentration differences will exist, but are not expected to be important since:

- LLW and ILW rooms are mixed across the Panels; and
- The repository is not backfilled so is relatively open to diffusion of materials in water across the panels.

Radiolysis and temperature are not significant sources of gradients in the repository as these wastes are not highly radioactive nor heat producing.

The Postclosure SA assumes that packages fail quickly and that there is no plugging or inhibition of release.

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 rocks. The movement of contaminants is described in Water-mediated transport of contaminants [3.2.02].

Screening Analysis

Global and local climate changes (see FEPs [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 effects of previous ice-sheet advances and retreats at depth (Section 4.5 of NWMO 2011), it is expected that there will be no significant chemical/geochemical effects at the depth of the repository.

It is recognized that the near-surface environment will be significantly affected by glacial-interglacial cycling and, therefore, the upper shaft (i.e., in the Surficial and Shallow Bedrock Groundwater Zones) will be influenced by climate change. However this part of the shaft seal is not relied upon for long-term performance and is simply backfilled with a relatively permeable sand-based engineered fill. No significant chemical effects are expected on this engineered fill.

FEP Screening

Screened out. The consequences of unexpected effects on the lower shaft seal (i.e., in the Intermediate and Deep Bedrock Groundwater Zones) are tested in 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 the repository with time. They can result from the activity of microscopic organisms, including archaea, bacteria, protozoans, yeasts, 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 FEP [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 recognized that extremophiles (e.g., various types of archaea) can survive and thrive outside the range at which most microbes flourish.

Screening Analysis

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 and has been included in the processes considered in the T2GGM gas generation and transport code (Section 4.2 of the T2GGM report, QUINTESSA and GEOFIRMA 2011b).

The potential poisoning of microbes is accounted for by variant calculation cases that consider reduced microbial degradation rates and no methanogenic reactions (see Sections 5.6 and 5.11 of the Gas Modelling report, GEOFIRMA and QUINTESSA 2011).

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.

- 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, in the presence of hydrogen consuming microbes, it can react with carbon dioxide to produce methane (NIREX 1994). Organic acids can also be 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 $^{14}CO_2$.
- Degradation of nitrate ions. Nitrate ions in waste and groundwater can participate in cellulose degradation, forming nitrogen (NIREX 1994).
- 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).
- 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, although, on the other hand, its high salinity might limit 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.

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.

Organic acids are produced in some microbially mediated decomposition of cellulose and other organic materials. In the absence of a material to maintain pH at high values, pH in the repository will tend to decrease. CO_2 gas produced from these reactions could dissolve in the water and also lower the pH.

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.

The reduction in oxygen by various processes is explicitly considered in the repository model leading to anaerobic and reducing conditions.

However, due to the limestone host rock, and the presence of concrete on the walls and floors of the tunnels and rooms, it is unlikely that pH would be reduced to a level at which ‘acid souring’ could occur, thereby effectively stopping further microbial activity (i.e., gas production).

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 FEPs [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. The anticipated 5 ºC decrease in geosphere temperature at the DGR horizon associated with glaciation (see Section 5.1 of the System and Its Evolution report, QUINTESSA 2011b) might reduce microbial activity. However, even the more recalcitrant organic materials in the DGR are expected to have degraded before the next glaciation so this effect is not relevant.

It is recognized that the near-surface environment will be significantly affected by glacial-interglacial cycling and this will 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.

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 time 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.

Screening Analysis

At repository closure, relatively short-lived radionuclides such as Co-60 and Cs-137 will dominate radiogenic heat production. Only retube wastes will have appreciable heating rates, but even these would result in a rise of only a few degrees centigrade locally, as the packages would be held at the surface until their heating power was sufficiently low. Overall, the thermal output from radioactive decay at repository closure of about 2 kW is an order of magnitude less than the natural geothermal flux through the repository panel footprint, and will decay to even lower values with time.

Corrosion of waste metals and organic degradation will result in heat generation. But these processes are slow, especially under anaerobic conditions, and will not cause noticeable heating of the wastes due to the low power output and the distribution of this heat across the repository (i.e., the geosphere provides a large heat sink).

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 and any increase in temperature dissipated before the emplacement of waste.

Concrete will also be used in the sealing of the repository. However, since a low heat generating concrete will be used for the monolith and bulkheads in the shafts, limited heat production is expected.

It is expected that the effects of the heating of surrounding materials and rocks as the asphalt in the shaft cools will be limited and minimized through the emplacement of the seal in a series of pours.

Any temperature increase from the seal concrete and asphalt emplacement would be dissipated within the surrounding geosphere and not persist for long times.

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 FEPs [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 of the repository is not expected – see Section 4.2 of the System and Its Evolution report (QUINTESSA 2011b).

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

FEP Screening

Screened out.

2.1.10.04 Temperature Dependence of Processes

Description

As described in FEPs [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

No significant temperature changes are expected as the repository does not contain any significant heat sources. The use of a low-heat concrete for the shaft monolith, as well as controlled pour rates, as is standard practice for large concrete pours, will ensure that there is no mechanical impact on the surrounding rock.

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

No significant temperature changes are expected as the repository does not contain any significant heat sources (see Section 4.2 of the System and Its Evolution report, QUINTESSA 2011b). Therefore, the hydraulic impact on the surrounding rock is expected to be insignificant.

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 mineralization, particularly of cements and concretes present as structural materials, packaging and backfill.

Mineralization converts cements and concretes to thermodynamically more stable forms that may exhibit different 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

No significant temperature changes are expected as the repository does not contain any significant heat sources. The repository will remain at around the natural temperature levels at the host rock horizon of about 22°C, dropping several degrees only during glaciation cycles. Processes are expected to occur at normal rates associated with the host rock ambient conditions, and will not be accelerated.

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°C in the presence of suitable substrates, but at significantly higher temperatures(70°C), they mostly 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 22°C (see discussion in Section 4.2 of the System and Its Evolution report, QUINTESSA 2011b), 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 FEPs [1.3.01 and 1.3.02]) may affect the temperature of the geosphere surrounding the DGR. Peltier (2011) 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 annual average, earth-surface temperatures at the site ranged between -4°C and +10°C. Permafrost occurs for part of the cycle, but its thickness (approximately the 0°C isotherm) rarely exceeded 60 m. Generally, permafrost is not continuous unless the depth of permafrost exceeds 60 to 90 m (Brown and Pewe 1973).

The temperature at the DGR horizon has been calculated for glacial conditions (Section 5.1 of the System and Its Evolution report, QUINTESSA 2011b). A temperature drop of as much as 5°C from the current value of around 22°C has been calculated.

The relatively small change in temperature at repository and deep shaft locations, and the absence of continuous permafrost at the site, indicate that temperature variations due to climate change are not a significant factor in the evolution of the repository.

FEP Screening

Screened out. Variant case for Normal Evolution Scenario considers reduced degradation rate (for example due to lower temperatures).

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. Five 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 radon 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.

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 is, therefore, considered in the Postclosure 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 anaerobic.

Screening Analysis

The degradation reactions of these metals are discussed in detail in the System and Its Evolution report (see Section 4.5.1 of QUINTESSA 2011b).

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 (see FEP [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:

- Cellulosic waste (generally comprising paper and other similar material); and
- Polymer waste (comprising less-biodegradable organics, such as plastics and resins).

In the presence of microbes, organic material is hydrolyzed 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 by microbial activity (Section 4.2.1.2 of QUINTESSA and GEOFIRMA 2011b). 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 constrain the increase) in the gas pressure during system evolution. A variant case is also considered where this conversion process is assumed not to occur.

Whereas biodegradation of cellulosics is well established, the biodegradability of resins is uncertain.

- One body of opinion considers that there would be little degradation of resins under anaerobic repository conditions. In general, the resins are found to be resistant to both chemical and biological degradation. For example, Torstenfelt (1989) reviewed the stability of ion-exchange resins in a cementitious environment and noted that the resins are very stable from attack by polar, oxidising or reducing agents.
- However, there is also a substantial body of evidence for the degradation of resins presented in the literature (e.g., Bowerman et al. 1988; Evans 2000; Bracke et al. 2004). For example, Bowerman et al. (1988) observed that the rate of biochemical attack on resins was very low, but following irradiation (1 MGy ^{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 maximizes the amount of gas generated in the repository from the degradation of resins.

FEP Screening

Include FEP in all scenarios.

2.1.11.04 Cement Degradation

Description

The action of radiation on concrete is to produce hydrogen gas from the radiolysis of free water in the cement pores.

Screening Analysis

Radiation could only potentially be important on 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, will be too distant to be significantly affected.

This process will be insignificant in the DGR due to the low radioactivity of the waste, and the decrease in radioactivity in the postclosure period.

FEP Screening

Screened out.

2.1.11.05 Asphalt Degradation

Description

Gas generated from the degradation of asphalt.

Screening Analysis

Other than aggregate or sand, asphalt consists of four different components: saturated hydrocarbons; aromatic hydrocarbons; resins; and asphaltenes. Under anaerobic conditions in the geosphere, asphaltenes are more or less unaffected by micro-organisms (Pettersson and Elert 2001) and the degradation of resins is expected to be very slow (see FEP [2.1.11.03]). Brodersen et al. (1991) state that with the present knowledge about biodegradation of bituminized waste, biodegradation seems to be of minor importance for the long-term evolution of asphalt. Any degradation would be slow, with only small volumes of CO_2 and CH_4 being produced (see Appendix E.6 of the System and Its Evolution report, QUINTESSA 2011b).

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 low levels of radioactivity in the wastes in the DGR, and the decrease in this radioactivity with time, indicates that radioactive decay is unlikely to have significant effects.

FEP Screening

Screened out.

2.1.13 Effect of 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 Postclosure SA assumes that a range of microbial populations are present in the repository at the time of closure, regardless of whether these are from the host rock or brought in with the waste packages. It is expected that the amounts of putrescible materials present underground will be minimized through the application of the appropriate managerial controls, and in any case these would be small relative to the amount of cellulosic material present in the LLW.

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 trigger, on average, at least one other nuclear fission. Nuclear criticality requires a sufficient concentration and localized mass (critical mass) of fissile isotopes (e.g., U-235, Pu-239) and also the 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.

CNSC (2010) provides minimum criticality screening values of 0.78 kg for U-235, 0.55 kg for U-233 and 0.48 kg for Pu-239, based on the pure isotope dissolved uniformly in an aqueous solution. It also indicates minimum concentrations in aqueous solutions of 11.6 g/L, 10.8 g/L and 7.3 g/L for U-235, U-233 and Pu-239 respectively.

The only source of Pu-239/241 and U-233 in the repository is that collected from failed fuel in the primary heat transport system (typically either sorbed on resins or onto piping and heat-exchanger surfaces. U-235 is present in similar small amounts from failed fuel, as well as in depleted uranium shielding (both about 0.2% enrichment).

