Seventh Case Study: Features, Events and Processes

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ABSTRACT

Title: **Seventh Case Study: Features, Events and Processes**
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Abstract

The Seventh Case Study is a postclosure safety assessment of a deep geologic repository for used CANDU fuel at a hypothetical site in a sedimentary rock environment, specifically the Michigan Basin in Ontario. The hypothetical site and watershed areas are the same as in the Fifth Case Study. The repository is placed at a depth of 500 m as a design assumption.

The Seventh Case Study also differs from the Fifth Case Study in that it considers the smaller Mark II reference container. The Mark II container has a thin outer copper coating for corrosion protection, an inner steel vessel for structural support, and capacity to hold 48 CANDU fuel bundles. These containers are pre-installed into bentonite buffer boxes, and then stacked in emplacement rooms in the repository. One purpose of the Seventh Case Study is to investigate the safety implications of this updated engineered barrier system based on the Mark II container.

The safety assessment of a repository must consider a broad range of factors that could potentially affect the behaviour of the repository, the release of contaminants, and the repository environment over the periods of interest. These factors may be features of the repository or site (e.g., waste type, repository depth), events (e.g., earthquakes, climate change) or processes (e.g., sorption), and are known collectively as FEPs. They are used as input for scenario identification and subsequent conceptual model development for the safety assessment.

However, not all potential FEPs are necessarily included in a given safety assessment. This report provides a structured and comprehensive list of possible FEPs relevant to the Seventh Case Study design and site. For each FEP, this report:

- provides a brief description of the FEP;
- discusses its relevance to the Seventh Case Study repository system; and
- identifies the scenarios where relevant FEPs are considered within the conceptual models developed for the Seventh Case Study.

The development of a safety case for a site-specific safety assessment would proceed in stages from conceptual to detailed studies. The Seventh Case Study is a scoping study and is based on a hypothetical repository and site. The present FEPs assessment is representative of the level of information and analysis that would be available during the early stages of siting.

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1. INTRODUCTION

1.1 BACKGROUND

The Seventh Case Study (7CS) is intended to illustrate NWMO's approach for assessing safety through an illustrative postclosure safety assessment for a deep geological repository for used nuclear fuel at a hypothetical site in sedimentary rock in the Michigan Basin in Ontario (NWMO 2018, Section 1).

The current study builds upon the previous Fifth Case Study (NWMO 2013).[1] In both studies the repository is placed at a 500 m depth, as a design assumption. The major differences between the two studies are the repository location and the reference container. In the Seventh Case Study the reference container is the Mark II container. This container has a 3-mm outer copper coating for corrosion protection, an inner steel vessel for structural support, and capacity to hold 48 used CANDU fuel bundles. In contrast, in the Fifth Case Study, the larger IV-25 container was used. The IV-25 container has a 2.5 cm thick copper shell for corrosion protection, an inner steel vessel for structural support, and capacity to hold 360 used fuel bundles. Because of the different containers, the repository layouts and designs are different in the two studies.

The repository in the 7CS is assumed to hold 5.22 million used fuel bundles (rather than the 4.6 million bundles held in the 5CS repository), which is the total reference used fuel inventory projected over the expected lifetime of the current fleet of Canadian CANDU power reactors (Garamszeghy 2016). This includes refurbishment of Bruce A, Bruce B, Darlington and Point Lepreau; but, no new reactors and no further refurbishment of Pickering or Gentilly-2.

1.2 SAFETY ASSESSMENT

The 7CS postclosure safety assessment has been developed following Canadian Nuclear Safety Commission (CNSC) regulatory guidance found in the CNSC document G-320 (CNSC 2006). The level of detail in the assessment is consistent with the pre-project stage, i.e., the 7CS is not a full safety case.

Consistent with G-320, the postclosure safety of the design concept is assessed by considering a range of future scenarios, from likely to "what if". Scenarios are postulated or assumed set of conditions or events that represent the possible future evolution of a repository and its surroundings (CNSC 2006). They are developed by consideration of the features, events and processes (FEPs) that could affect the repository and its evolution.

The Seventh Case Study considers the Normal Evolution Scenario and various Disruptive Event Scenarios. Variant or sensitivity cases of these scenarios are also investigated.

- The **Normal Evolution Scenario** is based on a reasonable extrapolation of site and repository features, events and processes. It accounts for the expected degradation of the

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[1] The Sixth Case Study was for a crystalline rock site.

site and repository, and addresses the effects of anticipated extreme conditions, particularly earthquakes, climate change and glaciation.

- **Disruptive Event Scenarios** postulate the occurrence of unlikely or "what if" events leading to possible penetration of barriers and abnormal loss of containment.

The Disruptive Event Scenarios are identified from the FEP screening analyses presented in Section 3.

1.2.1 Impacts of Concern

In the 7CS, radiological impacts on humans and non-human biota are evaluated for all scenarios considered. Impacts on non-human biota are calculated for the Normal Evolution Scenario and selected Disruptive Event Scenarios.

Impacts on humans and non-human biota of releases of potentially chemically hazardous elements from the repository are also assessed for the Normal Evolution Scenario and selected Disruptive Event Scenarios.

In keeping with the concept of a "critical group", the Seventh Case Study conservatively assumes that people live near the repository site in the future, and have lifestyles that maximize their potential exposure doses while behaving in an otherwise reasonable manner (see Section 1.4). Postclosure impacts should be greater for this critical group than for people living father away from the site.

1.2.2 Time Scale and Spatial Domain of Concern

Most of the initial radioactivity of the used nuclear fuel is due to the fission products in the fuel, which significantly decay within 500 years. However, there remains an inventory of actinides, including plutonium, which are potentially hazardous on time frames of about 200,000 years, and a residual level of radioactivity beyond that time frame due to extremely long-lived fission products.

Because 98% of the used fuel is natural uranium, as radionuclides decay, the total amount of radioactivity in the repository will eventually become similar to that of a large uranium ore body such as is found in other locations in Canada. This occurs on time scales of about one million years (see Figure 1-1). Therefore, for the Seventh Case Study, future impacts are assessed over a one-million-year baseline. This is the baseline for the FEPs analysis.

Some calculations may extend beyond this time to ensure that the time frame for peak impact has been identified. It is recognized that estimating impacts become increasingly uncertain at such long times. For this reason, complementary indicators of safety are also examined in the Seventh Case Study. These indicators may be more useful than the radiological dose rate for both medium time frames (e.g., radiotoxicity concentration in surface waters) and very long time frames (e.g., radiotoxicity flux from geosphere, and chemical element erosion fluxes from the geosphere) (Becker et al. 2002, Garisto et al. 2005a).

The spatial domain considered in the 7CS is the subregional watershed area (approximately 1,600 km^2) in which the repository is sited. The study specifically focuses on the local area that

includes the discharge points of groundwater from the repository, and the nearest major surface water bodies into which these discharges are collected. In this area, the concentrations of radionuclides released from the repository, and therefore the calculated dose rates, would be the highest. Further downstream from this location, radionuclide concentrations are expected to be significantly diluted, resulting in substantially lower dose rates to people or non-human biota residing there.

1.3   REPOSITORY ASSUMPTIONS

The repository, including the used fuel containers, is assumed to be designed, built and sealed as described in NWMO (2018, Section 4). This includes a quality assurance program to ensure that the repository meets specifications.

The repository is constructed, operated and closed according to the assumed schedule outlined in NWMO (2018, Section 4). Some key time lines are:
- used fuel bundles are at least 30-years old at time of placement;
- repository operation (i.e., filling of repository rooms) lasts 38 years;
- the post-operation monitoring period, with access tunnels open, lasts 70 years; and
- final decommissioning/closure takes up to 30 years.

Other more specific repository assumptions are described in the specific relevant sections.

Given the national importance of the project, and since funds will already have been put aside to cover its costs, it is fully expected that the repository will be properly closed. However, if it was abandoned without full closure for some reason, this would be considered for safety assessment purposes as a disruptive event scenario, specifically the Partially Sealed Repository Scenario. This scenario would require a general collapse of society.

1.4   FUTURE HUMAN ACTIONS AND CHARACTERISTICS

It is assumed in the 7CS that future humans will largely resemble present day humans in terms of societal behaviour, capabilities and actions. This means that:
- There is no credit taken for advances in science and technology that might reduce the risk from the repository, e.g. no "cure for cancer" and no simple waste transmutation process.
- People live in circumstances consistent with current North American practice. Specifically, people live in a variety of environments such as urban settings or individual farms, and tend to stay in one location for periods of years.
- Human activities that could affect the local environment (e.g. construction, water diversion) are consistent with present capabilities and take place for reasons that would make sense currently.
- Societal knowledge of the repository will provide control for some initial period, but cannot be relied on indefinitely to prevent inadvertent human intrusion into the site.
- Future human actions do not make the region around the repository site unsuitable for human habitation.

For dose assessment purposes, several reference groups of humans (i.e., critical groups) are considered in the 7CS. The characteristics of these critical groups (e.g., lifestyle and location) are conservatively selected, but consistent with the scenario, so as to maximize calculated dose

rates. For example, during temperate climates, the critical group is a self-sufficient farm household (with a mixed dairy, meat and vegetable diet) living near the repository site and drawing water from a well that intercepts the contaminant plume from the repository. The use of well water, rather than surface water, by the critical group significantly increases the calculated impacts of the repository.
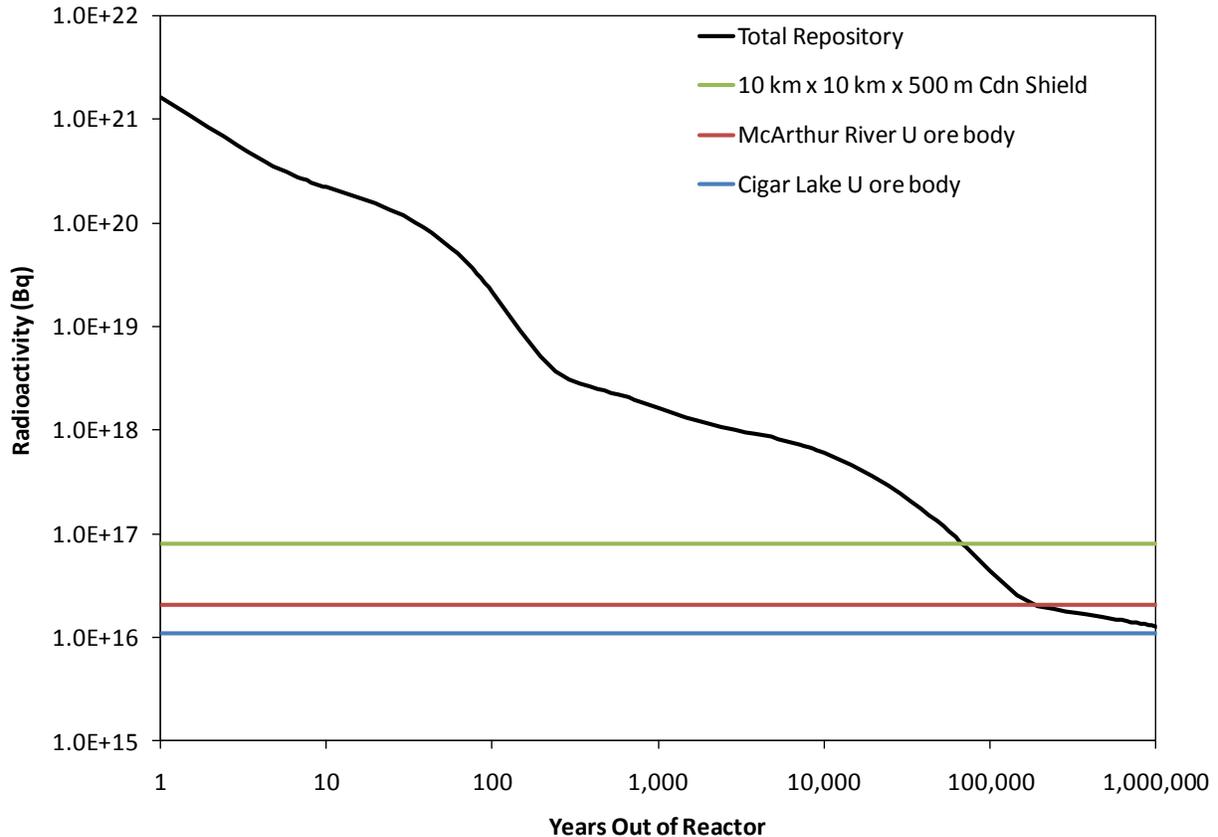
Note: The gamma-emitting fission products decay within about 500 years. The remaining fuel radioactivity becomes comparable to that of the granite in the surrounding watershed after about 10,000 to 100,000 years. On time scales of about 1 million years, the residual used fuel radioactivity is dominated by that of the uranium in the fuel (and its decay chain products), a level that is comparable to natural uranium ore bodies.

Figure 1-1: Total Radioactivity of the Used Fuel in the Repository

1.5   REPORT OUTLINE

This report supports the 7CS safety assessment by documenting the treatment of repository and site features (such as container size, rock permeability and human lifestyle), events (such as earthquakes and human intrusion), and processes (such as radioactive decay and contaminant transport) that were considered in developing the models used in the quantitative analyses.

Specifically, not all potential features, events and processes are necessary to include in a given safety assessment. This will depend upon the assessment basis, such as the aims of the assessment and regulatory framework. This report indicates whether and why possible FEPs are included or excluded in the quantitative analyses of the 7CS.

To provide a more comprehensive method for ensuring that all relevant factors are considered, and to provide a record of the reasoning, these factors were collected into a structured format. The structured format used in the Seventh Case Study was adapted from the organization developed by the OECD Nuclear Energy Agency (NEA 2000) for characterizing system level FEPs, by adopting some of the revisions to the NEA International FEP list currently under consideration (Little 2012). The current FEP list includes all Fifth Case Study FEPs.

The starting point for the 7CS FEPs screening was the FEPs analyses for the 5CS (Garisto 2013), which were reviewed and updated, as needed, in light of the 7CS reference container, the 7CS reference repository design and new scientific information.

The report is organized as follows:

- **Section 2** provides a list of all FEPs considered.
- **Section 3** examines each FEP in turn, provides a brief analysis for each FEP with references, and concludes whether the FEP should be specifically included or excluded in the quantitative analyses within the 7CS.

2. FEP SUMMARY LIST

Features, events and processes (FEPs) are factors that can affect the performance and safety of a deep geologic repository. The FEPs list used for the 7CS is structured differently from the international FEPs database developed by the OECD Nuclear Energy Agency (NEA 2000). Changes were made to the organization of the FEPs to accommodate proposed revisions to the structure of the NEA FEPs list (Little 2012).

All FEPs are organized under six main categories:

1. External Factors - describe factors outside the repository system;
2. Waste Package Factors - describe features (properties), events and processes associated with the waste package, including its contents;
3. Repository Factors - describe features (properties), events and processes associated with the repository and the excavation damaged zones;
4. Geosphere Factors - describe features (properties), events and processes associated with the geosphere environment in which the repository is located;
5. Biosphere Factors - describe features (properties),events and processes associated with the biosphere, including human behaviour and exposure factors; and
6. Contaminant Factors - describe the features (properties) of the contaminants in the waste packages.

In a number of cases, a given FEP has been divided into more specific sub-FEPs where it is useful to provide a more detailed breakdown. These are designated by a letter after the FEP number. For example, *[2.1.01] Waste Inventories* has been divided into *[2.1.01.A] Inventory of Radionuclides* and *[2.1.01.B] Inventory of Chemical Toxic Contaminants*.

The waste package, repository, geosphere, biosphere and contaminant factors can be considered as "internal" factors (i.e., they arise within the spatial and temporal boundaries of the repository system), whereas the external factors originate outside these boundaries. Hence, the waste package, repository, geosphere, biosphere and contaminant factors will be referred to as Internal FEPs and the external factors will be referred to as External FEPs.

The External FEPs are listed in Table 2-1 and the Internal FEPs are listed in Table 2-2. There are more than 40 External FEPs and almost 110 Internal FEPs. As previously noted, some of the Internal FEPs are further subdivided, as indicated in Table 2-2.

Table 2-1: External FEPs

1.1	**Repository Factors**	
	1.1.01	Site investigation
	1.1.02	Excavation and construction
	1.1.03	Placement of wastes and backfill
	1.1.04	Closure and repository sealing
	1.1.05	Repository records and markers
	1.1.06	Waste allocation
	1.1.07	As-built repository
	1.1.08	Quality control
	1.1.09	Schedule and planning
	1.1.10	Repository administrative control
	1.1.11	Monitoring
	1.1.12	Accidents and unplanned events
	1.1.13	Retrieval of wastes
1.2	**Geological Factors**	
	1.2.01	Tectonic movement and orogeny
	1.2.02	Deformation (elastic, plastic or brittle)
	1.2.03	Seismicity (earthquakes)
	1.2.04	Volcanic and magmatic activity
	1.2.05	Metamorphism
	1.2.06	Hydrothermal activity
	1.2.07	Regional erosion and sedimentation
	1.2.08	Diagenesis
	1.2.09	Salt diapirism and dissolution
	1.2.10	Hydrological response to geological changes
1.3	**Climatic Factors**	
	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 effects
	1.3.06	Warm climate effects (tropical and desert)
	1.3.07	Hydrological response to near-term climate changes
	1.3.08	Ecological response to climate changes
	1.3.09	Human behavioural response to climate changes

1.4	**Future Human Actions**	
	1.4.01	Human influences on climate
	1.4.02	Deliberate human intrusion
	1.4.03	Non-intrusive site investigation
	1.4.04	Drilling activities (human intrusion)
	1.4.05	Mining (human intrusion)
	1.4.06	Surface environment, human activities
	1.4.07	Water management (wells, reservoirs, dams)
	1.4.08	Social and institutional developments
	1.4.09	Technological developments
	1.4.10	Remedial actions
	1.4.11	Explosions and crashes
1.5	**Other External Factors**	
	1.5.01	Meteorite impact
	1.5.02	Species evolution
	1.5.03	Earth tides, reversal of earth's magnetic poles, polar wander and other unusual FEPs

Table 2-2: Internal FEPs Considered

2. WASTE PACKAGE FACTORS			
2.1	Waste Package Characteristics		
	2.1.01	Waste inventories	
		2.1.01.A	Inventory of radionuclides
		2.1.01.B	Inventory of chemical toxic contaminants
	2.1.02	Waste form materials and characteristics	
		2.1.02.A	Characteristics of used CANDU fuel (UO_2)
		2.1.02.B	Characteristics of Zircaloy
		2.1.02.C	Deposits on CANDU fuel bundles
		2.1.02.D	Characteristics of other waste forms
	2.1.03	Waste container materials and characteristics	
		2.1.03.A	Container design characteristics
		2.1.03.B	Container fabrication and installation defects
2.2	Waste Form Processes		
	2.2.01	Radiation effects (waste form)	
	2.2.02	Heat generation (waste form)	
	2.2.03	Used fuel dissolution	
	2.2.04	Zircaloy dissolution	
	2.2.05	Biological processes (waste form)	
	2.2.06	Gas sources and effects (waste form)	
	2.2.07	Nuclear criticality	
2.3	Waste Container Processes		
	2.3.01	Radiation effects (container)	
	2.3.02	Thermal processes (container)	
	2.3.03	Mechanical degradation (container)	
	2.3.04	Chemical and biological processes (container)	
		2.3.04.A	Stress corrosion cracking
		2.3.04.B	General or uniform corrosion
		2.3.04.C	Localized corrosion
		2.3.04.D	Microbial-induced corrosion
		2.3.04.E	Internal corrosion processes
	2.3.05	Gas sources and effects (container)	
2.4	Contaminant Release and Transport (waste package)		
	2.4.01	Diffusion (waste package)	
	2.4.02	Dissolution and precipitation (waste package)	
	2.4.03	Speciation and solubility (waste package)	

	2.4.04	Sorption and desorption (waste package)	
	2.4.05	Gas-mediated transport of contaminants (waste package)	
	2.4.06	Colloid interaction and transport (waste package)	
	2.4.07	Coupled solute transport processes (waste package)	
3. REPOSITORY FACTORS			
3.1	Repository Characteristics		
	3.1.01	Repository design	
	3.1.02	Buffer and backfill characteristics	
		3.1.02.A	Buffer characteristics and evolution
		3.1.02.B	Backfill characteristics and evolution
	3.1.03	Seals and grouts (cavern, tunnel, shaft)	
	3.1.04	Other engineered features (repository)	
3.2	Repository Processes		
	3.2.01	Thermal processes (repository)	
		3.2.01.A	Thermal conduction and convection (repository)
		3.2.01.B	Coupled heat transfer processes (repository)
	3.2.02	Hydrological processes and conditions (repository)	
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		3.2.02.B	Excavation damaged zone
		3.2.02.C	Groundwater movement (repository)
		3.2.02.D	Evolution of hydraulic conditions in the near-field
		3.2.02.E	Piping/hydraulic erosion of seals
		3.2.02.F	Coupled hydraulic processes (repository)
	3.2.03	Mechanical processes and conditions (repository)	
		3.2.03.A	Buffer and backfill swelling
		3.2.03.B	Formation and healing of cracks in seals
		3.2.03.C	Excavation damaged and disturbed zones
		3.2.03.D	Collapse of repository openings
		3.2.03.E	Evolution of stresses in the near-field
		3.2.03.F	Buffer and backfill creep
		3.2.03.G	Self-sealing of excavation damaged zone
	3.2.04	Chemical processes and conditions (repository)	
		3.2.04.A	Water chemistry and evolution (repository)
		3.2.04.B	Hydrothermal alteration (repository)
		3.2.04.C	Saline groundwater effects on clay-based seals
		3.2.04.D	Hyperalkaline fluid interaction (repository)
		3.2.04.E	Other chemical processes (repository)

	3.2.05	Biological processes and conditions (repository)	
		3.2.05.A	Biological processes (repository)
		3.2.05.B	Biological effects on groundwater movement (repository)
	3.2.06	Gas sources and effects (repository)	
	3.2.07	Radiation effects (repository)	
3.3	Contaminant Release and Transport (repository)		
	3.3.01	Advection and dispersion (repository)	
	3.3.02	Diffusion (repository)	
	3.3.03	Dissolution and precipitation (repository)	
	3.3.04	Speciation and solubility (repository)	
	3.3.05	Sorption and desorption (repository)	
	3.3.06	Colloid interaction and transport (repository)	
	3.3.07	Coupled solute transport processes (repository)	
	3.3.08	Gas-mediated transport (repository)	
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4.1	Geosphere Characteristics		
	4.1.01	Undisturbed rock lithology and stratigraphy	
	4.1.02	Discontinuities and lineaments	
	4.1.03	Undetected features (geosphere)	
4.2	Geosphere Processes		
	4.2.01	Thermal processes and conditions (geosphere)	
		4.2.01.A	Current geothermal state (geosphere)
		4.2.01.B	Permafrost (geosphere)
	4.2.02	Hydrogeological processes and conditions (geosphere)	
		4.2.02.A	Current hydraulic state (geosphere)
		4.2.02.B	Variable groundwater density (salinity)
		4.2.02.C	Water residence times (geosphere)
		4.2.02.D	Flow system evolution (geosphere)
	4.2.03	Geomechanical processes (geosphere)	
		4.2.03.A	Current stress state (geosphere)
		4.2.03.B	Stress state evolution (geosphere)
		4.2.03.C	Fracture/fault reactivation (geosphere)
		4.2.03.D	Time-dependant deformation (creep) (geosphere)
	4.2.04	Chemical processes and conditions (geosphere)	
		4.2.04.A	Current geochemical state (geosphere)
		4.2.04.B	Evolution of pore fluids (geosphere)
		4.2.04.C	Salt exclusion (geosphere)

		4.2.04.D	Redox stability (geosphere)
		4.2.04.E	Methane hydrate formation (geosphere)
		4.2.04.F	Dissolution/karst formation (geosphere)
	4.2.05	Coupled THMC processes (geosphere)	
		4.2.05.A	Self-sealing (geosphere)
		4.2.05.B	Coupled hydraulic processes (geosphere)
		4.2.05.C	Erosion and burial (geosphere)
		4.2.05.D	Glaciation/deglaciation (geosphere)
	4.2.06	Biological processes and conditions (geosphere)	
	4.2.07	Gas processes (geosphere)	
		4.2.07.A	Current gas state (geosphere)
		4.2.07.B	Gas generation (geosphere)
		4.2.07.C	Gas migration through porosity (geosphere)
		4.2.07.D	Gas migration through pathway dilation (geosphere)
	4.2.08	Erosion and sedimentation in fractures	
	4.2.09	Geological resources	
4.3	Contaminant Release and Transport (geosphere)		
	4.3.01	Advection and dispersion (geosphere)	
	4.3.02	Diffusion (geosphere)	
	4.3.03	Matrix diffusion (geosphere)	
	4.3.04	Dissolution and precipitation (geosphere)	
	4.3.05	Speciation and solubility (geosphere)	
	4.3.06	Sorption and desorption (geosphere)	
	4.3.07	Colloid interaction and transport (geosphere)	
	4.3.08	Gas-mediated transport of contaminants (geosphere)	
	4.3.09	Coupled solute transport processes (geosphere)	
5. BIOSPHERE FACTORS			
5.1	Surface Environment		
	5.1.01	Topography and morphology	
	5.1.02	Soil and sediment	
		5.1.02.A	Surface soils
		5.1.02.B	Overburden
		5.1.02.C	Aquatic sediments
	5.1.03	Near-surface aquifers and water-bearing features	
	5.1.04	Surface water bodies	
		5.1.04.A	Wetlands
		5.1.04.B	Lakes and rivers

		5.1.04.C	Springs and discharge zones
	5.1.05	Coastal features	
	5.1.06	Marine features	
	5.1.07	Atmosphere	
	5.1.08	Meteorology	
	5.1.09	Hydrological regime and water balance	
	5.1.10	Erosion and deposition (biosphere)	
	5.1.11	Ecological systems	
	5.1.12	Vegetation	
	5.1.13	Animal populations	
5.2	Human Behaviour		
	5.2.01	Human characteristics (physiology, metabolism)	
	5.2.02	Age, gender and ethnicity	
	5.2.03	Diet and liquid intake	
		5.2.03.A	Farming diet
		5.2.03.B	Hunter/gatherer diet
		5.2.03.C	Other diets
	5.2.04	Human habits (excluding diet)	
	5.2.05	Community characteristics	
		5.2.05.A	Community type
		5.2.05.B	Community location
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		5.4.04.B	Exposure of biota other than humans
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	5.4.07	Chemical toxicity effects	
	5.4.08	Radon and radon daughter exposure	
6. CONTAMINANT FACTORS			
6.1	Contaminant Characteristics		
	6.1.01	Radioactive decay and ingrowth	
	6.1.02	Chemical and organic toxin stability	
	6.1.03	Inorganic solids and solutes	
	6.1.04	Volatiles and potential for volatility	
	6.1.05	Organics and potential for organic forms	
	6.1.06	Noble gases	

3. FEP DESCRIPTION AND SCREENING ANALYSIS

3.1 OUTLINE

This chapter provides a description of each FEP, a brief 7CS screening analysis for each FEP, and a "FEP Screening" summary that lists the scenarios (if any) in which the FEP is explicitly included in the safety assessment models.

It should be clear that all FEPs are included in the sense that they are considered as described within this report. An explicit "include FEP" recommendation (in the "FEP Screening" section) generally means that there is a significant aspect of the FEP that is specifically included in an identified scenario, usually as a parameter for one of the 7CS models. Note that even if the FEP is not explicitly present, it may still be included implicitly as part of some other parameter - this would be noted in the screening analysis.

Note that the "include FEP" statement in the "FEP Screening" section of each FEP is intended as a summary indicator only - the screening analysis should be consulted for clarification of the importance of the FEP and how it should be treated in the 7CS.

3.2 SCENARIOS FOR THE SEVENTH CASE STUDY

The long-term safety of the repository is based on a multiple barrier approach. The Normal Evolution Scenario is the reference case, which considers the likely features, events and processes over the reference time frame.

Disruptive Event Scenarios are typically based on circumstances in which the engineered or natural barriers might be significantly bypassed. In the FEP analyses presented in this report, the following Disruptive Event Scenarios are identified as relevant to the hypothetical site and conceptual repository design for the 7CS (NWMO 2018, Section 6):

- Inadvertent Human Intrusion,
- Repository Seals Failure,
- Partially Sealed Repository,
- Poorly Sealed Borehole,
- Undetected Fault,
- Severe Erosion,
- Container Failure, and
- All Containers Fail.

A brief description of each disruptive scenario is given below.

3.2.1 Normal Evolution Scenario

In this scenario, the conditions around the repository change according to the expected or likely features, events or processes. For example, radioactivity in the fuel decays, the repository resaturates and the bentonite buffer swells to its design specification, and glaciation occurs on the 100,000 year time scale.

This scenario also includes variations in materials or conditions within the credible variability range or the limits of quality assurance. So for example, it considers the possibility of some containers being emplaced with flaws that were not detected by inspection.

3.2.2 Inadvertent Human Intrusion Scenario

The repository will be sealed and closed from surface to depth, preventing underground access. The site will be recorded and land use controls will be implemented to inform future land use after the repository has been closed. The siting process will also ensure that there are no known commercially viable natural resources near or below repository depth, so this would not be a factor favoring future intrusion. Also, the repository panels have a small footprint of ~2.8 km^2 (see Figure 3.1) and the repository is at a deep depth of around 500 m.

These factors limit the range of human activities that could directly affect the closed repository to a borehole unintentionally drilled into the repository as part of a future geological exploration program assuming knowledge of the repository was lost. This situation has a low probability of occurrence.

Nevertheless, the possibility of inadvertent human intrusion into the repository cannot be ruled out over long time scales. Such a borehole provides the potential for direct exposure to used fuel, if the drill bit intercepts a used fuel container and brings fuel pieces up to the surface. Furthermore, if the borehole is not sealed properly, it could provide an enhanced permeability pathway to the surface environment. This scenario is referred to as the *Inadvertent Human Intrusion Scenario*.

3.2.3 Repository Seals Failure Scenario

A second scenario by which the geosphere barrier can be bypassed is via the shafts (main, service and ventilation shafts). The shafts (with diameters from 7.6 m to 9 m) penetrate the geosphere, but are placed away from the waste panels, as shown in Figure 3-1. The shafts are carefully sealed during repository closure, in order to isolate the repository from its surroundings.

The *Repository Seals Failure Scenario* considers the possibility that the long-term performance of the shaft seals or their surrounding Excavation Damaged Zones (EDZs) is poor due to unexpected physical, chemical and / or biological processes; or that these seals and / or adjacent EDZs are somehow damaged by a seismic event. While these situations could result in an enhanced permeability pathway from the repository to the surface, they are very unlikely due to the extent of the seals, the quality control measures that will be applied during the selection of the seal materials (to ensure they are compatible with groundwater at the site) and due to the use of durable composite seals.

3.2.4 Partially Sealed Repository Scenario

The geosphere barrier is also bypassed via the shafts in the *Partially Sealed Repository Scenario*, in which the repository is assumed not to be sealed following the monitoring period (i.e., after all containers are deposited and all placement rooms are sealed). In this scenario,

the access tunnels and shafts remain open and are not maintained at least for an extended period. Since closing the repository is clearly important and funds would have been set aside for this purpose, this scenario would require a societal collapse or abandonment of the site for other unknown reasons. The likelihood of such a scenario is considered to be low.

3.2.5   Poorly Sealed Borehole Scenario

Another way in which the geosphere barrier can be bypassed is via the site characterization / monitoring boreholes. These boreholes are located in the vicinity of the repository and extend down to and below repository depth. These boreholes will be appropriately sealed on completion of site investigation / monitoring activities so they will have no effect on repository performance. However, if the borehole seals were to degrade extensively due to, for example, unexpected chemical interactions with groundwater and / or glacial meltwater, then the borehole could provide a small but relatively permeable pathway for the migration of contaminants from the repository horizon to the surface. This scenario is termed the *Poorly Sealed Borehole Scenario*. Such a situation is very unlikely due to the adoption of good engineering practices and quality control measures, including the appropriate selection of sealing materials, and the use of durable composite seals.

3.2.6   Undetected [Geological] Fault Scenario

For the Normal Evolution Scenario, it is assumed that site investigation and geosynthesis would detect the occurrence of transmissive vertical faults / fracture zones which could provide an enhanced permeability pathway from the repository horizon to the overlying aquifer within the footprint or vicinity of the repository. However, it is possible that site characterization does not identify all existing fracture zones at the site and, therefore, a scenario is defined to investigate the safety implications of a hypothetical transmissive fault that is either undetected or formed by the extension of an existing discontinuity. The hypothetical fault is assumed to be in close proximity to the repository and to extend from below the repository level to the shallow groundwater system. This scenario is termed the *Undetected Fault Scenario*. The likelihood of such a scenario is extremely low because the repository is located at a hypothetical site in the sedimentary Michigan Basin in Ontario. Fractures within the regional area are expected to be sparse and infrequent, and will not penetrate Paleozoic sedimentary rocks younger than Ordovician in age (NWMO, 2011). The sensitivity of calculated impacts to the distance of the fault from the repository perimeter and to the existence of a horizontal fracture that hydraulically connects the fault to the repository would be important to consider.

3.2.7   Severe Erosion Scenario

Glacial erosion is considered in the *Normal Evolution Scenario*; specifically, a small amount of net erosion (tens of metres over one million years) is assumed to occur in the Reference Case. However, a more severe glacial erosion rate is assessed in the Severe Erosion Scenario. Such a scenario is considered highly unlikely because of the absence of topographic features or other known factors that would tend to localize erosion by ice or water. Furthermore, future glaciations would tend to repeat the actions of their predecessors, by funneling into lake basins and deepening them, and maintaining the topographic highs where the ice flow velocities and erosion rates are relatively low and where sediments tend to accumulate.

3.2.8 Container Failure Scenario

The copper-coated used fuel containers are expected to last more than one million years based on thermodynamics, and on experimental and natural analogue evidence that copper is stable for very long periods under deep geological conditions (Kwong 2011; Scully and Edwards 2013). However, there are several mechanisms by which a container could fail sometime after it is installed in the repository. Random container failures that occur due to undetected defects in the as-placed containers (e.g., voids in the copper coating) are already considered in the *Normal Evolution Scenario*. In the 7CS, additional container failure mechanisms that occur after placement include, but are not limited to, the following.

- After the repository attains reducing conditions, the copper container should be immune to further corrosion. However, unexpected interactions between the groundwater and copper container (e.g., due to higher than expected sulphide concentrations) could damage the copper coating sufficiently over the time frame of interest that the steel vessel would be exposed to water, leading to weakening of the steel vessel due to corrosion and / or seepage of water into the container.

- A container could be damaged by a sufficiently large shear load. A large seismic event that causes significant rock slippage along an undetected fracture intersecting a placement room could produce such a shear load. (Containers would be placed far away from any known large water-conducting fractures.)

Although the specific container failure mode is not defined, the consequences are evaluated in the *Container Failure Scenario*. The key characteristics of this scenario are that only a few containers are affected, the container damage is significant, and the failure occurs well after repository closure. The likelihood of the Container Failure Scenario is low because, for example, the repository is located in a region of low seismic activity, containers would be placed sufficiently far from known fractures, and the site characterization program would ensure the absence of groundwater species detrimental to the long life of the copper containers. Repository operation, monitoring, and decommissioning and closure stages might affect groundwater chemistry, but the effect will last a relatively short time and will be buffered by bentonite.

3.2.9 All Containers Fail Scenario

The containers are designed to be corrosion resistant and robust. The inner steel vessel, for example, can sustain an external isostatic load of at least 45 MPa at 100ºC. Thus, the containers are expected to have a long lifetime. However, it is possible that some unexpected event or process may occur in the future such that there are multiple container failures in the repository. For example, the copper coating of the container could fail at long times due to unexpected interactions with groundwater caused by higher than expected sulphide concentrations in the groundwater; or, the passage of a beyond design-basis ice-sheet over the repository site causes the load on the containers to exceed their design limit. Consequently, an All Containers Fail Scenario is considered in which all the containers in the repository fail at 60,000 years, the time of the assumed first passage of an ice sheet over the site (NWMO 2018, Section 2). The likelihood of such a scenario is low in part because the site characterization program would ensure low sulphide in the groundwater at the site, and the external loads due to ice sheets have been conservatively calculated.
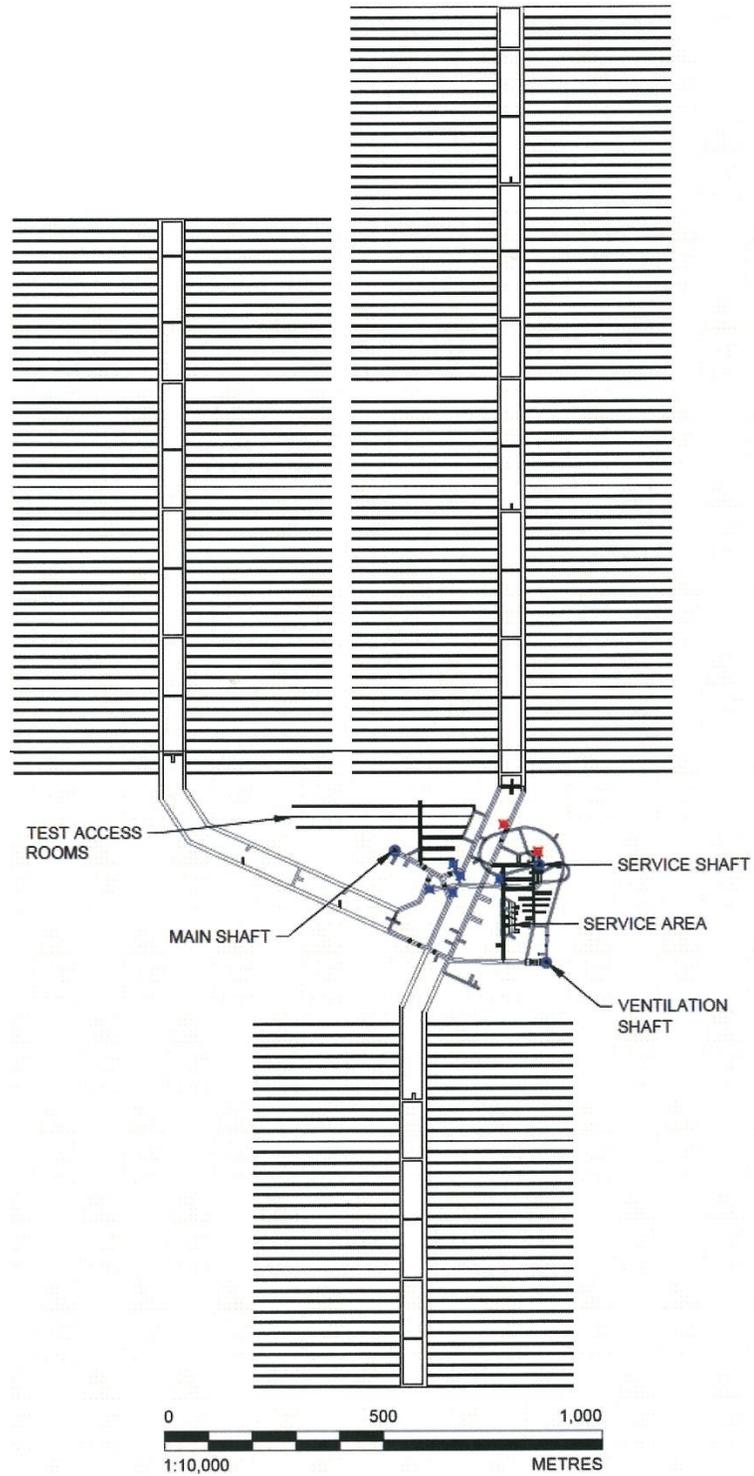
Figure 3-1: Plan View of Repository

3.3 FEP DESCRIPTION AND SCREENING ANALYSIS

Each FEP, identified in the lists given in Section 2, is described and screened in the following pages.

1. EXTERNAL FACTORS

FEP # 1.0.00   Scope of main category 1

<u>Description</u>

External factors are those with causes or origin outside the repository system domain. These factors include natural events and human decisions or actions, many of which could define scenarios or cases to be considered in the safety assessment. This category also includes decisions related to repository design, operation and closure.

The five subcategories under External Factors are:

      1.1 Repository factors
      1.2 Geological factors
      1.3 Climatic factors
      1.4 Future human actions
      1.5 Other external factors

1.1 Repository Factors

FEP # 1.1.00   Scope of subcategory 1.1

Description

Decisions on designs and waste allocation, and also events related to site investigation, operations and closure.

There are 13 subcategories under Repository Factors:

      1.1.01 Site investigation
      1.1.02 Excavation and construction
      1.1.03 Placement of wastes and backfill
      1.1.04 Closure and repository sealing
      1.1.05 Repository records and markers
      1.1.06 Waste allocation
      1.1.07 As-built repository
      1.1.08 Quality control
      1.1.09 Schedule and planning
      1.1.10 Repository administrative control
      1.1.11 Monitoring
      1.1.12 Accidents and unplanned events
      1.1.13 Retrieval of wastes

FEP # 1.1.01   Site investigation

Description

Investigations carried out to characterize a potential 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 interim safety assessments, using information from site investigation, could 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 certainty of the assessment modelling.

Site investigation activities could, in theory, affect the site or the postclosure safety. For example, investigation boreholes could be pathways to the surface if not properly sealed (see *Closure and repository sealing [1.1.04]*).

7CS Screening Analysis

The 7CS is a postclosure safety assessment of a geologic repository for used nuclear fuel located at a hypothetical site in the sedimentary Michigan Basin in Ontario. Since the site is hypothetical, there are no specific site data. Assumptions about the site characteristics will be made as follows:

-   a representative regional area encompassing a watershed in the Michigan Basin was selected for this case study, with boundaries corresponding to surface and groundwater divides (NWMO 2018, Section 2);
-   regional topography and surface waters hydrological properties were defined by a Digital Elevation Model and a river network in ArcGIS;
-   the geologic composition and structural features of the geosphere at the hypothetical site are consistent with a site on the Michigan Basin;
-   it is assumed that there are no fracture zones or discontinuities at the site;
-   measured geosphere property data are consistent with reported values obtained from site specific investigations for Ontario Power Generation's Deep Geologic Repository for Low and Intermediate Level Waste (Geofirma 2011);
-   groundwater is saline at repository depth with a total dissolved solids (TDS) content of about 280 g/L; and
-   other properties are selected to be consistent with conditions considered plausible for a Michigan Basin site that would be suitable for a repository (e.g., there are no identified commercially viable mineral resources at the site) (NWMO 2018, Section 1).

The case in which a site investigation borehole (or monitoring borehole) is not properly sealed is examined in the Poorly Sealed Borehole Scenario. All other scenarios assume that all site investigation activities have been carried out as expected, providing information on the site.

FEP Screening

Include FEP in all scenarios.

FEP # 1.1.02   **Excavation and 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.

The processes in this category are of concern mostly in relation to their potential impacts on the host rock, such as the following.

- Blasting and other rock excavation activities, and movement of heavy machinery in an excavated repository, could change the existing stress fields and create localized stress concentrations that result in formation of an excavation damaged zone. Other effects might include generation of fractures, and settling or subsidence. These effects could subsequently be amplified by earthquakes and related events.
- Dewatering of the host and nearby rock would affect the local hydrology and geochemistry. Large volumes of water would be drawn toward the excavation, possibly changing the groundwater composition near the repository and affecting formation and dissolution of minerals. Measures, for example grouting, will be taken in order to reduce these effects.
- The excavation and construction process will introduce foreign material, such as rock bolts, concrete, timbers, rail lines, shotcrete and grouting cement. Other foreign material could enter the open repository, including oxygen, surface microbes and nutrients such as nitrates and carbon. These materials could result in a variety of geochemical and biochemical conditions that could have undesirable effects on the performance of the engineered barriers.

7CS Screening Analysis

In the 7CS, it is generally assumed that the repository is constructed as designed (NWMO 2018, Section 4), under an appropriate quality assurance regime, and with measures taken to limit the extent of the excavation damaged zone (EDZ) around the repository openings and shaft.