The total mass of U-235, U-233 and Pu-239 in the combined LLW and ILW inventory is 1 kg, 0.005 kg, and 0.4 kg, respectively (derived from the inventory given in Section 3.5.2 of the Data report, QUINTESSA and GEOFIRMA 2011a). In all cases, these masses are mixed with other uranium and plutonium isotopes. Furthermore, these masses are dispersed in different wastes packages and emplacement rooms across the repository.

In a 10% resaturated repository, the water volume would be about 20,000 m^3. Assuming that this was sufficient to reach and dissolve out all these fissile isotopes, this leads to an aqueous solution density of less than 1 kg / 20,000 m^3 or less than 0.005 g/L, which is much less than the single parameter limit. Furthermore, the U-235 enrichment of ~0.2% is too low.

Therefore, criticality is not credible.

FEP Screening

Screened out.

2.2 Geological Environment

Description

Features and processes associated with the geological environment surrounding the repository including, for example, hydrogeological, geomechanical and geochemical features and processes, both in the 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 repository 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 Rock 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 rock 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 soils and unconsolidated 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 characterization. These properties will generally change with time and temperature.

Screening Analysis

The DGR will be located at ~680 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.

Regional and site-specific data show that heterogeneity within each stratigraphic formation/unit is small compared with the heterogeneities between formations/units. Therefore, it is assumed that each stratigraphic formation/unit is homogeneous.

FEP Screening

Include FEP in all scenarios.

2.2.02 Host Rock 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 characterization.

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 characterization 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 generalization 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. In this initial state, the rock could include atmospheric air and contaminants introduced into the repository during operation. 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 safety assessment models and calculations.

The rock is hundreds of millions of years old and stable. Bulk rock properties are expected to be time invariant over the duration of the assessment period, except for the shallow geosphere, where the properties may be influenced by glaciation – in particular, the change in permeability with permafrost.

As no significant temperature changes are expected at depth (see FEP [2.1.10]), host rock changes with temperature are not important.

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 the evolution of that zone. The extent of damage will decrease within increasing distance from the excavation. This zone of rock is generally known as the excavation damaged zone or EDZ. The most damaged rock, immediately adjacent to the excavation, may also be described as the Highly Damaged Zone (HDZ).

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 HDZ and EDZ around the repository emplacement rooms and tunnels are unlikely to have any significant impact due to the open repository design. However, the HDZ/EDZ along the monolith section of the tunnels may form a preferential pathway from the emplacement rooms to the shaft EDZ (Shafts [2.2.03.02]).

FEP Screening

Include FEP in all scenarios.

2.2.03.02 Shafts

Screening Analysis

The HDZ will be removed from the shaft wall prior to sealing the shafts, from about 180 m below surface to the repository horizon. The EDZ around each shaft may form a preferential pathway, with increased hydraulic conductivity, to the Shallow Bedrock Groundwater Zone.

The extent of the EDZ likely varies with the various rock formations due to their varying strength and stress conditions. It could also change with time – increasing due to stresses such as glaciation, and decreasing due to processes like creep or precipitation.

Modelling described in the Geosynthesis report (Section 6.4.3 of NWMO 2011) indicates that the EDZ is primarily due to stress relief and does not change much with time. The Postclosure SA, therefore, models the EDZ using conservative, time-invariant values for EDZ properties such as thickness and hydraulic conductivity.

It is possible that the EDZ will close with time, due to creep of clay minerals or precipitation of other minerals. However this process is conservatively not included in the present Postclosure SA model.

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. These are discussed under Disturbed zone (in geosphere) [2.2.03].

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 Paleozoic sediments at the Bruce nuclear site unconformably overlie Precambrian basement of the Huron Domain. The Huron Domain basement and the overlying Paleozoic rocks are overprinted by sparse ENE to NE-trending faults of Paleozoic age that displace the Proterozoic/Paleozoic unconformity. These faults are inferred by subsurface structure contouring and isopach mapping with limited well-control or through seismic interpretation. The closest interpreted fault structure is > 25 km away from the DGR footprint (Section 2.2.6.2 of NWMO 2011).

Investigations at the Bruce site have shown that the Paleozoic sediments are undeformed; dipping very gently (0.23° to 1.0°) to the southwest towards the basin depositional centre. A high degree of stratigraphic predictability and lateral facies consistency is observed between the DGR boreholes, and the DGR borehole stratigraphic data are consistent with expectations from interpolation of regional data to the site. This indicates that there is a lack of significant faulting in the vicinity of the DGR boreholes.

A 2-D seismic survey across the Bruce site identified several potential features interpreted to represent ancient and inactive basement-seated faults that extend upwards into the Upper Ordovician shales. However, the interpretation was uncertain due to data noise. Marker bed and other analyses, and two inclined DGR boreholes drilled to intersect the potential faults, have not found any evidence for the presence of faults near the DGR footprint. The most probably fault feature identified was located 1.25 km south of the DGR, and is interpreted as a Paleozoic aged fault that has been infilled. There is no evidence at the DGR site for the hydrothermal dolomite-style features found in the Middle Ordovician oil and gas fields in southwestern Ontario (Sections 2.2.6 and 2.2.8 of NWMO 2011)

Records of earthquakes in the region since the late 1800s up to 2009, and monitoring results from the seismograph stations around the Bruce site, show that the Bruce region experiences sparse seismic activity, with no apparent concentrations of activity that might delineate regional active faults or other seismogenic features.

FEP Screening

Include FEP in Vertical Fault Scenario only. In this scenario, it is conservatively assumed that there is a transmissive vertical fault in close proximity to the DGR.

2.2.04.02 Fractures and Joints

Screening Analysis

Regional jointing patterns have been used to investigate the history of tectonic forces in Southern Ontario (Section 2.2.6 of NWMO 2011). The presence, extent and nature of fractures and joints at the Bruce nuclear site have been investigated from cores taken from the DGR boreholes, and from acoustic televiewer logs of the boreholes.

Fractures are dominantly present at shallow depths. The fracture frequency decreases with increasing depth, and is low below approximately 180 m below ground surface (Sections 2.3.9 and 3.2 of NWMO 2011). This is to be expected because the increasing amount of overlying sediment and rock with increasing depth will resist stress relief fracturing due to the ENE orientated regional stress field; prevent fracturing due to historical changes in glacial loading (the percentage stress change is reduced with increasing depth); and tend to close fractures. The length scales of the shallow fracturing are such that, at the scale of the contaminant transport pathways, their impacts are subsumed within the measured hydraulic conductivities.

Fracture data from the site indicate consistency with regional observations. Vein in-filling and geometrical relationships suggest that these fracture sets were most likely formed during the Paleozoic (Section 2.3.10 of NWMO 2011). Also, the systematic joint patterns at surface and no significant joint offsets or zones with evidence of fault gouge suggest a lack of glacial-induced faulting proximal to the Bruce nuclear site (Section 2.3.10 of NWMO 2011).

Hydrogeological and geochemical evidence indicates that these small-scale fractures are closed and/or poorly connected, i.e., the hydraulic conductivities of the Ordovician (and the majority of overlying Silurian) formations are very low, and transport occurs by diffusive processes, e.g., Sections 4.6 and 5.5 of NWMO (2011).

Section 2.3.8 of NWMO (2011) notes that conditions are unsuitable for karst development in the Intermediate and Deep Bedrock Groundwater Zones. Paleokarst horizons do exist but the hydraulic conductivity does not appear to be significantly elevated and the horizons are not interconnected.

FEP Screening

Include FEP in all scenarios. However, there are no continuous discrete fracture networks, and so the presence of fractures is subsumed within the measured formation hydraulic conductivities.

2.2.04.03 Dykes

Screening Analysis

There is no evidence of dykes at the DGR site. At the regional scale, dykes have only been identified in the Precambrian basement (Section 2.2.3 of NWMO 2011).

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 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. Geotechnical testing of core samples from the DGR boreholes, existing underground structures in the Ordovician formations at shallow depths elsewhere in the region, and geomechanical modelling indicate that stable excavations can successfully be created (NWMO 2011). The boreholes themselves can be regarded as empirical 'trial excavations'. Optical and acoustic televiewer borehole logs indicate that there has not been any rock failure in the walls of the boreholes. The borehole cores indicate that the deep and intermediate geosphere have "excellent" Rock Quality Designation, with near 100% recovery of long intact core samples (Section 3.2 of NWMO 2011).

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. Geomechanical models of the stability of the open tunnels/emplacement rooms and shaft have been developed (Section 6.4 of NWMO 2011). These models show that the EDZ forms rapidly through stress relief, over timescales of the order of 100 years.

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. Present and historical earthquake distribution data, from the site and region, indicate that the basement beneath the site is presently tectonically quiescent.

A Probabilistic Seismic Hazard Assessment was performed for the Bruce nuclear site. The frequency of M6 or greater earthquakes within 200 km of the site was estimated at 10^{-4} per annum (Chapter 6 of AMEC GEOMATRIX 2011). This is approximately equivalent to an annual frequency of an M6 or greater event of 10^{-6} within a 20 km radius of the site, assuming roughly uniform probability across the area.

There is reason to believe that this rate could change as a result of future glaciation which causes vertical stress changes that may temporarily increase seismicity rates. Assuming Milankovitch control, future major glacial – interglacial cycles are anticipated to have a periodicity of around 100,000 to 120,000 years. However, a recently completed remote-sensing and field-based study looked at landforms within 50 km of the Bruce nuclear site and found no evidence for neotectonic activity associated with the most recent glacial cycle within the regional study area (Section 2.2.6 of NWMO 2011).

Earthquakes may result in rockfall from the roofs of the unsupported (i.e., not backfilled) tunnels and emplacement rooms. Glacial loading and unloading will tend to result in collapse from the pillars between the emplacement rooms. Eventually the void space in the repository will be filled by rockfall from the roof and pillars and the system will stabilize.

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 (Section 5.2 of NWMO 2011).

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 and paleoclimate groundwater simulations (Sections 4.6 and 5.4.6 of NWMO 2011) indicate that fresh glacial meltwaters were injected to the depth of the Salina G formation at the DGR site during the last glacial cycle. There was also injection of glacial meltwaters from outcrop to the deeper Salina A1 Upper Carbonate, which is a thin, relatively permeable formation, within the deeper Intermediate Bedrock Groundwater Zone.

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; however, transient hydrogeological models indicate that it could take >1 Ma for the equilibrium conditions to be achieved (Section 5.4 of NWMO 2011).

Site-investigation data, and geochemical and hydrogeological modelling (Chapter 8 of NWMO 2011) indicate that these disequilibrium heads are not due to historic glacial conditions, and that heads in the Intermediate and Deep Bedrock Groundwater Zones are unlikely to be significantly affected by future glaciations.

FEP Screening

FEP included in the Reference Case for Normal Evolution Scenario. However, a Simplified Base Case considers a more conservative, future equilibrium (i.e., non-evolving) condition to allow the effect of discounting the Ordovician under-pressures to be investigated.

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., changes in Eh and pH, and the dissolution and precipitation of minerals. The chemical conditions affect the mobility of contaminants. The main chemical processes included in the assessment are contaminant sorption and solubility (dissolution/precipitation reactions).