The following assumptions are made regarding excavation and construction of the repository:

- A controlled drill & blast excavation method is used, resulting in the formation of an EDZ, as discussed under *Excavation damaged zone [3.2.02.B]*;
- Minimal use of materials (e.g., rock bolts and grouting) for stabilization of openings;
- Excavation of the shafts through the permeable upper formations will be managed through grouting, freezing and liner installation such that dewatering will be local and temporary;
- Dewatering of the near-field rock zone will only affect the time scale for resaturation; and
- Engineered materials will be fabricated to specifications, so there will be minimal introduction of undesirable foreign materials.

The EDZ is taken into account explicitly in the 7CS safety assessment calculations; other aspects of the excavation and construction methodology are not critical to the safety assessment.

The impact of poor construction of the shafts or tunnels, resulting in a highly permeable EDZ around the shaft seals, is examined in the Repository Seals Failure Scenario and its variant cases. The Poorly Sealed Borehole Scenario examines the impact of a poorly sealed monitoring or site characterization borehole.

FEP Screening

Include FEP in all scenarios.

FEP # 1.1.03   Placement of wastes and backfill

Description

The placing of waste packages at their final position within the repository, and the placing of buffer and backfill materials, including methods and schedules of placement.

One issue of concern is the potential for faulty placement of containers, buffer and backfill. Containers might be damaged during handling, leading to premature failure and contaminant releases; the buffer might have voids, or not be packed uniformly around the container, or make poor contact with the container and surrounding backfill or rock. The container might move or settle in the buffer, leading to a thinner diffusive barrier. The backfill might not entirely fill a disposal room or might settle, and the void space might serve as a conduit for contaminant transport.

Several package placement options are possible, and each will have different merits and shortcomings. The placement option may affect the EDZ area around placement rooms, the nature of the rock boundary around the packages, the potential linkage with fractures in the rock, and the quality control on package emplacement and backfilling.

A repository may employ several different placement options to deal with different types of waste or different container designs.

Schedules of placement could be important for exposures during the operational phase, particularly if that phase takes several decades. One issue could be exposure to workers from placement rooms that have been filled. Another issue is the variations in rates and times at which various parts of the disposal repository heat up and resaturate, and consequent effects on thermal and hydraulic gradients.

7CS Screening Analysis

In the 7CS, the in-room container placement method is used, as illustrated in Figure 3-2. It is assumed that the containers and engineered barriers are placed in the repository to design specifications. This would be ensured through good design, operational procedures and the operational quality assurance program.

However, based on the possibility of manufacturing defects in the used fuel containers and of failure of the quality control procedures, some containers may be placed in the repository with small undetected defects in the copper coating. Consequently, for the purposes of the 7CS safety assessment, it is assumed that some defective containers are present in the repository at the time of closure.

FEP Screening
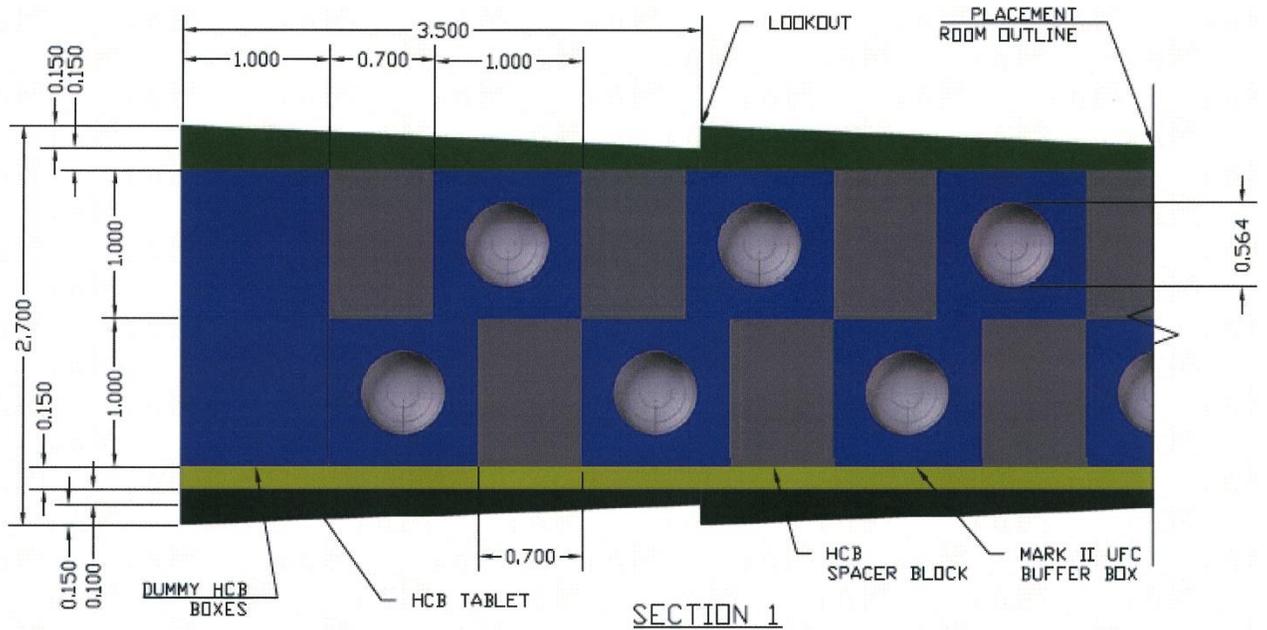
Include FEP in all scenarios.
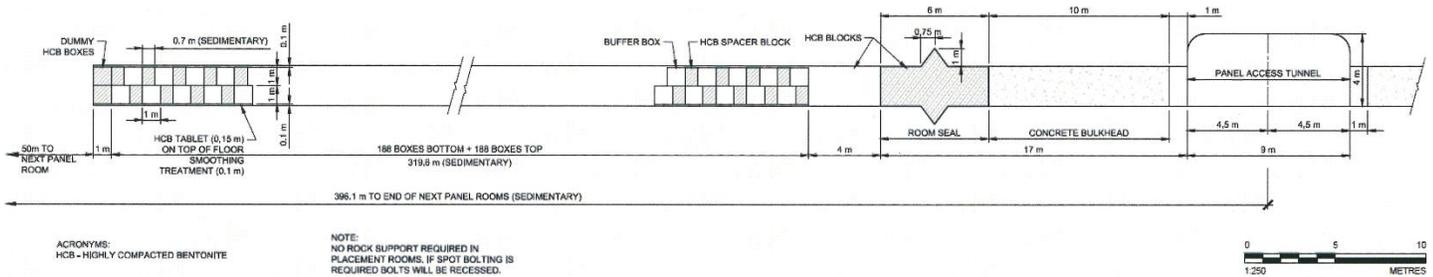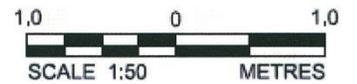
Figure 3-2: Longitudinal View of Mark II Container Placement (top) and Placement Room Seals (Bottom)

FEP # 1.1.04   Closure and repository sealing

Description

Factors related to the end of waste disposal operations, and the backfilling and sealing of access tunnels and shafts.

These closure activities are undertaken to prevent human access and to promote a return of the site to its pre-excavation hydrogeological conditions. The schedule for closure of individual sections of the repository, and complete closure and removal of surface facilities, may also need consideration.

It may be sufficient to consider closure to the reference design basis or it may be necessary to examine the consequences of incomplete closure. Incomplete closure could occur because of disintegration of society or lack of finances (which itself would be very unlikely because funds would have been set aside for closing the repository). Incomplete closure might involve leaving behind open shafts and placement rooms, or leaving behind open boreholes that have been forgotten.

It may be necessary to consider the potential for degraded performance of shaft and borehole seals, particularly for the long time frames over which these seals contribute to safety (see *Seals and grouts (cavern, tunnel, shaft) [3.1.03]*).

7CS Screening Analysis

It is assumed that closure of the 7CS repository is undertaken consistent with the reference design. Sufficient funding is reasonably assured through the NWMO regulatory basis and existing funding arrangements. Careful design, operating procedures and an appropriate quality assurance regime (NWMO 2018) will also ensure proper closure and sealing.

The Normal Evolution Scenario therefore includes the reference assumptions on closure and degradation of the shaft and repository seals over time. The possibility of degraded site investigation boreholes is considered in the Poorly Sealed Borehole Scenario. The effect of degraded performance of the shaft seals, due to, for example, unexpected deterioration of the seals, is considered in the Repository Seals Failure Scenario. In these scenarios, the hydraulic conductivities of the failed seal materials are conservatively assumed to be much higher than the design specifications from the time of repository closure.

The "what if" Partially Sealed Repository Scenario considers the case in which the repository is not sealed as planned following the monitoring period, and so the access tunnels and shafts remain open.

FEP Screening

Include FEP in all scenarios except the Poorly Sealed Borehole and Partially Sealed Repository Scenarios.

FEP # 1.1.05   Repository records and markers

Description

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

These records and markers would allow future generations to recall the existence and nature of the repository following closure, and influence activities 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 *Drilling activities (human intrusion) [1.4.04]*).

7CS Screening Analysis

It is expected that the 7CS repository will be recorded in various institutional records, including municipal, 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.

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.

It is assumed in the 7CS safety assessment that records, markers and memory are effective for 300 years after closure, 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.

FEP # 1.1.06   **Waste allocation**

Description

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

Canada's nuclear fuel waste is primarily used fuel bundles from CANDU nuclear reactors. Variations in this waste may occur because of variant fuel types, or because of significant differences in burnups, linear powers or cooling periods.

Another factor to consider is the possibility of co-disposal involving other types of radioactive and chemically toxic wastes that have quite different properties (degree of contamination, release rates, inventories, etc.). One important concern is that these properties are substantially different from used fuel bundles, such that potentially deleterious interactions occur between the different wastes, or their subsequent implications on safety are not understood or evaluated.

The waste allocations may also affect factors related to *Waste package characteristics [2.1]*, such as *Waste inventories [2.1.01]*.

7CS Screening Analysis

The scope of the 7CS is limited to used CANDU fuel bundles. The repository will hold 5.2 million bundles. There is no co-disposal involving other types of radioactive or chemically toxic wastes at the site.

Used CANDU fuel bundles are a relatively well defined waste and can be represented by a 'reference' fuel bundle. For the purposes of calculating radionuclide inventories and other fuel bundle parameters, the reference fuel bundle for the 7CS is the 37-element natural uranium standard Bruce fuel bundle. Analysis indicates that, for typical burnups, there are only small differences between this and the other CANDU power reactor fuel bundles presently used in Canada from an inventory perspective (Tait et al. 2000).

FEP Screening

Include FEP in all scenarios.

FEP # 1.1.07   As-built repository

Description

Potential differences between the design of the repository and the final as-built repository.

Specific concerns related to design assumptions include the following.

-   The final or as-implemented design might be different from the design considered in the safety assessment. For instance, the final choice of materials for the engineered barriers might be different due to limited availability of reference material, or the design might be modified to use materials with inferior or superior performance.
-   The final design might also be different because it includes detailed aspects such as underground openings that are needed for operations (e.g., equipment turnabout rooms, silos to store buffer) but were not considered in the conceptual design. Similarly, the construction of the repository might include changes in response to underground conditions.
-   The construction may include timbers, organics, tools, equipment and concrete that are left behind, but their effects are not considered in the safety assessment.
-   The design might not accommodate prolonged periods of monitoring during which, for example, swelling of the buffer might hinder or prevent the installation of backfill or the sealing and closure of placement rooms or tunnels.

7CS Screening Analysis

The repository design concept is based on the in-room container placement concept and is described in NWMO (2018, Section 4). The relevant repository parameters for the specific design considered in the 7CS are given in NWMO (2018, Section 4) and Gobien et al. (2018).

It is expected that the design will become progressively more detailed with time, and that future safety assessments would reflect the relevant details. In particular, the safety assessment in support of the decommissioning licence would be able to incorporate the as-built and as-operated repository features.

FEP Screening

Include FEP in all scenarios.

FEP # 1.1.08   **Quality control**

Description

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

Quality assurance is part of the management system expectations. This will include quality control objectives, procedures, and verification. These procedures will have an important direct role in safety assessments, and may be invoked to avoid detailed analysis of situations which could be prevented by quality control measures. For instance, these arguments might support the notion that it would be unlikely that an open (unsealed) site investigation borehole would exist after decommissioning.

Some specific issues are included in different categories, such as failure of defective containers in *Waste container materials and characteristics [2.1.03].* Examples of other issues of concern are the following.

- Improper operation may affect the long-term performance of the repository through a variety of means, such as the introduction of unwanted materials, the incomplete or defective closure of rooms and boreholes, and the loss of information on the existence of open boreholes.
- Containers might be improperly constructed. For example, internal structural supports might be defective or missing; or welds and coatings may not be uniformly applied. These construction faults might be rare and random. Conversely, they might be systematic, leading to 'common mode' failures involving a set of containers located in one part of the repository.
- There might be incomplete or inconsistent loading of the containers, especially given the large number of containers involved, the long duration time of facility operation and (possibly) the varying rates of arrival and processing of fuel bundles. An incompletely filled container might be structurally weak and have a different heat production compared with other containers. Inconsistent loading, and resultant heat production effects, could also occur if a container holds fuel bundles whose burnup levels are higher than the norm.

7CS Screening Analysis

The 7CS assumes that the repository is constructed, operated and closed according to the design basis in all scenarios, except the Partially Sealed Repository Scenario in which the repository is not closed (for unspecified reasons) following the post-operation monitoring period. These activities will be supported by NWMO's quality control program, which will be extended to meet the needs for construction, operation and closure, and the regulatory review (NWMO 2018, Section 11).

Although substantial failure of the quality assurance program is unlikely, the 7CS safety assessment assumes, even for the Normal Evolution Scenario, that a few containers are placed in the repository with undetected defects in the copper shell of the container, leading to relatively early failure of these defective containers and early release of contaminants from the repository.

The possibility that engineered barriers do not perform as expected, as a result of issues related

to quality control, is explored in disruptive scenarios. Thus, substantial quality assurance program failure is considered as a possible contributor to the Poorly Sealed Borehole and Container Failure Scenarios.

<u>FEP Screening</u>

Include FEP in all scenarios.

FEP # 1.1.09   Schedule and planning

Description

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

Relevant events may include phased excavation of caverns and placement of wastes, backfilling, sealing and closure of sections of the repository after wastes are placed, 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., decline of radioactivity and heat production from the wastes, material degradation, chemical and hydraulic changes during a prolonged open phase). There may be implications on the loss of records and markers (see *Repository records and markers [1.1.05]*) and exposure to workers during prolonged periods before closure.

7CS Screening Analysis

The reference schedule for the 7CS repository includes 38 years of operation, 70 years of extended monitoring and 30 years of decommissioning and closure.

FEP Screening

Include FEP in all scenarios. For the Partially Sealed Repository Scenario, it is assumed that the repository is not closed following the monitoring period.

FEP # 1.1.10   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 subsequent implications on *Scheduling and planning [1.1.09], Quality control [1.1.08]* and *Repository records and markers [1.1.05].*

7CS Screening Analysis

For the 7CS, it is assumed that adequate administrative controls are in place to ensure closure of the facility. The safety assessment implications of a failure to close the repository, for unspecified reasons, are addressed in the Partially Sealed Repository Scenario.

After closure of the repository, institutional controls (e.g., municipal land use controls), records or societal memory are assumed sufficient to prevent inadvertent human intrusion for 300 years. After this period, it is assumed in the safety assessment that controls are no longer effective, and the possibility of inadvertent intrusion into the repository is considered in the Inadvertent Human Intrusion scenario.

FEP Screening

Include FEP in all scenarios. Administrative control is implicitly assumed in most scenarios. Loss of control is considered in the Partially Sealed Repository and Inadvertent Human Intrusion Scenarios.

FEP # 1.1.11   Monitoring

Description

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

The extent and requirement for such monitoring activities may be determined by repository design, geological setting, regulations and public desires. Issues of special concern include the following.

-   Boreholes used to monitor performance, or other monitoring activities, could have unexpected deleterious effects such as the creation of new pathways for contaminant transport, particularly if the presence of the borehole is later forgotten.
-   The decision for final closure might never be taken if the periods of monitoring are prolonged, for reasons such as loss of, or changes to, institutional control.
-   Results from monitoring studies might be unreliable and lead to inappropriate actions. The results might incorrectly indicate the repository is functioning properly leading to no remedial activities. Conversely the results may incorrectly indicate that deficiencies exist leading to subsequent remediation that impairs the integrity of the repository.

7CS Screening Analysis

The repository in the 7CS is assumed to be monitored for about 70 years after all containers have been placed, and then closed (see *Schedule and planning [1.1.09]*). It is assumed that an effective and quality assured monitoring program will be implemented that does not compromise safety and ensures sensible decision making. Therefore, in the Normal Evolution Scenario, the monitoring program is assumed to have no effect on the postclosure system.

To assess the possible negative effects from monitoring of the repository, the Poorly Sealed Borehole Scenario is considered in which the seals in a monitoring borehole are assumed to degrade much more than expected, potentially providing a high permeability pathway through the host rock.

FEP Screening

The preclosure monitoring period is included in all scenarios.

FEP # 1.1.12   Accidents and unplanned events

Description

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

Accidents are events that are outside the range of normal operations, although certain types of accidents may be anticipated in repository operational plans. Unplanned events could also include deliberate deviations from operational plans (e.g., in response to an accident).

Malevolent acts include threat, theft, sabotage and attack.

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 placement, leading to early releases or enhanced transport of contaminants (see also *Placement of wastes and backfill [1.1.03]*); and
- sabotage or theft of the containers, seals, backfill, buffer or the host rock 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, deliberate destruction of nearby dams which could cause flooding of the repository, and activities aimed at preventing the use or closure of the facility.

7CS Screening Analysis

Accidents and unplanned events during construction and repository operation are generally not included in the 7CS postclosure assessment as it is reasonable to assume that any deleterious effects of such events would be corrected during the operation of the repository so that repository performance is not impaired. The depth of the closed repository would ensure that the repository was subsequently isolated from any subsequent accidents at surface. However the postclosure consequences of such preclosure events, if not fully corrected, would likely be degraded engineered barrier system performance and, are therefore likely bounded by the identified disruptive scenarios such as the Container Failure or All Container Failure Scenarios.

FEP Screening

Covered by other disruptive scenarios.

FEP # 1.1.13   Retrieval of wastes

<u>Description</u>

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

Repository designs may specifically allow for retrieval or rule it out. In some cases, an interim period might be planned between waste placement and final repository sealing, during which time retrieval is possible. Issues of concern include retrieval options which degrade repository performance, and options which may hinder subsequent decisions for retrieval. A related issue, the deliberate retrieval of the wastes or material (whether politically sanctioned or not) is discussed under *Deliberate human intrusion [1.4.02].*

<u>7CS Screening Analysis</u>

The 7CS repository is intended for disposal of used nuclear fuel with no intent to retrieve. However, the 7CS repository concept has features that improve retrievability, notably the extended monitoring period during which time the access tunnels and shafts remain open.

In the current safety assessment, it is assumed that there is no retrieval of waste after repository closure.

<u>FEP Screening</u>

Screened out.

1.2 Geological Factors

FEP # 1.2.00   Scope of subcategory 1.2

<u>Description</u>

Factors arising from the wider geological setting.

There are ten subcategories under Geological Factors:

      1.2.01 Tectonic movement and orogeny
      1.2.02 Deformation (elastic, plastic or brittle)
      1.2.03 Seismicity (earthquakes)
      1.2.04 Volcanic and magmatic activity
      1.2.05 Metamorphism
      1.2.06 Hydrothermal activity
      1.2.07 Regional erosion and sedimentation
      1.2.08 Diagenesis
      1.2.09 Salt diapirism and dissolution
      1.2.10 Hydrological response to geological changes

FEP # 1.2.01   Tectonic movement and orogeny

Description

Tectonic movement is the movement of continental plates in the lithosphere, relative to one another. The movement between plates can be classified as convergent, divergent or transcurrent. A convergent movement gives rise to processes such as: 1) orogeny, a large scale mountain building process involving crustal alteration (e.g., faulting and folding, see *Deformation (elastic, plastic or brittle) [1.2.02]*); 2) epeirogeny, a large scale mountain building process that generally leaves rock unaltered; and, 3) volcanism (see *Volcanic and magmatic activity [1.2.04]*) resulting from subduction. A divergent movement, where two plates move apart, results in the creation of new material (the space formed as the plates move apart is filled with cooled magma); such features commonly form at mid-oceanic ridges. A transcurrent boundary does not create or destroy crustal material, but the friction between plates can produce seismic activity (see *Seismicity (earthquakes) [1.2.03]*). Intraplate tectonic processes, related to in situ stresses and far field plate boundary conditions, may generate low level seismic activity deep within cratonic interiors (see *Seismicity (earthquakes) [1.2.03]*).

The movement of tectonic plates is typically in the range of a few cm per year, and the processes that originate from plate motions occur over periods of millions of years. The effects of such processes, however, can vary from slow processes, such as erosion and sedimentation (see *Regional erosion and sedimentation [1.2.07]*), to rapid processes, such as volcanism and seismic activity.

Among the potential effects that tectonic movement may have on a repository are the modification of groundwater flow (see *Flow system evolution (geosphere) [4.2.02.D]*) and contaminant transport pathways (see *Contaminant release and transport (geosphere) [4.3]*), the displacement of a container due to changes in the in situ stress field (see *Current stress state (geosphere) [4.2.03.A]* and *Stress state evolution (geosphere) [4.2.03.B]*), and damage to the repository and its contents.

7CS Screening Analysis

Tectonic activity is most likely to occur at or near plate boundaries. The hypothetical 7CS repository site is located in the sedimentary Michigan Basin in Ontario, within the stable interior of the large North American tectonic plate (see Figure 3-3). The Michigan Basin in Ontario is characterized by low levels of seismicity.

Based on present and historic relative plate motions, the hypothetical site within the Michigan Basin will remain far from the plate margin for tens of millions of years. Therefore, tectonic movement and orogeny are not important processes on the time scale of the 7CS.

Earthquakes are discussed under *Seismicity (earthquakes) [1.2.03]*.

FEP Screening

Screened out.
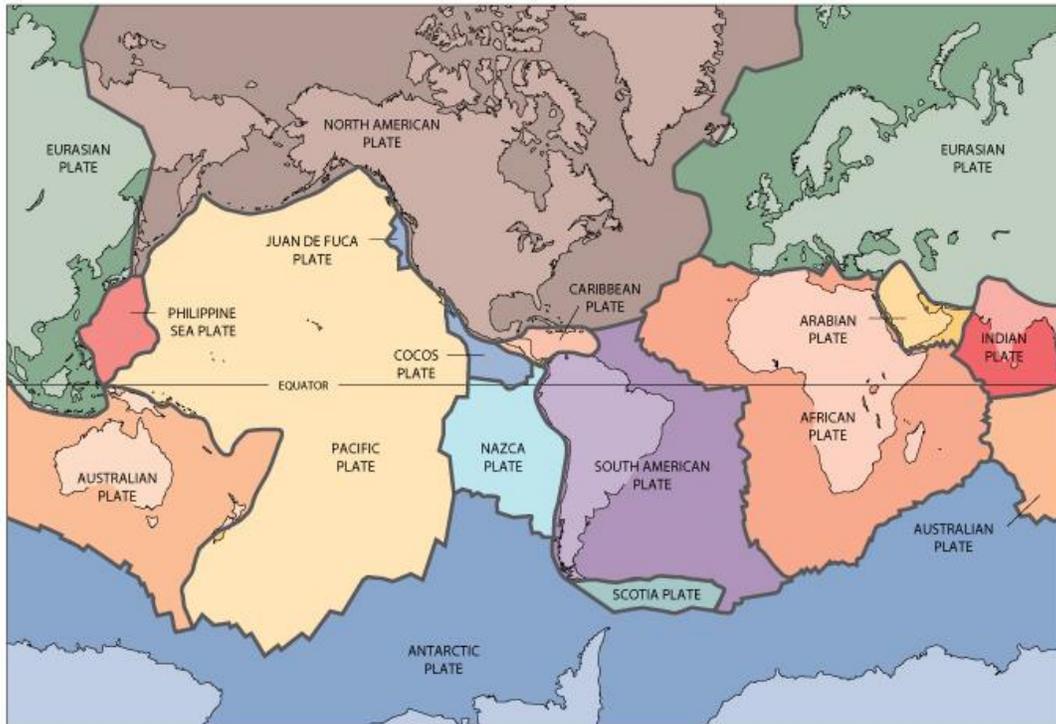
Note: U.S. Geological Survey map available at http://pubs.usgs.gov/gip/dynamic/slabs.html

Figure 3-3: North American Plate and Its Boundaries with Other Major Tectonic Plates

FEP # 1.2.02   **Deformation (elastic, plastic or brittle)**

Description

This FEP covers the physical deformation of the rock mass in response to changes in the stress field, including sudden faulting and fracturing, slow creep and extrusion, and compression of rocks. These deformation processes can be classified as being either elastic, plastic or brittle.

Elastic deformation is defined as recoverable strain, with the rock recovering to its original state after the applied stress is removed. For example, the surface of the Earth responds in an elastic manner to a large glacial load. Plastic deformation is defined as permanent strain, in which rocks flow under an applied stress until the strength of the rock is exceeded and deformation, such as folding, occurs. Brittle deformation occurs when stress exceeds the strength of the rock, causing the rock to break or fracture.

Fracturing refers to the rapid brittle deformation of the rock, which may or may not entail appreciable displacement along the fracture plane. A fault is a fracture in the Earth's crust accompanied by displacement of one side of the fracture relative to the other. Changes in the stress field are more likely to be accommodated by the reactivation and extension of pre-existing faults and fractures rather than by the creation of new faults. Creep is a rock deformation process that involves the slow, quasi-continuous movement of the rock mass and it generally localizes along existing discontinuities.

The geologic forces that cause the deformation of the rock mass can be compressional or extensional and may occur at different spatial scales. At large and regional scales, changes of the stress field are related to plate tectonics and glaciation processes, respectively. At a smaller scale, deformation processes may be caused by excavation of the repository, the swelling of the engineered barriers and the thermal gradient from the waste, generating small-scale perturbations in the host rock.

Creep and reactivation of existing faults, in the vicinity of the repository, may affect the hydraulic properties of the rock and alter groundwater flow conditions. This could lead to decreased radionuclide transport times and could introduce oxidizing waters into the repository near-field. Deformation processes, related to glacial loading, may also compromise the mechanical stability of the rock, including extrusion of rock into existing void spaces.

7CS Screening Analysis

The hypothetical 7CS repository site is located in the sedimentary Michigan Basin in Ontario. The Michigan Basin is located in the interior of the North American plate, one of the most tectonically stable regions on the planet. In this area, tectonic deformation due to tectonic movement and orogeny is unlikely over the time scale of interest (see *Tectonic movement and orogeny [1.2.01]*).

Over the next million years, the largest deformation force anticipated for southern Ontario is that caused by glaciation (see *Local glacial effects [1.3.05]*). The weight of the glacier(s) depresses the land underneath the ice sheet, which then slowly rebounds after the ice is removed. For example, much of the Canadian Shield outside of the Hudson Bay is still uplifting in a visco-elastic manner at about 5 mm/a (Peltier 2002). This slow rate of rebound, occurring over a large area, may contribute to an increase in low-magnitude seismic events (see *Seismicity*

(earthquakes) [1.2.03]), which may, in turn, influence the reactivation of small fractures in or around a repository (see *Fracture/fault reactivation (geosphere) [4.2.03.C]*). Smaller amounts of plastic deformation (creep) related to the in situ stress field may allow deformation and shearing of the placement rooms.

Deformation processes, related to glacial loading, could increase rock stresses in the repository and could cause failure of roof and pillars. However, the rooms and tunnels in the 7CS repository are designed for stability (e.g., pillar thickness) and are also backfilled, so rock failure and rockfall would not occur (Radakovic-Guzina et al. 2015).

Glacial-related deformation would preferentially cause movement along existing fractures rather than creation of new ones (Braun et al. 2008) (see *Geomechanical processes (geosphere) [4.2.03]*). In the 7CS, it is assumed that there are no open faults or fracture zones in or near the repository (NWMO 2018, Section 2) and no new glacial-related fracture formation is considered in the Normal Evolution of the 7CS. Although unlikely, the consequences of reactivation of a closed fracture near the repository due to glacial processes is considered through the Undetected Fault Scenario. The impact of a large seismic event that produces a shear load on a container, due to rock movement along a local fracture intersecting a placement room, is examined as part of the Container Failure Scenario.

The potential impacts of deformation processes on the hydraulic properties of the excavation damaged zone are addressed in the Normal Evolution Scenario

Effects of glaciation on hydrogeological conditions are described in *Hydrological response to geological changes [1.2.10]* and seismic reactivation of existing faults is discussed in *Seismicity (earthquakes) [1.2.03]*.

FEP Screening

This FEP is implicitly included in all scenarios because it is taken into account in the design of the repository and the properties of the excavation damaged zone.

FEP # 1.2.03   **Seismicity (earthquakes)**

Description

A seismic event is a sudden release of built-up stress via rapid relative movement of the Earth's lithosphere along faults or geologic interfaces.

Most large earthquakes, worldwide, are a consequence of tectonism and occur near tectonically and/or volcanically active plate margins (rifts and subduction zones). Intraplate tectonic processes, related to in situ stresses and far field plate boundary conditions, may generate low level seismic activity deep within cratonic interiors. In addition, some seismic events in the past have been associated with the release of vertical stresses and isostatic rebound that accompany major deglaciations (Wu 1998; Stewart et al. 2000).

The potential effects of seismic activity in the geosphere that will affect repository safety deal with the extension or reactivation of existing faults (see *Geomechanical processes (geosphere) [4.2.03]*). Fault movement could alter groundwater flow (changes in migration pathways, permeability and head distributions) and possibly groundwater composition (see *Hydrogeological processes and conditions (geosphere) [4.2.02]*). Within the repository itself, seismic activity could damage the containers and seals, liquefy the backfill materials, modify the EDZ properties, cause rock falls, and fracture the rock near the repository. Potential effects on the biosphere include liquefaction of soil, formation of new discharge areas, alteration of river courses, and destruction of dams. Multiple events occurring close together in time may have cumulative effects.

7CS Screening Analysis

The 7CS repository is located at a hypothetical site in the sedimentary Michigan Basin in Ontario. Because the 7CS site is hypothetical, there is no specific information available to support a seismic hazard assessment. However, Ontario is located in the interior of the North American plate, which is tectonically stable (AMEC 2011); and, so, seismic activity in Ontario is generally negligible, with few earthquakes of magnitude $5M_N$ or greater having been recorded in southern and northern Ontario (see Figure 3-4). Hence, it is reasonable to assume that the repository site is in a low-seismicity area; although, brief increases in seismic activity could occur with the release of vertical stresses as glaciers recede, but these periods are unlikely to last long (Atkinson and Martens 2007).

Generally, the effects of a seismic event are less severe underground than on the surface, except for very soft deposits (Bäckblom and Munier 2002), limiting the potential damage to the repository for a given event. Thus, the impact of post-glacial seismicity on a repository is expected to be within its design specifications and it is anticipated that the containers will generally be protected from the resulting shear stresses (Bäckblom and Munier 2002; Radakovic-Guzina et al 2015). Also, since the rooms and tunnels in the repository are designed for stability and are also backfilled, rock failure and rockfall would not occur.

A large seismic event could cause rock to slip along a fracture intersecting a placement room, producing a shear load on a container or containers. This would be unlikely to be important for the 7CS since the repository is sited to avoid fractures in the vicinity of containers, and the containers themselves are somewhat insulated from rock shear through the buffer material surrounding the containers. However, although an analysis of the effect of such a shear load on

the Mark II container has not been carried out, for the purposes of the 7CS, it is assumed that such a shear load is a potential cause of the Container Failure Scenario.

Seismic events could modify the properties of the excavation damaged zones by causing additional mechanical damage. However, studies indicate that this is not expected to be significant at relevant repository sites (Radakovic-Guzina et al 2015). In the 7CS, this possibility is further addressed through sensitivity studies that examine the effect of changes to the properties of the excavation damaged zones on calculated impacts.

With respect to potential effects on the buffer, the high clay content of the buffer will prevent any risk of liquefaction (15% clay is sufficient; Ivan et al. 2006).

FEP Screening

This FEP is included in all scenarios because it is taken into account in the design of the repository and the properties of the excavation damaged zone. Seismicity is one potential cause of the Undetected Fault Scenario.

Earthquakes in or near Canada, 1627 - 2015

EarthquakesCanada.nrcan.gc.ca
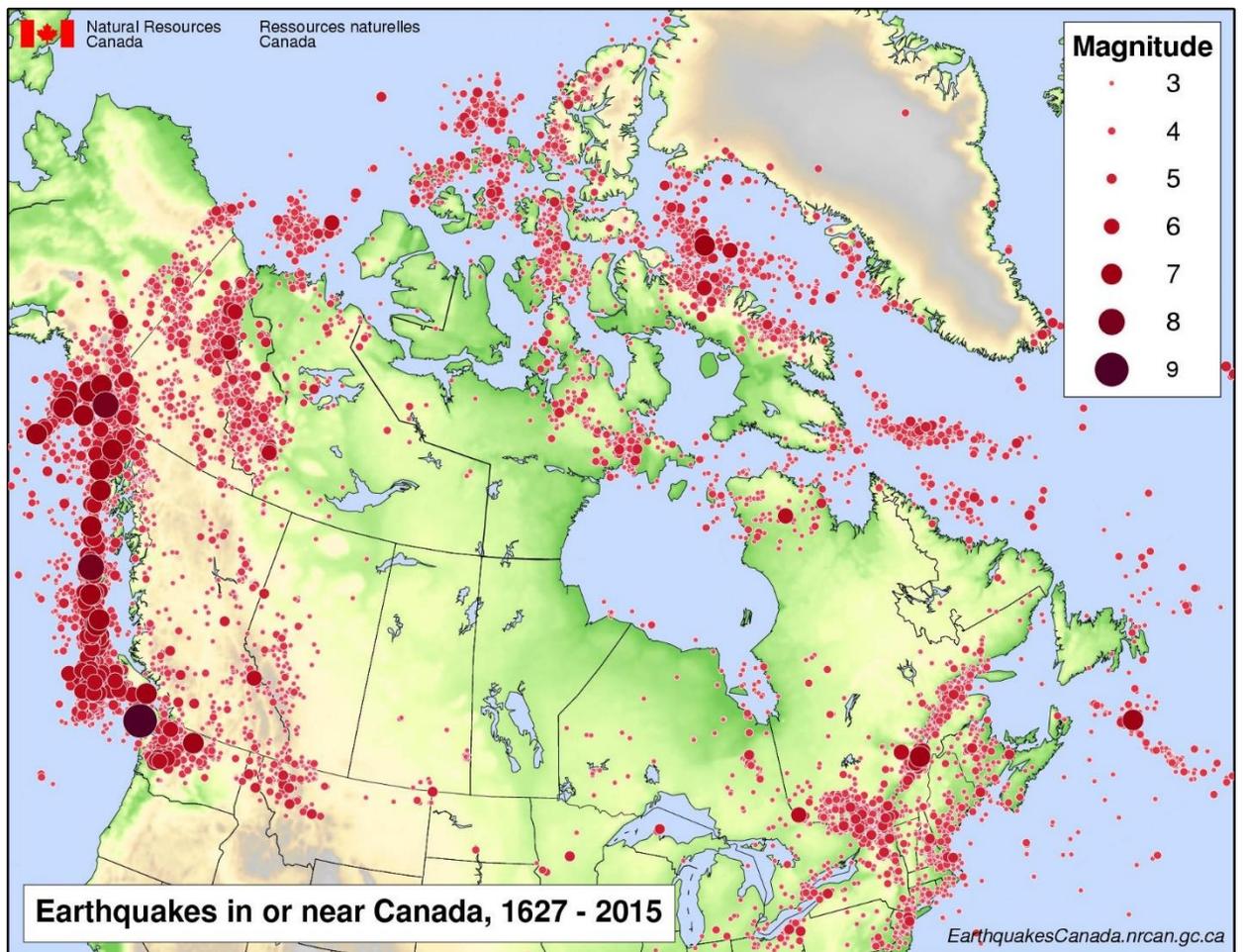
Note: Obtained from Natural Resource Canada website (http://earthquakescanada.nrcan.gc.ca/historic-historique/caneqmap-eng.php, accessed June 2017).

Figure 3-4: Major Earthquakes in Canada Since 1627

FEP # 1.2.04   Volcanic and magmatic activity

Description

Volcanic and magmatic activity refers to the intrusion of molten silicate material (magma) into the lithosphere, which sometimes reaches the Earth's surface. Volcanoes form when magma flows through a crustal vent or fissure to the surface, accompanied by the expulsion of ash and hot gases. If the magma crystallizes before reaching the surface, intrusive igneous bodies can also form beneath volcanoes.

Most extrusive magmatic and volcanic activity is at active plate margins, including subduction zones and oceanic ridges. To a lesser extent, magmatism also occurs in areas removed from plate boundaries where rising plumes of hot mantle reach the surface ("hot spots").

The high temperatures and pressures associated with volcanic and magmatic activity may result in permanent composition and texture changes in the surrounding rock (see *Metamorphism [1.2.05]*), possibly modifying its hydraulic properties and, hence, groundwater flow. Other effects of magmatism on the geosphere could include changes in stresses, yielding reactivation, creation and sealing of faults and/or ductile deformation of the rock, as well as changes in groundwater temperature and composition (see *Hydrothermal activity [1.2.06]*). Effects on the repository could include indirect changes (temperature, groundwater flow, groundwater chemistry and EDZ properties), or direct disruption by the intrusion of repository rooms by a magmatic dike or by a volcano-tectonic derived fracture. A volcano that intersects the repository, and also reaches the Earth's surface, may give rise to dispersion of wastes in a plume of volcanic ejecta.

7CS Screening Analysis

The 7CS repository is located at a hypothetical site in the sedimentary Michigan Basin in Ontario. This basin is located in the interior of the North American plate, a stable cratonic region where the earth's heat flux is low (Muzurek 2004) and where volcanic and magmatic activity (including mantle plumes) is currently non-existent.

Assuming that relative plate motions continue as they do today, volcanic and magmatic activity could develop again in approximately 20 million years, when southwestern Ontario may pass over a mantle plume ("hot spot") currently associated with magmatic activity in the Snake River Plain and Yellowstone areas of the western United States (Wood and Kienle 1990, Müller et al. 1993).

Volcanic and magmatic activity is not included in the 7CS because they would only occur well outside the time frame of interest for repository safety (1 Ma).

FEP Screening

Screened out.

FEP # 1.2.05　　　　**Metamorphism**

Description

Metamorphism is the process of chemical and physical changes that igneous and sedimentary rocks (and existent metamorphic rocks) undergo when subjected to new temperature and pressure conditions. Depending on the prevailing tectonic environment and conditions (see *Tectonic movement and orogeny [1.2.01]*), the metamorphism will develop differently, either as a response to: 1) magmatic intrusion, see *Volcanic and magmatic activity [1.2.04]*; 2) faulting processes, see *Deformation (elastic, plastic or brittle) [1.2.02]*; 3) hydrothermal fluid circulation; or 4) burial of rock leading to increased temperature and pressure.

7CS Screening Analysis

The 7CS repository is located at a hypothetical site in the sedimentary Michigan Basin in Southern Ontario. The host rocks are sedimentary and may be subject to metamorphic processes if heated by volcanic activity or through burial. However, Southern Ontario is located in a relatively stable tectonic environment (see *Tectonic movement and orogeny [1.2.01]*). No volcanic activity is expected for tens of millions of years (see *Volcanic and magmatic activity [1.2.04]*). Thus, the temperatures and pressures needed for metamorphism to occur in the host rock would not be present over the 1 million year time frame of the 7CS. Moreover, burial is not relevant on the time frame of the safety assessment because of the effect of glacial erosion.

Hydrothermal faults are discussed in *Hydrothermal activity [1.2.06]*.

FEP Screening

Screened out.

FEP # 1.2.06   Hydrothermal activity

Description

Hydrothermal activity refers to those processes associated with the circulation of high temperature groundwaters in the subsurface. Sources of heat are usually upwelling of magma from the mantle or thermal pulses resulting from orogenesis, though high temperatures are also generated internally in the crust by the decay of radioactive isotopes. The movement of most hydrothermal waters is driven by the density difference between hotter and colder water.

High temperature groundwaters are capable of stripping normally insoluble elements from the rocks they flow through, which are subsequently precipitated when the chemically altered waters move upwards and cool down or mix with groundwaters of different chemical composition. These mineral alteration processes are complex and strongly coupled; for example, mineral alteration could involve fracture infilling, which decreases groundwater flow and produces more saline groundwater, resulting in formation of a new set of mineral alteration reactions, and so forth. The hydrothermal fluids may also transport a wide range of dissolved gases (e.g., CO_2, H_2S), which may be released in response to changing temperature and pressure conditions along the flow path.

Effects of hydrothermal activity in the geosphere include: 1) enlargement of pores and fractures, 2) chemical alteration of the rock mineralogy, 3) changes in fracture properties due to mineral precipitation, and 4) variations in hydraulic conductivity. Groundwater flow and composition would also be affected by these processes.

7CS Screening Analysis

The 7CS repository is located at a hypothetical site in the sedimentary Michigan Basin in Ontario. There are locations within the Michigan Basin with evidence of ancient hydrothermal activity; however, the repository site is assumed to be distant from faults and features related to or affected by hydrothermal processes.

Ontario is part of a stable cratonic region, which is devoid of present day magmatic activity and where no such type of activity is likely to occur within the next 20 Ma (*Volcanic and magmatic activity [1.2.04]*). Furthermore, the present-day geothermal gradient is low in southern Ontario and no regional variation is documented (Mazurek 2004). Hence, temperatures of hydrothermal significance are not expected at repository depth over the 1 Ma period of interest for safety assessment.

FEP Screening

Screened out.

FEP # 1.2.07   Regional erosion and sedimentation

Description

Erosion refers to the large scale (geological) removal and transport of rocks and sediments at surface, and includes the combined effect of weathering and erosion. Sedimentation is the deposition of particles that have been transported by either fluvial or aeolian processes, following weathering and erosion elsewhere.

Weathering is the structural breakdown of rocks and minerals by the combined action of mechanical degradation and chemical water-rock interaction. The rate of weathering depends on both the environmental conditions and the mineralogical characteristics of the rock. Erosion is the process by which weathering products are removed and transported away by water, wind, mass movements and/or ice. Erosion is followed by the deposition of the eroded material on lake bottoms and river deltas, in dunes, etc.

Erosion includes the processes which result in: 1) localized incisions that remove large volumes of rock from a small area, and 2) broader ranging actions that remove large volumes of surface soil and rock from a widespread area.

Effects of erosion on the geosphere include changes in topography, which in turn may modify groundwater gradients, and recharge and discharge locations. Groundwater composition may also be affected by the weathering and erosion of the overlying soil layers and rock.

7CS Screening Analysis

The 7CS repository is located at a hypothetical site in the sedimentary Michigan Basin in Ontario.

Weathering and erosion by wind and water are very slow processes. The mean global erosion rate in cratonic areas from these processes is estimated to be on the order of 10 m/Ma during the last 200 Ma (Peulvast et al. 2009). Lowland rivers have been estimated to erode at a rate of less than 5 m/Ma (Einsele 2000). Erosion rates in the Canadian Shield and in its overlying sedimentary basins are expected to remain of this magnitude in the next million years, given that no tectonic uplift of the currently flat topography is anticipated.

The most relevant erosion event that could possibly affect the repository site in the 1 Ma safety assessment time frame is the development of ice sheets. Bell and Laine (1985) give an average glacial erosion estimate for Canada of 40-70 m/Ma. Hallet (2011) has examined the phenomenon of glacial erosion in the Michigan Basin. In the absence of topographical features or other known factors that would tend to localize erosion by ice or water, a conservative erosion rate of 100 m in one million years was estimated. The net change in surface thickness is unlikely to affect the deep low-permeability rocks at the 7CS site over the 1 Ma safety assessment time frame, although it will affect the surface environment and shallow geosphere.

Sedimentation due to wind and water erosion is expected to be low. However, there could be significant sediment deposits as a result of glaciers or glacial lakes, although these could be removed during subsequent glacial cycles.