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. Knowledge of geochemical conditions in the geosphere is 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 of the geosphere will affect the migration of contaminants. They are used to inform the selection of distribution coefficients that describe contaminant mobility (see Appendix D of the Data report, QUINTESSA and GEOFIRMA 2011a). The main geochemical conditions that affect groundwater transport of contaminants are pH and Eh.

The evolution of the repository and its contents are expected to cause some perturbation in these geochemical conditions but any effects are expected to be limited to the immediate vicinity of the DGR (Section 5.4.1 of the System and Its Evolution report, QUINTESSA 2011b). Although the chemical conditions in the near-surface will likely change, for example due to injection of glacial meltwaters, there is site-specific and regional geochemical evidence that deep groundwaters are ancient and, therefore, only slowly changing (e.g., Chapter 8 of NWMO 2011). Therefore, conditions in the geosphere are taken to time-invariant for the assessment.

FEP Screening

Include FEP in all scenarios.

2.2.07.03 Effects of Engineered Barriers

Screening Analysis

The engineering materials in the repository and shafts 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 (see Section 5.4.1 of the System and Its Evolution report, QUINTESSA 2011b).

Reactions between the shaft seal materials and the surrounding rock (EDZ) are unlikely as the materials are expected to be compatible – concrete monolith with limestone rock, bentonite clay with shales and limestones, asphalt with the shales. Unexpected reactions between shaft materials and EDZ in the rock are bounded by the Severe Shaft Seal Failure Scenario.

FEP Screening

Include FEP in Severe Shaft Seal Failure Scenario only.

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. However, for the Postclosure SA, these changes are assumed to have limited effect on the assessment calculations and a stylized approach using constant climate conditions is adopted (Section 2.3 of the Normal Evolution Scenario Analysis report, QUINTESSA 2011a). Geochemical evidence indicates that the waters below the Shallow Bedrock Groundwater Zone are ancient and will not be perturbed by climate change (e.g., Chapter 8 of NWMO 2011).

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., on 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. This is due to the age of the rock formations, and the high salinity, small porosity and low organic content of the current geosphere.

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 22^{o}C with a gradient of approximately 1.75^{o}C per 100 m depth (Section 5.1 of the Data report, QUINTESSA and GEOFIRMA 2011a).

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 (see FEP [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. There may be slight localized heating of the geosphere during the very early postclosure phase adjacent to rooms containing the most radioactive wastes; particularly the retube wastes. However, the duration of heating will be negligible on postclosure timescales and the temperatures will not be sufficient to alter the geosphere properties. Other potential sources of heat are not significant; see Thermal processes and conditions (in wastes, emplacement rooms, tunnels and shafts [2.1.10]).

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 formation.

It is recognized that the surface and near-surface environment will be significantly affected with the formation of discontinuous permafrost down to 60 m (see Section 5.2 of the System and Its Evolution report, QUINTESSA 2011b). However this will have no effect on the deeper geosphere properties.

It is expected that the geosphere temperature profile will respond by several degrees due to glacial – interglacial cycles (see Section 5.1 of the System and Its Evolution report, QUINTESSA 2011b). This will have negligible effect on the rock properties.

FEP Screening

Screened out.

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 in, 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 from 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

Methane gas is found in the regional oil/gas fields elsewhere in southern Ontario, and its generation is a consequence of the thermal history of the sedimentary basin and resultant evolution of organic materials originally deposited with the sediments (Section 2.2.8 of NWMO 2011).

There is no significant generation of gas in the deep geosphere in the area of the DGR. For example, pressurized gas at depth was not encountered during the drilling of the DGR boreholes. Trace amounts of gas have been found throughout the Intermediate and Deep Bedrock Groundwater zones. Measurements indicate formation average free gas saturations of 0 to 20% (Section 5.3 of NWMO 2011), although the values are uncertain due to the low rock porosity and other factors. Multiphase flow models (Section 5.4.9 of NWMO 2011) show that the presence of this non-wetting gas phase can explain the under-pressures observed in the Ordovician formations.

FEP Screening

FEP included in the Normal Evolution Scenario (Reference Case).

2.2.10.02 Gas Migration

Screening Analysis

Gas can migrate in the geosphere either in the gas phase (free gas) or through dissolution and subsequent transport in groundwater (dissolved gas). Gaseous radionuclides can be transported within the free gas phase or as dissolved gas. Gas 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 increase the area over which exchanges could take place (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 parameter uncertainty for gas permeability, capillary pressure curve, etc. Transport of free and dissolved gasses, dissolution and exsolution are considered as two-phase-flow processes.

FEP Screening

Include FEP in all scenarios.

2.2.10.03 Gas Dissolution

Screening Analysis

Gas can dissolve and exsolve in/from groundwater. Dissolution/exsolution is 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 of carbon dioxide (precipitation of carbonates). Calcite is present throughout the geosphere, including notable quantities within the shale lithologies (Section 2.3.5 of NWMO 2011).

Transport of bulk gas within the shaft and subsequent dissolution within the Shallow Bedrock Groundwater Zone is recognized 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, and throughout the geosphere (see also Effects of engineered barriers [2.2.07.03]).

FEP Screening

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 lower than the horizontal stresses.

Under natural conditions, gas reservoirs typically have pressures around the environmental head. Engineered underground gas storage systems typically allow gas pressures to be somewhat higher, but less than the lithostatic pressure. NAGRA (2008) considers pathway dilation to occur at 80% of lithostatic pressure.

Modelling for the DGR indicates that the gas pressures from gas generation within the DGR are likely to be of the order of the natural hydrostatic pressure (~7 MPa) at the DGR horizon on relevant (1 Ma) timescales, and much less than the lithostatic pressure of about 17 MPa (see Chapter 8 of the Gas Modelling report, GEOFIRMA and QUINTESSA 2011). In the longer term, the gas pressure in the DGR would likely equilibrate with any free gas phase present in the geosphere.

Therefore, formation of gas-induced fractures in the geosphere at the DGR site is not expected. However, it is possible that the gas pressure may be sufficient to cause ‘piping’ at the interface of the bentonite-sand shaft seals and the shaft wall under certain conditions (Section 5.5.2 of the System and Its Evolution report, QUINTESSA 2011b).

FEP Screening

Screened out for all scenarios except for the potential for piping at the interface between the bentonite-sand shaft seals and the shaft wall, which is bounded by the Severe Shaft Seal Failure Scenario.

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 nuclear site. Commercially useful petrochemical resources were not found. The DGR-series boreholes drilled at the site have confirmed the presence of hydrocarbons, but these are only present in small quantities and are not commercially exploitable. There is no indication that mineral resources are available in the Precambrian basement rocks.

Although significant deposits of salt and anhydrite are present to the south of the region, there are only minor deposits at the Bruce nuclear site and these are not commercially viable: the formations are too thin and the salt/evaporate content too low for brine extraction to be viable, or for the formations to be used for gas storage. There are no other significant mineral resources within the Paleozoic sediments.

Sand and gravel resources are present in the surficial deposits in the region and there is some extraction. Four disused quarries exist in the controlled development zone around the Bruce nuclear site. Sand and gravel extraction from the surficial deposits will not have any consequences for the performance of the DGR.

The Surficial and Shallow Bedrock Groundwater Zones are aquifers, and water is currently pumped from boreholes up to 120 m deep for municipal and domestic use in the region (see Section 2.4.4 of the System and Its Evolution report, QUINTESSA 2011b). It is expected that salinity levels will limit the depth of any well at the site to around 80 m (see FEP [2.4.05.03]).

FEP Screening

Include pumping of well water 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 repository.

Screening Analysis

Multiple lines of geological and geophysical evidence indicate that there are no large scale faults or fracture zones in the geosphere (see Large-scale discontinuities [2.2.04]). The reservoir rocks and structural formations that host commercially exploitable hydrocarbon reservoirs elsewhere in the region are not present at the Bruce nuclear site. These features would have been identified by the site investigation techniques employed at the DGR (Section 2.3 of NWMO 2011).

Multiple lines of hydrogeological and geochemical evidence indicate that the Deep Bedrock Groundwater Zone has been isolated for millions of years. This indicates that in the unlikely event that any undetected features are present, they are presently sealed and have been for a very long time.

FEP Screening

Include FEP in the Vertical Fault Scenario only to investigate the consequences of an undetected vertical fault in close proximity to the DGR. The Human Intrusion Scenario assumes that the repository might not be detected prior to the drilling of an exploration borehole.

2.3 Surface Environment

Description

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

The "Surface Environment" category of FEPs are inside the spatial and temporal boundaries of the repository 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 human 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 wind erosion and river meandering, , that could occur over a few centuries. 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 (such as denudation and deposition from ice-sheets) and human actions are discussed under Climatic processes and effects [1.3] and Future human actions (active) [1.4].

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 and the presence of depressions affect the amounts of moisture and soil that are retained locally, which in turn influences plant and animal communities.

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.

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

As noted in Tectonic movement and orogeny [1.2.01], there is no mountain building occurring in the region, only gradual erosion. In addition, the Normal Evolution Scenario considers ice-sheet advance and retreat. As discussed in Section 2.4 of the System and Its Evolution report (QUINTESSA 2011b), the current-day topography around the Bruce nuclear site and the larger region is relatively flat. It is expected that a relatively low-lying topography with bluffs or hills due to glacial moraines and related post-glaciation features, will be maintained during subsequent ice-sheet advances and retreats. Although the exact topography is not known, it is expected to be sufficient to drive water flow through the shallow bedrock zone aquifer at the site. However, the topography will be too small to significantly influence the low-permeability intermediate and deep bedrock groundwater zones.

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 characterized 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 current climate of the Bruce nuclear site is best described as temperate-boreal because of its 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 relatively close to Lake Huron and the resulting marsh and wetland areas associated with the watercourses and lake margins.

As climate changes (see Global climate change [1.3.01] and Regional and local climate change [1.3.02]), the nature of the biome at the site will change, as described in Section 6.3 of the System and Its Evolution report (QUINTESSA 2011b).

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 metres of the surface. Typically the top 0.2 to 0.3 m is the active surface soil region that 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 characterized 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, and organic content), different land-management practices (e.g., irrigation and fertilization needs, crop yields) and different contaminant transport properties (e.g., sorption). Microbial populations (or their absence) are an important component of soils and sediments.

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. 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.

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

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]).

Screening Analysis

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.

The soil type at the site may change over time, for example due to climate change (see Section 6.3.2.1 of the System and Its Evolution report, QUINTESSA 2011b).

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 high clay content can be relatively impermeable, and groundwater flow might be restricted or confined to channels and fractures. A localized 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.

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.

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

Screening Analysis

At the Bruce nuclear 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 nuclear site.

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 compacted sediments may eventually form surface soil and unconsolidated sediments when, for instance, a river changes its course or a lake dries up. They can be 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 due to climate-induced changes in lake level.

Screening Analysis

The Bruce nuclear 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, being 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 Section 2.4.2 of the System and Its Evolution report, QUINTESSA 2011b).

Although the precise characteristics of such water courses 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 (see Section 6.3.2.1 of the System and Its Evolution report, QUINTESSA 2011b). 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 tens of 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.

Screening Analysis

Groundwater flows westward through the Shallow Bedrock Groundwater Zone to discharge into Lake Huron. Layers of sand and gravel constitute local aquifers in the unconsolidated sediments above the Shallow Bedrock Groundwater Zone, whereas the till layers comprise aquitards (i.e., they restrict groundwater flow) (Section 2.3.6.2 of the System and Its Evolution report, QUINTESSA 2011b).

The aquifers in the area of the DGR are used for water abstraction and can provide the source for natural discharge to the surface (Section 2.4.4 of the System and Its Evolution report, QUINTESSA 2011b).

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, whereas 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 (see Other contaminated materials [3.3.03]).

Screening Analysis

Wetlands are present in the regional area and on the Bruce nuclear site (see Section 6.1.1 of the Data report, QUINTESSA and GEOFIRMA 2011a). The WWMF and the immediate surrounding area discharge into the Railway Ditch (originally excavated parallel to the abandoned rail line). The Railway Ditch drains into Stream “C” which flows slowly into the Baie du Doré, which is a provincially significant wetland. Under most prevailing current conditions, there is little circulation in the Baie du Doré, which appears to be more heavily influenced by wind and wave action than by broad circulation patterns in the lake. There is also a small wetland (4 ha), located east of the WWMF boundary, which is not a provincially significant wetland.

FEP Screening

Include FEP in all scenarios.

2.3.05.02 Lakes and Rivers

Description

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 nutrients, suspended sediment and contaminants through the water body. Contaminants may enter a lake at a localized 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 (see Regional and local climate change [1.3.02]) 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].

Screening Analysis

The Bruce nuclear site is situated on the shores of Lake Huron. There are no major rivers or lakes in the vicinity of the site other than Lake Huron.

Lake Huron is important as the ultimate receptor for any contaminants discharged from the DGR. It is the source of livelihood and sustenance (fishing) for local people – both current and historic. It also is on the water supply route for several million people. Therefore, it needs to be included in the assessment. The assessment needs to distinguish between the local near-shore conditions, as well as the larger lake conditions, in order to capture the effects of dilution.

The next glaciation cycle will change the local topography. However, the generally flat topography of southern Ontario and the Michigan basin, and the large scale dipping that forms the current Great Lakes, are likely to support some form of lakes in the vicinity. It is, therefore, reasonable for Postclosure SA purposes to assume a large lake similar to Lake Huron would exist in the vicinity.

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 beaver dams, 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 can run dry, possibly a seasonal occurrence. Climate changes (see Regional and local climate change [1.3.02]) 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

Under present-day conditions, any discharges from the repository would be captured in either the Guelph or Salina A1 upper carbonate formations, or the Shallow Bedrock Groundwater Zone. The Guelph and Saline A1 upper carbonate have low hydraulic gradients that are not immediately towards the lake. The Shallow Bedrock Groundwater Zone flows directly into Lake Huron. It is recognized that under future conditions, terrestrial discharge might be possible, for example due to significantly lower water levels in Lake Huron (see Section 6.3.4 of the System and Its Evolution report, QUINTESSA 2011b) and such a discharge is considered in the tundra variant case.

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 is characterized 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 Postclosure 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

The location of the DGR is inland. Therefore, there is no need to include marine features in the assessment.

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 agricultural or land-clearing fires; natural forest and grass fires; and fires from burning of peat, wood and other fuels for heating purposes. Forest and other fires can become potent agents for atmospheric contamination, if the material is contaminated.

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. 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 significant dilution potential. For instance, wind is a major environmental force in the transport of contaminants through the atmosphere. 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 indoor as well as outdoor atmospheric conditions need to be considered (see Dwellings [2.4.07]).

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. Particular consideration needs to be given to any local endangered or valued species.

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.

Vegetation will change with time, for example due to climate change (see Regional and local climate change [1.3.02]), with consequent changes to its properties and its effects on contaminant transport and exposure routes. Local ecosystems will also 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 transferred through 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 concentrations in both aquatic and terrestrial biota, and contaminant movement in surface waters.

Screening Analysis

The biosphere within the DGR system currently includes areas of farmed land and semi-natural land (including wetland). Farmland accounts for around 60% of the land use in the Bruce county, with cattle, pigs, sheep, goats and poultry, and crops such as oats, barley, canola and hay (Sections 6.4 and 6.5 of the Data report, QUINTESSA and GEOFIRMA 2011a).

As climate changes, the nature of the vegetation at the site will change, as described in Section 6.3 of the System and Its Evolution report (QUINTESSA 2011b).

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
- Wild food 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 groups of animals is those (both domestic and wild) that might serve as a source of food for local people.

- Habitat can affect 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 animal population 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 cattle, pig, sheep, goats, poultry) and fish are present in the area surrounding the Bruce nuclear site and represent potential pathways for human exposure to contamination (see Section 6.5 of the Data report, QUINTESSA and GEOFIRMA 2011a). The Bruce nuclear site and surrounding area also provides habitat for a variety of wildlife, including reptiles and amphibians (see Section 2.4.8.2 of the System and Its Evolution report, QUINTESSA 2011b).

As climate changes, the nature of the animal populations at the site will change, as described in Section 6.3 of the System and Its Evolution report (QUINTESSA 2011b).

Animals can become exposed to contaminants 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 characterized 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.

In addition to long-term variations (see Global climate change [1.3.01] and Regional and local climate change [1.3.02]), 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 current annual mean temperature for the site is 8.2 °C, with mean daily temperatures varying from -3.7 °C in January and February to 17 to 20.2 °C during June to August. The annual rate of precipitation is about 1000 mm/y with about 30% falling as snow. The average wind speeds in the area are about 3.5 m/s with generally stronger winds in the winter season. The prevailing winds are from the southwest. See Section 2.4.1 of the System and Its Evolution report (QUINTESSA 2011b) and its supporting references for further details.

The climate and weather affects the types of ecosystems and land use that are present in the area. The potential impact of climate change on the types of future ecosystems and land use at the Bruce nuclear site are described in Section 6.3.4 of the System and Its Evolution report (QUINTESSA 2011b).

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. Key components are run-off (precipitation water that flows laterally over the top of the soil into a water body), and interflow (precipitation water that flows laterally through the soil into a water body). They are important in determining the flushing rate of surface-water bodies. They may also carry contaminants, scavenged from the atmosphere or leached from soil and plants, to water bodies. Moreover, run-off and interflow are important components 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 for example due to climate change (see Global climate change [1.3.01] and Regional and local climate change [1.3.02]) 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 current 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. The potential impact of climate change on the future hydrological regime at the Bruce nuclear site is described in Section 6.3 of the System and Its Evolution report (QUINTESSA 2011b).

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 erosion and deposition, denudation, aeolian 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, unconsolidated sediment and bedrock by wind, water and ice may move contaminants laterally away from a discharge area, or it may bring uncontaminated soil and sediment 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 categorized as catabolism (breaking down of more complex molecules) and anabolism (building up of life molecules from simpler materials);
- Co-metabolism 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 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. The ecosystems, therefore, provide a potential exposure route for humans, but also provide the systems within which exposure of non-human biota may occur

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

The transfer factors and concentration ratios used to describe contaminant transport along biosphere pathways are based on laboratory and field measurements that include these processes in aggregate.

FEP Screening

Include FEP in all scenarios.

2.3.15 Biotic Intrusion

Description:

Includes contributions from both burrowing animals and plants.

Animals burrow in the ground for shelter, nesting, storage, and foraging. Burrows for shelter can extend to depths greater than 1 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.

Depending on the vegetation type in the vicinity of the repository and the repository design, 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 emplacement of radioactive waste in a DGR are calculated. Note 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 critical groups” and, therefore, is inside the spatial and temporal boundaries of the repository system domain. Note, however, that it excludes intrusive or intrusion 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 Liquid 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 metabolize 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 metabolize 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, human water ingestion rates, and human breathing rates (see Chapter 7 of the Data report, QUINTESSA and GEOFIRMA 2011a).

According to the CNSC Regulatory Guide G-320 (CNSC 2006): “The use of human receptors in a scenario may be based on the 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 stylized approach based on more general habits and conditions could be used.”

FEP Screening

Include FEP in all scenarios implicitly through use of radiation dose coefficients.

2.4.02 Age, Gender and Ethnicity

Description

Susceptibility to radioactive and chemically toxic materials varies with age, sex and reproductive status. In addition, 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. Exposure of the embryo and foetus is not generally more limiting than exposure of other age groups, except for a few radionuclides, such as P-32 and P-33 that are not of relevance in solid radioactive waste disposal (Thorne 2006). Therefore, for scenarios in which children or infants may receive exposure, the Postclosure SA assess all three age groups and data for adults, children and infants are provided in Chapter 7 of the Data report (QUINTESSA and GEOFIRMA 2011a).

Differences in dose rate due to gender are discussed in the OPG (2005b) report on alternative critical groups for the Postclosure SA, and the Whillans (2006) report on gender effects in radiation dose and risk assessment for deep geological disposal. According to OPG (2005b), 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 with 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 Postclosure SA to differentiate between doses to male and female receptors.

Ethnicity is not considered a relevant factor in the Postclosure SA.

FEP Screening

Include age in all scenarios.

2.4.03 Diet and Liquid 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 fruits 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 nuclear site.

Therefore, the Postclosure SA includes a self-sufficient farming household as the primary critical group (the Site Resident Group). The diet and liquid intakes of the farming household as well as the source of these foodstuffs is explicitly included in the assessment (see Section 2.3.3 of the Normal Evolution Scenario Analysis report, QUINTESSA 2011a, and Section 7.1 of the Data report, QUINTESSA and GEOFIRMA 2011a).

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 with a well would be the highest and, therefore, as noted in FEP [2.4.03.01], this diet and lifestyle is included in all scenarios.

The current diet of people living in the area includes 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 Site Resident Group noted in FEP [2.4.03.01] (see Section 7.1 of the Data report, QUINTESSA and GEOFIRMA 2011a). Therefore, some elements of a hunter diet are already included in the Site Resident 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 element, specifically with a large fish component. A diet with a significant fish component would also be an alternative of interest to current communities more distant from the DGR in terms of possible impact. Therefore, it is useful to demonstrate the implications of these alternative diets within the Normal Evolution Scenario. Two diets are evaluated – a high-fish diet based on current conditions, and a tundra lifestyle diet. The high-fish diet is also evaluated for the Vertical Fault Scenario which considered a release from the Guelph and Salina A1 upper carbonate into the near shore of the lake.