For the Normal Evolution Scenario, tens of metres of surface erosion over one million years is anticipated. This is unlikely to affect calculated impacts, given (1) the extremely low permeability of the intermediate and deep rock formations, and (2) the deep depth (500 m below ground surface) of the 7CS repository. The small amount (tens of metres) of surface erosion will mainly affect the shallow groundwater regime. Erosion is therefore not explicitly modelled in the Normal Evolution Scenario. The Severe Erosion Scenario explores the safety implications of a much higher erosion rate.

<u>FEP Screening</u>

Include FEP explicitly in the Severe Erosion Scenario.

FEP # 1.2.08   Diagenesis

Description

Diagenesis refers to the collection of processes by which sediments become a sedimentary rock. These processes, such as compaction, cementation, solution, replacement, and recrystallization of the sediment occur at shallow depths, are controlled mainly by temperature and pressure, and ultimately lead to sediment lithification. Because of the low ranges of pressure and temperature involved in diagenesis, the processes sometimes overlap low grade metamorphism.

7CS Screening Analysis

The 7CS repository is located at a hypothetical site in the sedimentary Michigan Basin in Ontario. No significant physical and chemical changes to the host rock properties are expected to occur over the safety assessment period given the age and mineralogy of the rocks, the limited temperatures and pressures at repository depth, and the fact that deep burial of the site is unlikely. See also *Volcanic and magmatic activity [1.2.04], Hydrothermal activity [1.2.06]* and *Regional erosion and sedimentation [1.2.07]*.

Therefore, diagenesis is not an important process at the repository site over the one million year time frame of interest and is not included in the 7CS.

FEP Screening

Screened out.

FEP # 1.2.09   Salt diapirism and dissolution

Description

This FEP refers to the large-scale evolution of salt formations.

Diapirism is the process by which a ductile mass of rock or sediment deforms and pierces overlying sediments (overburden). Salt formations are prone to developing diapiric structures due to their ability to 'flow'. The actual piercing is the last stage of a complex history of deformation, during which a wide range of intermediate salt structures form. Salt movement is usually triggered by a pressure difference within the salt bed due to differential loading of the overburden; however, in some cases, tectonic forces may also play a significant role in the deformation of salt.

Dissolution of salt may occur where unsaturated groundwater comes in contact with salt deposits. Transport of fresh meteoric water to subsurface salt accumulations may occur as a result of water flow in over/underlying permeable aquifers. The dissolution of salt often creates gravitational deformation in the overburden and could eventually yield the formation of sinkholes at ground surface.

Potential effects on the geosphere of salt diapirism and dissolution include: 1) the ductile deformation of overlying sediments; 2) changes in groundwater composition; and 3) formation of new faults and reactivation of existing ones, which would, in turn, alter groundwater flow. Effects on the repository could be the result of indirect changes (groundwater flow and chemistry) or direct disruption by the intrusion of a salt diapir into the repository rooms, or by structural collapse of the repository due to underlying salt dissolution.

7CS Screening Analysis

The 7CS repository is located at a hypothetical site in the sedimentary Michigan Basin in Ontario. The Michigan Basin contains significant salt formations. For example, salt is mined commercially at Goderich, Ontario. 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 (NWMO 2011, Section 2.2.5.4). 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.

There are no significant salt layers at the hypothetical repository site. Thin salt and evaporite layers are present in the Salina A1 Evaporite, but this layer is only a few metres thick at the repository site (NWMO 2018, Section 2). There is no evidence of collapse structures within the Salina Formations, or active salt dissolution more recently than the Late Silurian.

The repository is located in the Cobourg Formation of the Ordovician sediments. The Ordovician formations in the Michigan Basin do not contain significant salt deposits and have been stable for millions of years, as illustrated by their regional uniformity. 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.

<u>FEP Screening</u>

Screened out.

FEP # 1.2.10   Hydrological response to geological changes

Description

The large-scale geological changes described in *FEPs [1.2.01] to [1.2.09]* could cause changes in regional groundwater flow and pressures.

Within and below 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.

7CS Screening Analysis

The 7CS repository is located at a hypothetical site in the sedimentary Michigan Basin in Ontario. At the hypothetical site, it is assumed that the hydraulic pressure is hydrostatic – there is no pattern of over- and under-pressures in the different rock formations. The only geologically significant process expected to occur at the site on a 1 million year time frame is glaciation (see *FEPs [1.2.01] to [1.2.09]).*

Glaciation is likely to have an effect on the shallow groundwater flow field, particularly due to permafrost formation, and during ice-sheet advance and retreat. In the 7CS, the effects of glaciation are discussed as part of the Normal Evolution Scenario. Note that paleohydrogeologic simulations (NWMO 2018, Section 2) indicate that although the groundwater flow in the near surface would be affected by glaciation, groundwater flow at the repository horizon would be mainly unaffected by glaciation.

Glacial erosion over the million year time frame of interest could also affect regional groundwater flow. For this reason, erosion of tens of metres is considered in the Normal Evolution Scenario. The implications of more severe erosion are considered in the Severe Erosion Scenario.

A severe seismic event is considered as a potential cause for activation of a fault in the Undetected Fault Scenario (see *Seismicity (earthquakes) [1.2.03]*). Activation of a fault would affect groundwater flow in the geosphere.

FEP Screening

Include FEP, i.e., changes in regional groundwater flows due to geological changes, in the Normal Evolution, the Undetected Fault, and the Severe Erosion Scenarios.

1.3 Climatic Factors

FEP # 1.3.00   Scope of subcategory 1.3

<u>Description</u>

Factors related to global climate change and consequent regional effects.

There are nine subcategories under Climatic Factors:

      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 effects
      1.3.06 Warm climate effects (tropical and desert)
      1.3.07 Hydrological response to near-term climate changes
      1.3.08 Ecological response to climate changes
      1.3.09 Human behavioural response to climate changes

FEP # 1.3.01   **Global climate change**

Description

This FEP includes past and future long-term change of global climate. Global climate change could lead to local climate changes around a repository (see *Regional and local climate change [1.3.02]*) and, subsequently, changes in the performance of the repository.

The global climate undergoes constant change, with both cooling and warming trends over time. For example, the global climate could become warmer as a result of elevated levels of greenhouse gases in the atmosphere. Global climate can change over time due to variations in solar insolation, due to continental drift and changes in ocean current patterns, or due to dust generated by volcanic eruptions or meteorite impacts.

The most important feature of global climate change in the long-term is its characteristic glaciation-deglaciation cycling. The northern portion of North America has been covered with periodic continental ice sheets for the last two million years. This extreme climate cycling is the response to small amplitude changes in the effective intensity of solar radiation due to variations in the geometry of the Earth's orbit around the sun. Anthropogenic processes, such as greenhouse gas emissions, may artificially warm the global climate and delay the onset of future glaciations; however, glaciation is likely to re-occur within a million year time frame (Peltier 2011).

The impacts of global climate change are also discussed under: *Sea level change [1.3.03], Periglacial effects [1.3.04], Local glacial effects [1.3.05], Hydrological response to near-term climate changes [1.3.07], Permafrost (geosphere) [4.2.01.B], Flow system evolution (geosphere) [4.2.02.D]* and *Glaciation/deglaciation (geosphere) [4.2.05.D].*

7CS Screening Analysis

The 7CS repository is located at a hypothetical site in the sedimentary Michigan Basin in Ontario. Southern Ontario has experienced nine major glacial cycles in the last one million years, with glacial cycles roughly every 120,000 years. These glacial cycles are driven in large part by variations in solar insolation due to earth orbital patterns. Although global warming may delay the onset of the next global glacial cycle, the basic solar insolation variations will continue and glacial cycles could reassert themselves (e.g., Berger and Loutre 2002; Mysak 2008; Pimenoff et al. 2011). Therefore, it is prudent for the 7CS safety assessment to assume that glaciation will occur in the long-term and, consequently, glaciation is considered as part of the Normal Evolution Scenario (see Figure 3-5).

Other than glaciation, the likely variation in global climate over the next million years is not expected to have much effect on conditions at repository depth. Currently, the global climate is warming and estimates suggest there will be an increase in global average temperature, accompanied by a rise in sea levels, an increase in extreme weather, and changes in precipitation patterns (IPCC 2007, 2014). The potential effects of global warming are considered under *Regional and local climate change [1.3.02].*

FEP Screening

Include FEP in the Normal Evolution Scenario.
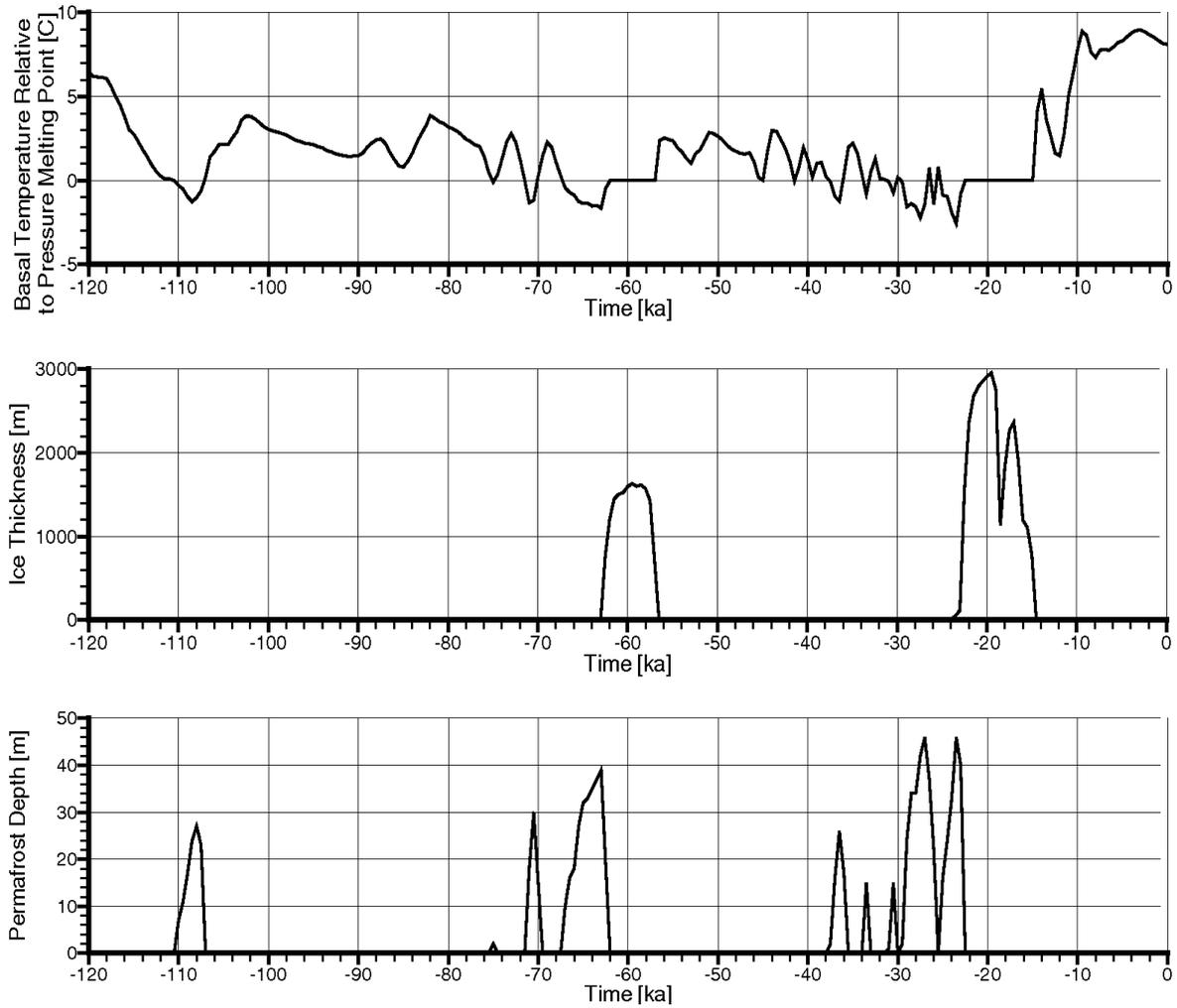
Figure 3-5: University of Toronto Glacial System Model Outputs for Simulation nn9930 at the Hypothetical Site of 7CS Repository (adapted from NWMO 2018, Section 2)

FEP # 1.3.02   Regional and local climate change

Description

This FEP is related to the climate at a repository site, on a local or regional scale, and its evolution with time. Climate is characterized by a range of factors, but most notably temperature and precipitation. Broad regional climate types in Canada include temperate, boreal and tundra climates.

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
• Associated with human activities such as de-forestation or extensive irrigation.

Climate change can occur as smooth or abrupt gradations, from one climate state to the next (Committee on Abrupt Climate Change, National Research Council, 2002). Climate change is not concerned just with the starting and ending states, because the processes that occur during the change between states may also be important.

The effect of the local climate on the surface environment is immediate. For example, cold weather and freezing temperatures reduce surface water flows, influence heating fuel needs, and modify the types of natural biota and agricultural crops that could be supported. In contrast, the effects on the deep geosphere and repository are less direct. The most important is likely the modification of the rate of surface water infiltration, which could influence the distribution of recharge and discharge zones at the repository site and, hence, the groundwater flow around the repository.

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

7CS Screening Analysis

The 7CS repository is located at a hypothetical site in the sedimentary Michigan Basin in Ontario. The Michigan Basin has been, in the past, and will be, in the future, affected by regional climate change. Thus, regional and local climate change is potentially important at the repository site, especially in the surface and near-surface groundwater systems.

In the near term (i.e., on the scale of centuries or perhaps thousands of 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 local lake and river levels and the location of 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 glaciation, it is expected that glacial cycling will resume in the long term. At the 7CS site, it is expected that this will involve extended periods when the site is under periglacial conditions - see *Periglacial effects [1.3.04],* and also when the site is covered by an ice sheet - see *Local glacial effects [1.3.05]*, as

illustrated in Figure 3-5. Thus, in the 7CS, the effects of regional and local climate change, in particular glaciation, are discussed as part of the Normal Evolution Scenario.

<u>FEP Screening</u>

Include FEP in Normal Evolution Scenario. The impact of normal climate variation is considered in all scenarios through the choice of metrological data.

FEP # 1.3.03   **Sea level change**

<u>Description</u>

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

The effects of sea level change can include flooding of the repository surface, changes in groundwater flow and contaminant transport patterns, and changes in groundwater composition.

A specific effect of potential interest in safety assessments is a change in the natural background iodine levels due to changes in proximity to oceanic sources.

<u>7CS Screening Analysis</u>

Sea level change will not be considered in the 7CS because the repository is located at a hypothetical site in Ontario, which is hundreds of kilometres from the nearest ocean and well above sea level.

<u>FEP Screening</u>

Screened out.

FEP # 1.3.04   Periglacial effects

Description

Periglacial effects cover the physical processes associated with cold, but ice-sheet-free, low precipitation environments (ice-covered processes are discussed in *Local glacial effects [1.3.05]*).

A key feature of such environments is the formation of permanently frozen subsurface soils and rock, called permafrost, which behaves as an impervious layer. Thus, permafrost layers will effectively isolate the surface from the groundwater system(s), forcing regional groundwater flows to discharge at local unfrozen zones (known as taliks), which often occur under lakes or large rivers. A volume of high salinity water (known as a cryopeg) may also form ahead of the permafrost freezing zone because salts are typically excluded from the lattice of developing ice (see *Salt exclusion (geosphere) [4.2.04.C]*). However, in the case of low permeability formations this will not happen as an intensive mass transport phenomenon but there will be more saline liquid inclusions within the permafrost.

Another important characteristic of periglacial environments is the seasonal change from winter (freezing) to summer (thaw), which can be associated with the movement of large volumes of water and an increased potential for erosion. Because permafrost can prevent meltwater produced during seasonal thaws from percolating downwards, thawing can result in the development of a highly saturated surficial soil layer and associated mass movement of soil on slopes (called solifluction). A tundra climate, characterized by cold and wet conditions, may cause the formation of pingos and palsas, affecting the natural biota as well as human activities.

The advance or retreat of ice sheets will lead to a change to or from periglacial conditions. These will be accompanied by changes in: 1) the overall landscape (see *Local glacial effects [1.3.05]*), 2) drainage patterns, and 3) watershed dynamics, all of which will impact groundwater flow. Associated changes in the plant, animal, and human communities will also affect exposure pathways.

7CS Screening Analysis

In the 7CS, the effects of glaciation are considered in the Normal Evolution Scenario (see *Global climate change [1.3.01]*). Periglacial conditions will precede and follow future ice sheet advance and retreat, as illustrated in Figure 3-5. The maximum extent of permafrost depth at the 7CS hypothetical site is approximately 65 m (see NWMO 2018, Section 2). Generally, permafrost is not continuous unless its depth exceeds 60 to 90 m (Brown and Pewe 1973). Therefore, although permafrost formation at the repository site would alter local groundwater flows, surface recharge and discharge can still occur.

The impact of periglacial conditions on the deep groundwater flow system (> 250 m depth) is expected to be limited because it will not become frozen, and because its high salinity and low permeability will isolate it from changes in the shallow groundwater zone. For example, regional paleohydrogeolgic modelling (NWMO 2018, Section 2) indicates that downward migration of glacial meltwater is largely retarded by the low permeability Ordovician formations and so meltwater does not penetrate into the deep groundwater zone.

The periglacial effects on the ecosystem (e.g., permafrost formation) will be potentially significant in terms of receptor characteristics and exposure pathways (Garisto et al. 2010).

In conclusion, periglacial effects are relevant for consideration in the 7CS. These effects should be considered from the point of view of impact(s) on groundwater flow and contaminant transport (see *Permafrost (geosphere) [4.2.01.B]*), as well as from the point of view of critical group characteristics and exposure pathways (see *Human behaviour [5.2]*, in particular *Diet and liquid intake [5.2.03]* and *Wild and natural land and water use [5.2.08]*).

FEP Screening

Include FEP in Normal Evolution Scenario.

FEP # 1.3.05   Local glacial effects

Description

Local glacial effects refer to the effect of glaciers, including ice sheets, within the region of a repository (e.g., changes in the surface topography, water flow paths and ground stresses). This is distinct from the effects on climate which are discussed under *Global climate change [1.3.01]* and *Regional and local climate change [1.3.02]*.

Erosional processes associated with glacial movement, and with glacial meltwaters beneath the ice mass and at the margins, can alter the local surface topography. For instance, erosion can form valleys and fjords, while sedimentation can form moraines and eskers (see also *Regional erosion and sedimentation [1.2.07]*).

The advance or retreat of an ice sheet may be accompanied by earthquakes (see *Seismicity (earthquakes) [1.2.03]*) and the reactivation of faults and fractures, notably during retreat when the weight of the ice sheet is released. The pressure of the ice mass on the landscape will also cause a wide-spread depression of the regional crustal plate, with isostatic rebound occurring after the ice sheet retreats.

The presence of an ice sheet will directly change hydraulic heads, possibly imposing an additional head equivalent to the height of the ice sheet. Such gradients may cause deep penetration of oxygenated water, possibly during the period of ice sheet advance or retreat. This could significantly alter groundwater composition at depth.

As a result of potential changes to the surface topography and fracture network, groundwater flow paths may change. The presence of permafrost around the ice sheet will also influence groundwater flow, including the location of discharge zones.

Finally, glaciation would also bring about changes to the biosphere, with the presence of a nearby ice sheet promoting formation of a tundra climate and biosphere. The characteristics of the critical group living near the repository site would also change.

7CS Screening Analysis

The 7CS repository is located at a hypothetical site in the sedimentary Michigan Basin in Ontario. As identified in *Regional and local climate change [1.3.02]*, over the next million years, the repository site is expected to be affected by glaciation and to be covered periodically by ice sheets. Thus, the effects of glaciation are included in the Normal Evolution Scenario.

The presence of an ice sheet will directly change hydraulic heads, possibly imposing an additional head 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 hydraulic gradients around the ice sheet to changes in the permeability of the rock at shallow depths due to permafrost formation (see *Hydrological response to near-term climate changes [1.3.07]*).

The ice-sheets may cause the introduction of oxygenated fresh water, possibly during the period of ice-sheet advance or retreat when head gradients are largest. This process could alter groundwater compositions in the shallow groundwater system, notably concentrations of

oxygen. However, this process would not affect the deep groundwater system (> 250 m depth), as indicated by the paleohydrogeologic simulations carried out for the 7CS, which show that glacial meltwater would not penetrate much below a depth of 250 m (NWMO 2018, Section 2). Glacial recharge penetrating below the shallow groundwater system (> 215 m depth) is not expected to be oxygenated or to influence redox conditions at the repository horizon (NWMO 2013, Section 2). Oxygen ingress is limited to depth of less than 200 m during the glaciation-deglaciation event (Bea et al. 2018).

For an ice-sheet thickness of 2-3 kilometres, the peak hydraulic pressure (which assumes the water table is at the top of the ice sheet) could increase the mechanical load on the containers by 20-30 MPa. This increased mechanical load is taken into account in the design of the repository and container. Similarly, the potential geomechanical effects from the ice-sheet loading on the repository and shaft would be taken into account for the specific site conditions. For example, the repository and shafts would be backfilled, and the repository would be generally aligned favourably with the normal rock stresses such that there would be little effect from ice-sheet loads.

Glaciation would bring about significant changes to the biosphere. Erosion of the bedrock may result in the reduction of the depth of the repository below ground surface, so erosion is considered in the Normal Evolution Scenario (see *Regional erosion and sedimentation [1.2.07]*). There would also be consequences for local humans and biota, as discussed in *Ecological response to climate changes [1.3.08]* and *Human behavioural response to climate changes [1.3.09]*.

FEP Screening

Include FEP in the Normal Evolution Scenario, which includes glaciation.

Local glacial effects are considered a potential cause of the Severe Erosion, Shaft Seal Failure and All Containers Fail Scenarios.

FEP # 1.3.06   **Warm climate effects (tropical and desert)**

Description

This FEP is related to warm tropical and desert climates, including seasonal effects, as well as meteorological and geomorphologic effects special to these climates.

If the regional climate becomes tropical, then the region may experience extreme weather patterns (monsoons, hurricanes) that could result in flooding, storm surges and high winds, with implications on both erosion and hydrology.

The high temperatures and humidity associated with tropical climates result in rapid biological degradation, and soils are generally thin. 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, and alkali flats might form resulting in 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 the use of distant water supplies). These changes may also be associated with rapid alteration of topography as a result of enhanced erosion.

7CS Screening Analysis

The 7CS repository is located at a hypothetical site in Ontario. Development of a significantly warmer climate (tropical or desert) in Ontario is unlikely over the 1 Ma time frame of interest for repository safety due to its northerly latitude and the dominance of glacial/interglacial cycling. 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. However, it would be reasonable to assume that the effects of greenhouse gas might significantly delay the onset of the next glaciation (Ganopolski et al. 2016). Warm climate effects are not considered in the 7CS.

FEP Screening

Screened out.

FEP # 1.3.07   **Hydrological response to near-term climate changes**

Description

This FEP refers to the changes in the hydrology and hydrogeology in response to climate change within a region. The climate may change over time to become wetter or drier, warmer or cooler, or a combination of these.

The hydrology and hydrogeology 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 (including the extent of soil saturation and surface runoff, changes in sediment load characteristics, and groundwater recharge). Vegetation and human actions may modify these responses.

Climate change may lead to: 1) glacial/interglacial cycling, 2) permafrost development, 3) sea level change, and 4) evolution of surface water bodies (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). These processes, driven by climate change, may cause changes in the hydrogeological surface boundary conditions (i.e., hydraulic heads, rate of recharge and/or discharge) and groundwater flow systems (i.e., the direction and rate of groundwater flow). For example, the presence of permafrost and a cold-based ice sheet would lead to a reduction in groundwater recharge; the presence of a warm-based ice sheet and retreat of the glacier would induce groundwater infiltration. An associated rise in sea level may lead to the intrusion of seawater into aquifers in coastal areas.

Other effects are discussed separately under *Periglacial effects [1.3.04], Local glacial effects [1.3.05], Warm climate effects (tropical and desert) [1.3.06], Ecological response to climate changes [1.3.08]* and *Human behavioural response to climate changes [1.3.09]*. More specific effects are described under *Hydrogeological processes and conditions (geosphere) [4.2.02], Surface water bodies [5.1.04]* and *Hydrological regime and water balance [5.1.09]*.

7CS Screening Analysis

The 7CS repository is located at a depth of 500 m at a hypothetical site in the sedimentary Michigan Basin in Ontario. Hydrogeological conditions at repository depth are likely to be characterized by low groundwater velocities and geochemically reducing conditions on the relevant time scale.

As identified in *Regional and local climate change [1.3.02],* over the next million years, the repository site is expected to be affected by glaciation and to be covered periodically with ice sheets. Thus, the effects of glaciation are included in the Normal Evolution Scenario.

Glaciation will mainly affect the shallow groundwater flow system at the 7CS site, as demonstrated by paleohydrogeologic simulations (NWMO 2018, Section 2). These show that groundwater flow in the deep groundwater zone (depth > 250 m) would not be significantly affected by glacial/interglacial cycling; so, transport in the deep groundwater zone will remain diffusion controlled (NWMO 2018, Section 2). Furthermore, glacial recharge penetrating below the shallow groundwater system (> 215 m depth) is not expected to be oxygenated or to influence redox conditions at the repository horizon (NWMO 2018, Section 2; Bea et al. 2018). These conclusions are supported by the geological record for the Michigan Basin (Sykes et al.

2011), which indicates that the effects of glaciation on groundwater flow and reducing conditions at repository depths are small.

Finally, because the repository site is assumed to be located far inland from the current coastlines, it would not be affected by sea level change.

<u>FEP Screening</u>

Include FEP in Normal Evolution Scenario.

FEP # 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.

7CS Screening Analysis

Ecosystems are responsive to climate changes. The current ecosystem in the vicinity of the 7CS 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 advancing 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.

The Normal Evolution Scenario includes glaciation, ecological response to glaciation is also considered as part of this scenario.

FEP Screening

Include FEP in the Normal Evolution Scenario.

FEP # 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 change.

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, which may, in turn, influence air quality and inhalation doses. The more extreme a climate, the greater is the extent of human control necessary over these resources to maintain agricultural productivity, e.g., through the use of dams, irrigation systems and controlled agricultural environments (greenhouses). Some climate changes may be sufficiently extreme that the region becomes uninhabitable. 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.

7CS Screening Analysis

The 7CS repository is located at a hypothetical site in the sedimentary Michigan Basin in Ontario. The characteristics of potential human critical groups at the site will change as a result of climate change.

Global warming in the next millennium can be expected to have minor impacts on human behaviour. More significant impacts are expected as the climate cools in the longer term as part of glaciation, 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 or energy, or by subsistence hunting, fishing and trapping – as 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 subsequent interglacial period, it is expected that agriculture and forestry would become re-established and communities would once again be established in the area. The different human behaviours could lead to changes in the importance of various exposure pathways.

The 7CS considers human response to climate change resulting from glaciation as part of the Normal Evolution Scenario. Based on Garisto et al. (2010), three potential critical groups could be defined: a self-sufficient farmer during periods of temperate climate, a self-sufficient hunter during periods of permafrost, and a self-sufficient fisher during periods when a large proglacial lake exists near the repository.

FEP Screening

Include FEP in the Normal Evolution Scenario.

1.4   Future Human Actions

FEP # 1.4.00   Scope of subcategory 1.4

Description

Human actions after the repository has been closed that can potentially affect the performance of the engineered or geological barriers. Passive behaviour and habits of the local population are covered separately under *Human behaviour [5.2]*.

There are 11 subcategories under Future Human Actions:

    1.4.01 Human influences on climate
    1.4.02 Deliberate human intrusion
    1.4.03 Non-intrusive site investigation
    1.4.04 Drilling activities (human intrusion)
    1.4.05 Mining (human intrusion)
    1.4.06 Surface environment, human activities
    1.4.07 Water management (wells, reservoirs, dams)
    1.4.08 Social and institutional developments
    1.4.09 Technological developments
    1.4.10 Remedial actions
    1.4.11 Explosions and crashes

FEP # 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 are contributing to global warming.
- Acid rain. Processes such as metal refining and fossil fuel burning can lead to the release into the atmosphere of nitrous oxides, sulphates and various heavy metals. These can combine with atmosphere moisture to form acid rain, which can interfere with the health of biota. Acid rain can also influence the transport of contaminants in the biosphere.
- Land use. 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.

7CS Screening Analysis

In the near-term, human induced global warming may cause changes whose impacts are locally important; for example, changes in precipitation rates and, hence, stream and river flows, and surface water levels. 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) and others (e.g., BIOCLIM 2004, Berger and Loutre 2002) note that initiation of a glacial episode in the next 60,000 years would be inhibited by current levels of greenhouse gases, which are, in turn, affected by human actions. Ultimately, however, it is expected that carbon dioxide concentration will return to historic levels and glacial-interglacial cycling will be re-established.

Therefore, human actions are a possible cause of global climate change, which is considered in the Normal Evolution Scenario.

FEP Screening

Include FEP in the Normal Evolution Scenario.

FEP # 1.4.02   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 dangerous contents.

Deliberate intrusion could occur for reasons that include the following:

-   undertaking remedial activities to correct real or perceived faults in the repository performance, an activity also discussed under *Remedial actions [1.4.10];*
-   authorised retrieval of useful materials from the repository, see also *Retrieval of wastes [1.1.13];*
-   unauthorised retrieval of fissionable or radioactive material for malicious reasons including sabotage and war; and
-   archaeological exploration, driven by the observed or inferred presence of repository structures or contents*.*

The potential effects of deliberate intrusion include removal of used fuel from the repository to the surface environment, and damage to the natural and engineered barriers.

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 are discussed under *Non-intrusive site investigation [1.4.03], Drilling activities (human intrusion) [1.4.04], Mining (human intrusion) [1.4.05], Surface environment, human activities [1.4.06]* and *Water management (wells, reservoirs, dams) [1.4.07].*

7CS Screening Analysis

Deliberate human intrusion is not included in the 7CS. It is assumed that any society wishing to recover materials from the repository would have the technology to understand and manage the hazards (i.e., they are responsible for their actions).

Malicious acts are not included either. The depth of the repository and the nature of the hazard mean that accessing the used fuel in the closed repository would require a significant effort. The resources required would make this scenario akin to a state-sponsored deliberate intrusion, and/or make it likely to be detected. The case of a borehole deliberately drilled into the repository to create an open pathway is addressed by the Inadvertent Human Intrusion Scenario.

FEP Screening

Screened out.

FEP # 1.4.03   **Non-intrusive site investigation**

Description

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

Investigations, such as prospecting for geological resources, might occur after information of the location of a repository had been lost. The evidence of the repository itself, e.g., discovery of an old shaft, might itself prompt investigation, including research of historical archives.

7CS Screening Analysis

Non-intrusive site investigations for any purpose are not considered in the 7CS because they would not affect the repository or contaminant transport.

If the investigations lead to further "intrusive" investigation or development, then the consequences of these latter actions are dealt with under separate FEPs. See, for example, *Drilling activities (human intrusion) [1.4.04], Mining (human intrusion) [1.4.05*], and *Water management (wells, reservoirs, dams) [1.4.07].*

FEP Screening

Screened out.

FEP # 1.4.04   **Drilling activities (human intrusion)**

Description

The possibility of any type of drilling activities 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 (human intrusion) [1.4.05]*.

Another important drilling activity, for water-supply wells, is discussed separately in *Water management (wells, reservoirs, dams) [1.4.07]*.

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

Drilling activities might be carried out for a wide number of reasons, including:
-   exploration for mineral and energy resources, possibly driven by the search for rare minerals whose importance has been enhanced by technological advances;
-   fracking of rock for natural gas;
-   production of geothermal energy;
-   injection of liquid wastes and other fluids; and
-   scientific studies.

Potential impacts include direct exposure to excavated waste or contaminated water and rock, and creation of altered gas, groundwater and contaminant transport pathways between the repository and surface environment. In addition, these activities could affect the characteristics of the critical group; for instance, the most exposed individuals might be the drill crew.

7CS Screening Analysis

Drilling of water wells is discussed separately under *Water management (wells, reservoirs, dams) [1.4.07]*.

Deep drilling at the repository site would not occur as long as institutional controls and societal memory were effective. Even if such controls have lapsed, drilling of boreholes that penetrate into the repository is very unlikely because of the depth of the repository, the small footprint of the repository rooms, and the lack of commercially viable natural resources at the hypothetical site (verified during siting at any real site).

Since the repository host rock does not contain known commercially viable mineral resources, one could argue against deliberate surveys of the site. However, if the repository were detected as an anomaly by remote measurement methods and deliberately targeted, then the contact of the borehole with the repository would likely be more carefully managed. For example, current regulations in Ontario require borehole stratigraphy information to be provided. This is typically done using gamma logging, which would indicate the presence of the repository as an unexpected large radioactive anomaly.

Nonetheless, because of the long time frames of interest, it is possible that institutional controls, markers and societal memory would have lapsed. Thus, the 7CS considers an Inadvertent

Human Intrusion Scenario in which an exploratory borehole drilled from the surface is assumed to pass through a used fuel container and to bring used fuel to the surface.

The impact of the failure of the seals in a site characterization borehole or a monitoring borehole is examined in the Poorly Sealed Borehole Scenario.

<u>FEP Screening</u>

Include FEP in Inadvertent Human Intrusion and Poorly Sealed Borehole Scenarios.

FEP # 1.4.05   Mining (human intrusion)

Description

The possibility of any type of mining or excavation activities 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 and natural gas;
-   excavation of another repository for the storage or disposal of nuclear waste;
-   excavation for storage or disposal of other wastes (e.g., CO_2);
-   excavation for storage of valuable materials such as petroleum products; and
-   construction of underground shelters for military purposes or to protect civilization during an ice age.

Potential impacts include direct exposure to in situ waste, excavated waste or contaminated water and rock; modifications to the performance of the repository system by creation of a large zone of unsaturated rock; creation of altered gas, 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 while 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.

7CS Screening Analysis

Land use controls and records would prevent or inform any mining activities in the vicinity.

In the future, if controls or records are no longer effective, then mining for minerals into or near the repository is still unlikely because the site selection process favours host rocks that are of no economic interest. Furthermore, other underground activities are unlikely at the 7CS hypothetical site, which is assumed to be in the Michigan Basin in Ontario, because the geology is uniform across a large area and so there is nothing unique about the repository site.

Finally, any deep mining activities would be preceded by boreholes to verify the nature of the rock. Given its size, it is likely that these boreholes would intersect the repository. Any future mining in the area would then be conducted knowing the repository was present and taking appropriate measures. This is a deliberate activity and is not addressed here.

The effects of exploratory boreholes are included, as discussed in *Drilling Activities (human intrusion) [1.4.04]*.

<u>FEP Screening</u>

Screened out.

FEP # 1.4.06   **Surface environment, human activities**

<u>Description</u>

Human activities carried out in the surface environment that can potentially affect the performance of the engineered or geological barriers, or the exposure pathways. These activities are undertaken without knowledge of the existence of the repository. Activities related to water management are discussed specifically under *Water management (wells, reservoirs, dams) [1.4.07].*

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;
- changes in land use such as removal of forests for agricultural or urban development and the drainage of low-lying areas for use as agricultural land; and
- major earthmoving projects, such as construction of dikes and dams (which could alter the landscape, and change groundwater recharge and discharge locations).

<u>7CS Screening Analysis</u>

The depth of the repository (500 m) in the 7CS means that there is no direct impact of surface excavations or activities on it. Excavation might occur into surficial deposits, which might contain repository contaminants (from groundwater movement). However, the impacts of such excavations are expected to be significantly less than the direct pumping and use of contaminated groundwaters - which is considered in all scenarios in the 7CS - and less than the impacts of intruding directly into the repository via an exploration borehole (considered in the Inadvertent Human Intrusion Scenario).

<u>FEP Screening</u>

Screened out.

FEP # 1.4.07   **Water management (wells, reservoirs, dams)**

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 *Surface environment, human activities [1.4.06].*

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

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

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

- Surface water sources could be a nearby spring, river, lake or reservoir which could be affected by runoff or subsurface discharge of contaminated water.
- 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 *Community characteristics – water source [5.2.05.C]*. Further consideration of irrigation water is discussed under *Rural and agricultural land and water use [5.2.09]* and *Urban and industrial land and water use [5.2.10]*.

7CS Screening Analysis

The 7CS repository is assumed located at a hypothetical site in the Michigan Basin in Ontario. Shallow water wells are used for domestic and agricultural purposes in the Michigan Basin. Therefore, well water extraction is considered in the 7CS after institutional controls are no longer effective. Surface waters could also be used as a water source and this is considered in the Normal Evolution Scenario.

The development of hydroelectric projects would not likely have large effects. The regional area around the 7CS hypothetical site has generally low topographic relief, so that any dams in the area would have low hydraulic head structures and these would have little effect on groundwater flows at repository depths.

FEP Screening

Include water well in all scenarios.

FEP # 1.4.08   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:

- 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.

7CS Screening Analysis

The 7CS assumes that societal knowledge of the repository will provide control for some initial period, but cannot be relied on indefinitely to prevent inadvertent human intrusion into the site.

The 7CS will specifically assume that adequate institutional control is maintained for at least 300 years following repository closure. After this period, the possibility of loss of institutional control eventually allowing inadvertent intrusion in the repository is considered. As well, because of the loss of institutional control, the land above the repository can be occupied by, for example, a farmer who drills a water-supply well.

The collapse of government control, following the operational period of the repository, is considered as one potential cause of the Partially Sealed Repository Scenario.

FEP Screening

Include FEP in all scenarios. In particular, consider that institutional control is maintained for 300 years following repository closure.

FEP # 1.4.09　　　　**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 people to intrude deliberately or otherwise into a repository, to cause changes that would affect the movement of contaminants, and to affect the 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, implies 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 that could lead to new exposure routes or levels (examples of recent changes include fish farming and hydroponics).

7CS Screening Analysis

Although changes in human society and technology are likely, they are unpredictable over the time period of interest. As noted in the FEP Description above, a lower level of technology might make it less likely that intrusion could be technically achieved, given the repository depth of 500 m. A higher level of technology might make intrusion more likely but might also imply increased knowledge of the risks and how to control them (e.g., during exploratory drilling).

Thus, in the 7CS, consistent with the recommendations of the International Commission on Radiological Protection (ICRP 2000) and CNSC Guide G-320 (CNSC 2006, Section 7.6.4), it is assumed that future humans will largely resemble present-day humans in terms of technologies and characteristics.

FEP Screening

Screened out.

FEP # 1.4.10   Remedial actions

Description

Actions that might be taken following repository closure to remedy problems with a waste repository arising from its sub-standard performance, disruptions 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.

7CS Screening Analysis

The 7CS repository will be operated in a staged manner, with a period of monitoring and closure after operations have ended, during which there will be access to the repository 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.

FEP # 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, introduction of groundwater contaminated with oxygen or organic material, and failure of seals or containers. See also *Accidents and unplanned events [1.1.12]*.

7CS Screening Analysis

Events of this type are not considered in the 7CS because no known non-nuclear explosive device could breach or otherwise seriously affect the rock, groundwater, seals or containers at the depth of the closed repository (about 500 m). The impacts to the critical group from the effects of a nuclear bomb exploding near a repository site, sufficient to cause damage at repository level, would outweigh any additional impacts arising from the repository.

FEP Screening

Screened out.

1.5 Other External Factors

FEP # 1.5.00   Scope of subcategory 1.5

<u>Description</u>

Any other external scenario-defining factors or events not accommodated in the FEP subcategories 1.1 to 1.4.

There are three subcategories in Other External Factors:

    1.5.01 Meteorite impact
    1.5.02 Species evolution
    1.5.03 Earth tides, reversal of earth's magnetic poles, polar wander and other unusual FEPs.

FEP # 1.5.01   Meteorite impact

Description

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

The impact could cause creation of a crater; activation, creation or sealing of faults; and physical and chemical changes in rock.

7CS Screening Analysis

The following analysis considers a range of potential impacts.

1. Wuschke et al. (1995) provide a generic safety assessment of the probability and consequences of a meteor impact on a 500 m deep and 4 km^2 used fuel repository, similar to the depth and size of the 7CS repository. Wuschke et al. (1995) estimated the probability of a significant meteor impact near the repository to be 1.4×10^{-11} per year, see Figure 3-6). Their calculations were based on a meteor that would produce an impact crater that would redistribute the rock to the level of the repository (see Figure 3-7). The entire contents of the repository would be redistributed within and around the crater. 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).

    The 1.4 million year old Pingualuit Crater in northern Quebec is an example of such a crater - the impact excavated a ~250 m deep crater with a diameter of 3.4 km; and it is estimated, using the meteorite crater data in Grieve and Robertson (1984), that another ~2 km of shattered rock underlies the crater floor.

    Wuschke et al. (1995) found the radiological risk from this meteorite impact on a used fuel repository to be very small (i.e., well below the reference health risk value of 10^{-5}/a used in the 7CS for disruptive scenarios), even though 100% of the radionuclides in the repository are released to the biosphere, largely because the probability of a meteor impact of sufficient magnitude to affect the repository was low.

2. Wuschke et al. (1995) also considered the case of a smaller meteorite that produces a crater whose zone of fractured rock extends to repository depth, but does not expose the waste. The diameter of the crater would be about 0.7 km and the depth of the excavated zone would be 66 m. The probability of this case is 4 times that of the base scenario (see above) and the dilution volume would be about 100 times smaller. The conservatively estimated risk from this case was 8% of the risk of the base case at 10^4 years, much less at earlier times and about the same at 10^5 years.

3. While the cumulative likelihood of a direct hit by a large meteor would increase over time (taking no credit for human intervention), the amount of radioactivity in the repository and the potential dose consequences decrease with time.

4. Wuschke et al. (1995) considered the risk of large but very unlikely meteorites. The consequences of a "likely" meteor can also be considered. Specifically, meteors with a one-in-a-million per year chance of directly hitting the repository would be about 0.1-1 m diameter. Such meteors hit the earth as a whole about 100 times per year. Although most

such meteors would breakup on their way through the atmosphere, if a 1 m diameter meteor did hit the ground intact it could create a crater up to 20 m diameter and 4 m deep. This would have no effect on the repository.

5. Human space debris falling to earth is also very unlikely to have an impact on the 7CS repository. Most debris is far too small to have an effect and would impact the earth with generally lower velocities than meteors. Even the International Space Station is not very massive (about 300 Mg), and would likely break up on re-entry. For comparison, a 10 m diameter meteor would be about 2000 Mg.

In conclusion, meteorites and human space debris impacts do not need to be considered in the 7CS.

<u>FEP Screening</u>

Screened out.

Asteroid Diameter
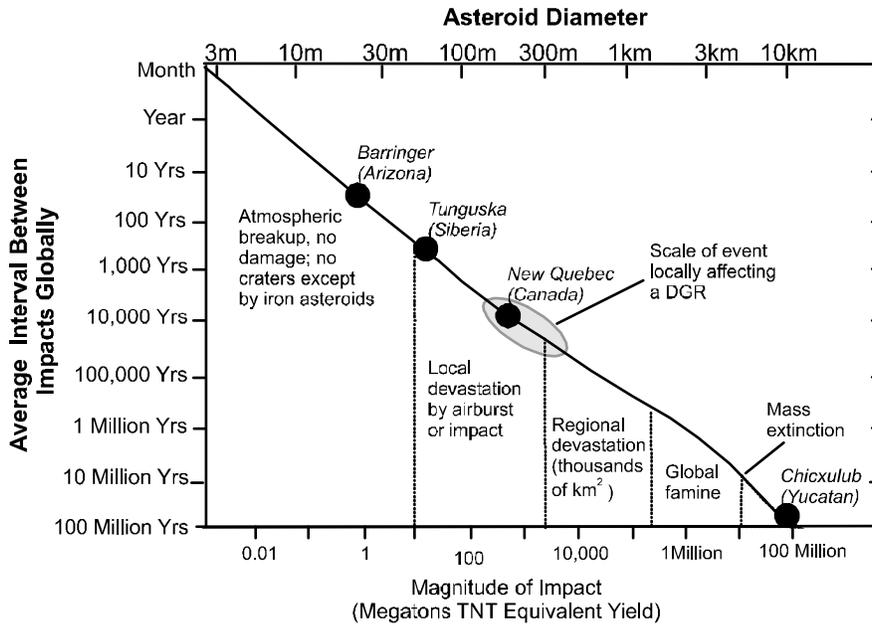
Note: Shaded region indicates the approximate magnitude of events that would produce a crater and shattered rock to a depth of 500 to 1000 m. For any given meteor impact, the chance of the impact occurring on the repository itself would be approximately 1 in 100 million, based on the size of the repository relative to the earth's surface area. Adapted from Morrison et al. (1994).