FEP Screening

A fisher diet and a tundra diet are considered in variant cases for the Normal Evolution Scenario and a fisher diet is also considered in the Vertical Fault 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 groups with differing diets. However, since a self-sufficient farming diet usually gives a reasonable or conservative estimate of dose, and since the fisher and tundra diets are included, as outlined in FEP [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 above ground, 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 Postclosure SA include (see Section 2.3.3 of the Normal Evolution Scenario Analysis report, QUINTESSA 2011a, and Section 7.1 of the Data report, QUINTESSA and GEOFIRMA 2011a):

- Time spent indoors;
- Time spent outdoors;
- Time spent immersed in water (bathing or swimming);
- Water source (well or lake), see also under FEP [2.4.05.03]; and
- Agricultural practices, if any (irrigation, ploughing).

The impact of climate change on habits is considered in a variant calculation case for the Normal Evolution Scenario (see Section 4.4.3 of the Normal Evolution Scenario Analysis report, QUINTESSA 2011a).

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:

2.4.05.01 Community Type

2.4.05.02 Community Location

2.4.05.03 Water Source

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 specialized 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 associated with specific types of community 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 Postclosure SA. The reference community is a rural farm household with food self-sufficiency as this generally results in the highest exposure.

FEP Screening

Include FEP in all scenarios.

2.4.05.02 Community Location

Description

The location of the community relative to the DGR.

A community most at risk might be situated on the discharge area of groundwaters that may have become contaminated by the DGR. Alternatively, the largest impacts might be experienced by a community situated at a downstream location, where contaminants from multiple groundwater discharge areas converge and accumulate.

Screening Analysis

In the Postclosure SA, it is assumed that a farm exists on above the DGR. The well, home and fields are conservatively located where potential radionuclide concentrations and, hence, calculated dose rates would be highest (see Section 2.3.3 of the Normal Evolution Scenario Analysis report, QUINTESSA 2011a).

Dose rates to communities living "downstream" are likely to be lower than for groups living near the DGR due to dilution in the surface environment, but are also explicitly addressed (see Section 4.4.2 of the Normal Evolution Scenario Analysis report, QUINTESSA 2011a).

For the Human Intrusion Scenario, in addition to site residents, consideration is given to the drill crew at the wellhead and a laboratory technician who examines contaminated core (see Section 2.2.2 of the Human Intrusion and Other Disruptive Scenarios Analysis report (QUINTESSA and SENES 2011).

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 other demands, such as for agriculture.

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.

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 sources might be required for a large 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.

There is also a need to consider the potential impacts of waste water processing, which may affect exposures to critical groups and biota.

See also the related discussions under:

- Water management (groundwater and surface water) [1.4.10] which includes more considerations on water-supply wells;
- 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 critical groups is an important consideration in the Postclosure SA.

The assessment assumes that potential exposures may arise from taking domestic and agricultural water from a well (which will have higher contaminant concentrations than the lake) that intersects a contaminant plume from the DGR (Section 2.3.3.2 of the Normal Evolution Scenario Analysis report, QUINTESSA 2011a). The reference well depth (80 m) is based on consideration of the local aquifer depth and typical practice for wells in the area (Section 5.4.3 of the Data report, QUINTESSA and GEOFIRMA 2011a). The groundwater becomes increasingly brackish at greater depths (see Section 2.3.7 of the System and Its Evolution report, QUINTESSA 2011b). The well is conservatively taken to be the source of domestic and agricultural water.

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 conservative assumption.

The Postclosure 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 Postclosure SA:

- the location, taken to cover part of a shaft (Section 2.3.3.2 of the Normal Evolution Scenario Analysis report, QUINTESSA 2011a), with the associated potential for gas release into the building;
- the building size, as specified by building height and width (Section 6.3 of the Data report, QUINTESSA and GEOFIRMA 2011a); and
- the building air infiltration rate, i.e., the number of air exchanges per hour (Section 6.3 of the Data report, QUINTESSA and GEOFIRMA 2011a).

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 that 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 liquid 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 contaminants from the waste reach the surface environment (e.g., Lake Huron itself and the wetlands adjacent to Baie du Doré). These areas include biota of interest in the assessment. Critical groups may also use these areas, for example, for recreation, hunting and gathering food.

Note that the use of this land by critical groups depends on the characteristics of such groups. As noted under Hunter/gatherer diet [2.4.03.02], some elements of a hunter diet, which makes use of natural/semi-natural land, are already included in the Site Resident Group.

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 is that related to agricultural practices that can affect the land form, hydrology and natural ecology, and that 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 fertilizers (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 additional 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 contaminants from the waste reach the surface environment. Critical 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 critical groups include (Section 2.3.3.2 of the Normal Evolution Scenario Analysis report, QUINTESSA 2011a):

- Raising poultry, pigs, sheep, goats, beef cattle and milk cows on local land;
- Growing 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-fertilize, 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 contaminants discharged from the DGR because the food and water they consume would likely come from wider geographical sources, and so any contamination in their food and water would be subject to significant dilution (e.g., 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 baseball, soccer 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

Leisure activities in the area around the DGR include use of land that may become contaminated by releases from the DGR, including hunting and foraging in natural and semi-natural areas, fishing and swimming (see Section 2.3.3.2 of the Normal Evolution Scenario Analysis report, QUINTESSA 2011a). The effect of potential leisure activities on the habits and behaviour of critical groups is, therefore, addressed (see Section 7.1 of the Data report, QUINTESSA and GEOFIRMA 2011a).

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 repository system, 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 Postclosure SA throughout the modelled system, including the repository, geosphere and biosphere. Section 3.5 of the Data report (QUINTESSA and GEOFIRMA 2011a) provides a list of radionuclides to be included in the Postclosure 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 form of radionuclides, including formation of organic forms, is not explicitly modelled in the Postclosure SA. Transport properties are generally more empirically based. For example, the effect of chemical speciation is implicitly accounted for in the selection of associated parameter values, e.g., solubilities and sorption coefficients, which are often derived from field values and reflect typical speciation.

FEP Screening

Implicitly 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 would 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 given in Tables 3.17 and 3.18 of the Data report, QUINTESSA and GEOFIRMA (2011a). Specific information on organic constituents in wastes is provided in the Inventory Report (OPG 2010).

The kinetics of degradation of organic toxins is neglected for the groundwater pathway (i.e., toxin amounts are assumed to remain constant). This is conservative since these compounds are likely to degrade over the long times relevant to Postclosure SA. Non-organic toxins are also assumed to be stable.

Although the specific chemical form of a toxin is not modelled, the Environmental Quality Standards used to assess their impacts are typically derived assuming the most limiting chemical form (Section 7.3 of the Data report, QUINTESSA and GEOFIRMA 2011a).

FEP Screening

Include FEP in all scenarios (i.e., toxins are stable).

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.

Screening Analysis

The contaminant inventories are identified in Chapters 2 and 3 of the Inventory Report (OPG 2010). The inventories of substances of potential concern are described in Waste inventory [2.1.01].

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 FEP [3.1.06]) or may form volatile compounds, such as C-14 incorporated into carbon dioxide or methane, I-129 forming iodine gas or methyl iodide, 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 Postclosure SA Gas Modelling report (GEOFIRMA and QUINTESSA 2011), bulk 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/shaft 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 exsolves, appearing as bubbles near a discharge area. See also Gas sources and effects [2.1.11 and 2.2.10].

Trace radioactive gases can potentially be entrained by, and transported with, bulk gas. The potential for certain radionuclides to volatilize, specifically Cl-36, Se-79 and I-129, is taken into account in the assessment model. (H-3 and C-14 are also considered to form radiolabelled gases). 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 volatilization is given in Section 2.3 and Appendix D of the Normal Evolution Scenario Analysis report (QUINTESSA 2011a).

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 relevance is Rn-222 (radon-222), the decay product of Ra-226 (radium-226). 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 Postclosure 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 (Appendix A of the Data report, QUINTESSA and GEOFIRMA 2011a).

FEP Screening

Include FEP in all scenarios but only for Rn.

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 emplacement. Contaminant releases from a waste repository can occur through numerous pathways during the natural evolution of the facility, dependent on the location of the emplacement rooms and the characteristics of the waste forms, waste packaging, and the engineered barriers.

Once released from their initial state at emplacement, contaminants migrate from the repository and are transferred to 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 Mineralization

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 emplacement in the repository.

The release of contaminants from their physical state at emplacement 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, the following 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. 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.
  - Diffusion of contaminants out of waste packages.

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 materials and 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 components).
  - 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, building basements (in particular for radon gas), wells, springs, rivers, lakes.
  - Dissolution of gas: Dissolution of gas released from the waste, waste form and engineered components 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 (e.g., drilling, excavation).
  - Natural disruption events and processes: Events occurring over a short period of time (e.g., seismic activity) and also 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. 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 recognize 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. The release of contaminants from ion-exchange resins may be more rapid and may be controlled by ion exchange upon ingress of saline porewater into the DGR.

Consideration of the three pathways of release has been incorporated into the modelling for the Postclosure 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 water 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 occur gradually. Their resaturation is described in Sections 2.3.1 and 2.3.2 of the Normal Evolution Scenario Analysis report (see QUINTESSA 2011a).

Groundwater flow rates in the host rock (and deep geosphere) are very low due to the very low permeability of the rock, and contaminant transport will be diffusion dominated (Section 5.5 of NWMO 2011). However, the DGR, shaft seals and the associated EDZs are comparatively more permeable. There may be advective flows from the DGR into the shaft/shaft EDZ depending on the pressure gradients and how the orientation and magnitude of these gradients evolve as the DGR and shaft resaturate, gas is generated in the DGR and the geosphere very slowly evolves from disequilibrium pressure conditions towards equilibrium conditions.

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 relevance 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

The majority of the wastes in the DGR have carbon steel packaging that will rapidly degrade and will not form a long-term barrier to waste-water contact or contaminant release. Some wastes are robustly packaged with stainless steel and concrete; these containers may have long lifetimes in the DGR which will act to limit/prevent waste-water contact and contaminants will only slowly diffuse through the containers. However, conservatively no account is taken of the packaging in the Postclosure SA.

In the Postclosure SA it is assumed that the water within each emplacement room is well-mixed due to diffusion. This well-mixed assumption is made because there is no backfill and diffusive mixing within the water in each room will, therefore, be relatively rapid on postclosure timescales. There will also be diffusive transport of radionuclides in water between different areas of the DGR. The block walls separating the rooms do not have any postclosure safety function and, therefore, they are assumed not to form a barrier to contaminant migration.

Following closure, the humidity in the DGR will rapidly reach 100%. Under these conditions a thin film of water will exist on the surfaces of the unsaturated wastes. Although this film is very thin, over postclosure timescales there may be diffusion of surface contaminants from the unsaturated wastes into the saturated wastes. However, this will only occur if concentration gradients develop, e.g., due to loss of contaminants from the saturated wastes. Overall, this potential release mechanism is considered to be of secondary importance. It can be neglected in the Postclosure SA, and its effects bounded by variant calculation cases, e.g., instantaneous repository resaturation.

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

Although advective flow is unlikely in much of the repository system, the model allows for its occurrence and, therefore, the model also includes dispersion.

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 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 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 have very low hydraulic conductivity (Section 5.4 of the Data report, QUINTESSA and GEOFIRMA 2011a), resulting in diffusion-dominated transport and negligible advection and hydrodynamic dispersion in the geosphere. However, advection is included in the geosphere model as it may be significant in some circumstances or rock formations, notably the Guelph, Salina A1 Upper Carbonate and the Shallow Bedrock Groundwater Zone.

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 relevance 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 (see Chapter 8, NWMO 2011).

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, but will occur in the shaft/shaft EDZ if there is advective flow within these features (see FEP [3.2.02.01.C]).

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 characterization 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]), and/or hydraulically isolated.

Small-scale fractures and joints are present throughout the Shallow Bedrock Groundwater Zone, although their frequency decreases with depth as the overlying sediment and rock increases (see Fractures and joints [2.2.04.02]). 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 taking place in an equivalent porous medium. Contaminant transport can also be treated as transport within an equivalent porous medium. This will tend to underestimate the advective transport velocity in the Shallow Bedrock Groundwater Zone, but this is inconsequential compared with the travel time in the Deep and Intermediate Bedrock Groundwater Zones. It will also 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 Analysis report, QUINTESSA 2011a) consistent with the results from modelling of current groundwater discharge from the Shallow Bedrock Groundwater Zone (see, for example, Section 5.2.2.2 of the Groundwater Modelling report, GEOFIRMA 2011). 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 4.4.3 of the Normal Evolution Scenario Analysis report, QUINTESSA 2011a).

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 Postclosure SA biosphere. For example, once contaminants are assessed to 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 Analysis report, QUINTESSA 2011a).

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, by release through a conservatively positioned well (used for drinking water and irrigation) and through direct release to the lake or near-shore sediments. This is consistent with the local hydrology at the Bruce nuclear site where any contaminants released to Shallow Bedrock Groundwater Zone are expected to flow directly into the lake with minimal interaction with the surface soils. So capillary action is expected to be an insignificant contributor to surface soil contamination.

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 Postclosure SA includes run-off in the water balance (see Section 6.1.2 of the Data report, QUINTESSA and GEOFIRMA 2011a). 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 (see FEP [3.2.02.03.E]) or infiltration (see FEP [3.2.02.03.B]). Transport of contaminant in the solid phase via run-off is taken into account through the consideration of soil erosion [3.2.03] (see Section 2.3.3 of the Normal Evolution Scenario Analysis report, QUINTESSA 2011a).

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 unconsolidated sediments, it is represented in terms of transport through a porous medium (see Section 2.3.3.2 of the Normal Evolution Scenario Analysis report, QUINTESSA 2011a).

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 nuclear site (see FEP [2.3.05] and Section 6.1.2 of the Data report, QUINTESSA and GEOFIRMA 2011a).

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 in the Postclosure SA. Detailed modelling is included in the Gas Modelling report (GEOFIRMA and QUINTESSA 2011), and impacts are presented in the Normal Evolution Scenario Analysis report (QUINTESSA 2011a) (see, for example, Sections 2.3.1.3 and 2.3.2.2) and the Human Intrusion and Other Disruptive Scenarios Analysis report (QUINTESSA and SENES 2011) (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 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 that affect the local distribution of contaminants on shorter timescales. This includes the downward movement of soil particles in time as soil formation proceeds or due to disturbance in the surface soil layers. In the aquatic environment, a similar process occurs 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

Large-scale erosion of surface contaminants would occur in the event of glaciation. This would remove, disperse and likely rebury any accumulation of long-lived radionuclides in the surface, reducing the potential impacts. This process is included in a variant calculation case in the present assessment.

The Postclosure SA does consider the local-scale transport of contaminants (in the biosphere) due to water erosion/deposition and atmospheric resuspension/deposition (see Figure 2-16 of the Normal Evolution Scenario Analysis report, QUINTESSA 2011a). These processes can affect contaminant levels in the soils used by the local farmer household receptor group.

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 as dissolved gases through the DGR and geosphere. Alternatively, gas pressures could be sufficiently high to form an unsaturated phase where two-phase flow is important, or to expel water and the associated dissolved contaminants from parts of the DGR and geosphere. Radioactive and chemically toxic gases, aerosols or particulates may also be transported along with other non-toxic gases.

Dissolved gases can come out of solution within the geosphere and enter the biosphere, and free gas can also discharge to the biosphere. 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 Postclosure SA considers the potential for gas generation and the resulting gas transport. The migration of gases from the repository through the shaft and geosphere is discussed in the Gas Modelling report (GEOFIRMA and QUINTESSA 2011), and in the overall assessment modelling as presented in the Normal Evolution Scenario Analysis report (QUINTESSA 2011a) (see, for example, Sections 2.3.1.3 and 2.3.2.2) and the Human Intrusion and Other Disruptive Scenarios Analysis report (QUINTESSA and SENES 2011) (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 domestic). 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 is explicitly modelled in the Postclosure SA. This includes the volatilization 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 (QUINTESSA 2011a) for the Postclosure 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 (QUINTESSA and SENES 2011).

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, and potentially the availability of water. Possible processes that could affect contaminant properties include the following.

- Microbially mediated conversion of contaminants from one chemical form into another (e.g., $^{14}CO_2$ to $^{14}CH_4$) with different properties.
- 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 bacteria could modify groundwater composition, affecting the pH and Eh and consequently 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 metabolize 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 whereas 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 Postclosure 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, QUINTESSA 2011a) and the gas generation model (see Section 4.2 of the T2GGM report, QUINTESSA and GEOFIRMA 2011b). Variant cases are assessed which evaluate the impact of decreased organic degradation rates and no methanogenic reactions.

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.

<u>FEP Screening</u>

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 (around 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 Postclosure SA, including (see Section 2.3.3 of the Normal Evolution Scenario Analysis report, QUINTESSA 2011a):

- Uptake of radionuclides and non-radionuclides from soils by plants;
- Uptake of radionuclides and non-radionuclides from soil, water, and plants by animals; and
- 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:

- Bioturbation in soils;
- Recycling of contaminants in animal droppings; and
- Recycling of contaminants in falling leaves.

These latter processes are implicitly treated by use of conservative 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 conservative, 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 rocks and unconsolidated sediments. These actions result in the transport of contaminated rock, sediment 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 in 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 Postclosure SA.

In the Human Intrusion Scenario, the consequences of moving waste to the surface as a result of drilling are evaluated (see Section 2.2.2 of the Human Intrusion and Other Disruptive Scenarios Analysis report, QUINTESSA and SENES 2011). In other scenarios, transport of contaminants due to water extraction from a well and irrigation of plants with well water is represented (see Figures 2.16 and 2.17 of the Normal Evolution Scenario Analysis report, QUINTESSA 2011a). 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 that 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 host rock and deep geosphere comprise very impermeable, low porosity geological formations. The pore dimensions are very small and they will, therefore, act to filter colloids due to physical exclusion, as well as electrostatic repulsion. Measurements of Cobourg Formation rock (see Section 4.3.6 of INTERA 2011), give median pore-throat radii of <10 nm for the host rock and overlying Ordovician formations – i.e., significantly less than typical colloidal dimensions.
- Joints in the host rock and overlying Ordovician formations are widely spaced and do not form a connected network; therefore, they do not form a pathway for migration of colloids.
- Fractures in the shaft EDZ might form a pathway for colloid migration. Although the hydraulic conductivity of the shaft EDZ will be significantly enhanced compared with the geosphere, it will still be low in absolute terms. Therefore, it is expected that there will be limited opportunity for colloid transport within the EDZ.
- The small pore size and low permeability of shaft seals are expected to limit migration of colloids by filtering. Colloid studies at Cigar Lake (Section 3.6 of Cramer and Smellie 1994) indicate that transport of particles from the uranium ore body through the clay zone was negligible, and also that the mobilization of clay particles from the clay into the surrounding sandstone has not been important, even in the presence of this low-ionic strength groundwater, where colloids should be easier to form than under DGR saline conditions.
- Confidence that colloids will be filtered is provided by BNFL (2002) who investigated colloidal size distributions, compositions and radionuclide activities associated with unlined near-surface LLW trenches under freshwater conditions. Although there were significant colloidal populations of similar composition in the wastes and geosphere (Quaternary glacial

sediments), and the number of colloids per litre increased with decreasing colloid size, there was no activity associated with colloids in the waste trenches. There was trace non-tritium beta activity associated with colloids in groundwater monitoring boreholes, and this activity was removed by a 12 μm filter. This implies that the presence of contamination on colloids was due to sorption onto the local colloidal population, rather than due to migration of colloids. At the Sellafield nuclear site, Cs-137 detected in groundwater monitoring wells is associated with colloids. Cs-137 never migrates any significant distance from the source (McKenzie and McCord 2010) due to filtering by the Quaternary sediments.

- It is anticipated that the surface of the concrete monolith within the DGR will become 'armoured' through carbonation reactions (Section 4.5.3 of the System and Its Evolution report, QUINTESSA 2011b), therefore, reducing the porosity and pore diameter. This will further reduce the potential for colloids to enter the shaft seals, except via the EDZ.
- As bentonite swells it is possible for colloidal material to be generated. These colloids comprise clay minerals that could enhance the transport of radionuclides. SKB is - experimental research indicates that bentonite colloids do not form in high ionic concentration fluids (Neretnieks et al. 2009), such as the porewaters in the Deep and Intermediate Bedrock Groundwater Zones.
- Erosion of bentonite can only occur where it is in contact with flowing fractures in the rock. There is the potential for this to occur in the fractured crystalline host rock being considered by SKB. The potential for this to occur at the DGR is dependent on the extent of fracturing, and flow rates within the shaft EDZ. However, it is expected that the DGR shaft EDZ will be significantly less permeable than the host rock being considered by SKB (5E-10 to 5E-8 m/s – see Figure 4-40 of SKB 2006) and, therefore, the potential for bentonite erosion is low.
- Consistent with the findings of Stumm (1992), the transport of any colloids within the Deep Bedrock Groundwater Zone is expected to be a diffusion process since diffusion rather than advection is considered the primary mechanism of contaminant transport. The diffusion coefficients for the colloids would likely be smaller than for true solutes, since there is likely to be greater interaction with the rocks and shaft seals.

<u>FEP Screening</u>

Screened out.

3.2.10 Dissolution, Precipitation and Mineralization

Description

The dissolution, precipitation and mineralization 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 is a process by which solids are formed from molecules in solution. Mineralization is a process by which crystalline materials form from a melt, a solution or amorphous solids; in the present context, only formation from a solution or amorphous solids are relevant.

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 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 that 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 precipitate incorporates a subsidiary compound which would not precipitate in isolation. For example, radium sulphate can be accommodated within the structure of precipitating barium sulphate, even if radium sulphate itself 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 mineralization 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 Mineralization

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 waste 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 from the waste forms is considered for all contaminants and the potential precipitation of C-14 in the repository is considered in the Postclosure SA (see FEP [3.2.11.01]).