Figure 3-6: Estimated Frequency and Severity of Meteorite Impacts on the Earth as a Whole
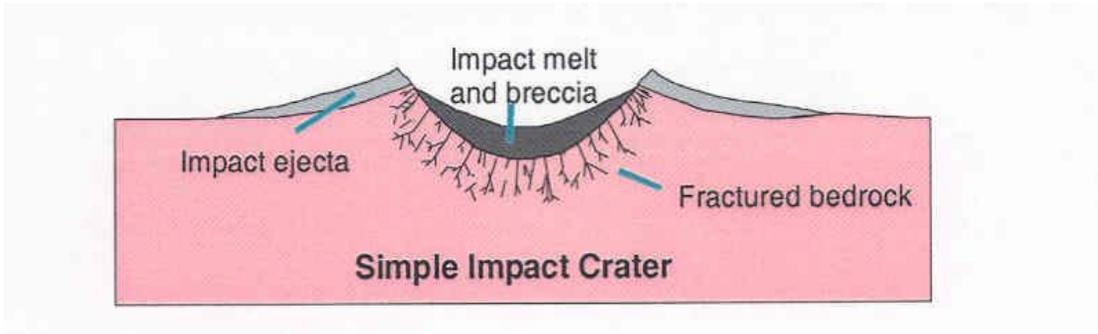
Note: In the base case of Wuschke et al. (1995), the bottom of the melt and breccia layer is approximately at repository level, i.e., 500 m below the original surface, and the rock below the repository level is fractured by the meteorite impact.

Figure 3-7: Cross-section of a Simple Meteorite Impact Crater

FEP # 1.5.02　　　　　**Species evolution**

<u>Description</u>

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

Over the time scales considered, natural evolution of plants and animal species is possible. The rate of evolution 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 and presumably will continue. 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.

<u>7CS Screening Analysis</u>

Biological evolution, whether driven by natural random genetic variation and selection or by deliberate future human actions, is not predictable in any quantitative manner. Change could increase or decrease sensitivity of species to radionuclides and other contaminants.

It is likely that some microbial adaptation would occur, but unlikely that it would lead to dramatically new species because the main materials present in the repository are also present in natural settings (uranium, iron, copper and bentonite clay). The repository environment would already have microbial species. Since the native species already span a variety of niches, the presence of a repository will likely affect which species prosper (and at which time) rather than fostering the creation of substantively different species by mutagenesis or natural evolution.

In the 7CS, consistent with the recommendations of ICRP Publication 81 (ICRP 2000), human doses are calculated for a reference person whose characteristics are based on current human physiology. Similarly, the general characteristics of biota are assumed to remain similar to current biota. Thus, species evolution is not considered in the 7CS.

<u>FEP Screening</u>

Screened out.

FEP # 1.5.03   Earth tides, reversal of earth's magnetic poles, polar wander and other unusual FEPs

<u>Description</u>

Unusual features, events and processes that have been identified and that do not clearly belong to one of the other categories.

<u>7CS Screening Analysis</u>

Consideration of the following unusual factors is excluded in the 7CS based on arguments that include very low probability or no significant effect.

(1) Earth tides or the movement of surface and groundwater caused by attraction to the moon - no significant effect.

(2) Telluric currents or the movement of electrical charges deep below the earth surface - no significant effect since natural currents and electric potentials are too low to affect, for example, contaminant transport (SKB 2014) .

(3) Reversal of the earth's magnetic poles, which has occurred roughly every 500,000 years - no significant effect.

(4) Changes in solar flux - low probability of significant change over a million years. Normal insolation variation is a factor in global climate change leading to glacial cycling and is already included in the 7CS. Large changes in the solar flux would have a much larger direct effect on humans than any secondary effects on a deep geologic repository.

(5) True polar wander or the shifting of the solid earth about its rotational axis in response to changes in mass distribution within the planet - no significant effect because this occurs very slowly, less than about 1° per million years (Besse and Courtillot 2002).

<u>FEP Screening</u>

Screened out.

2. WASTE PACKAGE FACTORS

FEP # 2.0.00   Scope of main category 2.

Description

Features and processes occurring within or near the waste package that could affect the thermal, mechanical, chemical, biological or hydraulic conditions in the repository and, hence, the release and transport of contaminants.

The four subcategories under Waste Package Factors are:

      2.1 Waste package characteristics
      2.2 Waste form processes
      2.3 Waste container processes
      2.4 Contaminant release and transport (waste package)

2.1 Waste Package Characteristics

FEP # 2.1.00   Scope of subcategory 2.1

<u>Description</u>

Features and processes within the waste package, as they exist at the time of placement and considering changes that could occur over long periods of time.

There are 3 subcategories under Waste Package Characteristics:

    2.1.01 Waste inventories
    2.1.02 Waste form materials and characteristics
    2.1.03 Waste container materials and characteristics

FEP # 2.1.01   Waste inventories

Description

Waste inventories describe the total content in the repository of the various waste materials, radionuclides and chemical substances. Potential waste forms are discussed under *Waste allocation [1.1.06]*.

This feature is primarily concerned with radionuclides but it should consider all other toxic wastes that might be placed in the repository. As a starting point, waste inventories should consider radionuclides and potentially chemically toxic elements that are:

-   part of the wastes for which the repository was designed, i.e., irradiated UO_2 fuel, Zircaloy cladding and bundle structural and related materials (such as bearing pads, brazes and CANLUB); and
-   introduced with the engineered barriers, such as large volumes of iron and copper, as well as materials that might be introduced inadvertently such as diesel oil.

A related consideration is the potential toxicity of mined rock (tailings) produced when excavating the repository. This topic might be included in a preclosure safety assessment, but the potential long-term impacts of the mined rock may need to be evaluated.

The following more specific factors are discussed under separate entries:

   2.1.01A Inventory of radionuclides
   2.1.01B Inventory of chemically toxic contaminants

FEP # 2.1.01.A   Inventory of radionuclides

Description

The mass of radioactive isotopes (radionuclides) of all elements in a waste form.

Inventories are required for all radionuclides in a waste form that may give rise to significant impacts. Inventories in used CANDU fuel bundles (uranium dioxide, Zircaloy and other bundle materials) are dependent on several factors, notably burnup and, to a lesser extent, the power rating of the fuel. The average level of burnup has gradually increased over the years, and there is a range of burnups around the average. Radionuclide inventories will be time dependent (see *Radioactive decay and ingrowth [6.1.01]*).

The presence of impurities in used CANDU fuel bundles may also be of concern. For instance, there are several possible sources of Cl-36 in irradiated CANDU fuel, but the most important is neutron activation of stable Cl-35, which is present as an impurity. Also, the impurities themselves may be chemically hazardous, e.g., Ag, Cr and Hg.

Radionuclides may be present in co-disposed wastes also (see *Waste allocation [1.1.06]*).

7CS Screening Analysis

For the 7CS, used CANDU fuel is the only waste form placed in the repository (see *Waste allocation [1.1.06]*).

The initial radionuclide inventories in the UO_2 and the Zircaloy cladding are included in the safety assessment. These are based on the reference 30-year cooled Bruce fuel bundle and a burnup of 280 MWh/kgU. This provides a conservative estimate of the radionuclide inventories in the average fuel bundle placed in the repository. Note that for the All Containers Fail Scenario, the radionuclide inventories are based on a fuel burnup of 220 MWh/kgU since the median burnup for all fuel bundles in the repository is less than 200 MWh/kgU (Wilk 2013).

The inventory calculations are described in Tait et al. (2000) and radionuclide inventories are provided in Tait et al. (2000) and Tait and Hanna (2001). These inventories include radionuclides generated by neutron activation of impurities in the fuel or Zircaloy.

Trace amounts of UO_2 could be present on the surfaces of manufactured fuel bundles. Thus, after irradiation, these surfaces could be contaminated by fuel and fission products. However, the amount of surface contamination will be small relative to the inventory of radionuclides in the UO_2 fuel itself and is neglected.

After placement of the fuel bundles in the repository, the change in radionuclide inventories due to radioactive decay and ingrowth is taken into account. The residual neutron flux and spontaneous fission rate is too small to affect radionuclide inventories over time frames of 1 million years.

FEP Screening

Include FEP in all scenarios.

FEP # 2.1.01.B   **Inventory of chemically toxic contaminants**

Description

The mass of isotopes (radioactive and stable) of all chemically toxic elements in a waste form.

Inventories are required for all chemical elements in a waste form that may give rise to significant impacts. Inventories in used CANDU fuel bundles (uranium dioxide, Zircaloy and other bundle materials) are dependent on several factors, notably burnup and, to a lesser extent, the power rating of the fuel. The average level of burnup has gradually increased over the years, and there is a range of burnups around the average. These inventories could include both stable and radioactive isotopes, and total inventories will be time dependent for many elements (see *Radioactive decay and ingrowth [6.1.01]* and *Chemical and organic toxin stability [6.1.02]*). The chemical form may also be an important factor.

The presence of impurities in CANDU fuel bundles may also be of concern when considering the possibility of transmutation by neutron activation.

Chemically toxic species may also be present in co-disposed wastes (see *Waste allocation [1.1.06]*) or in engineered barrier materials (e.g., copper in copper-coated containers).

7CS Screening Analysis

In the 7CS, used CANDU fuel is the only waste form placed in the repository (see *Waste allocation [1.1.06]*). The inventories of potentially chemically toxic elements in used CANDU fuel are provided in Tait et al. (2000) and Tait and Hanna (2001).

The engineered barriers may also contain potentially chemically toxic contaminants. The main engineered barriers in the repository are the carbon steel containers, the copper shell of the container, and the clay, cement and asphalt based sealing materials.

The 7CS considers the potential impact on humans and biota of releases from the repository of potentially chemically toxic elements for the Normal Evolution and the All Containers Fail Scenarios. The sources of these hazardous elements are the used fuel and the copper shell. Steel and engineered barrier materials are routinely disposed of in near-surface landfills and are not considered hazardous.

FEP Screening

Include FEP in Normal Evolution Scenario and All Containers Fail Scenario.

FEP # 2.1.02   **Waste form materials and characteristics**

<u>Description</u>

The physical, chemical and biological characteristics of the waste forms at the time of disposal.

The waste form will usually be conditioned prior to disposal by processes such as drying, vitrification, sealing and grouting. (Additional processes may take place for co-disposal waste forms.) Its physical, chemical and biological properties may be well known at the time of disposal, and will change in response to the conditions within the repository. Waste form processes are described under *Waste form processes [2.2]*.

The following specific factors are discussed under separate entries:

    2.1.02.A Characteristics of used CANDU fuel (UO_2)
    2.1.02.B Characteristics of Zircaloy
    2.1.02.C Deposits on CANDU fuel bundles
    2.1.02.D Characteristics of other waste forms

FEP # 2.1.02.A   Characteristics of used CANDU fuel (UO$_2$)

Description

The properties of used CANDU fuel, notably as they affect releases of radionuclides and chemically toxic elements.

Radionuclides and chemically toxic elements are not distributed uniformly in the UO$_2$ fuel. Factors such as generation asymmetries and diffusion under the temperature gradient in-reactor will result in accumulation of some gaseous nuclides as bubbles within grains or on grain boundaries, diffusion of gaseous and volatile nuclides to grain boundaries and to cooler regions (typically gaps between fuel pellets and between the fuel and Zircaloy cladding), and formation of "epsilon" phase alloy particles containing mainly Mo, Tc, Ru, Rh and Pd. These heterogeneities could have implications on contaminant release rates.

Alteration, decomposition and corrosion of the used fuel matrix, including grain growth, phase changes, and chemical and mechanical stability may also have significant effects on release rates. Other possibilities to consider are mechanical breakdown, phase changes (such as UO$_2$ transforming to U$_4$O$_9$ and U$_3$O$_8$) and selective leaching.

Corrosion/dissolution of the UO$_2$ fuel is discussed in *Used fuel dissolution [2.2.03].*

7CS Screening Analysis

The 7CS considers, as the reference waste form, the standard 37-element fuel bundle (see *Inventory of radionuclides [2.1.01.A]*) which is 495 mm long, 102 mm in diameter, and contains 21.7 kg of unirradiated UO$_2$ and 2.2 kg of Zircaloy (Tait et al. 2000). The extent of variation between other bundle types used in Canadian CANDU reactors is not significant for safety assessment purposes (Tait et al. 2000).

The fuel bundles are expected to be mostly intact at the time of placement, given the low defect rate of CANDU fuel in-reactor and the anticipated conditions during storage and transport. Less than 0.015% of the discharged bundles have minor damage or defects (such as pinhole failures in the fuel sheaths) based on statistics from 1994 to 2006 (IAEA 2010), although pre-1994 bundle defect rates were higher, i.e., < 0.1% (Tait et al. 2000).

The used fuel is composed of sintered UO$_2$ pellets with a typical diameter of about 12 mm. Sintered UO$_2$ is a stable ceramic material. Before irradiation, it has a density of 97% theoretical, a nominal irradiated grain size of 10-50 μm, and an oxygen/uranium ratio of about 2.001. Although some pellet cracking will have occurred during irradiation in the reactor, the fuel pellets are expected to be largely intact at the time of placement in the repository. Irradiation will have resulted in bubble formation both within the grains and on grain boundaries, and in the formation of "epsilon" phase particles consisting of Mo, Ru and other metals. About 2% of the mass of the unirradiated fuel has been converted to new nuclides - 98% of the fuel is unchanged. About 95% of the new nuclides remain within the UO$_2$ grains. The balance has moved into the grain boundaries or the fuel void spaces (e.g., fuel sheath gap).

The distribution of radionuclides (and other contaminants) in the fuel pellet is important; because the rate of release of radionuclides, after the container is breached and groundwater contacts the fuel, depends on their location in the fuel bundle. This is discussed under *Used*

fuel dissolution [2.2.03].

<u>FEP Screening</u>

Include FEP in all scenarios.

FEP # 2.1.02.B   Characteristics of Zircaloy

Description

The properties of the Zircaloy components of the fuel bundle (cladding, endcaps, endplates and spacers), notably as it affects release of radionuclides and chemically toxic elements.

One characteristic is the physical/chemical state of the cladding, as the cladding acts as a mechanical barrier that protects the irradiated fuel inside by preventing or limiting groundwater ingress and, subsequently, by limiting contaminant transport out of the cladding. Also included is the distribution of radionuclides within the Zircaloy cladding itself - some radionuclides (e.g., C-14) may be enriched in the Zircaloy oxide and more releasable on contact with water. The mechanisms by which Zircaloy corrodes, releasing contaminants bound within the Zircaloy cladding itself, is discussed separately under *Zircaloy dissolution [2.2.04]*.

The Zircaloy could also be affected by longer acting processes, such as the alteration, decomposition and corrosion of Zircaloy, including grain growth, phase changes, and chemical and mechanical stability.

7CS Screening Analysis

The 7CS models include parameters describing the properties of the Zircaloy alloy.

The reference 37-element fuel bundle contains 2.2 kg of Zircaloy in the form of cladding, endcaps, endplates and spacers. The reference Zircaloy is a zirconium-tin alloy (Zircaloy-4). The inside of a cladding tube has a thin graphite (CANLUB) coating. (Although various Zircaloy alloys have been used to make fuel bundles, the difference is not significant for safety assessment purposes.)

The inventory of activation products within the Zircaloy after irradiation, including from chemical impurities, is given in Tait et al. (2000). Most contaminants are assumed to be uniformly distributed within the Zircaloy because it is thin compared to neutron path lengths. However, some radionuclides (e.g., C-14) may be more concentrated in the zirconium oxide layer on the Zircaloy surfaces. Evolution of the Zircaloy and release of contaminants from the Zircaloy is discussed under *Zircaloy dissolution [2.2.04]*.

Most of the cladding will maintain some mechanical integrity for a long time, preventing water in a failed container from contacting the fuel. However, the possibility of failure of the cladding due to stress corrosion or delayed hydride cracking may be plausible at longer times and after groundwater enters the container. (Note that less than 0.1% of CANDU fuel is initially defected.) Rather than estimating this failure process in detail and providing an estimate of how much fuel protection is provided by the cladding, the 7CS neglects the presence of the Zircaloy cladding as a barrier to the corrosion of the UO_2 fuel and the release of contaminants from used fuel. In effect, the Zircaloy cladding is conservatively assumed to fail as soon as water enters the container.

FEP Screening

Include FEP in all scenarios.

FEP # 2.1.02.C   Deposits on CANDU fuel bundles

Description

The properties of material deposited on the outside surfaces of the fuel bundles while the bundles were in the reactor or during manufacture of the fuel bundles.

The deposits can contain irradiated UO_2 particles resulting from the presence on UO_2 particles on the outside surfaces of the unirradiated fuel bundles placed in the reactors. Other material can deposit on the outside surfaces of the fuel bundles while they are in the reactor, generally referred to as crud deposits.

7CS Screening Analysis

In the 7CS, the radionuclide deposits on the external bundle surfaces are neglected since they represent a very small fraction of the total radionuclide inventory of a used fuel bundle (Gobien et al. 2018). Furthermore, since it is assumed in the 7CS that the Zircaloy cladding is not a barrier to contaminant releases from the fuel, releases of contaminants from surface deposits would occur simultaneously with releases from the used fuel and, hence, they would represent a small fraction of the total contaminants released from the fuel bundles.

In contrast, the amounts of Fe, Ni, Cu, and Cr on the external bundle surfaces represent a small but non-negligible percentage of the total masses of these metals in a fuel bundle: Fe (1.5%), Ni (1%), Cu (2.5%), and Cr (1%). Consequently, for these metals, the surfaces masses are included in the chemical element related safety assessment calculations (see Gobien et al. 2018).

FEP Screening

Include FEP in all scenarios

FEP # 2.1.02.D **Characteristics of other waste forms**

<u>Description</u>

The properties of other waste forms found in the repository, notably as they affect releases of radionuclides and chemically toxic elements within these materials. See *Waste allocation [1.1.06]*.

Other waste forms may be present in the repository, including vitrified waste (from reprocessed or research wastes), and wastes immobilised in cement and bitumen. These wastes would likely have different contaminant release processes than used fuel. For instance, vitrified waste would be subject to leaching, recrystallization and cracking; and cement slowly transforms to stable silicates after an initial period of rapid leaching.

<u>7CS Screening Analysis</u>

In the 7CS, it is assumed that only used CANDU fuel is placed in the repository (see *Waste allocation [1.1.06]*). Thus, it is not necessary to define the characteristics of other waste forms.

<u>FEP Screening</u>

Screened out.

FEP # 2.1.03.   **Waste container materials and characteristics**

Description

The physical, chemical and biological characteristics of the containers at the time of disposal. Waste container processes are described under *Waste container processes [2.3]*.

The waste container materials and characteristics are discussed under:

    2.1.03.A Container design characteristics
    2.1.03.B Container fabrication and installation defects

FEP # 2.1.03.A   Container design characteristics

Description

The design-basis characteristics of the container. The container characteristics include dimensions, material, waste loading, void space and construction method.

Container design is driven by two main considerations:

-   to facilitate fabrication and handling during the operational phase; and
-   to protect the enclosed wastes for long time frames.

For postclosure safety, the container durability is the main consideration. The container material has a major influence on corrosion mechanisms and rates of container failure, and the structural design has a major influence on how the container will withstand external mechanical forces.

Other container characteristics may also be important, such as the following.

-   Container 'loading' is concerned with the mix and quantity of fuel bundles placed in a container. Issues that need to be examined include heat generation, shielding and criticality.
-   The void space may be an important factor in determining contaminant concentrations inside a failed container. It may also be an important consideration for criticality concerns.
-   The construction method may influence failure rates associated with fabrication defects (see *Container fabrication and installation defects [2.1.03B]*).
-   Design options that use different material to provide internal support might lead to additional corrosion processes (see *Internal corrosion processes [2.3.04.E]*).
-   The thermal conductivity of the container affects the rate at which heat is transported from the fuel into the surrounding buffer, and thus would affect the temperature in and near the container.
-   Different designs, including materials, might be employed over the decades-long operational phase. Different designs might also be used for wastes other than the reference CANDU fuel bundles (see *Waste Allocation [1.1.06]*).

7CS Screening Analysis

Only one container design is considered in the 7CS, as the only waste form considered is used CANDU fuel.

The 7CS container (see Figure 3-8) consists of a carbon-steel vessel that is coated with a thin layer (about 3 mm) of electrodeposited copper or cold-sprayed copper (NWMO 2018, Sections 4 and 5). The carbon-steel vessel provides mechanical strength, even under glacial loads; while the copper coating, which is not a load-bearing component, provides a durable corrosion barrier (NWMO 2018, Section 5). The container is surrounded by a buffer box containing highly compacted bentonite (MX-80) (see Figure 3-9). The buffer box protects the container during handling and placement in the repository.

The (empty) inner steel vessel has an inside volume of 0.39 m^3. The filled container has an internal void volume of 0.266 m^3 that is filled with air at atmospheric pressure.

The container can hold 48 fuel bundles (4 layers of 12 bundles). A full container weighs about 2.8 Mg, of which 0.92 Mg is U. A total of 108,833 containers are needed to hold 5.224 million fuel bundles.

More details on the design are provided in Gobien et al. (2018) and its references.

FEP Screening

Include FEP in all scenarios.
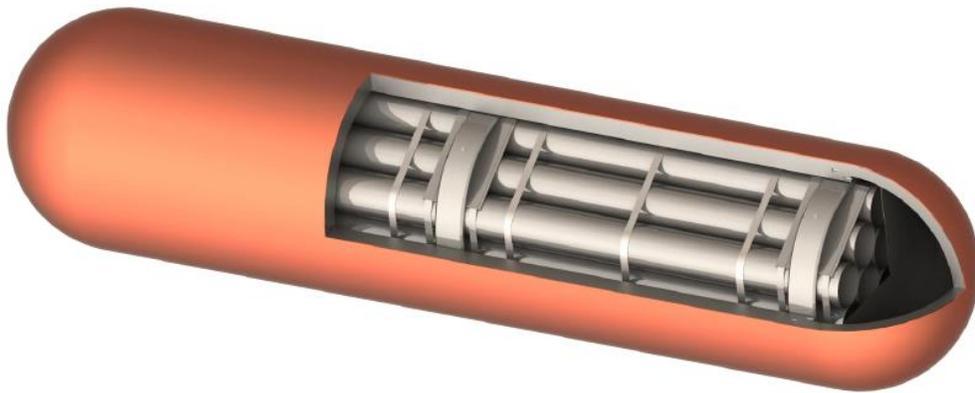
Figure 3-8: Cutaway Illustration of a Filled Mark II Container
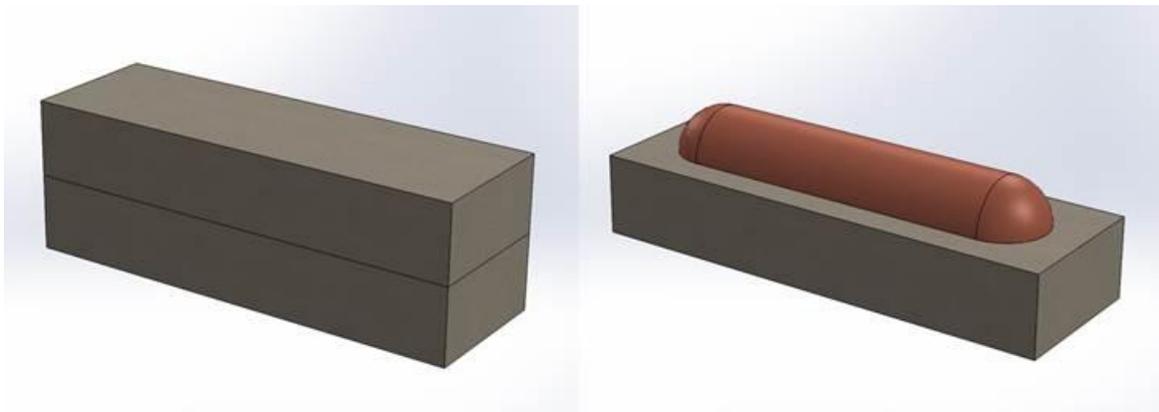
Note: The steel sheath is not shown in this figure.

Figure 3-9: Buffer Box for the Mark II Used Fuel Container

FEP # 2.1.03.B   Container fabrication and installation defects

Description

The presence of defects in waste containers - introduced during manufacturing, delivery, handling or loading and the container closure process - that are not detected prior to closure of the repository.

Some defects might be concentrated at weld joints and caused by the welding process, or they might be in a location that is not easily detected by non-destructive inspection methods. There might also be several small defects in each container, perhaps originating from the same cause.

These defects could lead to early failure of the container. Radioactive gases might be released soon after placement of the containers, or groundwater might access the container interior shortly after the resaturation of the buffer. Moreover, these defects might serve as focus points for various corrosion processes, causing a small defect to grow into a more substantial opening.

7CS Screening Analysis

The 7CS container design is robust, with a significant margin of safety for normal mechanical loads (see *Container design characteristics [2.1.03.A]*). The possibility of fabrication defects that significantly reduce mechanical strength are considered very low; as is the possibility that handling will introduce defects, given the protection provided by the buffer box.

The primary concern is the integrity of the copper corrosion barrier, which is not a load bearing component. The most significant concern is considered to be the presence of defects in the copper coating arising during fabrication. Although containers will be inspected multiple times, it is possible that some containers could be placed in the repository with undetected defects given the large number of containers. Such defects must be fairly small in order to be missed by the inspections.

The probability of undetected defects in the copper coating is currently not known since the container manufacturing and inspection processes have not been finalized. In the interim, based on experience with other nuclear components (Maak et al. 2001) and the number of containers in the repository (i.e., 108,333), it is assumed that 10 containers in the 7CS repository might have defects in the copper coating. The presence of some containers with defects in the copper coating is, therefore, included in all scenarios.

FEP Screening

Include FEP in all scenarios.

2.2 Waste Form Processes

FEP # 2.2.00.   Scope of subcategory 2.2

Description

Factors and processes related to the waste form that cause the characteristics of the waste form to change with time. Note that chemical processes or factors affecting the contaminants in the waste form are discussed separately under *Contaminant release and transport (waste package) [2.4]*.

There are seven subcategories under Waste Form Processes:

    2.2.01 Radiation effects (waste form)
    2.2.02 Heat generation (waste form)
    2.2.03 Used fuel dissolution
    2.2.04 Zircaloy dissolution
    2.2.05 Biological processes (waste form)
    2.2.06 Gas sources and effects (waste form)
    2.2.07 Nuclear criticality

FEP # 2.2.01   **Radiation effects (waste form)**

Description

The effects of the radiation emitted from the wastes on the waste form itself.

Radioactive decay of the radionuclides in the waste form generates alpha, beta and gamma radiation and decay products (e.g., He gas and radionuclide progeny). Alpha radiation and the corresponding recoil atoms can cause irradiation damage to the used fuel, potentially leading to mechanical damage of the used fuel (e.g., by buildup of He pressures within grain boundaries) and perhaps changing the fraction of radionuclides located at the grain boundaries, thereby making it easier for radionuclides to be released from the waste form.

Another important effect of radiation is radiolysis of water, which refers to the decomposition of water and its dissolved components by radiation. Radiolysis of water can produce highly reactive atomic or molecular radicals, and molecular species such as hydrogen, oxygen and hydrogen peroxide. This process is likely to have larger effects on the water within the container, where radiation fields are strongest. The effects of radiolysis will diminish with time as radiation field strengths decrease (beta and gamma radiation will be unimportant after about 500 to 1000 years, but low levels of alpha radiation will be persistent for millions of years).

Radiolysis can change the chemistry (i.e., composition) of the groundwater in contact with the fuel. For example, the groundwater can become oxidizing because reductants, such as hydrogen gas, are generally thought to be less reactive than oxidants such as hydrogen peroxide. These changes could affect the waste form dissolution rate and possibly the solubility of contaminants that are released from the waste form.

7CS Screening Analysis

Radioactive decay is included, insofar as it affects the radionuclide inventory and is a heat source.

The 7CS also explicitly considers the effect of water radiolysis, arising from the alpha, beta and gamma radiation fields generated by the fuel, on the rate of dissolution of the UO_2 matrix in a failed container (see *Used fuel dissolution [2.2.03]*).

The ongoing radioactive decay of the used fuel will give rise to irradiation damage of the used fuel matrix, primarily by alpha-decay, since high-energy alpha particles and recoil atoms can cause atomic displacements. However, given the temperature in the repository and the rate of alpha particle production, the effect of alpha irradiation on the used fuel matrix and on the radionuclide distribution within the fuel is small, especially in consideration of data for LWR high burnup fuel (about 45 GWd/tHM) scaled to CANDU burnups of about 10 GWd/tHM (Ferry et al. 2008; Desgranges et al. 2003; Wiss et al 2014). The main effect could be to allow release of He, but this is not important as no credit is taken for the fuel sheath as a barrier in the safety assessment and the container has enough capacity for the He gas. Thus, fuel radiation damage is not important in the 7CS. In particular, this means that the instant release fractions derived from data for post-discharge fuels are used in the safety assessment.

FEP Screening

Include FEP in all scenarios.

FEP # 2.2.02   Heat generation (waste form)

Description

The effects of the heat generated by the wastes on the waste form itself.

The heat generated by radioactive decay of the radionuclides in the fuel will increase the temperature of the waste form as well as the water entering defective containers. Generally, higher temperatures increase the rate of reactions undergone by the waste form. The higher temperature could also, in theory, affect the rate of migration of contaminants out of the UO_2 fuel grains, thereby potentially increasing instant release fractions with time and increasing the rate of release helium (produced by alpha decay) into the void regions of the fuel.

7CS Screening Analysis

The used fuel in the repository generates heat and so the temperature at the container surface first increases with time, reaching a maximum of about 93⁰C at about 47 years after container placement, decreasing to about 81⁰C after 600 years, decreasing slowly to about 50⁰C after 10,000 years, and returning to ambient conditions within approximately 200,000 years (Guo 2018; NWMO 2018, Section 5). The temperature of the used fuel within the container reaches a maximum temperature of 129⁰C within 47 years (Guo 2015, 2018).

The higher temperature of the fuel and water in a breached container can influence the dissolution rate of the fuel. In the 7CS, the effect of temperature is taken into account in calculating the dissolution rate of the fuel due to gamma and beta radiolysis, since gamma and beta radiation field s are most important within 500 years of repository closure. However, the rate of fuel dissolution due to alpha radiolysis and chemical dissolution are calculated for ambient conditions because these are important over a much longer time frame than the duration of the thermal pulse.

The rise in temperature of the used fuel should not significantly affect its properties, given that the temperature of the fuel in the repository is much lower than the temperature experienced by the fuel in a reactor. For example, diffusion coefficients of contaminants in the fuel matrix are low at expected repository temperatures, so contaminants within the fuel grains should not move into the grain boundaries of the fuel, even over the one million year time scale of interest for safety assessment calculations (Ferry et al. 2008, Desgranges et al. 2003). Consequently, instant release fractions should not change after the fuel is removed from the reactor.

Similarly, evidence indicates that only a small fraction of the helium generated by alpha decay would be released from the fuel grains into the void space of the fuel bundle or lead to micro-cracking of the fuel grains (Ferry et al. 2008, Jensen and Ewing 2001).

FEP Screening

Include FEP in all scenarios.

FEP # 2.2.03   Used fuel dissolution

Description

The processes by which used fuel corrodes or degrades, and releases radionuclides or chemically toxic elements.

The rate at which UO_2 matrix degrades in water depends on many parameters, notably the groundwater chemistry (electrochemical potential, pH, and concentrations of aqueous complexes such as carbonate). The electrochemical potential is particularly important, and the dissolution rate could be promoted by naturally occurring oxidants in the groundwater, by natural and man-made oxidants introduced during repository construction and operation, and by the radiolysis products generated when groundwater is exposed to the high radiation fields inside the container. These chemical reactions might be strongly affected by kinetics, which can be slow when changes in redox states are involved, and by precipitation of U(VI) corrosion products on fuel surfaces, which can inhibit the oxidative dissolution of the fuel.

Radionuclides are generally released from used UO_2 fuel by both a fast and slow process: instant release and congruent release, respectively. In instant release, the radionuclides located in gaps and grain boundaries are released relatively quickly when groundwater contacts the fuel. In congruent release, radionuclides located within fuel grains are released as the fuel matrix corrodes/degrades.

Other processes to consider are mechanical breakdown, phase changes (such as UO_2 transforming to U_4O_9 and U_3O_8) and selective leaching.

7CS Screening Analysis

CANDU fuel is fabricated from high-purity unenriched UO_2. The fuel undergoes a number of microstructural and compositional changes during in-reactor use, e.g., loss of sintering porosity and formation of fission products and activation products. Under the reducing conditions expected in the repository, the solubility of UO_2 is very low (~3×10^{-9} mol/L for a repository site in crystalline rock; Duro et al. 2010); whereas under oxidizing conditions the solubility of UO_2 is many of orders of magnitude greater.

While groundwater entering a breached container may be anaerobic, its radiolysis due to the radioactivity from the fuel will produce a variety of chemical species including oxidants. In the presence of oxidants, the dissolution of UO_2 is a corrosion reaction, in which the oxidant is consumed to convert the insoluble U(IV) to the much more soluble U(VI) (as UO_2^{2+}). The rate of this reaction will depend on redox conditions, including in particular the strength of the radiation fields from the fuel.

A good understanding of used fuel dissolution under expected repository conditions has been derived from experiments and theoretical modelling (Liu et al. 2016, Wu et al. 2014; He et al. 2012; Shoesmith 2007; Werme et al. 2004). This knowledge forms the basis of the used fuel dissolution model used in the 7CS safety assessment calculations. In this model, the fuel dissolution rate depends on the strength of the alpha, beta and gamma radiation fields and the fuel surface area (Gobien et al. 2018, Appendix B). After decay of the alpha field at long times, chemical processes control the rate of fuel dissolution.

Most of the fission products and actinides produced while the fuel is in the reactor are located within the UO_2 grains, close to their point of origin. Because of the high temperatures during reactor operation, some contaminants are able to move out of the grains and accumulate at grain boundaries or fuel void spaces (e.g., fuel sheath gap). However, this process stops after the fuel is removed from the reactor (see *Radiation effects (waste form) [2.2.01]*).

In the 7CS, the radionuclides located in the grain boundaries and void spaces are assumed to be released instantly as soon as groundwater contacts the fuel. This assumption is conservative because it ignores the likelihood that radionuclide releases from grain boundaries, which are controlled by the corrosion/dissolution properties of the grain boundaries, would be delayed under reducing conditions. The radionuclides located within the UO_2 grains are released congruently as the used fuel dissolves.

FEP Screening

Include FEP in all scenarios.

FEP # 2.2.04   Zircaloy dissolution

Description

The processes by which Zircaloy corrodes or degrades and releases radionuclides or chemically toxic elements.

Zircaloy is a corrosion-resistant alloy. It will corrode at a slow rate under typical groundwater conditions. Pitting/crevice corrosion is possible in the presence of radiolytically-decomposed saline groundwaters (particularly if early container failure allows cladding contact with groundwater while radiation doses are high). It can also form brittle hydrides if exposed to sufficient hydrogen gas, possibly from corrosion of the steel container.

Most radionuclides in Zircaloy are expected to be uniformly distributed in the Zircaloy because they are formed by neutron activation. Some may be preferentially located within the oxide surface layer. Radionuclides in the surface oxide layer could be more rapidly released after water contacts the cladding in a breached used fuel container. However, radionuclides or chemical impurities in the bulk metal would be released by congruent dissolution of the Zircaloy. Another release mechanism might involve the selective leaching of some nuclides.

7CS Screening Analysis

Zircaloy is a corrosion resistant alloy. Its corrosion rate is based on experimental data (Shoesmith and Zagidulin 2010).

In the 7CS, all radionuclides in the Zircaloy, except for C-14, are expected to be released congruently as the Zircaloy dissolves. For C-14, a significant fraction of its inventory in the Zircaloy is located within the zirconium oxide layer on the Zircaloy surface. This C-14 in the oxide layer is conservatively assumed to be released rapidly when water contacts the fuel (Gobien et al. 2018).

FEP Screening

Include FEP in all scenarios.

FEP # 2.2.05   Biological processes (waste form)

The biological and biochemical processes that affect the waste form. They can result from the activity of microscopic organisms, including archaea, bacteria, protozoans, yeasts, viruses and algae (collectively referred to as microbes).

A wide range of microbes will inevitably be introduced into the repository during its construction and in the operational phase. Some could even be present in the waste packages as delivered to the repository, whereas others would be introduced earlier, as the placement rooms are 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(s), individual microbial populations will only operate under particular conditions of temperature, pH, 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).

<u>7CS Screening Analysis</u>

In the 7CS, it is assumed that the waste form is unaffected by biological processes. Microbial activity is expected to be low or non-existent in a breached container because of the limited organic and nutrient sources present within the waste package, the high initial temperatures in the container, the high initial radiation fields and, over the long term, the high salinity of the groundwater at the 7CS repository site. Furthermore, UO_2 is a relatively thermodynamically stable material.

<u>FEP Screening</u>

Screened out.

FEP # 2.2.06 **Gas sources and effects (waste form)**

Description

Factors within and around the wastes resulting in the generation of gases.

Gas production may result from corrosion of various waste forms. It may also be produced by radioactive decay, e.g., He; radiolysis of water (see *Radiation effects (waste form) [2.2.01]*); and as byproducts of microbial activity. Potential gases include hydrogen, oxygen, carbon dioxide, methane, and hydrogen sulphide.

Gases could be transported away from the waste as dissolved species or in the gas phase. The latter process could cause changes in the local chemical and hydraulic conditions; for instance, elevated gas pressures could prevent the ingress of water into the container, could act as a driving force to expel contaminated water out of the container, or could result in unsaturated conditions that reduce water-phase transport. Gas production could also affect the mechanisms for contaminant transport, i.e., gas-induced and gas-mediated transport (see *Gas-mediated transport of contaminants (waste package) [2.4.05]*). Some gases might be flammable or might form an explosive mixture; for example, hydrogen and methane could mix with oxygen during the operational phase and explode to damage the repository.

7CS Screening Analysis

Gases are produced by radioactive decay of the radionuclides in the used nuclear fuel (helium, argon, and krypton). The buildup of such gases in an intact container would not affect the container, as noted in *Radiation effects (container) [2.3.01]*.

Contact of water with used fuel can result in generation of hydrogen gas by water radiolysis. For an intact container, the amount of residual water in the container will be small because of the controls in place while the container is filled. Hence, only small amounts of gas would be produced by radiolysis of the water within an intact container. This gas would remain in the container (or react with the metals inside the container) unless the container is subsequently breached. For breached containers, which fail thousands of years after closure (NWMO 2018), the amount of gas generated by corrosion of the carbon steel vessel is much larger than from corrosion of Zircaloy, radiolysis of water, or radioactive decay.

Thus, the generation of gases from the waste form itself is not included in the 7CS models.

FEP Screening

Screened out.

FEP # 2.2.07   Nuclear criticality

Description

The possibility of a nuclear fission chain reaction within the repository. A chain reaction is the self-sustaining process in which the neutrons released from one nuclear fission reaction trigger, on average, at least one other nuclear fission.

Nuclear criticality requires a sufficient concentration and localised mass (critical mass) of fissile isotopes (e.g., U-235 and Pu-239), the presence of neutron moderating materials (e.g., H, C) in a suitable geometry, and a lack of neutron absorbing elements. Nominal CANDU fuel consists of natural uranium and formation of a critical mass of U-235 is impossible without the presence of heavy water as a moderator, as in a CANDU reactor.

However, processes may exist that result in increased localized concentrations of other fissile isotopes; for example, rapid dissolution of the fuel matrix accompanied by precipitation of plutonium might yield a critical mass of Pu-239. Other fuel types might also have a different potential for criticality. For instance, co-disposal options might include fuel enriched in U-235 (possibly from research reactors), or MOX (mixed-oxide) fuels which would have substantially greater amounts of fissile nuclides. Vitrified wastes containing fuel process wastes could also have criticality concerns.

7CS Screening Analysis

The 7CS repository only contains CANDU fuel which is manufactured using natural uranium with an initial fissile U-235 content of 0.7 wt%. The U-235 content of the fuel is substantially depleted while the fuel is in the reactor (e.g., used fuel with a burnup of 280 MWh/kgU contains 0.11 wt% U-235). Thus, the U-235 in the repository cannot become critical, even if there was physical separation of the uranium, since the subcritical U-235 enrichment limit for uranium compounds mixed homogeneously with water with no limitation on mass or concentration is 0.93 wt% (CNSC 2010).

There is also about 2.5 kg of the fissile Pu-239 isotope in a container (48 bundles, 280 MWh/kgU burnup), along with smaller amounts of other non-fissile Pu (Tait et al. 2000). This is less than the 5-kg subcritical limit for Pu-239 solid metal (CNSC 2010); so, criticality is not an issue for a single breached container.

The risk of criticality as a result of redistribution of Pu-239 in a repository for CANDU fuel has been analyzed by Garisto et al. (2014) and McCamis (1992). The conclusions were that criticality outside the container is very unlikely, requiring the occurrence of several improbable events, i.e., physical separation of Pu-239 from neutron absorbers, followed by concentration of the Pu-239. Such a separation is very unlikely under the conditions expected in the 7CS repository because of the relatively small numbers of defective containers, the low dissolution rate of the fuel, the low solubility of plutonium, the presence of other plutonium isotopes, and the decay of Pu-239.

FEP Screening

Screened out.

2.3 Waste Container Processes

FEP # 2.3.00.   Scope of subcategory 2.3

<u>Description</u>

Factors and processes related to the waste container that cause the characteristics of the container to change with time. This category includes processes that are relevant specifically as container degradation processes, rather than processes that contribute to the general evolution of the near-field.

There are five subcategories under Waste Container Processes:

    2.3.01 Radiation effects (container)
    2.3.02 Thermal processes (container)
    2.3.03 Mechanical degradation (container)
    2.3.04 Chemical and biological processes (container)
    2.3.05 Gas sources and effects (container)

FEP # 2.3.01   Radiation effects (container)

Description

The effects of the radiation fields generated by the fuel on the container.

Examples of possible effects are container over-pressurization due to helium gas production from the decay of the actinides in the used fuel, radiation damage to the container metal, and/or sterilization of microbial populations near the container.

Gamma radiolysis of the groundwater around the container can lead to production of reactive atomic or molecular radicals, thereby affecting the groundwater chemistry. For example, the groundwater can become effectively oxidizing because hydrogen peroxide and other oxidants tend to be more reactive than reductants, such as hydrogen gas. Radiolysis can also change the pH of the groundwater. These changes could lead to enhanced corrosion of the containers.

7CS Screening Analysis

The container is exposed to gamma and neutron radiation from the used fuel. Gamma radiation is mainly from fission products, which decay almost completely within the first 500 years after placement. Gamma radiation interacts mainly with the electrons in the metal via the photoelectric effect and Compton scattering. (If the energy of the gamma photon is greater than 1.5 MeV then an electron/positron pair can form in the metal.) Gamma radiation increases the kinetic energy of electrons in the conduction band or excites electrons to a higher energy level. In either case, the electrons rapidly lose this excess energy, resulting in only internal heat production. Thus, the container would not be damaged by gamma radiation.

Relative to the interior of the container, the radiation field at the outer surface of the container would be greatly reduced by the shielding provided by the container. Only gamma radiation reaches the container surface and interacts with water and/or air outside the container. The gamma dose rate at the surface of a Mark II container containing 30-year old fuel with a burnup of 280 MWh/kgU is ~ 1.7 Gy/h (SNC-Lavalin 2014). Radiolysis of H_2O (liquid or vapour) and air produces small quantities of O_2 and other oxidants. However, there is no evidence for enhanced copper corrosion rates caused by gamma radiation except at high dose rates (> 100 Gy/h); at lower dose rates in the range of 10 to 100 Gy/h, the experimental data seem to indicate a lower corrosion rate in the presence of radiation (King et al. 2010).