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.

Screening Analysis

It is conservatively assumed that there is no solubility limitation of any contaminants in the geosphere (see FEP [3.2.11.02]).

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 in the near-surface zone. 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 immobilizes contaminants leaving them in place where they could eventually be accessed by plants, and thus may result in larger transfers of contaminants 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 Postclosure SA.

Many of the biosphere contaminant parameter values used in the Postclosure SA (e.g., plant concentration factors, soil Kd 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 Mineralization

Description

Changes to the mineral composition of the rocks and engineered repository materials that might affect the migration of contaminants.

A potential change in mineralization in the geosphere might be caused by the invasion of fluids that are hotter or cooler than 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 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 Paleozoic Era (248-545 Ma Before Present) according to NWMO (2011) (see Section 4.3 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 mineralization; however, glacial melt waters are not expected to be injected into the Deep Bedrock Groundwater Zone.

Mineralization can also affect the engineered repository materials (such as concrete and bentonite) (see Mineralization [2.1.08.06]) and the migration of contaminants through the materials.

Screening Analysis

There are not anticipated to be any significant changes to the mineralogy of the geosphere due to natural diagenetic processes or the development of a biogeochemical plume from the repository. There may be some dissolution of the DGR wall rock by CO_2 and organic acids generated in the repository. However, this is not expected to have any significant impacts (see Appendix G of the System and Its Evolution report, QUINTESSA 2011b).

There may be mineralogical changes to the shaft seals and shaft EDZ due to interactions between different seal materials, and seal-wall rock interactions (see Appendix E of QUINTESSA 2011b). In particular, mineralization changes to concrete need to be considered (see FEP [2.1.08.06]).

Analysis of the interaction between bentonite-sand and adjacent concrete indicates there will be some alteration at this interface, but this will be minimized by the use of low-heat, low-alkalinity cement in the shaft as well as the overall low permeability of the system. Changes in mineralization of the bentonite itself (e.g., due to illitization) will be insignificant, considering the local groundwater chemistry and the ambient repository temperature.

FEP Screening

Include FEP in all scenarios for concrete

3.2.11 Speciation and Solubility (Contaminant)

Description

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 in stable or metastable equilibrium with some specified solid phase. The solubility is dependent on the species, temperature, pressure, presence of other solutes, and the ionic strength. An element may also be present in groundwater bound to, or as a constituent of, 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, as in many low-temperature groundwaters.

Several dissolved species may co-exist. The nature of the dominant species may be important. For instance, clay and most rock minerals generally 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.

If kinetically favourable, an element will precipitate when its concentration (totalled over 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 much larger than the solubility limit predicted for the solid phase.

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 will tend to precipitate, provided that precipitation is kinetically favourable. See also Dissolution, precipitation and mineralization (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, although the effect is generally smaller than the effect of temperature, except when the solubility reaction includes a gaseous phase. Chemical kinetics could also have large effects on effective solubility limits.

Screening Analysis

The solubility of C-14 in the repository has been considered,; however, for all other contaminants, it is conservatively assumed that there is no solubility limitation (see Section 3.6.3.2 of the Data report, QUINTESSA and GEOFIRMA 2011a).

Speciation and solubility of contaminants in the shaft has been evaluated for several elements (see Appendix C of the Data report, QUINTESSA and GEOFIRMA 2011a). However, it is conservatively assumed that there is no solubility limitation of any contaminants in the shaft.

FEP Screening

Include FEP in all scenarios.

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 tend to promote 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 Postclosure SA, the potential speciation and solubility of contaminants in the geosphere has been evaluated for certain elements for Cobourg and Guelph porewater (see Appendix C of the Data report, QUINTESSA and GEOFIRMA 2011a). However, it is conservatively assumed that there is no solubility limitation of any contaminants in the geosphere.

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 affect 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 mineralized. 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 mineralization (biosphere) [3.2.10.03].

Screening Analysis

Contaminant speciation and solubility in the biosphere is not explicitly modelled in the Postclosure 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 mineralization (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 implicitly included in the Postclosure 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 could cause a change in the solubility of the radionuclides attached to waste forms, particularly ion-exchange columns. 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 highly saline porewaters of the host rock can permit ionic complexing that can raise certain individual element solubilities. This will promote desorption of radionuclides from the ion-exchange columns, a significant source of radioactivity in ILW in the DGR.

The Postclosure SA conservatively assumes that all elements, except C, are not solubility limited within the repository. It also assumes the C-14 on resins is readily released on contact with the repository water.

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

It expected that changes in repository temperature will be relatively small (up to 5°C) (see FEP [2.1.10]) and a change of this magnitude is not expected to affect solubility significantly. Furthermore, solubility limitation is only considered for C-14 in the repository (see FEP [3.2.11.01]).

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 ionization of water, i.e., the definition of neutral pH is a function of temperature varying from pK=14 at 25°C to pK~15 at 0°C (where pK is the dissociation constant for water).

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 Postclosure 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 assessment already adopts the conservative 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 for retardation. 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 with 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 the surface of 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; and
- 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) + Kd x (dry bulk density), where porosity and density refer to the properties of the solid sorbing medium.

Sorption models employing distribution coefficients are linear models that assume the processes are reversible, rapid and have no limits. However, non-linear effects can be significant, such as chemical kinetic effects that favour desorption over sorption, a limited availability of surface sites for sorption, 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 time will 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 FEP [3.2.12] above.

Screening Analysis

In light of uncertainties relating to the detailed evolution of chemical conditions in and around the waste packages in the repository, sorption is conservatively neglected for all contaminants for all waste packages (be they cementitious or non-cementitious).

Sorption onto concrete and asphalt shaft seals is also conservatively taken to be zero for all contaminants due to a lack of sorption data under relevant conditions, as is sorption onto the engineered shaft fill.

Data are available for bentonite under relevant conditions. Conservative reference values for certain key elements are presented in Table 4.25 of the Data report (QUINTESSA and GEOFIRMA 2011a). The sorption and desorption of these contaminants in the bentonite-sand are modelled assuming a linear sorption isotherm (i.e., a Kd approach). Irreversible sorption is not modelled and sorption properties are considered constant in time.

FEP Screening

Include FEP in all scenarios.

3.2.12.02 Sorption and Desorption (Geosphere)

Description

See FEP [3.2.12] above.

Screening Analysis

The highly saline conditions in the deep geosphere will inhibit some types of sorption reactions, notably ion exchange, but will have lesser or no effect on sorption by surface complexation. Sorption in the geosphere has been considered for certain elements that are of interest, that likely sorb by surface complexation, and for which there are some relevant data – see Table 5.13 of the Data report (QUINTESSA and GEOFIRMA 2011a). For all other elements and organics, it is assumed that there is no sorption in the geosphere. Irreversible sorption is not modelled and sorption properties are considered 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 soil and sediments.

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 Postclosure SA, sorption and desorption of contaminants in sediments and soils is modelled explicitly assuming a linear sorption isotherm characterized by Kd - see Table 6.6 of the Data report (QUINTESSA and GEOFIRMA 2011a). Sorption properties are assumed to be constant in time.

Irreversible sorption is not modelled. This could be a non-conservative 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 contaminant migration studies.

Screening Analysis

This postulates that sorption reactions may cause other chemical reactions that would not otherwise be considered in the Postclosure 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 is the retardation of anions that migrate through pore spaces in the rock, or the effective exclusion of anions from these pore spaces, by overlapping negatively charged electrical double layers near the surfaces of solid phases that form the pores' walls. Neutral species, cations and water itself may migrate through such pores much more readily than anions.

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 available to anions and results in a decreased transport porosity and decreased diffusivity of anions through the pore space.

Screening Analysis

Diffusion experiments undertaken using core samples from the DGR boreholes drilled at the Bruce nuclear site with iodide and tritiated water tracers have shown that ion exclusion effects occur (see discussion in Section 5.5.1.4 of the Data report, QUINTESSA and GEOFIRMA 2011a).

FEP Screening

Include FEP in all scenarios.

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 nuclear 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 FEPs [2.1.10 and 2.2.09]. There may be significant temperature changes in the Shallow Bedrock Groundwater Zone, but the assessment adopts the conservative assumption that most contaminants are not retarded in the Shallow Bedrock Groundwater Zone (see FEP [3.2.12.02]) 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 sorption are unlikely to significantly increase contaminant mobility in comparison with the base case conditions.

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 repository system because of the effects of chemical complexing agents.

This category is divided into:

3.2.13.01 Organics

3.2.13.02 Inorganic Ligands

3.2.13.03 Microbes

3.2.13.01 Organics

Description

Organic complexants include small organic species such as the methyl radical, and larger organic-based species such as humic and fulvic acids that 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.

Also in this category are chelating agents, which 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 contaminants 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-sorbing 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.

These organic complexing agents might be introduced into the repository, for example in pore 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) concluded 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 elements. However, contaminant transport out of the repository would not be much affected by complexation with organics because such complexed contaminants would be large and would diffuse very slowly into the host rock. Moreover, solubility limitation is conservatively neglected for all elements other than C in the DGR (see FEP [3.2.12.01]).

Small quantities of chelating 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.

Chelating agents could potentially result in some enhanced transport of contaminants via the shaft/shaft EDZ. However larger complexes would likely be filtered out – see Colloid-mediated migration of contaminants [3.2.09] and/or subject to anion exclusion – see Anion exclusion effects [3.2.12.5]. Solubility limitation is considered in the shaft/shaft EDZ for a limited number of radionuclides. The solubility limits chosen are conservative since they consider metastable phases. They are, therefore, likely to bound the effects of complexing agents.

Complexation could potentially result in some enhanced transport of contaminants via the shaft/shaft EDZ. However larger complexes would likely be filtered out – see Colloid-mediated migration of contaminants [3.2.09] and/or subject to anion exclusion – see Anion exclusion effects [3.2.12.5]. Solubility limitation is considered in the shaft/shaft EDZ for a limited number of radionuclides. The solubility limits chosen are conservative since they consider metastable phases. They are, therefore, likely to bound the effects of complexing agents.

Similarly the Postclosure SA only considers sorption for a limited range of radionuclides onto bentonite-sand. This is conservative and uses minimal credible sorption coefficients for the bentonite-sand and geosphere materials - see Tables 4.25 and 5.13 of the Data report, QUINTESSA and GEOFIRMA (2011a).

FEP Screening

Screened out by use of conservative parameter values.

3.2.13.02 Inorganic Ligands

Description

Inorganic ligands include simple inorganic ions such as chloride, fluoride, carbonate and sulphate anions. These complexing agents are all present within the porewaters and/or might be introduced to the porewaters by water/rock reactions (e.g., dissolution of calcite in the rock adds carbonate to the porewater). These agents are also present within the wastes to some degree and might be introduced to the pore water via waste degradation.