The neutron flux at the container surface, generated by the fuel inside the container (with a burnup of 280 MWh/kgU), varies from about $2x10^6$ n/(m²·s) for 30 year old fuel to $1.5x10^4$ n/(m²·s) for one million year old fuel (Tait et al. 2000). The neutron flux is predominantly from fast neutrons with E > 0.3 MeV. Over a one million year time frame, the total neutron fluence experienced by the container material would be less than 10^{19} n/m². Defect formation from fast neutrons requires a neutron fluence of about 10^{20} n/m² in copper and iron at 70 - 80°C to cause significant hardening (Fabritsiev and Pokrovsky 2002; Eldrup et al. 2002). Consequently, it is unlikely that the container metals would be affected by neutron radiation from the used fuel.

Helium is generated in the fuel by alpha decay. The amount of helium in the fuel increases with time. After 1 million years, fuel with a burnup of 280 MWh/kgU would contain about 0.029 mol of He/kg U (Tait et al. 2000). If all this helium is released from the fuel into the void volume of an intact container (0.27 m³), the pressure inside the container would increase by about 0.25

MPa at 25°C. However, most of the helium generated by alpha decay is expected to be retained as interstitial atoms or bubbles within the fuel (Ferry et al. 2008), so the helium pressure inside an intact container would increase by much less than 0.25 MPa. Thus, the helium generated by alpha decay would not affect the lifetime of the container.

FEP Screening

Screened out.

FEP # 2.3.02   Thermal processes (container)

<u>Description</u>

The effects of the rise in temperature, due to heat production from radioactive decay, on the container.

After placement of the containers in the repository, the temperature in the repository is controlled by the heat generated by radioactive decay of the nuclides in the used fuel as well as by the thermal properties of the engineered barriers (container and buffer) and the host rock. The geometry of the repository system (e.g., placement room spacing) is also important.

<u>7CS Screening Analysis</u>

The 7CS repository is designed such that the temperature at the surface of the container remains less than 100ºC.

In the 7CS, the container surface temperature increases to a maximum value of about 93ºC at about 47 years after placement of the containers in the repository; it decreases to about 81ºC after 600 years, slowly to about 50ºC after 10,000 years; and reaches ambient temperatures at about 200,000 years (Guo 2018; NWMO 2018, Section 5).

The elevated temperatures can affect the mechanical and chemical properties of the container. It will also affect the viability of microbes present in the vicinity of the container. These aspects are discussed further under *Mechanical degradation (container) [2.3.03]* and *Chemical and biological processes (container) [2.3.04]*.

<u>FEP Screening</u>

Include FEP in all scenarios.

FEP # 2.3.03   **Mechanical degradation (container)**

Description

The alteration and puncture or collapse of the container.

Mechanical degradation of a container can result from processes such as:

- creep which may be temperature dependent;
- loss of ductility or strength, caused by hydrogen embrittlement, phase transformations or grain growth for example;
- internal forces generated by the pressure of internal gases (such as helium from radioactive decay or hydrogen from reactions between iron and water), or by the formation of expanding corrosion products (such as hematite from iron);
- external forces arising from hydrostatic and lithostatic pressures, swelling buffer, and thermal ex pansion. These forces may be non-uniform, such as in the case of partially saturated buffer; and
- failure of internal support. Some container designs may use a filler material to provide internal support. This material may compact, shrink or otherwise fail to perform their expected function and lead to container collapse.

7CS Screening Analysis

The Mark II container used in 7CS consists of a thin (3 mm) copper corrosion barrier and an inner carbon steel load-bearing vessel. It has a diameter of 0.56 m and a total length of 2.51 m, with hemispherical heads on each end. The steel layer is 46.2 mm thick at the main cylinder and 30 mm thick at the hemispherical ends.

The copper layer, which is electroplated or cold-sprayed onto the outer surface of the steel vessel, is strongly bound to the surface and does not detach even if the steel vessel is deformed (Boyle 2013).

The steel vessel is designed to withstand a mechanical load greater than 45 MPa, at temperatures less than 100ºC, without excessive deformation (Boyle 2013). An external pressure test (at room temperature) showed that the steel vessel can withstand 54 MPa external pressure, verifying the engineering safety margin. With a hydrostatic pressure at repository depth of 5 MPa and a bentonite swelling pressure of ~1 MPa (Gobien et al. 2018), this means that steel vessel could withstand an additional load of about 39 MPa, which would correspond, for example, to the maximum hydrostatic pressure head associated with a ~4.3 km thick ice sheet. Given that the maximum ice sheet thickness at the repository site is expected to be about 3.0 km (NWMO 2018, Section 2), this provides some margin for handling off-normal loads. Therefore, mechanical failure is not expected to be important over a one million year period. However, the possibility that a greater than design basis ice sheet passes over the repository, leading to mechanical failure (i.e., collapse) of many containers, is one potential cause of the All Containers Fail Scenario.

If the copper coating is intact, processes that could lead to mechanical degradation of the steel vessel are not significant in the one million year time frame of interest. The generation of gases from radioactive decay is insignificant (see *Radiation effects (container) [2.3.01]*) and the lack of water or oxygen access to the interior of the container prevents any significant formation of rust or other reaction products.

A manufacturing defect in the copper coating of a container could, in due course, lead to a penetration of the copper coating. In this case, corrosion of the steel exposed to groundwater would eventually lead to breach of the steel vessel (see *General or uniform corrosion [2.3.04.B]*). At that point, the steel vessel would begin to corrode from the inside and would gradually weaken and, in theory, would collapse due to the bentonite swelling pressure acting on the container. (There is no net hydrostatic pressure acting on a breached container vessel.) The collapse of breached containers is taken into account in the calculation of contaminant source terms in the safety assessment calculations.

The possibility that a large seismic event causes shearing of several containers is considered in the Container Failure Scenario.

FEP Screening

Include FEP in all scenarios.

FEP # 2.3.04   Chemical and biological processes (container)

Description

The chemical processes that affect the physical, chemical and biological characteristics of the containers with time. This category includes processes that are relevant specifically as container degradation processes, rather than processes that contribute to the general evolution of the near-field.

The container degradation processes are discussed under:

      2.3.04.A Stress corrosion cracking
      2.3.04.B General or uniform corrosion
      2.3.04.C Localized corrosion
      2.3.04.D Microbial-induced corrosion
      2.3.04.E Internal corrosion processes

FEP # 2.3.04.A   Stress corrosion cracking

<u>Description</u>

A potential failure mechanism for metallic containers resulting from the attack by a combination of various chemical agents and tensile stresses, under particular corrosion potential conditions.

Stress corrosion cracking, and related processes like hydride embrittlement and cracking, may mechanically weaken the container and promote subsequent failure or other corrosion mechanisms. These processes might be accelerated if a chemical agent is attracted to and accumulates at a defect or crack site. Metals, such as copper, might be susceptible to stress corrosion cracking in aqueous solutions that have organic species such as acetate; high amounts of hydrogen sulphide; or nitrogen-containing species such a nitrate, nitrite or ammonia. Many of these chemicals result from microbial activity, but the latter could be an important issue if groundwaters near the repository contain nitrogen residues from blasting.

<u>7CS Screening Analysis</u>

Stress corrosion cracking of the copper shell is not considered to be a viable failure mechanism in the 7CS because the various factors (oxidants, tensile stress and stress corrosion agents) necessary for crack initiation and propagation are not expected to be operative simultaneously in the repository environment (NWMO 2018, Section 5; King et al. 2010)

Copper stress corrosion lifetimes are predicted to be in excess of 1 million years (King et al. 2010), beyond the time frame of concern for the 7CS.

<u>FEP Screening</u>

Screened out.

FEP # 2.3.04.B   General or uniform corrosion

<u>Description</u>

Corrosion processes where the surface of the container is uniformly worn away by chemical or physical attack.

All metals are subject to uniform corrosion at rates that are dependent on the chemical and physical (and possibly biological) environments. Some metals (such as titanium alloys) might be passivated by the formation of a protective surface layer, while others (such as copper) might be thermodynamically stable; however, all will undergo uniform dissolution.

The rates of uniform corrosion will be affected by groundwater composition. For instance, the presence of sulphides in groundwater will likely increase the corrosion rates of copper alloys.

<u>7CS Screening Analysis</u>

The copper coating on the 7CS reference container (see Figure 3-8) protects the underlying steel vessel from corrosion. Under anaerobic conditions, copper corrosion accompanied by the evolution of hydrogen does occur in the presence of sulphides. However, sulphide is not widely found in groundwaters in sedimentary rock in Canada (INTERA 2011). Consequently, the uniform corrosion rate of copper is low under the expected 7CS repository conditions. Calculated uniform corrosion depths are on the order of tens of micrometres after 1 million years (NWMO 2018, Section 5; Kwong 2011; Scully and Edwards 2013) compared to a copper shell thickness of 3 mm; so, uniform corrosion should not affect the integrity of the container.

Experiments carried out in the past decade suggest that oxidation of copper by pure, oxygen-free water is possible (Hultquist et al. 2009; Szakálos et al. 2007). Further studies are underway in Sweden, as well as by the NWMO, to address this topic. Preliminary results indicate extremely small quantities of hydrogen in similar experiments, although the tests were not definitive (SSM 2011; Hultquist et al. 2013). However, it appears that the hydrogen produced by the copper-water reaction would suppress the corrosion reaction and, thus, the copper-water reaction should not be a significant corrosion mechanism within the repository (Scully and Edwards 2013).

However, one possible cause of the All Containers Fail Scenario is an unforeseen interaction between the copper container and groundwater (e.g., due to higher than expected sulphide concentrations from microbial sulphate reduction) that leads to higher than expected copper corrosion rates. In addition, for this scenario, the (uniform) corrosion rate of steel is used to calculate the rate of hydrogen generation (NWMO 2018, Section 7).

In the 7CS, it is assumed that a few containers are placed in the repository with undetected defects in the copper coating (see *Container fabrication and installation defects [2.1.03.B]*). These containers are assumed to eventually fail due to corrosion of the steel exposed to water, after penetration of the copper coating. However, these processes (penetration of the copper coating and steel vessel) are not explicitly modelled in the 7CS. Rather, for the purposes of the safety assessment calculations, the defective containers are assumed to be breached at arbitrary times within the first million years after repository closure (NWMO 2018, Section 7).

FEP Screening

Include FEP in all scenarios.

FEP # 2.3.04.C   Localized corrosion

Description

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

These corrosion processes could occur on the surface of a container under a section of compacted buffer, under a hydrothermally formed deposit, under an embedded surface defect or particle, under a biofilm, in a closure weld, or in passive metals which form protective oxides that may become incomplete over time. The corrosion sites may concentrate chloride ions and hydrogen ions (or atomic hydrogen which could promote stress-induced cracking; see *Stress corrosion cracking [2.3.04.A]*), which initiate or accelerate corrosion.

One concern is that the localized corrosion effects may lead to container failure long before uniform corrosion processes. Another possibility is the formation of weaknesses in the container, which then contribute to mechanical failure (see *Mechanical degradation (container) [2.3.03]*).

7CS Screening Analysis

The copper coating on the 7CS reference container (see Figure 3-8) protects the underlying steel vessel from corrosion. Pitting, crevice corrosion and under-deposit corrosion are not expected to be important for copper metal over time frames up to 1 million years (NWMO 2018, Section 5; Kwong 2011; Scully and Edwards 2013; King et al. 2010) for the reasons outlined below.

Crevice corrosion is a significant concern for many alloy systems; however, it is unlikely with copper or would be self-limiting (King et al. 2010). "Ants-nest" corrosion is a form of localized corrosion peculiar to copper (e.g., air conditioning equipment); however it requires moist air and an organic acid, conditions unlikely to exist in a repository (King et al. 2010).

Pitting of copper is observed in various environments, particularly in water-distribution pipes such as residential copper pipes. However, modelling, laboratory and field tests indicate that the near-field environment of a container limits the extent of pitting through consumption of oxygen. Continuous pit growth is not possible under expected repository environments (NWMO 2018, Section 5; King et al. 2010).

In conclusion, the copper coating on the 7CS container is sufficiently thick to protect against localized corrosion for the one million year assessment period (NWMO 2018, Section 5; Kwong 2011; Scully and Edwards 2013; King et al. 2010). Thus, localized corrosion is not considered in the 7CS safety assessment.

FEP Screening

Screened out.

FEP # 2.3.04.D   Microbial-induced corrosion

Description

Corrosion of a container induced by the action of microbes or their metabolites.

Microbial induced corrosion has the potential to affect many metals, particularly metals that are required trace elements in living organisms or that are utilized as a source of energy. For instance, it is thought that copper might be susceptible to microbial-induced corrosion under anaerobic conditions. Issues to be considered include the formation of biofilms, pitting corrosion, the effects of sulphate-reducing bacteria, and the formation and effects of metabolic by-products, such as ammonia and hydrogen bisulphide.

7CS Screening Analysis

Microbial-induced corrosion of copper has been observed under various environmental conditions. However, microbial activity is suppressed in the 7CS repository by the presence of very saline groundwaters for which the water activity is less than 0.96 (NWMO 2018, Section5; Stroes-Gascoyne and Hamon 2008, Stroes-Gascoyne et al. 2006). Specifically, microbial activity near the copper containers is expected to be very low because of the low water activity, the lack of nutrients, the small void space and the initially-high container surface temperature (NWMO 2018, Section 5; Kwong 2011; King et al. 2010).

In the unlikely event that microbial activity does occur at the buffer/rock interface (where conditions may be somewhat more favourable for microbes), transport of microbially-produced reactants (such as sulphides produced by reduction of sulphates) to the container would be limited by diffusion within the buffer layer and would, therefore, contribute to the slow rate of copper corrosion, but would not cause failure over the one million year assessment time frame.

FEP Screening

Screened out.

FEP # 2.3.04.E   **Internal corrosion processes**

Description

Corrosion processes that are initiated or supported by processes occurring inside the container.

An example of internal corrosion is galvanic coupling between dissimilar metals used in the container design, including the Zircaloy cladding and used fuel itself. For instance, such reactions might occur between a titanium alloy container with internal carbon steel elements.

Another example is corrosion by air or water left in the container during fabrication, possibly enhanced by radiolysis.

In addition, the internal corrosion reaction products might have complex effects. Gas generated by internal corrosion under wet anaerobic conditions may inhibit further water entry into a breached container. Formation of iron corrosion products like magnetite might lead to expansion forces that increase the size of the void in the defected container.

7CS Screening Analysis

For intact containers there is an insufficient mass of corrosion agents within the container (i.e., water, O_2) to cause significant internal corrosion even though it may be backfilled with air.

In the 7CS, it is assumed that there are a few containers in the repository with small undetected defects in the copper coating (see *Container fabrication and installation defects [2.1.03.B]*). If the steel below the defect is (eventually) exposed to groundwater, it will corrode and the steel container will eventually be breached and flooded with groundwater, leading to corrosion of the internal steel components. However, corrosion of the internal steel components is not modelled except in the All Containers Fail Scenario since this would not affect calculated impacts given the small number of containers with undetected defects.

In the All Containers Fail Scenario, all containers fail by an unspecified mechanism and, so, the amount of hydrogen gas generated by corrosion of the inner steel components is significant and could affect the evolution of the repository, including the transport rate of contaminants out of the repository. Hence, for the All Containers Fail Scenario, the corrosion rate of the breached steel vessel is used to determine the rate of hydrogen gas generation (NWMO 2018, Section 7).

Corrosion of the used UO_2 fuel and Zircaloy is described separately under *Waste form processes [2.2]*.

FEP Screening

Include FEP in the All Containers Fail Scenario.

FEP # 2.3.05   **Gas sources and effects (container)**

Description

Factors within and around the containers resulting in the generation of gases and their subsequent effects on the container.

Gas production (mainly hydrogen) may result from corrosion of the containers.

Gases could be transported away from the container as dissolved species or in the gas phase. The latter process could cause changes in the local chemical and hydraulic conditions; for instance, elevated gas pressures could prevent the ingress of water into the container, could act as a driving force to expel contaminated water out of the container, through the buffer and out of the repository, or could result in unsaturated conditions that reduce water-phase transport. Gas production could also affect the mechanisms for contaminant transport, i.e., gas-induced and gas-mediated transport (see *Gas-mediated transport of contaminants (waste package) [2.4.05]*). Some gases might be flammable or might form an explosive mixture; for instance hydrogen could mix with oxygen during the operational phase and explode to damage the repository.

7CS Screening Analysis

The oxygen gas initially present in the repository after closure of the repository would be consumed by a number of reactions, including reactions with residual iron in the repository (e.g., rock bolts) and with the copper coating on the containers (this reaction has been considered in the design of the thickness of copper coating), as well as by reactions with microbes in the backfill and buffer. This has no impact on the integrity of the containers.

For a breached container, hydrogen gas is generated by corrosion of the carbon steel vessel. Since only a few containers are expected to fail initially, the amount of gas generated by steel corrosion is small and, at the groundwater pressures that occur at repository depths, the actual volume of this gas is also small. Analyses indicate a positive benefit can be expected from H_2 generation in a breached container due to prevention of groundwater contact with used fuel and the decrease in the fuel dissolution rate (Rollin et al. 2001, Shoesmith 2008). Neglecting the presence of H_2 gas would, thus, be conservative.

The fate of the H_2 gas generated in a breached container depends on its generation rate. If the gas is formed sufficiently slowly then it would dissolve in the water in the breached container and slowly diffuse away from the container. However, if the gas generation rate is sufficiently high, then a H_2 bubble will form inside the breached container. At sufficiently high gas pressures (i.e., greater than the hydrostatic plus swelling pressure of the bentonite buffer around the container), the hydrogen gas would "breakthrough" the buffer and move to the buffer/rock interface. Here, the gas would move along the placement room excavation damaged zone, which has a higher porosity and permeability than the rock, until the gas pressure decreases sufficiently that there is no driving force for advective gas movement. The gas pathway through the buffer re-seals after the gas passes and the effectiveness of the buffer is not impaired (Harrington and Horseman 2003).

The discussion above is applicable if only a few containers in the repository fail. In the All Containers Fail Scenario, the amount and rate of H_2 gas generation is sufficiently high that it could affect the performance of the used fuel repository. Consequently, the generation of

hydrogen gas by corrosion of the steel vessels and the subsequent behaviour of this gas, including its effect on the transport of gaseous contaminants, is explicitly considered for the All Containers Fail Scenario (NWMO 2018, Section 8).

FEP Screening

Include in the All Containers Fail Scenario.

2.4 Contaminant Release and Transport (waste package)

FEP # 2.4.00.   Scope of subcategory 2.4

Description

Factors and processes related to contaminant transport within the container and through defects in the container. This category includes contaminant chemical processes (such as dissolution and precipitation, speciation and solubility, and sorption / desorption) that affect the release rates of contaminants (i.e., the source terms) from a defective container.

There are seven subcategories under Contaminant Release and Transport (waste package):

    2.4.01 Diffusion (waste package)
    2.4.02 Dissolution and precipitation (waste package)
    2.4.03 Speciation and solubility (waste package)
    2.4.04 Sorption and desorption (waste package)
    2.4.05 Gas-mediated transport of contaminants (waste package)
    2.4.06 Colloid interaction and transport (waste package)
    2.4.07 Coupled solute transport processes (waste package)

FEP# 2.4.01   Diffusion (waste package)

Description

Diffusion refers to the movement of ions, molecules and/or colloids, primarily as a result of concentration gradients. The effect of diffusion is to cause spreading of contaminants from regions of high concentration to regions of lower concentration.

In the waste package, diffusion is an important process. After water contacts the used fuel in a defective container, contaminants released from the fuel diffuse throughout the water-filled void space of the container. Diffusion controls the rate at which dissolved contaminants migrate out of the holes in the container and into the buffer surrounding the container. Diffusion is also an important process for gaseous contaminants.

The main variables that will affect the diffusion of solutes within and out of the container are:

- the fraction of the container filled with water, which affects diffusion of both dissolved and gaseous contaminants;
- temperature; and
- reactions within the container, including precipitation (see *Dissolution and precipitation (waste package) [2.4.02]*) and sorption (see *Sorption and desorption (waste package) [2.4.04]*).

7CS Screening Analysis

In the 7CS, diffusion of contaminants within and out of breached containers is modelled implicitly or explicitly. Diffusion coefficients are temperature dependent.

Containers are conservatively assumed to fill with water immediately after the steel vessel is breached. After water fills the container, dissolved contaminants are released from the fuel, diffuse through the container and diffuse out of the container into the buffer. For simplicity, diffusion within the container is assumed to be relatively fast, so contaminants are uniformly distributed throughout the water-filled volume of the container. The transport rate of a contaminant out of a breached container is limited by either its diffusion rate through the hole(s) in the container or its diffusion rate through the buffer (NWMO 2012b).

The behaviour of gas phase contaminants is not modelled in the 7CS, except in the All Containers Fail Scenario. In this scenario, gaseous contaminants are assumed to be well mixed with the hydrogen gas (generated by corrosion of the steel) in the container (i.e., gaseous diffusion is assumed to be fast) and to move out of the container with the hydrogen gas, after the hydrogen pressure is sufficiently high to "breakthrough" the buffer layer, and into the excavation damaged zone of the placement rooms. In this case, gaseous contaminants move by advection not diffusion out of the container.

FEP Screening

Include FEP in all scenarios.

FEP # 2.4.02   **Dissolution and precipitation (waste package)**

Description

This FEP describes the influence of dissolution and precipitation in the waste package on contaminant transport. Dissolution and precipitation can be important processes in the container because dissolved species are more mobile. Precipitates can also hinder transport by sorbing contaminants and plugging transport pathways.

The maximum or saturated concentration of a solute is known as the solubility limit (see *Speciation and solubility (waste package) [2.4.03]*). The solubility is primarily determined by the properties of the solute and solvent but also depends on temperature and groundwater composition.

Formation of some precipitates can be kinetically hindered, and the first precipitated solid phase generally has an amorphous structure (Oswald's Rule) which later transforms into a more stable crystalline form, e.g., Fe(III) initially precipitates as amorphous ferric hydroxide, $Fe(OH)_3$, which later transforms to crystalline goethite (FeOOH).

Co-precipitation is a variant of precipitation in which a precipitate incorporates a subsidiary compound which would not otherwise precipitate in isolation. For example, precipitation of barium sulphate can induce precipitation of radium sulphate even though the latter is undersaturated. Thus, an element may precipitate even though it is soluble in isolation.

After groundwater enters a breached container, contaminants are released from the fuel in the container by dissolving into the groundwater (see *Used fuel dissolution [2.2.03]*). Thus, the largest concentrations of most contaminants are inside the container, where precipitation may take place if these concentrations exceed the corresponding solubility limits. The mass of these precipitates could increase until dissolution of the waste form ceases, after which, it would decrease as the precipitate itself dissolves.

The waste package will experience the largest variations in temperature and radiolysis effects, and the groundwater entering the container will likely undergo composition changes due to reactions with the buffer. These changes to the chemical environment within the container could affect contaminant solubility limits, leading to dissolution and / or precipitation of contaminants.

7CS Screening Analysis

Dissolution of the used nuclear fuel matrix, dissolution of contaminants from the used fuel, and precipitation of contaminants in a failed container are explicitly modelled in the 7CS. Solubilities are conservatively selected or calculated based on a reference groundwater composition and are assumed to be time independent during any given simulation. Hence, the effect of dissolution and precipitation in the waste package on contaminant transport is explicitly modelled in the 7CS.

FEP Screening

Include FEP in all scenarios.

FEP # 2.4.03   Speciation and solubility (waste package)

<u>Description</u>

This FEP discusses the influence of contaminant speciation and solubility in the waste package on contaminant transport.

Speciation is the distribution of an element among different chemical species (i.e., the types and concentrations of an element among its various chemical forms in an aqueous solution). It will be affected by groundwater chemistry (pH, redox conditions, etc.) and temperature. The nature of the dominant species may affect contaminant transport since, for instance, cations are more strongly sorbed by clay materials than anions.

Complexing agents in the groundwater entering the waste package (organics such as humic and fulvic acids; inorganic ions such fluoride, carbonate and nitrate anions; etc.) could chemically bind with a contaminant to form stable species which, in turn, can increase (or decrease) the solubility of the contaminant and can modify the contaminant transport properties by, for instance, forming a neutral or anionic complex that is less likely to sorb.

Solubility refers to the maximum quantity of the solute that dissolves in a given amount of solvent or solution at a specified temperature. The solubility limit will be affected by the groundwater chemistry and temperature. Precipitation can affect contaminant transport because dissolved species are more mobile. Precipitates can also hinder transport by sorbing contaminants and plugging transport pathways.

An element will precipitate when its total concentration exceeds its solubility limit in the given groundwater. However, because of kinetic factors, the amorphous form of a solid precipitates first (Oswald's Rule) and then transforms into the more stable crystalline phase. From a practical viewpoint, if the crystalline phase is slow to form, then the effective solubility of the element would equal the solubility limit of the amorphous solid. Another complicating effect is the possible formation of several solids of the element, only one of which would be the solubility limiting solid for the element.

Solubility limits, and thus formation or dissolution of precipitates (see also *Dissolution and precipitation (waste package) [2.4.02]*), could be different at different locations in the repository because of differences in groundwater composition and temperature. However, contaminant concentrations are expected to be highest in a breached container because contaminants are diluted as they move away from the contaminant source, i.e., the used fuel. Thus, precipitation of contaminants is most likely to occur within the failed container. The evolution of the chemical environment in the defective containers may affect solubility limits as well.

An element may also be present in groundwater as particulates; see *Colloid interaction and transport (waste package) [2.4.06]*.

<u>7CS Screening Analysis</u>

The solubility of a contaminant in a failed container is explicitly taken into account in the 7CS. If the concentration of a contaminant in the container exceeds its solubility limit, then the contaminant precipitates. Precipitation limits the contaminant concentration in the container and, hence, the transport rate of the contaminant out of the container. The solubility of a

contaminant in the container depends on the composition of the groundwater entering the container, which, in turn, may be affected by the interaction of the groundwater with the buffer and container materials (see *Speciation and solubility (repository) [3.3.04]*).

In the 7CS, PHREEQC (Parkhurst and Appelo 1999) calculations are used to calculate the solubilities of many elements (e.g., Np, Pu, Se, U and Zr) based on the reference groundwater composition for the 7CS hypothetical repository site (Duro et al. 2010). Conservative values are selected for the solubilities of other elements. The solubility values calculated by PHREEQC are used in the 7CS, but the chemical speciation information available from PHREEQC is not explicitly used in the 7CS.

The thermodynamic PHREEQC calculations did not include the potential effect of humic acid complexation on element solubilities (Bryan et al. 2012, and references therein; Antoniou and Pashalidis 2012, 2014; Reiller 2005; Ibrahim and Omar 2005, and references therein). However, such effects are expected to be small at the 7CS repository site because: (1) natural organic concentrations in sedimentary groundwaters are generally low; (2) humic acid complexation is more important under acidic conditions than for the neutral to basic pH conditions expected in the repository (Reiller 2005); and (3) even if humic acid complexes are formed, they are unlikely to move through the buffer because of their large size. Although the presence of humic acid may also enhance the formation of intrinsic actinide colloids (Antoniou and Pashalidis 2012, 2014), such colloids would likely not be able to move through the buffer material surrounding the container (see *Colloid interaction and transport (waste package) [2.4.06],* and *Colloid interaction and transport (repository) [3.3.06]*).

FEP Screening

Include FEP (i.e., solubility) in all scenarios.

FEP # 2.4.04   **Sorption and desorption (waste package)**

<u>Description</u>

This FEP describes the influence of sorption and desorption of contaminants in the waste package on contaminant transport. Sorption describes the physicochemical interaction of a dissolved species with a solid phase, by which the dissolved species are removed from solution. Desorption is the opposite process. Sorption processes are important because they can slow down the migration of contaminants (dissolved species are more mobile than sorbed species), and contribute to the spread of their releases as a function of time (and in space if dispersive effects are important). Thus, sorption will attenuate peak concentrations, and the delay times would allow for additional decay or decomposition of the contaminant.

Sorption and desorption are often described by a simple partition coefficient (K_d), also called the distribution coefficient. This parameter is defined as the ratio of the amount of a contaminant sorbed onto the solid relative to that in solution. Factors that affect sorption include the solid and liquid composition, the form of the species in solution (see *Speciation and solubility (waste package) [2.4.03]*), accessible porosity in the solid, and the presence of colloids (see *Colloid interactions and transport (waste package) [2.4.06]*).

Models employing distribution coefficients (K_d) are linear models which assume that sorption is reversible and rapid and that the sorption capacity of the solid is unlimited. However, non-linear effects can be significant. These include: kinetic effects which favour sorption over desorption (or vice versa); sorption sites which become saturated, i.e., the solid sorbs a limited amount of solute; and removal of sorption sites because of competition by other ions in the groundwater. Such effects could reduce the extent of sorption.

Sorption is element-specific and depends on the speciation of the element, as well as the solid phase composition and surface characteristics. Sorption in a water-filled defective container could occur onto the iron corrosion products formed by corrosion of the steel vessel. This process would be more important at later times when the mass of corrosion products in the container is large. Sorption and desorption processes may change with time if the composition of the groundwater in the container changes with time.

<u>7CS Screening Analysis</u>

For conservatism, sorption of contaminants in the used fuel container is not modelled in the 7CS. Note, however, that sorption of contaminants onto the buffer and backfill materials is modelled, as discussed in *Sorption and desorption (repository) [3.3.05]*.

<u>FEP Screening</u>

Screened out.

FEP # 2.4.05   Gas-mediated transport of contaminants (waste package)

Description

The transport of contaminants in and out of the waste package in a gas or vapour phase, or as fine particulate or aerosols suspended in gas or vapour.

Gaseous contaminants may be generated from used fuel, e.g., C-14 as carbon dioxide or methane. If a gas phase exists in the waste package, e.g., before saturation of the repository, the gaseous contaminants (including aerosols and particulates) may move through the gas phase (by diffusion), or be transported with the gas phase (by convection or advection), out of the waste package. Alternatively, gas pressures could be sufficiently high to form an unsaturated phase where two-phase flow is important, or to expel contaminants dissolved in groundwater from parts of the waste package.

7CS Screening Analysis

In the 7CS, gas phase transport of gaseous contaminants is not modelled during the unsaturated phase of the repository because there are no breached containers during this period.

As noted in *Gas sources and effects (container) [2.3.05]*, if hydrogen gas generation (from corrosion of the steel vessel) in a breached container is fast enough that gas pressures become high (i.e., greater than the hydrostatic and swelling pressure of the buffer around the container), then the gas would "breakthrough" the buffer and move to the buffer/rock interface. Here, the gas would move along the placement room excavation damaged zone, which has a higher porosity and permeability than the rock, until the gas pressure decreases sufficiently (given the small number of failed containers) that there is no driving force for advective gas movement. Thereafter, the gas would likely slowly dissolve in groundwater and diffuse out of the repository.

Any hydrogen gas moving (by advection) from the failed containers to the excavation damaged zone would carry gaseous contaminants (e.g., C-14) from inside the container to the excavation damaged zone. From here, as for the hydrogen gas, these contaminants would slowly dissolve and diffuse out of the repository. Given the long transport time for contaminants to migrate from the repository to the surface, the possible accelerated release of contaminants from the waste package to the excavation damaged zone would not much affect the calculated impacts for gaseous contaminants.

For the All Containers Fail Scenario, the rate of hydrogen production is high. Therefore, the effects of gas generation are considered in this scenario, including the analysis of the dose consequences of gas-mediated transport of radionuclides out of the waste package, through the repository and geosphere, and into the biosphere (NWMO 2018, Section 8).

FEP Screening

Include FEP in the All Containers Fail Scenario

FEP# 2.4.06   Colloid interaction and transport (waste package)

Description

This FEP describes the formation and transport of colloids, and their interaction with contaminants in the waste package. Colloids are small organic or inorganic particles in the nanometre to micrometre size range, small enough to form long-lasting suspensions in a liquid phase. Colloids may influence contaminant transport by serving as a mobile carrier of otherwise highly-sorbing (and, therefore, potentially immobile) contaminants.

Several classes of colloids can be defined. Contaminants may themselves be colloids (also called intrinsic colloids), such as polymeric plutonium. Contaminants may also be sorbed onto other naturally occurring colloids (also called pseudo-colloids) which may have:

  - an inorganic base such as mineral fragments and clay;
  - an organic base such as humin (insoluble humic substances such as plant residues); or
  - a microbial base such as bacteria.

Colloids are unstable thermodynamically and exist because of the slow kinetics of their agglomeration into solids (called coagulation or flocculation). The stability of colloids is influenced by a wide range of factors, such as pH, redox potential, particle size distribution and chemical composition of the groundwater (e.g., major cations) and surface chemistry of the colloids. Colloid stability generally decreases as ionic strength (salinity) increases.

Colloids occur naturally in groundwaters. They could enter the repository with groundwater, or be introduced with backfill material such as crushed granite, or produced in the repository as rock flour from the use of explosives or drilling. Colloids may also be produced in the repository during degradation of the wastes or engineered barrier materials. For example, colloids in the buffer and backfill could be formed from clay particles, particularly if fresh water reaches the repository. However, due to the small size of the pores in dense buffer, colloid transport through the buffer would not likely occur.

7CS Screening Analysis

Due to the small size of the pore spaces in the buffer, and the high salinity of the groundwater in the 7CS, colloid transport out of the container would be unlikely. Hence, in the 7CS, contaminant-colloid interactions are neglected in the container, including formation of intrinsic colloids.

FEP Screening

Screened out.

FEP # 2.4.07   **Coupled solute transport processes (waste package)**

Description

This FEP concerns transport of dissolved contaminants within and out of the waste package that is driven by temperature, hydraulic and/or electrical gradients. Solute transport in a concentration gradient is classical diffusion and is covered under *Diffusion (waste package) [2.4.01]*. Solute movement driven by other gradients are referred to as coupled ("off-diagonal") solute transport and, depending on the driving gradient, are called thermal diffusion or Soret effect (thermal gradient), hyperfiltration (hydraulic gradient) and electrophoresis (electrical gradient).

Since these processes depend on gradients other than concentration gradients, they might contribute to solute movement if diffusion rates are low.

7CS Screening Analysis

In the 7CS, diffusive transport within a breached water-filled container is assumed to be sufficiently fast (on the time scale for contaminant transport out of the container) that contaminants are uniformly distributed within the container (see *Diffusion (waste package) [2.4.01]*). Coupled solute transport processes, if they occur, would therefore not affect the rate at which contaminants move within the container.

In the 7CS, the release of a contaminant out of a breached the container is driven by the difference in the concentration of the contaminant on the inside and the outside of the breached container. Inclusion of coupled solute transport processes could, in theory, increase mass transport out of the container; however, hydraulic and temperature gradients between the interior and exterior regions of the container should be small compared to the concentration gradient. For example, the temperature gradient should be small because of the high thermal conductivity of the container materials (copper and iron). Furthermore, an analysis of the effects of coupled processes and their implications for solute transport has been carried out by Soler (2001). The range of values considered by Soler (2001) for the various coupling coefficients are approximately applicable to the clay-based engineered sealing materials in the 7CS repository, and so the results of Soler (2001) are indicative of the effects within the engineered barrier system of the 7CS. Soler concluded that coupled processes have no significant effect on time scales of 1000 years or more.

Therefore, coupled solute transport processes within and out of the waste package are considered to have a minimal effect and are not included in the 7CS.

FEP Screening

Screened out.

3. REPOSITORY FACTORS

FEP # 3.0.00   Scope of main category 3.

Description

Features and processes occurring within or near the repository, excluding the waste packages, that could affect the thermal, mechanical, chemical, biological or hydraulic conditions in the repository and, as a consequence, the transport of contaminants through the repository and into the geosphere.

There are three subcategories under Repository Factors:

  3.1 Repository characteristics
  3.2 Repository processes
  3.3 Contaminant release and transport (repository)

3.1 Repository Characteristics

FEP # 3.1.00   Scope of subcategory 3.1

<u>Description</u>

Features and processes within the engineered components of the repository (excluding the waste packages), as they exist after repository construction and waste placement, and considering changes that could occur over long periods of time.

There are 4 subcategories under Repository Characteristics:

    3.1.01 Repository design
    3.1.02 Buffer and backfill characteristics
    3.1.03 Seals and grouts (cavern, tunnel, shaft)
    3.1.04 Other engineered features (repository)

FEP # 3.1.01   Repository Design

Description

The position of the repository within its host rock, and the positioning of the container, buffer, backfill and other engineered barriers within the repository. Repository design will also specify the particular materials to be used.

On the large scale, layout refers to the siting of the repository within the host rock such that its placement rooms avoid or minimize contact with unfavourable zones of rocks such as conductive faults and fractures. The groups of placement rooms might all be on the same level, or at different levels. In some sites, a placement room or access tunnel may straddle a fracture zone, so bulkheads and seals would be used to provide isolation between containers and the fracture zone.

On the room scale, layout refers to the positioning of containers, buffer, backfill and other engineered barriers within a placement room. For instance, the in-room placement option generally has containers centrally located in a tunnel and surrounded by concentric layers of buffer and perhaps backfill. The in-floor placement option generally has containers placed in boreholes drilled into the floors of tunnels and completely surrounded by buffer, with backfill used only in the tunnels. Other placement options are possible, such as long boreholes drilled into tunnel walls and large galleries or silos.

Note that the final repository layout will likely differ from its initial design. One reason is to minimize contact with unfavourable zones of rock, which would be best achieved as the repository is being excavated and more information becomes available on the location of unfavourable zones. Another possible reason is to accommodate changes in the design basis or excavation methods that develop over the decades of repository operation.

7CS Screening Analysis

The 7CS room layout (see Figure 3-2) is based on containers placed horizontally (perpendicular to the placement room axis) in each room. Each container is surrounded by a highly compacted 100% bentonite "buffer box". Bentonite blocks are placed between the adjoining buffer boxes, for thermal spacing, as shown in Figure 3-2 (NWMO 2018, Section 4).

The access tunnels are mainly filled with dense backfill blocks (a 5:25:70% bentonite:clay:aggregate mixture), with gaps filled with light backfill pellets (50:50% bentonite:sand). A concrete bulkhead is placed at the end of each placement room. During decommissioning a placement room seal (100% bentonite) is installed next to the concrete bulkhead as shown in Figure 3-2. This seal is keyed into the host rock.

The shafts are sealed primarily with a 70:30% bentonite:silica sand mixture; concrete is used at the base of the shaft and at other places for mechanical support; an asphalt or high-density buffer may be used in places for seal redundancy.

The 7CS assumes that the rock is homogenous and so all placement rooms are identical. In reality, there may be some variation in the layout to adapt to local conditions. However, minor variations in the placement room layout are not expected to have a large effect on contaminant releases from the repository, based on the results of previous studies.

The repository layout in terms of the placement room locations is considered explicitly in the 7CS because contaminant release pathways may vary depending on the location of the failed containers in the repository.

<u>FEP Screening</u>

Include FEP in all scenarios.

FEP # 3.1.02   Buffer and backfill characteristics

<u>Description</u>

The physical, chemical and biological characteristics of the buffer and backfill.

Buffer and backfill are sometimes used interchangeably. In this report, we adopt the following definitions.

- Buffer refers to the material immediately surrounding a waste container. Its primary role is to control the hydraulic and chemical conditions near the container (e.g., preventing water flow and maintaining a diffusion-controlled transport environment).
- Backfill refers to the material primarily used as filler in the placement rooms and tunnels. It may play a chemical role in retarding contaminant transport and a mechanical role in preventing collapse of underground openings.
- Buffer and backfill materials may include clays and cement, and mixtures of these with aggregates such as silica sand or crushed rock.

The buffer and backfill characteristics are discussed further under:

   3.1.02.A Buffer characteristics and evolution
   3.1.02.B Backfill characteristics and evolution.

FEP # 3.1.02.A   Buffer characteristics and evolution

Description

Properties of the buffer and their evolution with time. This includes consideration of:

- the gap fill material between the container and the buffer, which may be employed in some repository designs; and
- additives to the buffer to improve performance. Examples of potential additives are ferrous minerals to control Eh, stable iodine to enhance isotopic dilution of I-129, and reactive materials (such as graphite and phosphates) to delay transport of selected contaminants.

General characteristics of the buffer that affect groundwater flow and contaminant transport include composition, density, hydraulic conductivity, porosity and sorption (see *Sorption and desorption (repository) [3.3.05]*). The properties of the buffer may not be uniform (since buffer placement might not be uniform) and the thermal and unsaturated conditions may cause shrinkage cracks to form conduits for advective water movement or enhanced diffusion pathways. Conversely, swelling pressures might force buffer into fractures or surrounding backfill to seal off transport paths. Similar comments apply to the gap backfill and additives.

The properties of the buffer will change with time as it undergoes chemical and physical evolution, starting from initial conditions that include a high temperature, low moisture level and residual atmospheric gases. The influx of groundwater will saturate the buffer, possibly in a non-uniform fashion, and lower temperatures, promoting evolution of the buffer and its porewater. For instance, evolution of buffer could result in loss of soluble material and accumulation of insoluble salts; silica cementation; alteration of montmorillonite to illite; and a reduction in swelling, self-healing capacity or sorption properties if calcium-rich waters replace sodium in bentonite or if incoming groundwaters are highly saline. The issue of hydrothermal alteration of the buffer is addressed in *Hydrothermal alteration (repository) [3.2.04.B]*. The initial and evolving conditions could also have different implications for the growth of microbes (see *Biological processes and conditions (repository) [3.2.05]*).

The properties of the gap backfill will also change with time. The conditions in this layer if adjacent to the container could be of particular relevance for the growth of biofilms on the container (see *Biological processes and conditions (repository) [3.2.05]*).

The properties of additives included in the buffer may also change with time. This is especially true for additives chosen to control chemical conditions, e.g., Eh, since the implication is that control is achieved as the additive undergoes chemical reactions.

7CS Screening Analysis

The containers in the 7CS are surrounded by highly compacted 100% bentonite (NWMO 2018, Section 4). Dense backfill blocks and 100% bentonite pellets are also used in the placement room (see Figure 3-2). (Additives to improve buffer performance are not used in the 7CS.)

Initially, moisture will be driven out of the buffer closest to the container as water vapour due to container heating. The buffer near the containers could dry, shrink and crack. Eventually, however, groundwater will enter the repository from the geosphere and saturate the buffer. As the buffer saturates, it swells and gaps or cracks in the buffer will self-seal; its properties (hydraulic conductivity and diffusivity) will become similar to that of intact material (Graham et al.

1997).

The time scale for saturation may be thousands of years at the 7CS repository site. Although, there will be some equilibration of density among the various buffer components as pressures are equalized, differences in the densities of the various buffer components will remain even after long times. The saturated buffer has swelling pressure of only 0.6 to 0.7 MPa, due to the salinity of the groundwater (about 280 g/L) at the 7CS site, and it is essentially impermeable to groundwater flow because of its very low permeability.

A summary of buffer properties and stability is provided in SKB (SKB 2010) and Posiva (Juvankoski 2012). Important buffer parameters are thickness, permeability, porosity, contaminant diffusivity and sorption capacity. These are explicitly included in the 7CS models for contaminant transport. Transport properties will depend on temperature. The temperature at the container/buffer reaches a peak value of about 93°C at about 47 years after container placement; thereafter, the temperature decreases slowly to near ambient temperatures at about 200,000 years after placement (see *Thermal processes (container) [2.3.02]*). In the 7CS, buffer properties are conservatively selected throughout the assessment period.

Physical/chemical evolution of the buffer is judged to be an insignificant factor in the 7CS over 1 million years, as shown in *Hydrothermal alteration (repository) [3.2.04.B]*.

Small changes to the buffer porewater chemistry would initially occur due to dissolution of accessory minerals (e.g., calcite and gypsum) in the buffer. The pH of the porewater is buffered by calcite equilibrium. In the long term, the porewater composition becomes similar to that of the host rock groundwater, which is saline. The impacts of groundwater salinity on the physical properties of the buffer (e.g., swelling pressure) are accounted for in the 7CS. These changes to porewater chemistry would, however, not affect buffer transport properties (Arcos et al. 2006, 2000), which are treated as time invariant in the 7CS.

Buffer material can erode in the presence of freshwater because clay particles lose their cohesiveness under these conditions and become available for dispersion by diffusion or advection (Birgersson et al. 2009). Buffer erosion by exposure to fresh glacial meltwater that reaches the repository is an important factor in the SKB SR-Site assessment because there is a fracture intercepting the deposition hole that allows buffer particles to move away from the container (SKB 2011). In the 7CS, glacial meltwater does not penetrate to repository depth (NWMO 2018, Section 2) (see also *Local glacial effects [1.3.05]*), so erosion of the buffer is not considered in the 7CS.

The evolution of biological processes within the buffer is discussed under *Biological processes and conditions (repository) [3.2.05]*.

FEP Screening

Include FEP in all scenarios.

FEP # 3.1.02.B   Backfill characteristics and evolution

Description

Properties of the backfill and their evolution with time.

General characteristics of the backfill that affect groundwater flow and contaminant transport include composition, density, hydraulic conductivity and porosity (see also *Sorption and desorption (repository) [3.3.05]*). The properties may not be uniform; for instance, there might be several grades of backfill, the placement method may lead to settling, and the thermal and unsaturated conditions may cause shrinkage cracks to form. Conversely, swelling pressures might force backfill into fractures and seal off transport paths.

These properties and their effects will change with time as the backfill undergoes chemical and physical evolution, starting from initial conditions that include a high temperature, low moisture level and residual atmospheric gases. The issue of hydrothermal alteration of the backfill is addressed under *Hydrothermal alteration (repository) [3.2.04.B]*. The influx of groundwater will saturate the backfill, lower its temperature and expose it to the groundwater. For instance, evolution of backfill could result in loss of soluble material and accumulation of insoluble salts; silica cementation; and a reduction in swelling capacity if calcium-rich waters replace sodium in bentonite or if incoming groundwaters are highly saline. Local erosion of the backfill may occur if groundwater velocities are sufficiently high. The evolving conditions could also affect the growth of microbes (see *Biological processes and conditions (repository) [3.2.05]*).

7CS Screening Analysis

Tunnels and access drifts are backfilled with blocks of dense backfill consisting of 5 wt% bentonite, 25 wt% glacial clay and 70% crushed granite aggregate (Gobien et al. 2018), with gaps around the dense backfill blocks filled with light backfill (a 50:50 mixture of bentonite and granitic sand).

A summary of backfill properties and stability is provided in SKB (SKB 2010; Pusch 2001) and Posiva (Juvankoski 2012). Oscarson and Dixon (1989) summarize the clay compositions that could be used for backfill in Canada.

Evolution of the backfill parameters with time, including the potential for erosion, is judged to be an insignificant factor in the 7CS under the expected physical and chemical conditions in the repository, for the same reasons discussed in *Buffer characteristics and evolution [3.1.02.A]*, and is not modelled. The specific issues of hydrothermal alteration and microbe growth are addressed in *Hydrothermal alteration (repository) [3.2.04.B]* and *Biological processes and conditions (repository) [3.2.05]*, respectively.

Contaminants can be transported through the backfill by diffusion or with moving groundwater. Important backfill characteristics are its thickness, porosity, and contaminant diffusivity and capacity factors. These parameters are explicitly included in the 7CS transport models and are treated as time-invariant.

FEP Screening

Include FEP in all scenarios.

FEP # 3.1.03   Seals and grouts (cavern, tunnel, shaft)

Description

The physical, chemical and biological characteristics of the placement room, tunnel, shaft and borehole seals, including grouts, at the time of disposal and their evolution with time.

Seals and grouts are used to control water flow into the repository during the excavation and operations phase. However, seals and grouts also have a longer term role in the performance of a repository: to eliminate or control alternative routes for groundwater flow and radionuclide transport along the tunnels, shafts and boreholes, and into fractures that intersect the tunnels, shafts and boreholes (see also *Excavation damaged and disturbed zones [3.2.03.C]*). Bulkhead seals are intended to close off a placement room once it has been filled with waste.

The properties of the seals and grouts that are important include composition, density, hydraulic conductivity and porosity, and their ability to make a water-tight contact with the host rock.

These properties could change with time, affecting the performance of seals and grouts over different time frames. Changes could arise from microbial degradation, leaching or dissolution of soluble elements, and alteration to less effective mineral phases. Hydrostatic and lithostatic pressures could cause physical extrusion or cracking, affecting the performance of the seals. Long-term thermal and mechanical tectonic processes may act to degrade the effectiveness of the seals. Cement-based seals may be particularly susceptible to degraded performance because of leaching and dissolution. These changes might be enhanced during unsaturated conditions and when the repository is open to atmospheric gases, particularly if a seal with self-healing characteristics relies on excess water. For instance, the self-healing properties of cement develop when hydration products form within fractures as water infiltrates and so are dependent on the establishment of fully saturated repository conditions. (See *Hyperalkaline fluid interaction (repository) [3.2.04.D]* for the potential effects of cement leaching on the near-field.)

The main concern is that new and undesirable patterns of groundwater flow and contaminant transport could emerge. For instance, failure of borehole and shaft seals could lead to formation of a conduit connecting the repository to the surface environment; in the case of the shaft, the conduit size might be sufficiently large to support convection cells. Failure of bulkhead and tunnel seals could interconnect different disposal rooms so that contaminants could readily move throughout the repository and exit at some location where transport to the accessible environment is most favourable.

7CS Screening Analysis

The 7CS repository includes a combination of bulkheads, seals and backfill within the repository access tunnels and shafts. For example, the shaft would be mainly sealed with a combination of a 70%:30% bentonite:silica sand mixture, asphalt, and concrete. The use of composite seals incorporating highly compacted bentonite blocks and high performance concrete bulkheads, along with durable cement-based grouts for fractures and clay-granite mixture for backfill, would significantly limit advective water flow through the sealing materials.

In the Normal Evolution Scenario of the 7CS, all seals are assumed to perform as designed over the time scale of interest. Therefore, the access tunnels and shafts have low permeability.

The bentonite swelling component will achieve its low permeability state upon saturation of the repository. The degradation of the clay seals will be slow for reasons similar to those discussed in *Buffer characteristics and evolution [3.1.02.A]*. Degradation of the concrete will also be slow because of the low groundwater flow velocities. However, for conservatism, degraded concrete properties are used in the 7CS safety assessment from the time of repository closure.

The integrity of the seals in the bottom ~400 m of the shafts (70%:30% bentonite:silica sand mixture, asphalt, and concrete) would not be affected by freeze/thaw cycles because these seals are below the maximum depth of permafrost (~65 m) at the 7CS site (see *Periglacial effects [1.3.04]*). Although, the integrity of the seals in the top 65 m of the shafts (concrete and engineered fill) could, in theory, be affected by freeze/thaw cycles, this would not affect the calculated impacts of the 7CS repository because, in the safety assessment calculations, a water well collects most of the contaminants diffusing from the repository into the Guelph layer (which is about 150 m below ground surface).

The consequences of significant degradation of shaft seals and borehole seals (relative to their design specifications) are investigated in the 7CS in the Repository Seals Failure Scenario and Poorly Sealed Borehole Scenario, respectively.

FEP Screening

Include in all scenarios. The effects of significantly degraded seals are investigated in the Repository Seals Failure and Poorly Sealed Borehole Scenarios.

FEP # 3.1.04   Other engineered features (repository)

Description

The physical, chemical and biological characteristics of engineered features other than containers, buffer, backfill and seals. This category includes processes which are relevant specifically as degradation processes acting on the features, rather than processes that contribute to the general evolution of the near-field.

Examples of other engineered features are rock bolts, shotcrete, railway lines, tunnel liners, silo walls, concrete flooring, and any other services, equipment and detritus not removed before closure. The function of many of these features is to facilitate activities or provide worker safety during the operation phase, but they have little or no intended function after closure and decommissioning. For example, rock bolts and concrete are used to stabilize openings, and a railway line may be used to move containers from a shaft to a placement room. The main concern is that these materials could have undesirable long term effects. For instance, iron-water reactions could lead to the formation of hydrogen gas and leaching of concrete could lead to the production of large local concentrations of calcium ions and an elevated pH (see also *Chemical processes and conditions (repository) [3.2.04]*).

Features used to stabilize openings may not be effective over long time frames (see *Mechanical processes and conditions (repository) [3.2.03]*).

7CS Screening Analysis

The possible effects associated with other engineered features are not explicitly modelled in the 7CS because all engineering features would be chosen during repository design to avoid any significant adverse effects. For example, the current design does not include concrete flooring in the placement rooms.

Any cabling or ducting would be removed from placement rooms after containers have been placed. The room bulkhead concrete seal would be placed far enough from the first container and use a low-pH concrete formulation in order to minimize effects of any alkaline plume on the container.

Rock bolts and shotcrete within a room would generally be left in place. These would be a small source of gas and alkalinity, respectively, in the long term. But for a site in competent sedimentary rock these would not be present in significant enough amounts to affect the postclosure performance. Gas transport will be impeded by the very low permeability of the buffer and host rocks, and the change in alkalinity will be buffered by the carbonate minerals in the buffer and host rocks.

FEP Screening

Screened out.

3.2 Repository Processes

FEP # 3.2.00   Scope of subcategory 3.2

Description

Processes within the engineered components of the repository, excluding the waste package, as they exist at the time of placement and considering changes that could occur over long periods of time. Note that chemical processes or factors affecting the contaminants in the repository are discussed separately under *Contaminant release and transport (repository) [3.3]*.

There are seven subcategories under Repository Processes:

> 3.2.01 Thermal processes (repository)
> 3.2.02 Hydrological processes and conditions (repository)
> 3.2.03 Mechanical processes and conditions (repository)
> 3.2.04 Chemical processes and conditions (repository)
> 3.2.05 Biological processes and conditions (repository)
> 3.2.06 Gas sources and effects (repository)
> 3.2.07 Radiation effects (repository)

FEP # 3.2.01   **Thermal processes (repository)**

<u>Description</u>

This FEP covers the thermal processes that affect the repository, repository contents and near-field rock, and the overall evolution of the near-field thermal conditions with time (e.g., changes in temperature caused by radioactive decay heat, conduction and convection).

Thermal processes and conditions are discussed further under:

    3.2.01.A Thermal conduction and convection (repository)
    3.2.01.B Coupled heat transfer processes (repository)

FEP # 3.2.01.A   Thermal conduction and convection (repository)

Description

Heat transport, or the transport of heat energy, can occur by conduction, convection (flow) or radiation. Heat can also be transferred between different phases, such as the condensation or evaporation of water. In the context of heat transport in a rock mass, conduction is the most relevant process. Under steady state (time-independent) conditions, heat transport in solids is determined solely by the thermal conductivity of the medium. Under transient (time-dependent) conditions, the heat storage capacity of the medium (which is related to the specific heat capacity and the density of the medium) is also a factor.

Ambient temperatures in the repository will be determined by natural geothermal gradients. However, elevated temperatures will occur in the repository because of the heat production from radioactive decay of the nuclear wastes. These temperatures will change with time, rising from ambient conditions after construction starts, reaching a maximum shortly after closure, and slowly returning to ambient conditions after thousands of years. The magnitude of the temperature increase will be strongly affected by the thermal conductivity of materials surrounding the waste containers. Finally, the temperature increase is non-uniform across the repository because the density of containers is, for example, higher in the centre of the repository than at the perimeter of the repository. The non-uniformity could also be affected by the uneven distribution of fuels with higher heat generation in the repository, variations in the thermal properties of materials placed in the repository and the host rock itself, and by the rate and pattern of desaturation and resaturation of the repository.

Another specific issue of interest is the generation of steam, in localized areas, if the temperature in the repository becomes sufficiently high. Steam may increase cracking of buffer and backfill materials due to increased gas pressures, may modify groundwater circulation patterns, and may increase the rates of container corrosion and other chemical reactions. The condensation of steam in cooler areas may lead to pockets of water (perched water) in unsaturated materials.

The following effects of elevated temperatures in the repository are discussed elsewhere:
-   redistribution of moisture in the buffer, possibly leading to localized formation of cracks (see *Buffer and backfill characteristics [3.1.02]*);
-   changes in groundwater movement (see thermal buoyancy effects under *Hydrothermal activity [1.2.06]* and resaturation effects under *Hydrological processes and conditions (repository) [3.2.02]*);
-   redistribution of mechanical stresses (see *Mechanical processes and conditions (repository) [3.2.03]*); and
-   changes in chemical reaction rates, including container corrosion (see *Chemical and biological processes (container) [2.3.04]* and *Chemical processes and conditions (repository) [3.2.04]*).

7CS Screening Analysis

Heat is generated in a used fuel repository by radioactive decay of the used fuel. For the 7CS, the initial thermal power of a container is about 170 W, based on 48 bundles with a burnup of 220 MWh/kgU and 30 years cooling. This thermal power decreases with time.

The heat generated by the used fuel causes a temperature perturbation that propagates in all directions from the repository. Heat conduction in rock is roughly linear, so the heat flow from the repository is independent of the geothermal heat flow and will be superimposed on it. The peak temperatures in the repository are determined by: the total thermal power output of the used fuel in the repository; the thermal power distribution, which varies in both space and time; the geothermal gradient; the ambient surface temperature; and the thermal diffusivity of the engineered materials and rock.

The 7CS room size and spacing are such that the peak temperature at the container surface is ~93°C at about 47 years after placement; thereafter, the temperature decreases slowly to near ambient temperatures at about 200,000 years after closure (see *Thermal processes (container) [2.3.02]*).

The highest rock temperatures will be reached ~68 years after closure in the near-field rock adjacent to the buffer. This will cause the rock to expand, thereby increasing rock stresses which, in turn, may cause spalling of the rock and increase the extent of the rock damaged zone (see *Excavation damaged and disturbed zones [3.2.03.C]*).

In the 7CS, for the purposes of safety assessment calculations, the temperature in the engineered barriers around the container is conservatively selected to be representative of the quasi-steady-state thermal conditions of the repository within the first 10,000 years after repository closure. Material property values, such as diffusion coefficients and solubilities, are chosen to be consistent with this higher temperature. In contrast, the properties of the tunnel backfill, which is much farther from the containers, are based on the ambient long-term temperature.

The maximum temperature at the interface between the engineered sealing materials and the host rock is about 85°C, occurring after 68 years (Guo 2018). Temperature in the placement rooms would be about 49°C after 10,000 years, with the rock temperatures after 10,000 years in the area within 137 m and 228 m of the plane of the repository being above 25°C (and decreasing). The properties of the host rock are not strongly sensitive to this temperature range, and, therefore, are based on the ambient long-term temperature conditions (see *Evolution of hydraulic conditions in near-field [3.2.02.D]*).

Finally, convection is not expected to be important in the 7CS due to the relatively low temperature gradients and the low permeability of the repository seal materials and host rock.

FEP Screening

Include FEP in all scenarios.

FEP # 3.2.01.B   Coupled heat transfer processes (repository)

Description

This FEP includes heat transfer by all gradients, with the exception of temperature gradients

Heat transfer driven by gradients, other than temperature gradients, is often referred to as a coupled ("off-diagonal") transport process and is called thermal filtration (pressure or hydraulic gradient), Dufour effect (chemical density or concentration gradients) or Peltier effect (electrical gradient). Heat transfer due to temperature gradients is discussed under *Thermal conduction and convection [3.2.01.A]*.

Coupled transport processes could contribute to the heat transfer in the engineered barriers of a repository, especially if thermal gradients are low enough.

7CS Screening Analysis

An analysis of the effects of coupled processes and the implications for heat transport has been performed by Soler (2001) for the Swiss Opalinus Clay Project. The coupled processes examined for heat transport were thermal filtration (hydraulic gradient), the Dufour effect (chemical gradient) and the Peltier effect (electrical gradient).

The range of values considered for the various coupling coefficients in this Opalinus Clay study are approximately appropriate for the clay-based engineered sealing materials in the Canadian repository concept, and so the results of Soler (2001) are indicative of the effects within the engineered barrier system of the 7CS repository.

Soler (2001) concluded that none of the coupled processes were important for heat transport. This can be expected because coupled processes are generally only important when the direct process (in this case, the temperature gradient) is small. However, there is a significant thermal gradient in the repository, as long as there is significant heat output from the containers.

On the basis of these results, coupled heat transport processes in the repository are considered to be a small effect and are not included in the 7CS.

FEP Screening

Screened out.

FEP # 3.2.02   **Hydrological processes and conditions (repository)**

Description

This FEP describes the hydrological and hydrogeological processes that affect repository seals and other engineered features (excluding the waste package), as well as the overall hydrological evolution of the excavation damaged zone (EDZ) and near-field with time. This includes the hydraulic influences on repository components (excluding the waste package) by the surrounding geology. The movement of contaminants is described in *Contaminant release and transport (repository) [3.3]*.

Hydrological processes and conditions are described further under:

  3.2.02.A Desaturation and resaturation of the repository
  3.2.02.B Excavation damaged zone
  3.2.02.C Groundwater movement (repository)
  3.2.02.D Evolution of hydraulic conditions in the near-field
  3.2.02.E Piping / hydraulic erosion of seals
  3.2.02.F Coupled hydraulic processes (repository)

FEP # 3.2.02.A   Desaturation and resaturation of the repository

<u>Description</u>

This FEP covers the establishment of unsaturated conditions near the repository during the construction and operational phases, and the return to saturated conditions following repository closure.

During the construction and operational phases, dewatering of the rock will occur in response to pumping. Groundwater will seep into the repository from the surrounding rock and will be pumped away, resulting in drawdown of the water table above the repository and creating an unsaturated zone in the excavation damaged zone (EDZ) and host rock near the repository.

Following closure, water will flow towards the repository and the near-field will resaturate. Flow directions will stabilize following saturation and will be consistent with the original flow field. The process of resaturation may require a long time, as ingress of water may be restricted because of low host rock permeabilities and/or effective seals. The rate of resaturation will likely vary at different locations within the repository. In sparsely-saturated rock, high near-field porewater pressures as a result of repository heating could change the flow field and affect resaturation time. The time of unsaturated conditions and the time to resaturate different areas will affect the local temperature, chemistry, stress states (including buffer swelling) and groundwater flow rates. Nearby sections of rock may never return to their original moisture state because of hysteresis.

The bentonite buffer and backfill will uptake water during the resaturation process, resulting in swelling of these materials. Swelling in response to the addition of water is a natural property of bentonite, resulting in the development of its barrier properties (low hydraulic conductivity and high swelling pressure) and self-sealing capabilities.

During the postclosure phase, all processes in the near-field will occur in an initially unsaturated and initially oxidizing environment. Reaction rates, flow dynamics and chemical conditions will be different from those identified and predicted for fully saturated conditions. Aerobic microbes and reaction processes will utilize the available free oxygen and will re-establish reducing conditions in the near-field.

<u>7CS Screening Analysis</u>

The desaturation/resaturation behaviour of the repository is complicated as it involves coupled thermal-hydraulic (and to a lesser extent, mechanical) processes. Models are available to estimate these effects (Åkesson et al. 2010), and are being improved by calibration against large-scale in situ experiments (Vietor 2012; Garitte and Gens 2012). However, the fundamental property of interest is how long this process will take, because the time period prior to complete resaturation is not expected to be detrimental to container or sealing material performance; and, because there are no releases of contaminants during the resaturation period since all containers remain intact during this period.

In the 7CS, saturation of the repository is slow because of the host rock has low permeability (NWMO 2018, Section 5). It is conservatively assumed that saturation occurs 1,000 years after closure. A "time delay" is included in the 7CS models to represent the saturation time and the time needed to breach containers with defects in their copper coating. Thus, in this limited

sense, resaturation of the repository is accounted for in the 7CS.

FEP Screening

Include FEP in all scenarios.

FEP# 3.2.02.B   Excavation damaged zone

<u>Description</u>

The excavation damaged zone (EDZ) is the zone of rock immediately surrounding placement rooms, tunnels, shafts and other underground openings that may be mechanically disturbed during excavation.

The EDZ is formed as a consequence of 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 whose properties are significantly different than those of the surrounding host rock. Relevant properties are permeability, porosity, mechanical strength, fracture frequency and fracture connectivity.

Formation of the EDZ may increase the possibility of collapse of repository openings (see *Collapse of repository openings [3.2.03.D]*).

The EDZ may affect groundwater flow and contaminant transport by providing a more permeable pathway than the host rock or buffer/backfill. The EDZ may comprise a number of hydraulically isolated areas, or it might comprise a web of damaged rock that interconnects all repository openings. The EDZ can be more extensive in particular parts of the repository, such as along the top of repository rooms (or between boreholes in the in-floor placement option), and may also extend deep into the host rock to form hydraulic connections with nearby fractures. The permeability and porosity of the EDZ, compared with the surrounding host rock, may be such that groundwater flow occurs preferentially within the EDZ. If it is sufficiently large, the EDZ could act as a hydraulic cage, decreasing groundwater velocities within the repository.

The formation of a hydraulic cage would likely decrease contaminant advective transport, but it could also enhance contaminant transport by diffusion by creating a zero concentration boundary condition. Moreover, the EDZ could function to gather contaminants from different parts of the repository and channel them towards a fracture zone in the host rock.

For a repository in rock containing saline waters, the EDZ may accumulate salts derived from the evaporation of these waters, which will migrate towards the low pressure (atmospheric) environment of the repository during its operational period. Closure and resaturation of the repository will allow the salts to re-dissolve and yield an initial repository-water composition that is more saline than the ambient groundwater, which may have a bearing on the chemical stability of the containers, buffer and backfill.

Another consideration is evolution of the properties of the EDZ. The EDZ will become unsaturated to some degree while the repository is operational. After saturation of the EDZ, the higher repository temperatures could promote hydrothermal interactions, causing mineral alteration, and perhaps fracture formation and/or infilling. In particular, the EDZ thickness could increase. Other properties, such as permeability, could be affected by hydrothermal reactions in the EDZ, intrusion into the EDZ of backfill, and seismic events. Stress relief cracking or degradation of seals could extend and hydraulically connect isolated EDZ regions.

7CS Screening Analysis

Studies of the EDZ in tunnels at Atomic Energy of Canada Limited's Underground Research Laboratory (URL), in sparsely fractured crystalline rock excavated by controlled-blast techniques, have indicated the presence of the EDZ as a thin inner (0.3 m) and outer (1 m) layer around the placement rooms, particularly along the tunnel center top and bottom (Martino 2000). There were no indications of radial breakouts extending deeper into the rock to nearby fractures. These studies have not been conclusive with respect to the axial hydraulic connectivity of the EDZ.

The Geosynthesis report for Ontario Power Generation's deep geological repository for low and intermediate level waste collated information on the properties, extent and temporal evolution of the EDZ in sedimentary rocks (NWMO 2011, Section 6.3.1). The key factors influencing the EDZ properties are stress magnitude and orientation, excavation shape and method, and the rock response (brittle or plastic). In general, the extent of the EDZ measured around underground openings was typically less than 1.5 times the radius of the openings. The increase in the hydraulic conductivity of the EDZ relative to undisturbed host rock ranged from 5 to 10^4. Modelling (NWMO 2011, Section 6.4.3) also indicated that the EDZ is primarily due to stress relief and does not change much with time.

In the 7CS, inner and outer EDZs are included in the groundwater flow and transport models, with the inner EDZ being more permeable and porous than the outer EDZ. These zones are cautiously assumed to be fully hydraulically connected axially along the placement rooms and tunnels. However, the seals at placement room ends are expected to provide a hydraulic break from the EDZ in the tunnels (see Figure 3-2). The hydraulic properties of the EDZ are assigned a range of values to investigate the sensitivity of calculated results to EDZ properties.

Changes in mechanical stresses, e.g., due to seismicity or temperature changes, could in theory affect EDZ properties. EDZ properties selected for use in the 7CS already account for the effects of thermal stresses. The potential impact of changes in EDZ properties due to, for example, seismicity is addressed through sensitivity cases in which the hydraulic conductivity of the EDZ is increased relative to its reference value. Thus, in the 7CS, the EDZ is modelled 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 in the host rock, or precipitation of secondary phases, e.g., during operation of the repository. However, these processes, which would reduce the hydraulic conductivity of the EDZ, are conservatively ignored in the 7CS.

FEP Screening

Include FEP in all scenarios.

FEP # 3.2.02.C   Groundwater movement (repository)

Description

This FEP covers the factors influencing the movement of groundwater in the near-field, i.e., in the repository and the nearby surrounding rock, including the excavation damaged zone.

Groundwater movement through the repository will be influenced by advection, convection, and dispersion through the various media. Unsaturated conditions could persist for long periods of time such that gas transport or two-phase flow may be possible (see *Gas sources and effects (repository) [3.2.06]* and *Gas processes (geosphere) [4.2.07]*). Groundwater might preferentially move around the repository if the excavation damaged zone (EDZ) acts as a 'hydraulic cage' (see *Excavation damaged zone [3.2.02.B]*), or it might be shunted through the repository, which can act as a conduit in an impermeable host rock. Variations in hydraulic conductivity in the near-field may lead to other preferential flow paths, such as along the top of a tunnel room, or at the interface between the buffer and backfill or the backfill and rock. Variations in hydraulic head may also produce local flows and stresses that affect the performance of repository seals.

Groundwater movement in the near-field could also be affected by such events as the onset of glaciation, significant degradation of repository seals, and seismic events which activate existing fracture zones.

The movement of groundwater is of concern because it may lead to the subsequent transport of dissolved or suspended contaminants. However, contaminants can also move by diffusion in relatively stagnant waters. Further discussion of contaminant transport is provided under *Contaminant release and transport (repository) [3.3]*.

7CS Screening Analysis

The 7CS explicitly accounts for groundwater flow in the repository (buffer and backfill) and near-field rock zones (e.g., EDZ) because flow can influence contaminant transport. Only the groundwater flow field following repository saturation is needed because there are no breached containers and, hence, no contaminant releases before saturation of the repository.

In the 7CS, the buffer and backfill are treated as homogenous; the EDZ is considered to be homogeneous but anisotropic, with different properties in the axial and radial directions (Gobien et al. 2018).

The potential influence of gas generation in the repository on groundwater and contaminant movement near the repository is considered in the 7CS for the All Containers Fail Scenario (see *Gas sources and effects (repository) [3.2.06]*) (NWMO 2018, Sections 7 and 8). Gas generating reaction(s) could affect groundwater and contaminant movement by, for example, consuming water entering the repository and/or changing the pressure evolution and resaturation time of the repository.

FEP Screening

Include FEP in all scenarios.

FEP # 3.2.02.D   Evolution of hydraulic conditions in the near-field

Description

This FEP focuses on the naturally induced changes in the hydraulic conditions in the near-field (apart from the desaturation-resaturation transient, which is discussed under *Desaturation and resaturation of the repository [3.2.02.A]*).

Processes acting over long periods of time could change the pattern of groundwater and contaminant movement through and near the repository. For example, precipitation reactions initiated by decreases in groundwater pressure (for saline fluids) could lead to the plugging of inlets or outlets, while dissolution reactions and erosion could form flow channels (possibly in the seals). These effects would change hydraulic heads and subsequently groundwater flow and contaminant transport in the near-field. Some combinations of plug formation and channelling, coupled with temperature increases, might lead to large, local hydrostatic pressures. Localized percolation, driven by temperature gradients, could lead to early failure of seals and grouts, particularly in large openings such as the repository tunnels and shafts.

7CS Screening Analysis

The hydraulic properties of the geosphere and repository are expected to be fairly steady after resaturation for a number of reasons. First, the repository seals and low permeability host rock limit groundwater flows within the near-field. Second, reactions between the groundwater and the backfill/buffer materials that could, with time, affect the hydraulic properties of these sealing materials are limited, as discussed under *Chemical processes and conditions (repository) [3.2.04]*, and are neglected. Third, the peak temperature of around 93°C at container surfaces is not sufficient to drive significant flows within this low-permeability system nor affect contaminant transport, given that the transport times to the surface are much longer than the thermal transient. Finally, although some degradation of concrete seals will occur with time, this is accounted for in the 7CS groundwater modelling by using degraded concrete properties from the time of repository closure.

The effect of groundwater salinity on the physical properties (e.g., swelling pressure and hydraulic conductivity) of the backfill and buffer materials has been considered when selecting the values of these properties for use in the 7CS (Gobien et al. 2018). However, reactions between the saline groundwater and the backfill/buffer materials that could, with time, affect the hydraulic properties of these sealing materials are limited, as discussed under *Saline groundwater effects on clay-based seals [3.2.04.C]*, and are neglected.

Large earthquakes, which are unlikely at the hypothetical site, could cause movement along existing faults. However, it is assumed in the 7CS that there are no known faults or fracture zones at the repository site. The effect of an undetected fault is considered in the Undetected Fault Scenario.

Thus, for the constant climate simulations carried out in the 7CS, the groundwater flow models assume constant hydraulic/thermal conditions corresponding to those after saturation. An indication of the significance of variations in hydraulic conditions is provided by considering sensitivity cases with, for example, different hydraulic conductivities for the engineered barrier materials.

Because repeated glacial cycles are expected to occur in the time frame of one million years for the safety assessment, the effect of glaciation is considered within the 7CS Normal Evolution Scenario. The groundwater flow field changes with time during glaciation due to evolution of ice sheets over the repository site. Although glaciation will certainly affect the near-surface groundwater system, it will not significantly affect groundwater movement at repository depth because of the low permeability of the deep rocks. This is confirmed by the paleohydrogeologic simulations carried out for the 7CS (NWMO 2018, Section 2).

In the 7CS, disruptive scenarios are assessed under constant temperate climate conditions, so there is no ice sheet advance and retreat and, hence, no direct change in hydraulic conditions due to glaciation in these scenarios. Furthermore, except perhaps for the Severe Erosion Scenario, the system failures that initiate disruptive scenarios are conservatively assumed to occur at the time of closure rather than gradually. Consequently, there would be no change in hydraulic conditions with time for all disruptive scenarios except perhaps the Severe Erosion Scenario.

FEP Screening

Include FEP in the Normal Evolution and Severe Erosion Scenarios.

FEP # 3.2.02.E   **Piping / hydraulic erosion of seals**

Description

The process of erosion of bentonite-based seals.

Over the lifetime of a repository, various physical and chemical processes will act to degrade bentonite-based seals (buffer, backfill, or shaft seals), causing an increase in the hydraulic conductivity of the seals. This could occur, for example, due to:

1. removal of particulates of the sealing material by flowing groundwater at the interfaces with the near-field rock, creating void spaces which would be filled as the remaining material expands, decreasing swelling pressures;
2. illitization of the bentonite, causing a loss of swelling pressure (see *Hydrothermal alteration (repository) [3.2.04.B]*); and
3. the flushing of deep groundwaters by glacial meltwater, causing erosion of the sealing material adjacent to the near-field rock and a loss of swelling pressure.

Suspended particulates may be sufficiently small to diffuse away or to be transported by flowing groundwater. They may also transport sorbed contaminants or may clog hydraulically active fractures, altering groundwater flow paths in the near-field rock.

If a preferential flow path was initiated in a seal, it is feasible that positive feedback will act to enhance the flow channel. An example of this type of positive feedback is illustrated by the failure of an earth dam due to piping where, in a short space of time, a small leak becomes a large breach as the increasing flow rates erode material in increasingly large quantities. This type of failure mechanism would be more likely to occur in the backfill mix of bentonite and sand than in the bentonite of the buffer due to possible inhomogeneous mixing of the material and the particle size distribution of the sand.

Preferential pathways may also expose the container to an increased supply of corrosive agents and accelerate localised copper corrosion.

7CS Screening Analysis

Erosion of sealing materials is not considered to be a significant process under the normal low-flow conditions expected in the deep, stable rocks at the 7CS site. Transient disturbances (i.e., seismicity and glaciation) are also unlikely to cause erosion of sealing materials because (1) there are no transmissive fracture zones or faults at the repository site, which are needed to carry away eroded material, given the low permeability of the deep rock, and (2) glacial meltwater does not reach the repository depth (NWMO 2018, Section 2).

Hence, erosion and piping of seals is not considered in the 7CS.

FEP Screening

Screened out.

FEP # 3.2.02.F   Coupled hydraulic processes (repository)

<u>Description</u>

This FEP concerns fluid flow driven by temperature, chemical or electrical gradients, rather than flow due to hydraulic pressure gradients. Fluid flow driven by these gradients are referred to as coupled ("off-diagonal") transport, and are called thermal, chemical and electrical osmosis, depending on the driving gradient. Fluid flow driven by hydraulic head gradients is called advection and is discussed under *Groundwater movement (repository) [3.2.02.C], Evolution of hydraulic conditions in the near-field [3.2.02.D],* and *Hydrogeological processes and conditions (geosphere) [4.2.02].*

These coupled transport flow processes are often negligible under normal engineering conditions. However, it is expected that advection will, in general, be quite low in the engineered barriers of a repository and, thus, these coupled processes could potentially affect groundwater flow in these materials.

<u>7CS Screening Analysis</u>

An analysis of the effects of coupled processes and their implications for solute transport has been provided by Soler (2001) for the Swiss Opalinus Clay formation. The range of values considered for the various coupling coefficients in the Opalinus Clay study are approximately appropriate for the clay-based engineered sealing materials in the 7CS repository. Thus, the results of the Opalinus Clay study can be used to provide an indication of these effects within the proposed engineered barrier systems for the 7CS.

Soler (2001) concluded that only thermal osmosis may be relevant with respect to fluid (and solute) transport in a repository. However, when mass conservation calculations were done with 2-D and 3-D models, the results showed no significant effect on time scales of 1000 years or more, in part, because temperature gradients (associated with the placement of used fuel in the repository) would have dropped considerably after 1000 years. It was considered possible that coupled processes might be important during the resaturation phase. However, the resaturation phase is not explicitly modelled in the 7CS because all containers are intact during this period and so contaminants are not released from the repository during the resaturation phase.

On the basis of these results, coupled processes are considered to be a small effect and are not included in the 7CS.

<u>FEP Screening</u>

Screened out.

FEP # 3.2.03   Mechanical processes and conditions (repository)

<u>Description</u>

The mechanical processes that affect buffer, backfill, seals and other engineered features (excluding the waste packages), and the overall mechanical evolution of the near-field with time. This includes the effects of hydraulic and mechanical loads imposed on repository components by the surrounding geology.

Mechanical processes and conditions are discussed further under:

     3.2.03A Buffer and backfill swelling
     3.2.03B Formation and healing of cracks in seals
     3.2.03C Excavation damaged and disturbed zones
     3.2.03D Collapse of repository openings
     3.2.03E Evolution of stresses in the near-field
     3.2.03F Buffer and backfill creep
     3.2.03G Self-sealing of excavation damaged zone

It should be noted that these processes can be strongly coupled; for instance, buffer and backfill swelling pressures, evolution of stresses and collapse of openings could affect one another. Elements of these processes are also discussed with other factors, such as those affecting the rate and time of resaturation of the repository (see *Hydrological processes and conditions (repository) [3.2.02]*), faulty placement or settling of containers (see *Placement of wastes and backfill [1.1.03]*) and the effects of earthquakes (see *Seismicity (earthquakes) [1.2.03]*). See also related issues under *Geomechanical processes (geosphere) [4.2.03].*

FEP # 3.2.03.A   Buffer and backfill swelling

Description

The process of buffer and backfill swelling during saturation of the repository.

The buffer and backfill contain a swelling bentonite clay component that expands as it becomes saturated with water. The material is typically installed in a 60-90% saturated state and may initially lose moisture due to thermal gradients. However, it is expected that groundwater will eventually enter the repository and saturate these materials. Because the buffer and backfill will be physically confined by the repository room host rock and bulkhead plugs, they will develop a swelling pressure as they resaturate. The swelling will induce (possibly uneven) mechanical loads on the containers and the surrounding rock, closure of any open gaps, and possibly compression of unsaturated buffer. The extent of swelling pressure also depends on the dry clay density of the material and its chemical composition (particularly the smectite content).

The swelling pressure will change with time; initially, as the moisture content changes in the repository, and later as smectite clays are converted into illitic clays by reactions with groundwater components such as potassium.

The placement of buffer and backfill by a combination of mechanical and pneumatic means may lead to non-uniform swelling pressures. As well, the rate of saturation may vary at different locations in the buffer and backfill. Prior to full saturation, differential swelling pressures may exist as water is slowly taken up, possibly leading to displacement of some material and movement of the containers. This process might be most important for buffer and backfill which are likely to have different design densities. However, designs using multiple layers of backfill with different design densities (sometimes called 'light' and 'dense' backfill) might exhibit similar effects.

7CS Screening Analysis

The buffer and backfill are specifically designed to swell as they become saturated with water. This swelling will heal (i.e., close) any open gaps (e.g., those formed by drying of the buffer near the container) and increase the hydrostatic pressure on the surrounding rock, helping to support the roof of the repository rooms and tunnels. The swelling characteristics of buffer and backfill materials are described by Pusch (2001) and Dixon (2000).

The high salinity of the groundwater in the 7CS host rock affects the swelling properties of the buffer and backfill (see *Saline groundwater effects on clay-based seals [3.2.04.C]*). This is taken into account in the design of the repository. The 7CS assumes that the buffer and backfill swell as per their design basis.

The swelling of the buffer would provide a load on the container. The steel vessel is designed specifically to accommodate these loads.

Saturation of the buffer may be non-uniform and, so, differential swelling pressures may exist causing displacement of some material and movement of the containers; however, these effects are expected to be minor. The non-uniform swelling pressures are also expected to be small relative to the container strength, and will resolve as the buffer re-saturates. Possible non-uniform loads would be considered as part of the container design basis. Non-uniformities in

buffer density remaining after saturation are not expected to be significant enough to be explicitly considered in the 7CS safety assessment.

Tunnels in the 7CS repository are primarily backfilled with blocks of dense backfill (the gaps around the dense backfill blocks are filled with light backfill pellets), which have a modest swelling capacity as described in *Backfill characteristics and evolution [3.1.02.B]*.

The swelling properties of bentonite clays can change with time due to illitization or similar chemical processes. This is not important at the 7CS site over one million years, as discussed under *Hydrothermal alteration (repository) [3.2.04.B]*.

<u>FEP Screening</u>

Include FEP in all scenarios.

FEP # 3.2.03.B   Formation and healing of cracks in seals

Description

The formation and healing of cracks in buffer, backfill, seals and grouts.

Cracks in these materials may develop during the unsaturated period when temperatures are high. Cracks may form because of, or be related to, failed seals, damage to the nearby rock (including the excavation disturbed zone), cave-ins, faulty buffer materials, voids in the buffer and backfill, enhanced groundwater flow along the top of a drift and/or faulty placement of containers, buffer or backfill. Cracks may also form preferentially near the container when buffer temperatures are highest and moisture contents lowest. These cracks may persist because the self-healing capacity of these materials might be impaired or ineffective. For instance, the swelling capacity of clay-based materials may be insufficient to seal large cracks or a large number of small cracks, particularly if their mass has been reduced by wide-spread extrusion into surrounding void spaces. The presence of saline groundwaters may also limit swelling capacity.

7CS Screening Analysis

Gaps will be present in the buffer, backfill and seals during the saturation phase, but there is no release of dissolved contaminants during this period because all containers remain intact. After saturation, the gaps in these materials would be closed by the swelling of the bentonite clay component in the buffer and backfill. A design requirement for the 7CS repository is that a sufficient amount of swelling clay be included in these materials to provide this capacity. Experiments (Oscarson et al. 1996; Oscarson et al. 1990) indicate that the sealing process takes place quickly after water reaches the crack(s). Therefore, the 7CS does not consider cracks within the buffer and backfill clay-based seals.

The concrete in the repository could degrade with time. Hence, in the 7CS, the concrete components in the repository are assigned the properties of degraded concrete from the time of repository closure.

Alternatively, cracks in concrete, grouts and the host rock (e.g., EDZ) might fill due to geochemical processes; these processes are not included in the 7CS.

FEP Screening

Screened out.

FEP # 3.2.03.C   Excavation damaged and disturbed zones

Description

The excavation damaged zone (EDZ) is the zone of rock immediately surrounding placement rooms, tunnels, shafts and other underground openings that is mechanically disturbed during excavation. The EDZ is characterized by irreversible structural changes in the rock, such as the formation of microcracks. Farther away from the excavation, an excavation disturbed zone is formed where any changes are potentially reversible, such as elastic displacements. The excavation disturbed zone has the same flow and transport properties as the host rock but possibly modified hydromechanical (e.g., pore pressure, rock stress) and geochemical (e.g., redox state) conditions.

The extent and properties of these two zones 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, these zones could comprise a layer of rock whose properties are significantly different from those of the surrounding host rock. Relevant properties are permeability, porosity, mechanical strength, fracture frequency and fracture connectivity.

The character of fractures and microcracks in the EDZ is a function of the rock type, the in situ stresses, and the excavation method. Hence, EDZ properties are site-specific. For example, there is a tendency for some sedimentary rocks and rock salt to creep and self-seal over time, while crystalline rocks do not exhibit this type of behavior.

Several primary factors can affect the transport-related characteristics of the EDZ. In drill-and-blast tunnels, damage is often more prevalent in the floor of such excavations because higher explosive charge densities are typically used in lifter holes in the floor. There is some evidence that permeability may not be continuous across blast rounds in environments with a high strength to stress ratio (Simmons 1992). Mechanically excavated tunnels generally exhibit less damage associated with the excavation method in such environments (Emsley et al. 1997). In contrast, stress-induced damage in environments with a low strength to stress ratio may create a continuous zone of connected permeability along the axis of both drill-and-blast and mechanically excavated tunnels.

Clay-rich rocks exhibit other complex behaviors including desiccation cracking and swelling in response to changes in humidity and moisture content. Other processes, such as thermal loading, can intensify the existing damage, or create new damage around underground openings.

7CS Screening Analysis

A recent review of EDZ properties in sedimentary rock is provided in Fracture Systems Ltd. (2011).

The excavation damaged inner and outer zones around the underground openings are included in the 7CS modelling. The EDZ is assumed to be axially connected. The size and properties of the EDZ would be affected by the host rock properties and the thermal induced stresses, as discussed in more detail under *Excavation damaged zone [3.2.02.B]*. This is taken into account when selecting the parameter values used in the 7CS to describe the EDZ.

Modelling of the extent of EDZ around shafts in the sedimentary rock formations of the Michigan Basin for the proposed Ontario Power Generation's deep geological repository for low and intermediate level waste indicated that the EDZ in these rocks largely occurred within a short period after excavation, and then did not change much further even with earthquakes and glaciation (NWMO 2011, Section 6.4.3). In the 7CS, the EDZ properties are assumed constant and sensitivity cases are used to determine the effect of potential changes in EDZ properties (e.g., due to earthquakes) on the calculated impacts of the repository.

The excavation disturbed zones are not included in the 7CS conceptual models because they would not affect groundwater movement or contaminant transport.

<u>FEP Screening</u>

Include FEP in all scenarios.

FEP # 3.2.03.D   Collapse of repository openings

Description

In the context of this FEP, the term 'collapse' is used to refer to the stability of the underground openings. In geotechnical engineering, the term stability is associated with the absence of large-scale failures or deformations that are unfavorable to the function and safety of the engineered structure.

Construction, commissioning and operation of the facility will occupy several decades, and excavation of the repository will result in the removal of substantial volumes of rock. Excavation will create stresses across the repository, which may be increased by seismic events and ice-sheet loading and unloading during the lifetime of the repository. These stresses could lead to rock falls from roofs and tunnels, which might also induce fragmentation of concrete linings and the failure of waste packages.

7CS Screening Analysis

The stability of the underground openings in the repository is an important aspect of the repository design during both the operational and postclosure phases of the repository.

In the 7CS, the repository is designed for long-term stability, including the sizing and orientation of rooms and tunnels, spacing of rooms and containers, and alignment with local stress fields. Furthermore, collapse of repository openings cannot occur after closure of the repository because all openings are filled with buffer and backfill materials. These materials exert a swelling pressure on the surrounding rock, which would fill any small gaps which may exist along the interface of the buffer or backfill with the host rock after filling.

FEP Screening

Screened out.

FEP # 3.2.03.E   Evolution of stresses in the near-field

Description

This FEP deals with the evolution of stresses in the near-field rock.

Prior to excavation of the repository, the host rock is initially in a pre-stressed state due to the regional tectonic and gravitational stresses. After excavation of the repository, the stresses will be locally re-aligned to be parallel and perpendicular to the excavation surfaces, with corresponding changes in stress magnitudes. In the immediate vicinity of the opening, an excavation damaged zone (EDZ) is created, which is characterized by irreversible structural changes in the rock, such as the formation of microcracks. Farther away from the opening, an excavation disturbed zone (EdZ) is formed where any changes are potentially reversible, such as elastic displacements. The EDZ and EdZ are discussed in *Excavation damaged and disturbed zones [3.2.03.C]*. Stress relief processes may also lead to collapse of repository openings (see *Collapse of repository openings [3.2.03.D]*).