Screening Analysis

Inorganic complexes with certain radionuclides have the potential to increase the solubility of these nuclides. This effect will be particularly important in the highly saline porewaters, (see FEP [3.2.11.04]), of brine strength, which will permit considerable complex formation, e.g., $^{137}CsCl°$ or $^{90}SrCO_3°$. This complexing may also modify the transport properties of a radionuclide, principally because the charge of the species within which the radionuclide is transported differs from that of the uncomplexed radionuclide. For example uncomplexed ^{137}Cs is transported as a monovalent cation (Cs^+), whereas chloride-complexed ^{137}Cs is transported as neutral $^{137}CsCl°$. This complexing has the potential to influence the sorption properties of the radionuclide; in this example Cs^+ would sorb to negatively-charged mineral surfaces, but $^{137}CsCl°$ would be effectively unsorbed.

Solubility limitation is considered in the shaft/shaft EDZ for a limited number of radionuclides. The solubility limits chosen are conservative since they consider metastable phases. They are, therefore, likely to bound the effects of complexing agents.

Similarly the Postclosure SA only considers sorption for a limited range of radionuclides onto bentonite-sand. This is conservative and uses minimal credible sorption coefficients for the bentonite-sand and geosphere materials - see Tables 4.25 and 5.13 of the Data report, QUINTESSA and GEOFIRMA (2011a).

FEP Screening

Screened out by use of conservative parameter values.

3.2.13.03 Microbes

Description

Micro-organisms may produce subtle effects on contaminant transport by sorbing contaminants or by acting as colloids. Micro-organisms may also influence the chemical environment, thereby affecting the chemical form of the contaminants and potentially promoting retardation (e.g., through creating conditions favourable for precipitation of the contaminant) or enhanced transport (e.g., through creating aqueous species that may complex with the contaminants).

Screening Analysis

The Postclosure SA conservatively neglects sorption onto biological substrates including biofilms.

The potential for microbes to act as colloids is screened out, consistent with the treatment of colloids (Colloid-mediated migration of contaminants [3.2.09]) and organic complexes (FEP [3.2.13.01]).

FEP Screening

Screened out by use of conservative parameter values.

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 co-metabolism (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.

<u>Screening Analysis</u>

The following human 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 Analysis report, QUINTESSA 2011a):

- 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; and
- Air to plants to animals to humans.

Different types of food types are also of relevance, including agricultural, wild and recreational foodstuffs (e.g., recreational fishing) (see Section 7.1 of the Data report, QUINTESSA and GEOFIRMA 2011a).

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 Section 7.2.2 of the Data report, QUINTESSA and GEOFIRMA 2011a.

<u>FEP Screening</u>

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 an environmental medium 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 medium 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 more significant exposures 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 liquid 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 Postclosure SA, which requires calculation of the associated contaminant concentrations (see Appendix D of the Normal Evolution Scenario Analysis report, QUINTESSA 2011a). 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, QUINTESSA and GEOFIRMA 2011a).

Although drugs may be administered by inhalation and injection (making contaminants more available than if incorporated in ingested food), 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. 2004b):

- 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 for the current assessment.

FEP Screening

Screened out.

3.3.03 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 relevance 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. Environmental concentration of radionuclides and non-radioactive hazardous substances are included in the principal assessment end points given in Section 3.5 of the Postclosure SA main report (QUINTESSA et al. 2011).

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 categorized 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 generally only of concern from internal exposure. Chemicals may be sorbed through skin or surfaces of other biota, but subsequent impacts are usually from internal exposure. However, there may be exceptions, for example allergic skin reactions that occur with nickel.

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 and inhalation 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 (in the specific case of tritiated water vapour, skin sorption could be more important than inhalation), the injection of contaminated drugs, and uptake through wounds or from deliberate skin incisions (e.g., decorative markings made by rubbing soil into cuts);
- 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 for radionuclides (see Section 2.3.3 of the Normal Evolution Scenario Analysis report, QUINTESSA 2011a).

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 (300 years – Section 3.8 of the Postclosure SA main report, QUINTESSA et al. 2011) 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. 2004b). 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; and
- Wild and indigenous species.

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 include 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 sediments.

The exposure pathways are similar to those for humans - inhalation, ingestion, external contamination or irradiation. However the relative importance of these pathways will 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
- 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

Impacts on non-human biota are an end-point of interest for the Postclosure SA (see Sections 3.4.3 and 3.4.4 of the Postclosure SA main report, QUINTESSA et al. 2011).

As the environmental concentrations are expected to be low, in the Postclosure SA, the impacts on biota are assessed by comparing calculated concentrations in environmental media to No-Effect Concentrations and/or Environmental Quality Standards (see Sections 7.2.2 and 7.3 of the Data report, QUINTESSA and GEOFIRMA 2011a). If these screening level criteria are exceeded, then more detailed modelling would be needed.

FEP Screening

Include FEP in all scenarios.

3.3.05 Dosimetry and Biokinetics

Description

Dosimetry and biokinetics 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 half life and energy and type of radioactive emissions of the radionuclide; and
- The age at exposure.

Different species will have different dosimetry and biokinetics. Thus, dosimetry and biokinetics are separated into two FEPs:

3.3.05.01 Dosimetry and Biokinetics for Humans

3.3.05.02 Dosimetry and Biokinetics for Biota Other Than Humans

3.3.05.01 Dosimetry and Biokinetics for Humans

Description

The approach to dosimetry and biokinetics 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 affect 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 with 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, affect the tissues of the body. Chemical toxics can have a wide variety 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 Postclosure SA, the potential impact of radioactive and non-radioactive contaminants is the key result of interest.

Radiation dosimetry is included in the Postclosure SA through the use of whole body effective internal and external dose coefficients based on the 1990 and 2007 recommendations of the ICRP (ICRP 1991 and 2007).

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, QUINTESSA and GEOFIRMA 2011a).

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 assessed through comparison with benchmarks that are based on intake rates (FEP [3.3.07]) or environmental standards.

FEP Screening

Include FEP in all scenarios.

3.3.05.02 Dosimetry and Biokinetics for Biota Other Than Humans

Description

The dosimetry and biokinetics 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 TRVs can be reported as intake levels such as the No Observed Adverse Effect Level or a concentration that 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 Postclosure SA, the potential impact of radioactive and non-radioactive contaminants on biota is of interest.

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 derived for radionuclides (Section 7.2.2 of the Data report, QUINTESSA and GEOFIRMA 2011a). If the No-Effect Concentrations are exceeded, an Ecological Risk Assessment will be carried out for any radionuclides with concentrations estimated to exceed the No-Effect Concentrations.

The potential effects of chemicals are generally assessed through comparison with benchmarks that are based on intake rates or media concentration (FEP [3.3.07]).

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 (deterministic) 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 Biota Other Than Humans

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 concern, 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 Postclosure SA, radiological doses to humans are of interest, as discussed in Sections 3.4.1 and 3.4.2 of the Postclosure SA main report (QUINTESSA et al. 2011).

Radiological toxicity effects are, therefore, considered within the assessment. Specifically, the dose rates to critical groups of humans are assessed. These dose rates can be translated into risks of cancer and hereditary disease using the linear no-threshold model (ICRP 1991, 2007).

FEP Screening

Include FEP in all scenarios.

3.3.06.02 Radiological Toxicity/Effects for Biota Other Than Humans

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. Another possible concern, synergistic impacts, is discussed under Chemical toxicity/effects for biota other than humans [3.3.07.02].

Screening Analysis

In the Postclosure SA, radiation doses to non-human biota are assessed, as discussed in Section 3.4.3 of the Postclosure SA main report (QUINTESSA et al. 2011).

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 derived for radionuclides (Section 7.2.2 of the Data report, QUINTESSA and GEOFIRMA 2011a).

Should more detailed calculations be required for non-human biota, then calculated doses may be compared with dose benchmarks available from recognized agencies such as UNSCEAR, Environment Canada, 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 components of 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 also relates to some radioactive elements; for instance:

- naturally occurring uranium is a heavy metal and as such is chemically toxic; and
- technetium-99 may be more chemically toxic than radiotoxic (Coffey et al. 1984, Gerber et al. 1989).

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 Postclosure 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 Biota Other Than Humans

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. 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 relevance is synergistic effects (and its opposite, antagonistic effects) or the combined effects of two or more radiotoxic or chemotoxic species on man. Two or more toxic substances may interact with each other, or interact jointly, to produce biological effects that can be different in extent and kind than those from either substance separately. That is, even if the two substances affect the same physiologic function, their effects may be more than additive, or two substances affecting different physiologic functions may have more serious cumulative effects on a human. 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 is an endpoint of interest in the Postclosure SA; see Section 3.4.4 of the Postclosure SA main report (QUINTESSA et al. 2011).

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 of the Data report, QUINTESSA and GEOFIRMA 2011a).

Should such Environmental Quality Standards be exceeded, then more detailed analysis would be needed, considering for example TRVs.

FEP Screening

Include FEP in all scenarios.

3.3.07.02 Chemical Toxicity/Effects for Biota Other Than Humans

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 in relation to intake levels such as the No Observed Adverse Effect Level 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 by the appropriate national regulatory authority. Environmental Quality Standards are usually set taking factors such as No Observed Adverse Effect Level s and EC20 into account.

Screening Analysis

The potential effects of chemicals on non-human biota is an endpoint of interest in the Postclosure SA; see Section 3.4.4 of the Postclosure SA main report (QUINTESSA et al. 2011).

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 of the Data report, QUINTESSA and GEOFIRMA 2011a).

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 WWMF (OPG 2005c).

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 the 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 Postclosure SA (see Section 3.5.1 of the Data report, QUINTESSA and GEOFIRMA 2011a); therefore, Rn-222 may arise and is assessed with consideration being given to degassing from water and soil (Sections 6.1.2 and 6.2.1 of the Data report, QUINTESSA and GEOFIRMA 2011a).

The dose rate from exposure to Rn-222 calculated in the assessment 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) (Section 7.2.1 of the Data report, QUINTESSA and GEOFIRMA 2011a).

FEP Screening

Include FEP in all scenarios.

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7. ABBREVIATIONS AND ACRONYMS

BNFL	British Nuclear Fuels Limited
CNSC	Canadian Nuclear Safety Commission
DGR	Deep Geologic Repository
EC20	Concentration at which 20% of the population is affected
EDL	Electrical (or diffuse) double layers
EDZ	Excavation Damaged Zone
Eh	Reduction potential
EIS	Environmental Impact Statement
FEPs	Features, Events and Processes
HDZ	Highly Damaged Zone
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
ILW	Intermediate Level Waste
L&ILW	Low and Intermediate Level Waste
LHHPC	Low-Heat, High-Performance Cement
LLW	Low Level Waste
NEA	Nuclear Energy Agency
NWMO	Nuclear Waste Management Organization
OPC	Ordinary Portland Cement
OPG	Ontario Power Generation Inc.
PSR	Preliminary Safety Report
SA	Safety Assessment
TDS	Total Dissolved Solids
TRV	Toxicological Reference Values
WWMF	Western Waste Management Facility