In addition, the evolution of stresses in the near-field can result from swelling of the buffer and rock matrix, thermal expansion due to heat from the used fuel and volume changes. At longer time frames, stresses may evolve due to external factors, such as glacial loading (see *Local glacial effects [1.3.05]*) and earthquakes (see *Seismicity (earthquakes) [1.2.03]*). Changes in effective stress are related to the pore pressure distribution and its evolution.

7CS Screening Analysis

Stress fields and concentrations will be considered as part of the repository design for a specific site.

Temperature changes caused by the heat generated by the used fuel can cause differential thermal expansion and, thus, a local stress redistribution that can result in sporadic fracturing of the rock mass around the room, particularly within 1 m of the room boundary (Radakovic-Guzina et al. 2015). A highly damaged zone is not formed. The influence of thermal stresses on EDZ properties is taken into account in the 7CS. After the placement rooms and tunnels are backfilled, collapse of repository openings is unlikely (see *Collapse of repository openings [3.2.03.D]*).

The geometry of the repository excavations, particularly the orientation of the disposal tunnels with respect to the principal stress directions, has a significant effect on the stress redistribution and resulting stress magnitudes. The geometry of fractures (i.e., the individual fractures and fracture zones) could have localized effects on the stress distribution. This stress redistribution process is well understood and can be modelled with various codes (Radakovic-Guzina et al. 2015).

After saturation of the repository, significant changes in stresses would only occur as a result of seismic activity or glaciation. However, glacial loading and seismic loading have a relatively small effect on damage and stability of the placement rooms due to the confinement provided by the engineered backfill (Radakovic-Guzina et al. 2015).

The Michigan Basin in Ontario is a low seismic area, but seismic activity is possible over long time frames (see *Seismicity (earthquakes) [1.2.03]*). Earthquakes are, in general, a transient

load. Changes to the local stresses would require significant shifting or shearing of the rock. Such changes could be important if the shearing intercepted a container or a seal (see *Seismicity (earthquakes) [1.2.03]*); but, the repository would be located sufficiently far from large fractures that significant shearing would not be expected. The safety implications of a shearing load damaging a container are considered in the Container Failure Scenario.

Stresses at the repository level from glaciation are considered in the design of the container and repository (see *Local glacial effects [1.3.05]*). Glaciation could also lead to changes in hydraulic conditions through hydro-mechanical coupling (see *Geomechanical processes (geosphere) [4.2.03]*).

<u>FEP Screening</u>

FEP is implicitly included in all scenarios, through repository layout and sizing and through parameter values for the excavation damaged zone.

FEP # 3.2.03.F   Buffer and backfill creep

<u>Description</u>

The plastic movement of buffer and backfill material under an imposed load.

The buffer and backfill materials can creep or move as a result of imposed loads, such as the weight of the container. This could lead to settling of the container, which might affect the relative amounts of buffer barrier around the container, as well as the load distribution on the container.

<u>7CS Screening Analysis</u>

The effects of buffer and backfill creep are expected to be minor. For example, detailed studies for the much larger container considered by the Swedish nuclear waste management organization indicated movement on the order of a couple of millimetres in 1 million years (SKB 2011, Pusch and Adey 1999). Thus, any container settling or tilting as a result of creep is expected to be insignificant over the time frame of interest.

<u>FEP Screening</u>

Screened out.

FEP# 3.2.03.G   Self-sealing of excavation damaged zone

<u>Description</u>

Self-sealing is a process that leads to a reduction of the hydraulic conductivity of a fracture. The phenomenon is widely observed in argillaceous rocks. Self-sealing occurs by three primary mechanisms:

1. Swelling of (usually) clay minerals by water uptake;
2. Filling of fracture aperture by generation of infilling materials or mineral precipitation; and
3. Mechanical deformation (e.g., plastic deformation under changing stress field).

<u>7CS Screening Analysis</u>

As noted in the description, self-healing due to swelling and deformation is usually observed in clay-rich sedimentary rocks. The Cobourg Limestone host rock at the 7CS hypothetical site is an argillaceous limestone, and the overlying shales have a clay component. However, because the clay levels are low, and because self-healing would reduce the hydraulic conductivity of the EDZ, this process has been conservatively neglected in the 7CS.

Precipitation of minerals from the highly saline fluids at the repository site could also fill fractures within the excavation damaged zone, but this is assumed to be insignificant and is neglected in the 7CS.

<u>FEP Screening</u>

Screened out.

FEP # 3.2.04   Chemical processes and conditions (repository)

<u>Description</u>

The chemical and geochemical processes that affect the seals and other engineered features (excluding the containers and their contents), and the overall chemical evolution of the near-field with time. This includes the effects of chemical and geochemical influences on repository components by the waste packages and surrounding geology.

Chemical processes or factors affecting contaminants in the repository are discussed separately under *Contaminant release and transport (repository) [3.3]*, including precipitation and sorption of contaminants (see *Dissolution and precipitation (repository) [3.3.03], Speciation and solubility (repository) [3.3.04]*, and *Sorption and desorption (repository) [3.3.05])*. Similarly, chemical processes affecting the container are discussed separately under *Chemical and biological processes (container) [2.3.04]*.

Under this category the following topics are specifically considered:

    3.2.04.A Water chemistry and evolution (repository)
    3.2.04.B Hydrothermal alteration (repository)
    3.2.04.C Saline groundwater effects on clay-based seals
    3.2.04.D Hyperalkaline fluid interactions (repository)
    3.2.04.E Other chemical processes (repository)

It should be noted that chemical processes in the repository and geosphere occur concurrently and are often interrelated - see *Chemical processes and conditions (geosphere) [4.2.04]*.

FEP # 3.2.04.A   Water chemistry and evolution (repository)

Description

Groundwater chemistry conditions within the repository, and their evolution with time; including alteration of the chemical composition of groundwater passing through the repository by chemical interactions between incoming groundwater and the materials in the repository.

Much of the material in the repository will react chemically in the moist thermal environment in the repository over time scales of hundreds to thousands of years. For instance, corrosion of the container will release corrosion products, which will change the composition of groundwater in the repository and possibly affect contaminant sorption and transport in the buffer and backfill, and possibly in parts of the geosphere. Residual air in the repository after closure, elevated concentrations of nitrates from explosives and the production of oxidants by radiolysis, could lead to formation of a moving redox front as oxidants are consumed by inorganic reactions with iron, other transition metals and other elements (such as sulphur) with variable redox states. The leaching of concrete and seals could produce high concentrations of calcium ions and increase the local pH (see *Hyperalkaline fluid interaction (repository) [3.2.04.D]*).

The evolution of groundwater may never reach a final equilibrium state because of intrusion of water from various sources, including migration of saline water, and/or infiltration of oxygenated or non-oxygenated surface water during glaciation.

7CS Screening Analysis

The porewater composition in the repository, including the electrochemical potential and pH, is important in determining the properties of contaminants (e.g., sorption coefficient and solubility) and is included explicitly in the 7CS.

The general electrochemical redox state (i.e., reducing or oxidizing) can be an important parameter for transport properties (notably sorption). In the 7CS, it is expected that the repository will be oxidizing initially due to trapped air from placement operations, but will return to its natural reducing state on the same time scale as the saturation process. After conditions become reducing, they should stay reducing for the one million year time frame of interest due to the repository depth and the extensive redox-buffering capacity of the rock. Even glaciation would not affect redox conditions in the repository (NWMO 2018, Section 2), for example, it is expected that the depth of O_2 ingress under one glaciation/deglaciation cycle in a hypothetical sedimentary basin is 200 m (Bea et al. 2018). This would be considered and confirmed as part of the siting process. Because transport of dissolved contaminants is only important after saturation of the repository, 7CS properties can simply be based on assuming "reducing" conditions.

The water contacting the used fuel in a failed container evolves with time as the groundwater from the geosphere resaturates the repository, resulting in dissolution and depletion of the soluble solids in the buffer (Arcos et al. 2006) and ion exchange of the sodium cations in bentonite clay with calcium cations in groundwater. This process is expected to take tens of thousands of years (NWMO 2018, Section 5). This time-dependent process is not explicitly modelled in the 7CS. Instead, solubilities within breached containers are calculated (at 25ºC) for a range of cases bounded by the reference groundwater alone and the reference groundwater equilibrated with bentonite and carbon steel (Duro et al. 2010). The uncertainties

assigned to these element solubilities reflect both the uncertainties in the groundwater composition and the thermodynamic data used in the solubility calculations. Furthermore, to account for the potential effect of the higher temperatures near the container, the solubility values used in the safety assessment are taken to be a factor of 10 higher than the thermodynamically calculated solubilities at 25ºC.

Detrimental effects on the physical and chemical properties of bentonite due to copper-bentonite interactions are unlikely, as is the case for all metals with low corrosion rates (Carlsson 2008, Karnland et al. 2000). For breached containers, the products of water radiolysis or iron corrosion could leave the container and react with the bentonite clay. Reactive radiolysis products such as H_2O_2 and $OH\bullet$ are likely to react with the fuel and iron corrosion products (e.g., Fe^{2+}) so only very small quantities would reach the bentonite. The effect of the hydrogen gas generated by water radiolysis and iron corrosion is discussed under *Gas sources and effects (repository) [3.2.06]*. Iron corrosion products such as Fe^{2+} could leave the breached container and interact with the bentonite buffer (Wersin et al. 2008, Charlet and Tournassat 2005), possibly affecting its physiochemical properties. However, any effects would likely be spatially limited to the innermost few centimetres of buffer near the container-buffer interface (Wersin et al. 2008). Hence, in the 7CS, it is assumed that buffer properties are mainly unaffected by chemical interactions with the waste package materials themselves or their corrosion products.

<u>FEP Screening</u>

Include FEP in all scenarios.

FEP # 3.2.04.B   Hydrothermal alteration (repository)

Description

Alteration of the buffer and backfill clay components due to chemical interactions with incoming groundwater and with other materials in the repository.

More general types of reactions include alteration of the minerals and other material in the repository. For instance, preferential dissolution of silica or silicates (such as quartz) will occur over time in minerals subjected to slightly higher temperatures and either acidic or basic pH levels. Dissolved silica may then migrate and precipitate along cracks, fractures and pores, including cracks created during drying of the buffer. These precipitates may serve to block line conduits and prevent expansion of the buffer and backfill. Calcite and gypsum are other common minerals that are readily dissolved and precipitated. Gypsum has the unusual property of being less soluble at higher temperatures, and so may migrate toward the repository.

These changes could affect the swelling capacity of the clay-based buffer, backfill and seals, as well as their sorptive properties. For example, if the high-swelling montmorillonite mineral is converted into illite, the clay loses its swelling capacity.

Hydrothermal reactions are also discussed under *Buffer and backfill characteristics [3.1.02]*, and under *Seals and grouts (cavern, tunnel, shaft) [3.1.03]*.

7CS Screening Analysis

Hydrothermal alteration of the clay materials in the 7CS repository (i.e., buffer and backfill) is not extensive because the maximum temperatures in the repository are relatively low, i.e., the peak temperature at the surface of the container is about 93°C (Guo 2018; NWMO 2018, Section 5), and the reference groundwater does not contain very high concentrations of reactive species, notably potassium cations (Gobien et al. 2018). The fraction of montmorillonite in the bentonite near the surface of the container (where temperatures are hottest) that is converted to illite is about 1.02% over one million years, as shown in Table 3.1. Farther away from the container, the fraction of montmorillonite converted to illite would be much smaller. Therefore, hydrothermal alteration is not included in the 7CS.

FEP Screening

Screened out.

Table 3-1: Calculation of the Fraction of Smectite Converted to Illite in 1 Ma

Huang et al. (1993) suggest the following second-order rate law for smectite illitization:

$$-\frac{dS}{dt} = A\,e^{-Ea/RT}\,[K^+]\,S^2$$

where S is the smectite fraction, A is frequency factor ($8.08\ 10^4$ /s), t is time (s), Ea is activation energy (117.15 kJ/mol), R is the gas constant, T is the temperature (K), and $[K^+]$ is the potassium ion concentration (mol/L). Huang et al. (1993) carried out their experiments at high temperatures (> 250°C); therefore, in applying their results to the 7CS repository, it is implicitly assumed that the extrapolation to lower temperatures is valid.

At the 7CS site, the pore water K^+ concentration is about 0.32 mol/L (NWMO 2018). The temperature near the container surface reaches a peak value of about 93°C at about 47 years; it decreases to about 81°C after about 600 years; decreases to about 50°C at 10,000 years; and then decreases slowly to near ambient temperatures at about 200,000 years (Guo 2018). Based on the equation of Huang et al. (1993), and conservatively assuming that the temperature at the container surface is 93°C for 100,000 years, it is determined that approximately 1.02% of the smectite (or equivalently montmorillonite) initially present near the container is converted to illite over 1 Ma. In the buffer farther away from the container, less montmorillonite would be converted to illite because of the lower temperatures.

FEP # 3.2.04.C   Saline groundwater effects on clay-based seals

Description

This FEP is concerned with the effect of saline groundwaters on the properties of clay-based repository seals, such as the buffer and backfill. Saline groundwaters can affect both the physical properties (e.g., swelling pressures) and chemical properties of bentonite.

When wet, bentonite swells and becomes highly plastic. It is able to function as an efficient sealant, being able to move into crevices and fractures, etc. 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.

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 could also cause reductions in swelling pressure, making the material less effective in sealing cracks, as discussed separately under *Hydrothermal alteration (repository) [3.2.04.B]* and *Hyperalkaline fluid interaction [3.2.04.D]*.

7CS Screening Analysis

The high salinity of the groundwater at the 7CS affects both the physical and chemical properties of the clay-based sealing materials in the repository. For example, the high salinity reduces the swelling pressure of the bentonite buffer to approximately 0.6 to 0.7 MPa. (This is partly due to the exchange of Na cations in the original bentonite with Ca cations in the groundwater, which converts the Na-bentonite clay into a Ca-bentonite clay.) The modified clay properties are taken into account in the design of the 7CS repository.

Chemical reactions between the clay-based materials and saline groundwater, which could lead to embrittlement of bentonite and loss of swelling pressure, are likely limited due to the low temperatures (< 93ºC) and the low permeability of the surrounding rock (Savage 2005, and references therein). Although there is no direct experimental data on bentonite stability under the highly saline Na-Ca-Cl groundwater conditions at the 7CS repository site, there are some natural analogs; notably, some Spanish bentonites that have been exposed to saline Na-Cl (sea) water over millions of years show no significant mineral alteration (Laine and Karttunen 2010, Savage 2005).

In the 7CS, the changes in groundwater composition due to cation exchange between the bentonite and groundwater are accounted for in the calculation of the chemical element solubilities (Duro et al. 2010).

See also *Hydrothermal alteration (repository) [3.2.04.B]* and *Hyperalkaline fluid interaction [3.2.04.D]*.

FEP Screening

Included in all scenarios.

FEP # 3.2.04.D   Hyperalkaline fluid interaction (repository)

Description

The interaction of bentonite-based seals (buffer, backfill and tunnel seals) with hyperalkaline fluids derived from degradation of any cements present in the repository.

Groundwater in the repository will react with cement in the repository causing its pH to rise from neutral values to around 12 or 13 by dissolution of the small amounts of NaOH and KOH hydroxides present in the cement. As these high-pH waters are displaced by incoming groundwaters, the pH will be controlled by dissolution of $Ca(OH)_2$ which will buffer the pH at around 12.5. The rate of this process is controlled by the rate of water turnover, which is likely to be slow because of the very low hydraulic conductivity of the host rock and bentonite layer. Consequently, hyperalkaline conditions are likely to be maintained for thousands of years.

The rate and products of bentonite-hyperalkaline leachate reactions are uncertain, and will be system dependent, but hydroxide ions in the water are likely to react with smectite minerals in the clays to form zeolites, calcium-silicate-hydrate minerals or gels. Calcium ions in the hyperalkaline fluid could also exchange with the sodium ions in smectite minerals. Such alteration may detrimentally impact clay swelling behaviour, transport properties (porosity, permeability) and sorption properties. The extent of such reactions will be partially controlled by the supply of hyperalkaline fluids and by the high pH-buffering capacity of smectite. Similar reactions would occur when cement is in direct physical contact with the buffer or backfill.

7CS Screening Analysis

Reactions between bentonite and hyperalkaline pore fluids generated from adjacent cement based materials would affect the swelling capacity, plasticity and sorption properties of the bentonite in the 7CS repository. However, the effect is expected to be localized to a small zone of the bentonite-based seal that is in contact with the cement because the reserves of alkalinity in the concrete would be limited, and because of the high pH-buffering capacity of the bentonite and groundwater at the 7CS repository site (Wang et al. 2010, Gaucher and Blanc 2006, Gaucher et al. 2004). Furthermore, in the 7CS, the effect of hyperalkaline fluid interactions is limited by minimizing the amount of concrete used in the repository, and by using a low-pH concrete formulation.

FEP Screening

Screened out.

FEP # 3.2.04.E   Other chemical processes (repository)

Description

Other chemical processes not otherwise considered. These can include the following:

1. Corrosion of repository metals (e.g., rock bolts);
2. Degradation of cement;
3. Migration (dissolution and precipitation) of dissolved salts caused by formation of chemical concentration gradients due to heterogeneities in temperature, redox conditions and/or repository materials; and
4. Formation of colloids from repository materials, e.g., clay particles and iron oxy-hydroxides.

7CS Screening Analysis

The chemical processes listed below are not explicitly included in the 7CS because they are expected to be either insignificant, or are included indirectly, or can be conservatively ignored.

- The corrosion of rock bolts is not modelled. The use of rock bolts will be minimized in the 7CS repository and so their corrosion should only affect a very small fraction of the sealing materials in the repository (see *Water chemistry and evolution (repository) [3.2.04.A]*).
- Degradation of cement is not modelled explicitly in the 7CS, instead its effect is implicitly included by using degraded cement properties from the time of repository closure. Degradation of cement generates an alkaline fluid plume that can interact with clay-based materials in the repository. This is discussed under *Hyperalkaline fluid interaction (repository) [3.2.04.D]*.
- The chemical evolution of the buffer leading to substantial filling of pores in the buffer with precipitants (which then prevents contaminant movement) is neglected in the 7CS.
- Colloids formed within the breached containers (e.g., iron oxy-hydroxides) would be filtered by the buffer and not pass into the geosphere. Formation of clay-particle colloids by erosion of clay-based materials in the repository is unlikely because the high salinity of the groundwater makes the clay particles in the clay adhere strongly. (see *Buffer characteristics and evolution [3.1.02.A]*).

FEP Screening

Screened out.

FEP # 3.2.05   Biological processes and conditions (repository)

Description

The biological and biochemical processes that affect the seals and other engineered features (excluding the waste packages), and the overall biological or biochemical evolution of the near-field with time. This includes the effects of biological and biochemical processes occurring in the surrounding geosphere.

Organic material is likely to be naturally occurring in the engineered barriers, notably in the clay used in the buffer and backfill, and will also be introduced during the period the repository is open. This material, together with elevated temperatures, could promote the growth of microbes. The residual air in the repository may promote growth of some microbes, but anaerobic species are also viable.

Microscopic organisms, including bacteria, protozoans, yeast, viruses and algae, may also affect the performance of different engineered barriers. Some specific biological effects are discussed elsewhere, notably *Microbial-induced corrosion [2.3.04.D]*. Other specific concerns are:

    3.2.05.A Biological processes (repository)
    3.2.05.B Biological effects on groundwater movement (repository)

It should be noted that biological and biochemical processes in the repository occur concurrently and are often interrelated and, on a broader level, can also be strongly coupled with other processes occurring in the surrounding geosphere (see *Biological processes and conditions (geosphere) [4.2.06]*).

FEP # 3.2.05.A   Biological processes (repository)

Description

Biological activity in the repository and its effects on groundwater composition.

The type of microbial species, their population levels, and their activity levels will influence the conditions in the repository. Biological activity (micro-organisms, bacteria) could change the composition of groundwater in the repository. For instance, the byproducts of microbial and bacterial activity could have an important influence on the oxygen content, electrochemical potential (Eh) and pH of the groundwater. This, in turn, could promote corrosion of the container and affect contaminant behaviour in the repository.

Natural viruses may also be present and influence microbial populations.

Microbial activity could be a source of complexing agents within the backfill region and host rock, before encroachment of saline groundwater. These complexing agents could affect the speciation of contaminants as discussed under *Speciation and solubility (repository) [3.3.04]*.

Microbial effects on container corrosion are covered in *Microbial-induced corrosion [2.3.04.D]*.

7CS Screening Analysis

The microbial population within the repository will vary after placement of the containers as the conditions change from warm, wet, oxygenated and with large porosity; to hot and dry near the container; and finally to warm, wet, reducing and with small pores. The dominant microbial species will vary from aerobic heterotrophs to anaerobes. The viability of the latter will be very limited within and near the repository because of the low water activity associated with the salinity of the groundwater and the presence of dense bentonite.

Before intrusion of saline groundwater, microbes within the backfill and near-field rock could contribute to the porewater chemistry via oxygen consumption and the development of redox conditions. However, this process is expected to occur relatively quickly after closure and is not explicitly modelled in the 7CS. Note that during this period, i.e., before saturation of the repository, all containers remain intact and contaminants are not released from the repository.

FEP Screening

Screened out.

FEP # 3.2.05.B   Biological effects on groundwater movement (repository)

<u>Description</u>

This FEP describes the influence of biological processes on groundwater movement in the repository.

The growth of microorganisms may result in the formation of reactive biofilms at interfaces, such as on the walls of the 1) container, 2) repository and 3) any fractures in the near-field host rock. The availability of carbon sources, nutrients, terminal electron donors and terminal electron acceptors is flow-dependent and will control biofilm growth and community composition (Stroes-Gascoyne et al. 2000b). Biofilm formation can have an impact on the porosity and permeability of fractures and porous media (Coombs et al. 2010 and references therein). Biofilms can reduce fluid flow by constricting pore throats and by increasing the tortuosity of pore flow paths; in addition, biofilms can alter pH, redox state, groundwater chemistry, and rock surfaces (Coombs et al. 2010). Porosity and permeability can be reduced by microbially mediated precipitation ("biomineralization"), which can result in plugging or cementation of pore spaces, thereby potentially influencing the rate and volume of groundwater movement.

<u>7CS Screening Analysis</u>

The effects of biological processes on groundwater movement, if any, are expected to be small. Furthermore, biological effects - such as the growth of microbial colonies - would likely decrease the rate of groundwater flow through the repository by reducing the porosity of engineered barriers. Thus, in the 7CS, the effects of biological processes on groundwater movement are conservatively neglected.

<u>FEP Screening</u>

Screened out.

FEP # 3.2.06   Gas sources and effects (repository)

Description

Factors within and around the repository resulting in the generation of gases and their subsequent effects on the repository system.

Gas production may result from corrosion of various waste forms, container and engineered materials, such as iron used in rock bolts (see *Chemical and biological processes (container) [2.3.04]*). Gases may also be produced by radiation effects, including helium as a product of radioactive decay and gases produced by radiolysis (see *Radiation effects (waste form) [2.2.01]*), and as byproducts of microbial activity. Potential gases include hydrogen, carbon dioxide, methane, and hydrogen sulphide.

Gases could be transported out of the near-field as dissolved species or in the gas phase. This latter process could cause changes in the local chemical and hydraulic conditions; for instance, elevated gas pressures could act as a driving force to expel contaminated water through the buffer out of the repository, or they may result in unsaturated conditions that reduce water-phase transport. Elevated gas pressures could also prevent the ingress of water into the buffer and container. Gas production could also affect the mechanisms for radionuclide transport, i.e. gas-induced and gas-mediated transport (see *Gas-mediated transport of contaminants (waste package) [2.4.05]* and *Gas-mediated transport (repository) [3.3.08]*). Some gases might be flammable or might form an explosive mixture; for instance, hydrogen and methane could mix with oxygen during the operational phase and explode, damaging the repository (see *Accidents and unplanned events [1.1.12]*).

7CS Screening Analysis

In the 7CS repository with no failed containers, the main sources of gas in the repository would be the initially trapped air, hydrogen gas from corrosion of iron components left within the repository, and hydrogen gas from gamma radiolysis of water outside the container. Formation of methane gas from decay of organics in the clay-based sealing materials is not likely because microbial activity is low (due to the high density of the backfill and buffer); and the organic carbon in the clay-based materials has been stable for millions of years and, so, is probably recalcitrant.

The primary exposed metal within the repository will be copper, which is stable under reducing repository conditions, but would likely react with the initially trapped oxygen, rapidly consuming it. The hydrogen gas generated by radiolysis is generated sufficiently slowly that it would dissolve in the groundwater, given the hydrostatic pressures at depth, and diffuse away from the container.

For failed containers, the major gas source would be hydrogen gas generated by corrosion of the steel inner vessel. A smaller amount of gases is also produced by radioactive decay (e.g., helium). If hydrogen gas generation is sufficiently fast, then a hydrogen bubble forms that inhibits water contact with the container. Once the hydrogen pressure is sufficiently high, i.e., on the order of the hydrostatic pressure plus swelling pressure, the gas can create a channel through the buffer and move to the interface with the rock. At the buffer/rock interface, the gas would move along the placement room excavation damaged zone, which has a higher porosity and permeability than the host rock, until the gas pressure decreases sufficiently that there is no

driving force for advective gas movement. The gas pathways through the buffer re-seal after passage of the gas and have no effect on the buffer permeability (Harrington and Horseman 2003).

Hydrogen gas generated from corrosion of the steel vessel in a failed container can be beneficial as it decreases the fuel dissolution rate (Rollin et al. 2001). This effect is conservatively neglected in the 7CS. This hydrogen gas could also potentially react with and reduce the Fe(III) in the montmorillonite present in bentonite. However, this effect is assumed to be small since hydrogen is generally non-reactive at temperatures below 100ºC even at high pressures (Wersin et al. 2003). Although experimental data to support this assumption for saturated bentonite are limited, some evidence is provided by results of experiments in which synthetic dry clay samples were reacted with hydrogen gas at 90ºC and 120ºC for 30 to 45 days. In these experiments, less than 6% of the total structural Fe(III) initially present in the clays was reduced by the hydrogen (Didier et al. 2012).

In the Normal Evolution Scenario, the number of failed containers is small and the amount of iron structural components (e.g., rock bolts) in the repository is expected to be minimized by design. Therefore, the amounts of gases (mainly hydrogen) generated in the repository are small in practical terms, and the rate of gas production is also comparatively low. Therefore, for the Normal Evolution Scenario, the 7CS does not consider the effects of gas formation on contaminant migration and other processes in the repository.

In the All Containers Fail Scenario, all containers are assumed to fail. The amount and rate of gas generated by corrosion of these failed containers are significant and, therefore, the potential effects of gas generation on groundwater movement and contaminant transport is considered in this scenario (NWMO 2018, Section 8).

FEP Screening

Include FEP in the All Containers Fail Scenario.

FEP # 3.2.07   Radiation effects (repository)

Description

This FEP deals with the effects of radiation on the sealing materials around the container.

Radiation could cause sterilization of microbial populations near the container. The effects of radiolysis of the groundwater in the sealing materials could potentially affect the groundwater chemistry, i.e., the electrochemical potential (Eh) and pH, and result in chemical changes to the bentonite in the sealing materials.

Sealing materials would also be subjected to an alpha-radiation field from the actinides escaping from the container and absorbed by the sealing materials. Radiation damage from alpha-irradiation could detrimentally affect the properties of the sealing materials.

7CS Screening Analysis

In the 7CS, for the purposes of calculating contaminant inventories and radiation fields, the containers are assumed to be filled with 30-year old fuel bundles with a burnup of 280 MWh/kgU. The gamma radiation fields (alpha and beta radiation cannot pass through the container) on the outside surface of such containers are on the order of 1.5 Gy/hr at placement (SNC-Lavalin 2014). Allowing for decay of the gamma radiation field, the cumulative dose to clay near the container would be about 0.64 MGy. For comparison, irradiation tests of MX-80 bentonite to a total dose of 30 MGy over 1 year at a temperature of 90-130°C indicated some thermally-induced mineral transformations, but no apparent radiation effects (Pusch 2001). Therefore, radiation damage of the clay from the used fuel gamma fields will be negligible and this factor is not modelled in the 7CS.

Laboratory tests of clay saturated with alpha-emitting nuclides indicated that montmorillonite (the mineral giving bentonite its swelling properties) is destroyed and converted into an amorphous silicon mass at doses of about 5×10^{18} alphas/g (Pusch 2001, p.110). However, conservative calculations for the SKB KBS-3 container indicated that the affected buffer zone would be small and would have no overall effect on the buffer's performance (Pusch 2001, p.110). Since the amount of alpha-emitting nuclides within a 7CS container is smaller than that in the SKB KBS-3 container, this process should be unimportant for the 7CS and so is not modelled.

FEP Screening

Screened out.

3.3 Contaminant Release and Transport (repository)

FEP # 3.3.00   Scope of subcategory 3.3

Description

Factors and processes related to contaminant transport within and near the repository, including the excavation damaged zones.

There are eight subcategories under Contaminant Release and Transport (repository):

      3.3.01 Advection and dispersion (repository)
      3.3.02 Diffusion (repository)
      3.3.03 Dissolution and precipitation (repository)
      3.3.04 Speciation and solubility (repository)
      3.3.05 Sorption and desorption (repository)
      3.3.06 Colloid interaction and transport (repository)
      3.3.07 Coupled solute transport processes (repository)
      3.3.08 Gas-mediated transport (repository)

Note that the first seven subcategories are FEPs related to water mediated transport of contaminants. Gas-mediated transport of contaminants, regardless of the mechanism, is only dealt with under FEP 3.3.08.

FEP# 3.3.01   **Advection and dispersion (repository)**

Description

Advection at the repository (near-field) scale is of importance following the placement of the buffer because, during this time period, groundwater is able to flow into and saturate the buffer and backfill materials. Dispersion (lateral and longitudinal) is the spreading of contaminants in response to velocity variations along the flow path(s).

After the sealing materials (i.e., bentonite) have acquired a sufficient swelling pressure due to uptake of water, transport in the near-field should occur mainly by diffusion, although advection and dispersion could be important in the EDZ depending on the site and EDZ properties.

The main variables that will affect the advection and dispersion of contaminants through the buffer, backfill and EDZ are hydraulic conductivity, porosity, temperature, initial water content and water availability, gas content, and buffer and backfill composition (Posiva Oy 2012, 2014).

7CS Screening Analysis

In the 7CS, all containers remain intact during resaturation of the repository. Hence, there is no need to model contaminant transport during the resaturation phase. After saturation, transport of contaminants by advection and dispersion through the repository (i.e., the buffer, backfill and EDZs) is modelled explicitly in the 7CS. Because of the low hydraulic conductivity of the buffer used in the 7CS, contaminant transport through the buffer will be diffusion dominated (see *Diffusion (repository) [3.3.02]*). In the tunnel backfill and EDZs, contaminant transport could occur by both advection and diffusion, with the dominant mechanism depending on the groundwater velocity in these zones. In the 7CS, groundwater velocities in the near-field geosphere are low, so contaminant transport is diffusion dominated in the backfill and EDZ.

FEP Screening

Include FEP in all scenarios.

FEP# 3.3.02   Diffusion (repository)

Description

The migration of contaminants in the near-field repository (buffer, backfill and EDZs) caused by molecular diffusion. Diffusion occurs due to concentration gradients.

In the near-field, diffusion is an important process in the: 1) transport of contaminants out of failed containers, through the buffer and/or backfill and into the geosphere; 2) transport of corrosive substances from the geosphere to container surfaces (e.g., sulphide, oxygen); and 3) transport of solutes into and out of the buffer, which could cause alteration of buffer materials.

The main variables that will affect diffusion of solutes through the buffer and backfill materials are: density, temperature, porosity, water content, gas content, pore geometry (i.e., connectedness of the pore spaces), sorption (see *Sorption and desorption [3.3.05]*), porewater composition – which affects speciation (see *Speciation and solubility [3.3.04]*) – and material composition. For example, anions move slower than cations through buffer and backfill materials because of anion exclusion effects (Van Loon et al. 2007)

7CS Screening Analysis

Transport of contaminants by diffusion is important in the near-field repository (buffer, backfill and EDZs) and is modelled explicitly in the 7CS. For example, contaminant transport through the buffer is diffusion dominated because of the low hydraulic conductivity of the buffer material. In the 7CS, contaminant transport through the backfill and EDZs is also diffusion dominated.

FEP Screening

Include FEP in all scenarios.

FEP # 3.3.03   Dissolution and precipitation (repository)

Description

This FEP describes the influence of dissolution and precipitation of contaminants in the repository (excluding the waste package) on contaminant transport. Dissolution and precipitation can be important processes because dissolved species are more mobile.

The maximum concentration of a solute is known as its solubility limit (see *Speciation and solubility (repository) [3.3.04]*). It is primarily determined by the properties of the solute and solvent, but also depends on the temperature and the groundwater composition. If solute concentrations exceed the solubility, then a solid would precipitate.

Formation of some precipitates can be kinetically hindered, and the first precipitated solid phase generally has an amorphous structure (Oswald's Rule) which later transforms into a more stable crystalline form at a rate that depends on temperature and other factors. Co-precipitation is a variant of precipitation in which a forming precipitant incorporates a subsidiary compound which would not precipitate in isolation. For example, precipitation of barium sulphate can induce precipitation of radium sulphate, even if the latter is undersaturated. Thus, an element may precipitate even though it is soluble in isolation.

Most contaminants will have their largest concentrations inside the waste package, which is the source of the contaminants, and precipitation may occur there (see *Speciation and solubility (waste package) [2.4.03]*). Solute concentrations generally decrease away from the waste package, so precipitation is less likely outside the waste package. However, it could occur there if the chemical environment (including groundwater composition, Eh, pH, temperature, etc.) changes abruptly or if in-growth from radioactive decay produces a local increase in concentration. It should be noted that the solubility of some solids decrease with an increase in temperature (e.g., anhydrite) and they might dissolve at a cooler area of the repository and precipitate at a warmer location (e.g., near the container).

7CS Screening Analysis

A contaminant will precipitate inside a water-filled failed container if its concentration exceeds the solubility limit of the contaminant. Contaminant precipitation within a failed container is modelled explicitly in the 7CS (see *Dissolution and precipitation (waste package) [2.4.02]*).

Contaminant concentrations outside a failed container would be less than within the container itself because contaminants are diluted as they diffuse away from the container. Thus, precipitation of contaminants is unlikely to occur outside a failed container if chemical conditions are similar throughout the engineered barrier system. Furthermore, neglect of contaminant precipitation outside a failed container is usually conservative (i.e., precipitation decreases contaminant concentrations and, hence, contaminant fluxes into the geosphere). For these reasons, precipitation of contaminants in the buffer/backfill is not modelled in the 7CS.

FEP Screening

Screened out.

FEP # 3.3.04   **Speciation and solubility (repository)**

<u>Description</u>

This FEP discusses speciation and solubility of contaminants in the repository, excluding the waste package, as it relates to contaminant transport. Speciation is the distribution of an element among its different chemical species. Solubility refers to the maximum quantity of the solute that dissolves in a given amount of solution at a specified temperature. Speciation and solubility depend on groundwater composition (pH, Eh, etc.) and temperature.

Dissolution of a solid may produce a number of chemical species. The nature of the dominant species may be important. For instance, clay and most rock minerals sorb cations more strongly than anions.

An element will precipitate when its total concentration exceeds its solubility limit in the given groundwater. However, because of kinetic factors, the amorphous form of a solid first precipitates (Oswald's Rule) and then transforms into the more stable crystalline phase. From a practical viewpoint, if the crystalline phase is slow to form, then the effective solubility of the element would equal the solubility limit of the amorphous solid.

Solubility limits, and thus formation or dissolution of precipitates (see *Dissolution and precipitation (waste package) [2.4.02]* and *Dissolution and precipitation (repository) [3.3.03]*), could be different at different locations in the repository because of differences in the composition of the groundwater and/or temperature at the two locations.

Complexing agents in the repository groundwater (organics such as humic and fulvic acids; byproducts of microbial activity; inorganic ions such as fluoride and nitrate anions; etc.) could chemically bind with a contaminant to form another stable species. The formation of such new species can increase (or decrease) the solubility of the complexed element and can modify transport properties, for instance, by forming a neutral or anionic complex that is less likely to sorb.

A contaminant may also be present in groundwater as particulates; see *Colloid interaction and transport (repository) [3.3.06]*.

<u>7CS Screening Analysis</u>

Precipitation of contaminants inside a failed container is explicitly modelled in the 7CS (see *Dissolution and precipitation (waste package) [2.4.02]*). However, as noted in *Dissolution and precipitation (repository) [3.3.03]*, precipitation of contaminants outside failed containers is neglected because the concentration of a contaminant outside a failed container should be below its solubility limit (assuming that chemical conditions are similar throughout the repository) and because it would be conservative to neglect such precipitation in calculating contaminant transport rates into the geosphere.

Hence, speciation and solubility of contaminants in the repository system outside failed containers is not explicitly modelled in the 7CS.

However, as noted in *Water chemistry and evolution (repository) [3.2.04.A]*, the interaction between the buffer and groundwater is modelled in the 7CS to determine the composition of the

groundwater entering failed containers. This latter composition is used for calculating contaminant solubilities inside failed containers.

<u>FEP Screening</u>

Screened out.

FEP # 3.3.05   Sorption and desorption (repository)

Description

This FEP describes the sorption and desorption of contaminants in the near-field repository (excluding the waste package), as it relates to contaminant transport. Sorption describes the physicochemical interaction of dissolved species with a solid phase, by which the dissolved species are removed from solution and bind to the solid surface. Desorption is the opposite process.

Most cases of interest involve groundwaters containing trace concentrations of contaminants, for which two sorption-desorption mechanisms are important.

-   Ion-exchange processes involve an electrostatic or ionic attraction between charged dissolved species and oppositely charged surfaces.
-   Chemisorption involves the formation of a chemical bond (Meyers 2002). Neutral species and (usually) anions are generally not strongly sorbed.

Sorption and desorption are often described by a simple distribution or partition coefficient (K_d). This parameter is defined as the ratio of the amount of a contaminant sorbed onto the solid relative to that in solution. Factors that affect sorption include the solid and liquid composition, the form of the species in solution (see *Speciation and solubility (repository) [3.3.04]*), the accessible porosity in the solid, and the presence of colloids (see *Colloids interaction and transport (repository) [3.3.06]*). Sorption and desorption processes may change with time if the groundwater composition changes with time.

Sorption models employing K_d values are linear models that assume the sorption processes are reversible, rapid and that there is no limit to the sorption capacity of the solid. However, non-linear effects can be significant, such as chemical kinetic effects which favour sorption over desorption (or vice versa), a limited availability of sorption sites which become saturated, and removal of sorption sites because of competition by other ions in groundwater (particularly for saline groundwaters). These effects could reduce the extent of sorption.

Sorption is element-specific and depends on the speciation of contaminants, as well as the solid phase composition and surface characteristics. The sorption properties of bentonite and other clays generally show a strong dependence on the charge of the species. Anion exclusion likely impacts both the sorption and diffusion of anionic species.

Sorption processes occur mainly in the buffer and backfill materials of the engineered barrier system. (Additionally, special additives designed to sorb key elements may be deliberately placed in the repository.) Sorption is important because it can slow down the migration of contaminants, and contribute to the spread of their releases as a function of time (and in space if dispersive effects are important). Thus sorption will attenuate peak concentrations, and the delay times would allow for additional decay or decomposition.

7CS Screening Analysis

In the 7CS, sorption and desorption of contaminants in the buffer, backfill and excavation damaged zones are modelled explicitly assuming a linear sorption isotherm. Sorption properties are considered to be constant with time, after repository saturation and attainment of reducing conditions, as the buffer and backfill materials are not expected to change significantly

over the one million year time frame of interest. However, the sensitivity of calculated impacts on near-field sorption coefficients is investigated in the 7CS.

No sorption-specific additives are present in the 7CS repository sealing materials.

Irreversible sorption is not modelled in the 7CS. This is expected to be a conservative assumption.

FEP Screening

Include FEP in all scenarios.

FEP # 3.3.06   **Colloid interaction and transport (repository)**

Description

This FEP describes the formation and transport of colloids, and their interaction with contaminants in the repository, excluding the waste package. Colloids are small organic or inorganic particles in the nanometre to micrometre size range - small enough to form long-lasting suspensions in a liquid phase.

Colloids are unstable thermodynamically and exist because of the slow kinetics of their agglomeration into solids (called coagulation or flocculation). The stability of colloids is influenced by a wide range of factors, such as pH, redox potential, particle size distribution, chemical composition of the groundwater (e.g., major cations) and surface chemistry of the colloids. Colloid stability generally decreases as ionic strength (salinity) increases.

Several classes of colloids can be defined. Contaminants may themselves be colloids (also called intrinsic colloids), such as polymeric plutonium. Contaminants may also be sorbed onto other naturally occurring colloids (also called pseudo-colloids) which may have:

  - an inorganic base such as mineral fragments and clay;
  - an organic base such as humin (insoluble humic substances such as plant residues); or
  - a microbial base such as bacteria.

Colloids occur naturally in groundwaters and surface waters. They could enter the repository with groundwater, be introduced with backfill material such as crushed rocks, or be produced in the repository as rock flour from the use of explosives or drilling. Colloids may also form in the repository during degradation of the wastes or engineered barrier materials.

Colloids may influence contaminant transport by serving as mobile carriers of otherwise highly-sorbing (and, therefore, potentially immobile) contaminants. However, because of their size, colloid transport through dense clay based materials may not be possible.

7CS Screening Analysis

For colloid-facilitated contaminant transport to be important, three criteria must be satisfied: (1) colloids must be generated; (2) contaminants must associate essentially irreversibly with the colloids; and (3) colloids must be able to move through or with the groundwater (Ryan and Elimelech 1996).

Colloids in the buffer/backfill could be formed from clay particles or organic materials. Buffer porewaters contain about 10 mg/L organics (Stroes-Gascoyne et al. 2000a), an amount considered as borderline for having an influence on contaminant transport (Andersson 1999). However, due to the small size of the pores in the engineered barriers, colloid transport through these materials should be inhibited (Cramer and Smellie 1994, p.240; Pusch 2001, p.142). Furthermore, the high salinity groundwater at the repository depth (with a TDS concentration of 280 g/L) will cause colloid aggregation.

Therefore, colloidal transport within the buffer/backfill is not considered important in the 7CS.

FEP Screening

Screened out.

FEP # 3.3.07   **Coupled solute transport processes (repository)**

Description

In principle, dissolved contaminant (solute) flow can be driven by temperature, hydraulic, chemical and/or electrical gradients. Solute transport in a concentration gradient is called diffusion, and along with transport by advection, is covered in other FEPs (see *Advection and dispersion (repository) [3.3.01]* and *Diffusion (repository) [3.3.02]*).

Solute flow driven by gradients other than concentration gradients, as listed above, are referred to as coupled ("off-diagonal") transport, and are called thermal diffusion or Soret effect (thermal gradient), hyperfiltration (hydraulic gradient) and electrophoresis (electrical gradient).

Because these processes are driven by gradients other than concentration gradients, they might contribute significantly to solute flow, particularly if diffusion rates are low.

7CS Screening Analysis

An analysis of the effects of coupled processes and their implications for solute transport has been provided in the context of the Swiss Opalinus Clay Project (Soler 2001). The range of values considered for the various coupling coefficients in this study are approximately applicable to the clay-based engineered sealing materials in the Canadian repository concept, and so the results of Soler (2001) are considered indicative of the effects within the engineered barrier system of the 7CS.

Soler (2001) concluded that only thermal osmosis (fluid flow driven by a temperature gradient) might be important for fluid (and solute) transport. But, when mass conservation calculations were done with 2-D and 3-D models, the result showed no significant effect on time scales of 1000 years or more, in part because temperature gradients would have dropped considerably after 1000 years. In the 7CS, all containers remain intact during the early thermal period of the repository and there are no releases of contaminants. Therefore, coupled solute transport processes are considered to have a small effect on contaminant transport and are not included in the 7CS.

FEP Screening

Screened out.

FEP # 3.3.08   Gas-mediated transport (repository)

Description

The transport of contaminants in the repository in gas or vapour phase, or as fine particulate or aerosols suspended in gas or vapour.

Gaseous contaminants may be generated from the used fuel, e.g., C-14 as carbon dioxide or methane. If a gas phase exists in the repository, e.g., before saturation of the repository, the gaseous contaminants (including aerosols and particulates) may move through the gas phase (by diffusion), or be transported with the gas phase (by convection or advection), out of the repository. Alternatively, gas pressures could be sufficiently high to form an unsaturated phase where two-phase flow is important, or to expel contaminants dissolved in groundwater from parts of the repository and geosphere.

7CS Screening Analysis

In the Normal Evolution Scenario of the 7CS, gas phase transport of gaseous contaminants is not modelled because gas pressures would not be sufficiently high to permit two-phase flow out of the repository, as discussed under *Gas-mediated transport of contaminants (waste package) [2.4.05]*.

For the All Containers Fail Scenario, the rate of hydrogen production would sufficiently high that the effects of gas generation need to be considered, including an analysis of the dose consequences of gas-mediated transport of radionuclides from the repository to the biosphere (NWMO 2018, Section 8).

FEP Screening

Include FEP in the All Containers Fail Scenario

4. GEOSPHERE FACTORS

FEP # 4.0.00   **Scope of main category 4.**

<u>Description</u>

Features and processes occurring within the geosphere that could affect the thermal, mechanical, chemical, biological or hydraulic conditions in the geosphere and, as a consequence, the transport of contaminants through the geosphere.

The three subcategories under Geosphere Factors are:

      4.1 Geosphere characteristics
      4.2 Geosphere processes
      4.3 Contaminant release and transport (geosphere)

4.1 Geosphere Characteristics

FEP # 4.1.00   Scope of subcategory 4.1

Description

The characteristics of the geosphere, both in the undisturbed state before construction of the repository and as modified by the construction of the repository.

There are three subcategories under Geosphere Characteristics:

      4.1.01 Undisturbed rock lithology and stratigraphy
      4.1.02 Discontinuities and lineaments
      4.1.03 Undetected features (geosphere)

FEP# 4.1.01   Undisturbed rock lithology and stratigraphy

<u>Description</u>

This FEP is concerned with the characteristics of the host rock in which the repository is sited.

The undisturbed system is a far-field feature and includes the characteristics of the host rock within which the repository is sited. The undisturbed rock includes that portion of the repository host rock unaffected by construction or excavation (i.e., excludes the excavation damaged zones, see *Excavation damaged and disturbed zones [3.2.03.C]*) and encompasses the surrounding rock mass, within which processes such as advection, dispersion, and retardation occur. The undisturbed rock serves to isolate the repository from the surface environment and is affected by the repository location and depth, as well as time.

The relevant material properties of the undisturbed rock must be adequately characterized. These properties include the vertical and lateral extent of the geological host and bounding units, as well as their thermal and hydraulic conductivities, fracture frequencies and connectivities, compressive and shear strengths, porosities, tortuosities, thicknesses, structures, rock matrix, mineral compositions, groundwater compositions and salinities, and porewater pressures. These properties may play an important role in determining where surface water infiltrates into the geological system, where deep groundwaters eventually discharge, and how the interaction of groundwaters with repository materials and with the host rock takes place.

These properties could change with time and/or temperature, and therefore an assessment of the inhomogeneities, and the uncertainties in these properties, is also part of their characterization. For example, rock properties measured in the laboratory may be significantly different from in situ values due to stress relief cracking after drilling. As well, 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 must 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.

<u>7CS Screening Analysis</u>

In the 7CS, the repository is located at a hypothetical site in the Michigan Basin in Ontario. The stratigraphy of this sedimentary basin is described in NWMO (2018, Section 2) (see Figure 3-10), and the repository is 500 m underground. Each layer is characterized by properties relevant to liquid and gas flow (e.g., thickness, permeability, porosity, gas entry pressure, etc.) and contaminant transport (e.g., diffusion coefficient, dispersivity, sorption distribution coefficient, tortuosity, etc.). It is assumed that each layer is homogeneous throughout the model domain.

The Michigan Basin in Ontario is old and stable, and it is not expected that the characteristics of the host rock would change over time except near the repository itself (see *Excavation damaged and disturbed zones [3.2.03.C]*). Thus, in the 7CS, the characteristics of the host rock are considered to be invariant for the million year period of interest, after saturation has occurred, although glaciation may temporarily affect host rock properties in the permafrost zone.

The reference geosphere does not contain any fractures (see *Discontinuities and lineaments [4.1.02]*.)

In the 7CS, groundwater modelling is used to help understand the hydrogeology at the repository site (NWMO 2018, Section 7). In addition, the impact of glaciation is studied for various paleohydrogeolgic sensitivity cases (NWMO 2018, Section 2). At a real site, these models can be checked for consistency with independent information (e.g., paleohydrogeology, fluid chemistry and groundwater residence times), as discussed by Mazurek et al. (2003).

In the 7CS, contaminant transport properties (e.g., diffusivity, sorption) are represented by a range of values that encompasses their variability (see *Contaminant release and transport (geosphere) [4.3])*. The implications of higher rock permeabilities on groundwater flow and contaminant transport are also investigated.

FEP Screening

Include FEP for all scenarios.
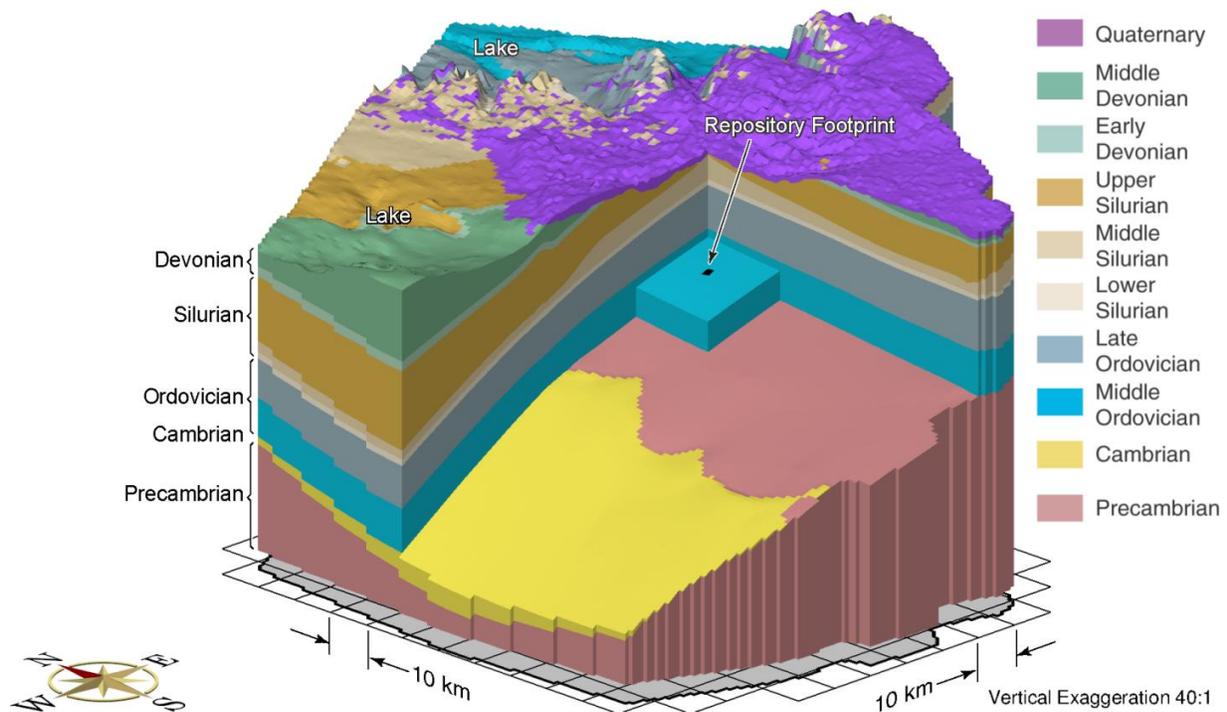
Figure 3-10: Block Cut View Showing Spatial Extent of the Bedrock Units

FEP # 4.1.02   Discontinuities and lineaments

Description

This FEP relates to the properties and characteristics of discontinuities in the host-rock and other geological units, including brittle and ductile features described as fractures (faults, joints and veins), shear zones and dykes, as well as the topographic linear expressions (lineaments) of such discontinuities.

Faults and joints are planar features that create discontinuities in the rock in the form of fractures. While faults entail a relative movement of the fault blocks along a plane, joints are characterized by the absence of appreciable displacement. Joints typically have a regular spacing and sub-parallel orientations and they may also occur in conjugate sets. Veins are mineral-filled (e.g., calcite, gypsum, dolomite) fractures with or without measurable offset. Shear zones are wide bands of deformed rock where individual fractures cannot be singled out, whereas deformation is expressed as shear textures. Dykes (igneous or sedimentary) create or follow discontinuities in the rock by the vertical or near vertical intrusion of rock mass that discordantly cross-cuts the surrounding stratified or massive formations. Creep may occur also in intact rock and along pre-existing discontinuities, and is likely to change the hydraulic and transport properties of discontinuities (e.g., Glamheden and Hökmark 2010; Eloranta et al. 1992). In particular, the fracture connectivity and channelling properties could change, such that the preferential flow paths through the sedimentary rock mass could alter with time.

Faults also indicate preferential planes of displacement that might be reactivated in the future and, together with joints, can provide valuable information on the stress field. Other features, such as igneous dykes and surface lineaments, may provide information on the potential for future magmatic or seismic activity, and on the drainage patterns of surface water, respectively.

Some discontinuities may be 'open', particularly in the near-surface zones, and would present a route for groundwater flow, while others may be 'closed' due to compressive stresses or 'sealed' by precipitation of secondary, fracture-filling minerals. Where 'open', discontinuities and shear zones might form preferential groundwater and contaminant transport pathways, reducing the effectiveness of some portion of the geosphere to act as a barrier, or by focusing contaminant releases into the biosphere at particular discharge points.

7CS Screening Analysis

The repository in the 7CS is located at a hypothetical site in the Michigan Basin in Ontario - a large area with relatively simple structural features (see *Undisturbed rock lithology and stratigraphy [4.1.01]*), low seismicity and with no volcanic or magmatic activity expected over the next million years. It is appropriate to consider the discontinuities at the site because they will have a large influence on groundwater flow around the repository and, hence, on contaminant transport.

At the 7CS site, it is assumed that there are no fracture zones or discontinuities in the deep geosphere zones. Near surface fractures and faults are not explicitly described at the site. Rather, any effects of such structures are implicitly incorporated into the groundwater flow models via the selected values of the hydraulic conductivities of the shallow geosphere layers. Furthermore, because of the low seismicity, no new fractures should develop at the site; and, because there is no volcanic or magmatic activity expected over the period of interest, no igneous dykes will intrude into the geosphere near the repository. Finally, it is assumed that the

repository would be engineered taking into account the local rock strength such that its construction and thermal stresses would not result in formation of fractures beyond any excavation damaged zone which may develop.

Deep rocks generally contain various physical discontinuities at some scale in the form of faults, fractures, etc. These may exist in different geometries and at differing spatial scales. Thus, at any proposed repository site, there would be some uncertainties in the fracture set(s) (location, length, orientation, etc.). The impact of features undetected by site characterization is discussed under *Undetected features (geosphere) [4.1.03]*.

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 formation hydraulic conductivities.

FEP# 4.1.03   Undetected features (geosphere)

Description

Undetected features include natural or man-made features within the geosphere, which are not detected during the site investigation or during excavation and operation of the repository. The lack of appropriate techniques, and an insufficient level of study, may be the cause for overlooking certain features at any given point in time. The nature of the geological environment will indicate the likelihood that certain types of undetected features may be present, and the site investigation may be able to place bounds on the maximum size of, or minimum proximity to, such features.

Possible undetected features may include sedimentary heterogeneities, faults and fracture zones (including excavation-related faults), unexpected splays or branching of known fractures, brine pockets, old boreholes and mine workings. Uncertainty regarding the presence of undetected features can be reduced by implementation of advanced techniques (e.g., 3-D seismic data acquisition and drilling of inclined boreholes) and by comprehensively screening a site for its natural resource potential. Tectonic discontinuities (faults), however, may go unrecognized if their vertical throw is smaller than the minimum resolution threshold of seismic data (~5-10 m), or if fault displacement is primarily by strike-slip; in these cases, faults may remain undetected prior to drilling and excavation.

Undetected features could play a significant role in the transport of groundwater to and from the repository. See also related factors in *Future human actions [1.4]*, such as *Drilling activities (human intrusion) [1.4.04]*.

7CS Screening Analysis

The repository in the 7CS is located at a hypothetical site in the sedimentary Michigan Basin in Ontario. It is assumed that there are no fracture zones or discontinuities in the deep geosphere zones at the 7CS repository site (NWMO 2018, Section 2) that affect groundwater flow and contaminant transport.

However, it is recognized that the geological information available at a real repository site may be ambiguous and that there could be undetected geosphere features. Thus, the effect of an undetected fracture zone or fault is examined as part of the Undetected Fault Scenario. Because of the low seismicity at the 7CS site, this fault does not grow over the million year period of interest.

FEP Screening

Include FEP in Undetected Fault Scenario.

4.2 Geosphere Processes

FEP # 4.2.00   Scope of subcategory 4.2

<u>Description</u>

These FEPs concern processes within the geological environment as they exist both in the undisturbed state before construction of the repository and as modified by the construction of the repository and by other effects occurring over long periods of time.

There are nine subcategories under Geosphere Processes:

      4.2.01 Thermal processes and conditions (geosphere)
      4.2.02 Hydrogeological processes and conditions (geosphere)
      4.2.03 Geomechanical processes (geosphere)
      4.2.04 Chemical processes and conditions (geosphere)
      4.2.05 Coupled THMC processes (geosphere)
      4.2.06 Biological processes and conditions (geosphere)
      4.2.07 Gas processes (geosphere)
      4.2.08 Erosion and sedimentation in fractures
      4.2.09 Geological resources

FEP # 4.2.01   **Thermal processes and conditions (geosphere)**

Description

This includes thermal processes that have an effect on the host rock, and the overall evolution of thermal conditions with time. These processes include the natural geothermal gradient, the long-term presence of the repository (i.e., heat from the used fuel), and the freezing temperatures at surface propagating into the geosphere associated with a periglacial environment and ice sheets.

The subcategories under Thermal processes and conditions (geosphere) are:

    4.2.01.A Current geothermal state (geosphere)
    4.2.01.B Permafrost (geosphere)

FEP# 4.2.01.A   Current geothermal state (geosphere)

Description

The geothermal regime refers to sources of geological heat, such as deep crustal heat and natural radiological decay, as well as the distribution of heat by conduction and convection (transport in fluids) and the resulting thermal field or gradient. This includes the effects of changes in conditions (e.g., temperature) caused by the excavation and long-term presence of the repository, in particular the heat-generating used fuel.

The thermal regime can have mechanical, hydraulic, chemical and biological implications. For example, thermal expansion could lead to formation of fractures and cracks in the rock mass, and thermal buoyancy could drive groundwater movement and form convection cells in permeable zones. Changes in the thermal regime could influence the hydraulic conductivity of the porous medium – as a result of the temperature dependency of groundwater density and viscosity. In addition, the growth of microbes might be promoted.

7CS Screening Analysis

Temperatures in the 7CS repository and geosphere are determined by the thermal properties of the rock and engineered barrier materials, the heat generated by the fuel, and the background geothermal gradient (Guo 2018). The initial temperature conditions are largely determined by the steady geothermal flux and rock properties, corresponding to a thermal gradient of about 12.9ºC/km at the site, and a temperature at repository horizon of about 17ºC. This corresponds to a heat flux of about 0.03 W/m^2.

After used fuel emplacement, the maximum temperature at the interface between the engineered sealing materials and the host rock is about 85ºC after 68 years, decreases to about 50ºC after 10,000 years and then returns to ambient (17ºC) within 200,000 years. The peak temperature is lower at the edges and corners of the repository (Guo 2018), and temperatures 1000 m away from the repository are not affected by the presence of the repository. Temperatures at the surface are unaffected by the presence of the repository (Guo 2018).

Thus, in the 7CS, the geosphere around the repository is mainly unaffected by the thermal plume (see *Geomechanical processes (geosphere) [4.2.03]*), except for potential effects on the properties of the excavation damaged zones (see *Excavation damaged and disturbed zones [3.2.03.C]*).

Contaminant transport times to the surface are much longer than the duration of the temperature transient in the 7CS. Hence, the effects of temperature changes (in the geosphere) on groundwater flow and contaminant transport are not expected to be important and are neglected in the 7CS. Also, the temperature transient occurring before saturation of the repository is neglected because all containers are intact during this period and, so, there is no transport of contaminants out of the repository.

FEP Screening

Include FEP in all scenarios because the geothermal state and properties form the basis of repository design.

FEP# 4.2.01.B   Permafrost (geosphere)

Description

Long-term climate change can result in a lowering of ground temperatures and the development of permafrost to depths ranging from tens to hundreds of metres, depending mostly on the: 1) magnitude and duration of freezing temperatures, 2) thermal conductivity of the rock units, and 3) local geothermal gradient. Development of permafrost, and glacial cycling, are likely to be the only processes that could impact the sub-surface thermal regime over the time scales of interest to safety assessment. Permafrost conditions are likely to persist over many thousands of years in the periglacial environment in front of an ice-sheet terminus (Peltier 2002, Peltier 2011).

The development of permafrost will have a number of impacts on the evolution of the geosphere. Expanding groundwater in pores and fractures will exert mechanical stress on the rock, and may modify the fracture network. A further impact of permafrost development is the modification of material properties as a result of the transformation of interstitial water content to ice, which exhibits very different mechanical behaviour and hydraulic properties (e.g., reduced hydraulic conductivity). The reduced hydraulic conductivity, coupled with the laterally extensive development of permafrost ahead of the ice sheet terminus, results in a fundamental change to groundwater flow paths, potentially shutting off existing recharge and discharge zones, modifying head gradients, and altering regional and local flow paths. As permafrost develops and subsequently melts, a dynamic groundwater flow system may evolve until new recharge-discharge equilibrium is established.

Freezing may also result in more saline groundwaters (see *Salt exclusion (geosphere) [4.2.04.C]*), although the significance of this is thought to be limited (Smellie and Frape 1997). In addition, the formation and melting of methane hydrates in response to permafrost conditions is also a consideration (see *Methane hydrate formation (geosphere) [4.2.04.E]*).

7CS Screening Analysis

The 7CS repository is assumed to be located at a hypothetical site in the Michigan Basin in Ontario. Based on analysis of past glacial cycles in the Michigan Basin (NWMO 2018, Section 2), permafrost is expected to form at the hypothetical repository site. The depth, lateral extent and duration of the permafrost layer are highly relevant properties for safety assessment calculations since a permafrost zone is often modelled by assigning low hydraulic conductivities (e.g., $K=10^{-13}$ m/s) to rock units in the permafrost zone (Walsh and Avis 2010).

In the 7CS, glaciation is only considered as part of the Normal Evolution Scenario. The glacial cycle at the 7CS site includes permafrost formation (NWMO 2018, Section 2), which strongly affects the hydraulic conductivity of the host rock. Hence, permafrost formation is considered in the Normal Evolution Scenario.

FEP Screening

Include FEP in the Normal Evolution Scenario.

FEP # 4.2.02 Hydrogeological processes and conditions (geosphere)

<u>Description</u>

This FEP includes the hydrogeological processes that affect the host rock and the overall evolution of the hydrogeological conditions with time.

Hydrogeological processes include the movement of water through the geological formations in which the repository is located and their controlling factors. Understanding these processes requires knowledge of hydraulic potentials and gradients (e.g., recharge and discharge zones, groundwater flow pathways, and the degree and extent of water saturation) and factors that may drive the flow, such as density effects caused by salinity and temperature gradients. Knowledge of the interactions between regional and local flow systems under various boundary conditions is also required.

The four subcategories under Hydrogeological processes and conditions (geosphere) are:

      4.2.02.A Current hydraulic state (geosphere)
      4.2.02.B Variable groundwater density (salinity)
      4.2.02.C Water residence times (geosphere)
      4.2.02.D Flow system evolution (geosphere)

FEP # 4.2.02.A   Current hydraulic state (geosphere)

Description

This FEP describes the hydraulic conditions that can be expected in the geosphere before and following construction of the repository. Typically, the movement of groundwater can be divided into three different zones with respect to depth in the geosphere: shallow, intermediate and deep groundwater zones. In the shallow groundwater zone, advection is the dominant mechanism for transport, with groundwater velocities typically exceeding the rate of diffusion. The groundwater velocities will typically be greater than 10^{-3} m/s (Normani et al. 2007, Sykes et al. 2011) and residence times for groundwater in this zone are typically less than 1000 years. The intermediate groundwater zone is a transition zone, where decreasing permeability with depth results in reduced groundwater velocities. In the intermediate groundwater zone, the role of advection as a transport mechanism is reduced and the rate of groundwater movement due to advection approaches that of diffusion. The movement of groundwater in the deep groundwater zone is dominated by diffusion and groundwater velocities will typically be less than 10^{-3} m/s (Normani et al. 2007).

In a crystalline rock geosphere, hydraulic conditions are typically hydrostatic. In sedimentary basin environments, over-pressured and under-pressured zones have also been identified. Additionally, in sedimentary formations, gas phases may be present, resulting in water saturations of less than one.

7CS Screening Analysis

The repository in the 7CS is assumed located at a hypothetical site in the sedimentary Michigan Basin in Ontario. The sedimentary rocks at repository depth have low permeability and the groundwater is saline. Thus, transport of contaminants at repository depth occurs by diffusion (NWMO 2018). The high salinity at depth will also act to reduce the impact of any hydraulic gradients. Closer to the surface, where permeabilities are higher, advection will be the predominant mechanism for groundwater flow and contaminant transport.

Sedimentary domains have been observed to have non-hydrostatic hydraulic pressure distributions with depth (e.g., Intera 2011). However, it is assumed that there are no abnormal pressure distributions at the 7CS site (NWMO 2018, Section 2).

In the 7CS, the main geosphere hydrological processes and conditions related to groundwater flow are: host rock permeability, hydraulic heads driven by surface topography, and the effects of a water supply well. These processes and conditions are assumed to be time-independent for all scenarios and all sensitivity cases for the reasons outlined below.

First, the transient hydrological conditions, between the time of repository closure and the time at which the repository becomes saturated, are not modelled in the 7CS because, during this saturation period, all containers are intact and contaminants are not released into the geosphere.

Second, because the 7CS site is assumed to be in a stable geological environment, the largest changes to the geosphere would likely arise due to glaciation. During glaciation, the groundwater flow field is transient because of the advance and retreat of ice-sheets over the site (Walsh and Avis 2010). However, the paleohydrogeologic simulations carried out for the 7CS

indicate that glacial perturbations do not materially change mass transport rates at repository depth, i.e., diffusion remains the dominant transport mechanism (NWMO 2018, Section 2). For this reason, in the 7CS, safety assessment calculations are carried out assuming a constant temperate climate for all scenarios and sensitivity cases. The effects of glaciation on the calculated impacts of the repository are discussed qualitatively as part of the Normal Evolution Scenario.

The 7CS also explicitly considers the effects of uncertainty in the geosphere permeability profile on groundwater flow through evaluation of alternative geosphere permeability cases.

See also *Variable groundwater density (salinity) [4.2.02.B]*.

<u>FEP Screening</u>

Include FEP in all scenarios.

FEP # 4.2.02.B　　　　**Variable groundwater density (salinity)**

Description

Variations in groundwater density provide a driving force for groundwater flow. Groundwater density variations can result in the development of convection cells, yielding localized flow zones. In circumstances where the flow regime is dominated by diffusion, solute transport occurs as a result of concentration gradients.

In sedimentary and crystalline shield environments, the fluid density can vary by more than 25% and the fluid viscosity by an order of magnitude. Fluid density and viscosity are a function of groundwater total dissolved solids (TDS) concentrations, and TDS concentrations typically increase with depth.

The hydraulic conductivity of a porous media depends on groundwater density and viscosity. This dependency requires groundwater flow calculations to be coupled with the movement of salinity in variable salinity environments, giving rise to non-linearities in the general groundwater flow equations.

The presence of increased density at depth in the geosphere will act to reduce differences in hydraulic potential.

7CS Screening Analysis

In the 7CS, the repository is located at a hypothetical site in the sedimentary Michigan Basin in Ontario. Groundwater found at depth in the Michigan Basin has high salinity (i.e., a TDS content of 280 g/L), which can, in certain instances, be an indicator of long groundwater residence times (NWMO 2018). Additionally, because the energy required to displace dense brine is higher than that required to displace fresh groundwater, high groundwater densities can be evidence of relatively stagnant (minimal groundwater flow) zones. Higher groundwater densities at depth will promote the stability of the geosphere at depth.

The groundwater flow model used in the safety assessment calculations for the 7CS does not include the effects of variable-density, i.e., salinity. However, the impact of salinity on groundwater flow has been examined in the Regional-Scale hydrogeologic modelling (NWMO 2018, Section 2). This later model shows that the relative difference in the mean life expectancy between the steady-state case with no brine and the case with density-dependent flow is trivial. For a system dominated by low permeability units, as in the 7CS, the mean life expectancy is not sensitive to fluid density effects. Based on these results, the decision to neglect salinity in the safety assessment calculations is valid.

FEP Screening

Include FEP implicitly in all scenarios through Regional-Scale hydrogeologic modelling calculations.

FEP # 4.2.02.C   Water residence times (geosphere)

Description

Water residence time refers to the time frame during which a volume of water has resided within, and interacted with, the geosphere. Rock-water interactions will be controlled by groundwater residence time.

Residence time can sometimes be used to represent apparent groundwater age at a specific location within a formation, representing the time elapsed since groundwater entered the subsurface. In this context, residence time is used to indicate both the apparent groundwater age and the groundwater mean life expectancy within the subsurface (where mean life expectancy is the average time frame required for a particular volume of water to move from its current location along a flow path to a discharge point at ground surface):

Residence time = apparent groundwater age + mean life expectancy.

The apparent groundwater age and mean life expectancy can be estimated from: 1) hydraulic properties and flow geometry of the formation, 2) concentrations of isotopes associated with radioactive decay or production, 3) stable isotopic or chemical indicators of the recharge conditions of the water or the origin of solutes, and 4) the groundwater transit time through the subsurface to an exfiltration point, as defined by parameters such as flow path length, porosity, and tortuosity (Sykes et al. 2011).

Note that it is necessary to distinguish between the residence times of waters and various solutes. Their transport properties and origins may differ and, hence, so may their residence times.

7CS Screening Analysis

The 7CS repository is located at a hypothetical site in the sedimentary Michigan Basin in Ontario. The groundwater salinity at the site increases with depth and groundwater at repository depth has a TDS concentration of about 280 g/L (NWMO 2018, Section 2). Typically, higher salinities are indicative of longer groundwater residence times and relatively slow rates of groundwater and solute transport. Because the repository site is hypothetical, there is no information on the apparent groundwater age.

In the 7CS, mean life expectancy calculations have been used to estimate contaminant transport times to the surface (NWMO 2018, Sections 2 and 7). These show that the repository is situated in rock in which the mean life expectancies are 10^8 to 10^9 years, suggesting that transport in the deep geosphere is diffusion controlled.

FEP Screening

Include FEP in all scenarios through Regional-Scale hydrogeologic modelling calculations.

FEP # 4.2.02.D   Flow system evolution (geosphere)

Description

Various processes occur over time that will affect the evolution of groundwater flow systems in the geosphere. Geological processes, such as erosion and glaciation, will affect hydraulic potentials and gradients at repository depths. A change in overburden thickness associated with erosion may result in volumetric deformation within a rock body. During glacial cycling, increased loading may result in consolidation, whereas unloading may lead to elastic rebound, swelling and, in some cases, fracturing. Glacial loading may also lead to infiltration of glacial meltwater and changes to groundwater flow pathways.

In sedimentary basins, sedimentation may be an additional factor affecting the physical properties of rock systems. Precipitation of minerals from solution will impact the porosity of the rock mass, which, in turn, impacts fluid pressures.

Characterization of the groundwater system evolution requires information on groundwater compositions and an understanding of the processes controlling movement of water through the relevant geological formations surrounding the repository. Identification of recharge/discharge zones, groundwater flow regimes, potential density effects (i.e. due to salinity gradients) and temperature gradients, which may influence flow, is required. Other physical properties required to characterize the flow system include rock mass permeability, hydraulic conductivity, porosity and degree of saturation.

A volumetric deformation in rock mass, caused by an increase or decrease in load, will result in a corresponding change in pore pressure. The changes in pore pressure, induced by changes in the pore volume of the rock mass, have the potential to create non-hydrostatic pressure distributions within the flow system. Non-hydrostatic groundwater pressures can be classified as overpressured or underpressured with respect to hydrostatic conditions. The processes, typically identified as contributing to overpressured conditions in the geosphere, are: 1) glacial cycling, 2) gas generation, and 3) differences in fluid density, which promotes convection. The main causes typically identified for underpressured conditions include glacial cycling and exhumation (due to, for example, erosion).

This FEP is also associated with *Current hydraulic state (geosphere) [4.2.02.A]*, *Erosion and burial (geosphere) [4.2.05.C]*, and *Glaciation/deglaciation (geosphere) [4.2.05.D]*.

7CS Screening Analysis

In the 7CS safety assessment calculations, the groundwater flow system is time-invariant except for the Normal Evolution, All Containers Fail and Severe Erosion Scenarios, for the reasons discussed below.

The transient hydrogeological conditions between the time of repository closure and the time at which the repository becomes saturated are not modelled in the 7CS. All containers are intact during this period and so there are no contaminant releases into the geosphere.

The repository in the 7CS is located at a hypothetical site in the Michigan Basin; a large area with low seismicity and no volcanic or magmatic activity. Thus, in the future, the largest likely changes to the groundwater flow system would arise due to glaciation, which causes the

groundwater flow system to change with time due to permafrost formation, which affects rock permeability, and changes to the surface hydrogeologic boundary conditions during ice sheet advance and retreat. In the 7CS, glaciation is considered as part of the Normal Evolution Scenario; in contrast, disruptive scenarios are assessed only under constant temperate climate conditions.

For the All Containers Fail Scenario, the hydrogen gas generated in the repository by corrosion of the inner steel vessels of the breached containers affects the evolution of the groundwater flow system (NWMO 2018, Section 8). In this scenario, the groundwater flow system evolves in accordance with the changes in volume and pressure of the hydrogen gas in the repository.

In the conceptual model for the Severe Erosion Scenario, the total amount of eroded material increases over the one million year time frame of interest (see also *Evolution of hydraulic conditions in near-field [3.2.02.D]*). Consequently, in this scenario, the groundwater flow system would evolve as erosion removes more and more of the surface rock overlying the repository.

Finally, for the remaining disruptive scenarios, changes to the repository system that could affect the evolution of the groundwater flow system (e.g., the permeability of the shaft seals in the Repository Seals Failure Scenario) are conservatively assumed to occur at the time of repository closure. Thus, the groundwater flow system is time-invariant in these scenarios.

FEP Screening

Include FEP in Normal Evolution, All Containers Fail and Severe Erosion Scenarios.

FEP# 4.2.03   **Geomechanical processes (geosphere)**

Description

This FEP considers the mechanical processes and conditions that affect the host rock. This includes the effects of changes due to the excavation and long-term presence of the repository. Geological events are described elsewhere: *Seismicity (earthquakes) [1.2.03]* and *Local glacial effects [1.3.05]*. The mechanical processes occurring in the repository itself are discussed under *Mechanical processes and conditions (repository) [3.2.03]*.

There are four subcategories under Geomechanical processes (geosphere):

    4.2.03.A Current stress state (geosphere)
    4.2.03.B Stress state evolution (geosphere)
    4.2.03.C Fracture/fault reactivation (geosphere)
    4.2.03.D Time-dependent deformation (creep) (geosphere)

FEP# 4.2.03.A   Current stress state (geosphere)

Description

The present-day stress regime is a basic attribute of the host rock and is intrinsically related to its geological and geomorphological setting. The initial stress state is expected to vary with depth, and may be influenced by geological structures such as faults, fractures, or contrasting geomechanical properties of different lithostructural domains. It constitutes an essential component in the repository system. Determination of the in situ stress state in the rock mass is a critical element of any site characterization program. The initial stress state is a fundamental factor in rock mass classification and stability analysis. As a boundary condition, it is a crucial factor in the setup of a geomechanical model for the numerical analysis of the system.

In general, the 3D state of stress at a point is specified by six components (three normal stress and three shear stress components). Alternatively, the state of stress may be described in terms of three principal stresses, σ_1, σ_2 and σ_3, being termed as the major, the intermediate and the minor principal stress, respectively ($\sigma_1 \geq \sigma_2 \geq \sigma_3$; compression positive). Each principal stress is defined by its magnitude and orientation (Brady and Brown 2006). The orientations of the three principal stresses are normal to each other (i.e., the orientations constitute units which are not entirely independent of each other). The normal stress components, which are acting in vertical (σ_v) and in two distinct horizontal directions (σ_H and σ_h, the major and the minor horizontal normal stress components, respectively), are normally considered. In stress measurements, using hydraulic fracturing in a vertical borehole, it is (often implicitly) assumed that σ_v, σ_H and σ_h are the principal stresses.

7CS Screening Analysis

For the 7CS, it is expected that the rock mass is competent and is able to withstand the presence of the repository with minimal engineering support (see *Excavation and construction [1.1.02]*). Knowledge of the present day stress state is a prime requirement for the repository design and construction. It affects the layout of the underground spaces, and has an effect on the shape and extent of the excavation damaged zone. The repository is assumed to be appropriately aligned with the principal stresses. The changes in the stress-state of the geosphere due to repository construction is discussed under *Stress state evolution (geosphere) [4.2.03.B]*.

While the repository site is assumed to have low seismicity, the occurrence of earthquakes and glaciation is likely on a million year time frame. However, the fracture network is assumed to be unaffected by glacial-related deformation and/or seismic activity, as described in *Discontinuities and lineaments [4.1.02]*.

The impact of hydro-mechanical coupling has been shown to be important during glaciation (NWMO 2018, Section 2; Walsh and Avis 2010). Hydro-mechanical coupling was included in the paleohydrogeologic simulations carried out for the 7CS (NWMO 2018, Section 2).

FEP Screening

Include FEP in all scenarios (since geomechanical analysis forms basis of repository design).

FEP# 4.2.03.B   Stress state evolution (geosphere)

Description

This FEP relates to the future geological and geomorphological setting of the host rock over relevant geological times. It is related to the geodynamic development of the host rock formation in connection with related geological processes, such as uplift, erosion, subsidence, sedimentation and tectonic stress regimes.

Uplift, in combination with erosion, will lead to a decrease in the magnitudes of the relevant stress components, σ_H, σ_h and σ_v of the host rock (see *Current stress state (geosphere) [4.2.03.A]*). The magnitudes of the decrease in these stress components will be unequal. The stress release will be greatest in the vertical direction and smallest in horizontal directions (due to the continuous confinement). Consequently, the ratio of the horizontal and vertical stresses σ_H/σ_v will increase, and further the orientations of the principal stresses might reverse. For instance, a vertical maximum stress may become one of the minimum stresses after a decrease in its magnitude (Bock 1975). With continued uplift and erosion, the growing stress anisotropy may be released by inelastic processes (e.g., by the formation of surface-parallel extension fractures or through a slip along pre-existing fractures).

In the case of subsidence, in combination with sedimentation, the higher overburden pressure will tend to produce higher values of the total stress and the ratio of the horizontal to the vertical stress components will shift towards unity ($\sigma_H/\sigma_v \rightarrow 1$), i.e., an isotropic stress state. This would generally mean more favorable boundary stress conditions for the repository.

7CS Screening Analysis

The 7CS repository is located at a hypothetical site on the sedimentary Michigan Basin in Ontario, a large area with low seismic activity and no expected volcanic and magmatic activity over the next million years. The regional tectonic stress regime in the Michigan Basin is not expected to change substantially over the relevant time scales.

Coupled thermal-mechanical-hydraulic analyses were carried out by Radakovic-Guzina et al. (2015) to determine the repository and geosphere responses and evolution during excavation, operations and postclosure phases. The analysis focused on the scale of the placement rooms and repository panels. Rock mass damage was found to be primarily driven by thermally-induced stress changes occurring within approximately 1000 years of repository closure. In contrast, glacial ice-sheet loading and strong earthquake ground motion did not materially influence rock damage. The maximum loading on the fuel containers was predicted to be about 30 MPa. Finally, the EDZ was predicted to extend not more than 1 to 3 metres into the enclosing host rock formation from excavated surfaces.

The stress field at repository level may change in response to glaciation and erosion. The changes brought about by glaciation (i.e., ice sheet advance and retreat) are expected to be temporary and are taken into account in the design of the repository (e.g., the repository is backfilled; and the container can withstand a mechanical load greater than 45 MPa at 100ºC without deforming).

Glacial erosion could progressively remove a fraction of the rock overlying the repository. Thus, the Normal Evolution Scenario assumes a small amount (tens of metres) of surface erosion

occurs in the first one million years. Erosion of tens of metres of material would decrease the vertical stresses at repository level by a minor amount (about 4%).

The Severe Erosion Scenario considers cases in which 100 m of rock (or more) overlying the repository is eroded over a one million year time frame. The stress changes caused by erosion of 100 metres of material would be larger (but less than those caused by glaciation itself); but, the effects of such stress changes on the repository have not been assessed and so are not included in the 7CS safety assessment analyses.

For the Severe Erosion scenario, the changes in the geosphere stresses and their effect on the repository could be significant and would need to be assessed.

FEP Screening

Include FEP in all scenarios (e.g., containers are designed to withstand additional stresses due to glaciation). Changes in the stress state of the geosphere needs to be assessed for the Severe Erosion Scenario.

FEP# 4.2.03.C   Fracture/fault reactivation (geosphere)

Description

Discontinuities in crystalline and sedimentary rock can include joints, faults, fractures, and bedding planes. These discontinuities may be open to groundwater flow, particularly near the surface, while others may be closed or sealed due to increasing compressive stresses at depth or due to the precipitation of secondary fracture-filling minerals. When stresses are altered in a rock mass, displacement is more likely to occur along pre-existing discontinuities rather than the formation of new fractures in the intact rock. Three different types of processes can be anticipated to occur in the rock in the far-field that may cause displacements along the pre-existing fractures in the rock.

1. Tectonic processes: these result from stresses associated with plate tectonics. These tend to occur over very long time scales that are not relevant to repository safety.
2. Excavation-induced processes: there could potentially be displacement along existing features due to the stress redistribution caused by the excavation of the repository.
3. Glaciation-induced processes: glacial cycles will substantially change the stress state in the host rock and around the repository due to the ice loading, which could result in reactivation of pre-existing discontinuities (e.g., Ojala et al. 2004.)

Reactivation of or displacements along existing discontinuities can have a number of consequences. They may result in localized changes in the groundwater flow paths as new preferential pathways are established, possibly reducing contaminant transport times to the surface. Fracture displacement could cause displacement of the groundwater within the fractures and, in the worst case, a direct disruption in the placement room that may lead to a mechanical failure of the container.

7CS Screening Analysis

The 7CS repository is located at a hypothetical site in the sedimentary Michigan Basin in Ontario, a large area with low seismic activity. It is assumed that there are no active or inactive fractures/faults in the reference geosphere (NWMO 2018).

Although the repository site exhibits low seismicity, earthquakes are likely to occur in the region over the one million year time frame of interest (see *Seismicity (earthquakes) [1.2.03]*). These are unlikely to create new fractures but could reactivate existing faults. The impact of an undetected fracture/fault that is reactivated due to, for example, a large seismic event is examined in the Undetected Fault Scenario.

The repository design and layout would ensure that containers are not located in the immediate vicinity of existing faults or fractures. However, a strong seismic event could cause rock shearing along a weakness in the rock, leading to container failure. This is examined in the Container Failure Scenario.

FEP Screening

Include FEP in the Undetected Fault and Container Failure Scenarios.

FEP# 4.2.03.D   Time-dependent deformation (creep) (geosphere)

Description

Creep of the rock mass is a slow, quasi-continuous (time-dependent) deformation process that occurs in intact rock and along pre-existing discontinuities in the rock. Creep may occur in the geosphere because of the imposition of differential stresses resulting from tectonic, climatic (e.g., ice loading/unloading) and repository excavation processes. The driving force behind creep displacements is the occurrence of deviatoric stresses. Theoretically, rock mass creep deformations (i.e., shear displacements along fractures and fracture zones) may proceed until either no deviatoric stresses remain, or until the deviatoric stresses have been sufficiently reduced.

Creep can lead to slow and long-term changes in geosphere properties - for example, in the hydraulic and transport properties of discontinuities (e.g., Eloranta et al. 1992). In particular, the fracture connectivity and channeling properties could change such that the preferential flow paths through the rock mass are altered with time. Creep of the rock mass around the repository excavations may lead to deformation of the bentonite buffer, galleries and shafts, and, in an extreme and very unlikely case, could affect the waste package.

Creep is affected by a number of variables, including temperature, initial stress state, geometry of the discontinuities, and the deformation characteristics of the discontinuities and the rock mass.

7CS Screening Analysis

The relevance of creep will be site-specific because it will largely depend on the local characteristics of the host rock, such as lithology, stress state and the network of discontinuities (e.g., fractures, joints, bedding planes). In general, creep is more relevant in sedimentary rock, particularly shale, compared to crystalline rock.

The 7CS repository is located at a hypothetical site in the sedimentary Michigan Basin in Ontario, a large area with low seismic activity and no expected volcanic and magmatic activity over the next million years. It is assumed that there are no fractures or faults in the reference geosphere. Thus, rock creep is not expected to be an issue for the 7CS.

FEP Screening

Screened out.

FEP # 4.2.04   Chemical processes and conditions (geosphere)

<u>Description</u>

Included under this FEP are the chemical and geochemical processes (and conditions) that affect the host rock, and which influence the overall evolution of system conditions with time. Chemical processes are significant controls on groundwater and porewater evolution, and understanding of chemical processes is necessary in order to fully characterize the long-term geochemical stability of the geosphere and the repository system.

Chemical processes or factors affecting contaminants in the geosphere are discussed separately under *Contaminant release and transport (geosphere) [4.3]*, including precipitation and sorption of contaminants (see *Dissolution and precipitation (geosphere) [4.3.04], Speciation and solubility (geosphere) [4.3.05]*, and *Sorption and desorption (geosphere) [4.3.06])*.

There are six subcategories under Chemical processes and conditions (geosphere):

    4.2.04A Current geochemical state (geosphere)
    4.2.04B Evolution of pore fluids (geosphere)
    4.2.04C Salt exclusion (geosphere)
    4.2.04D Redox stability (geosphere)
    4.2.04E Methane hydrate formation (geosphere)
    4.2.04F Dissolution/karst formation (geosphere)

It should be noted that chemical processes in the repository and geosphere occur concurrently and are often interrelated - see *Chemical processes and conditions (repository) [3.2.04]*.

FEP# 4.2.04.A   Current geochemical state (geosphere)

Description

Characterization of the hydrogeochemical regime requires knowledge of the groundwater chemistry, including: dominant species, element solubilities, concentrations of complexing agents, redox (reduction or oxidation) conditions, rock and mineral composition, rock-water interactions (including weathering processes), salinity, and chemical and thermal gradients in the groundwater. The dissolved and particulate constituents of groundwater in the geosphere will be determined by chemical and geochemical reactions. These constituents may or may not be in thermodynamic equilibrium with minerals encountered along the groundwater flow path or within the non-conductive pores.

The influence that repository activities may have on groundwater chemistry must also be considered with respect to the dominant controls on the current groundwater chemistry. Mixing due to repository excavation activities, for example, could cause changes in near-field chemistry. Such changes could yield conditions that would promote mineral dissolution or mineral precipitation reactions, which could alter near-field geometry and groundwater flow conditions.

7CS Screening Analysis

The main chemical conditions/properties of the geosphere that affect transport of contaminants are included in the 7CS, specifically: redox boundary, groundwater composition and sorption. For example, the reference groundwater composition at the repository site is used in the calculation of chemical element solubilities and in the selection of contaminant sorption coefficients. Variability or uncertainty in the chemical conditions is accounted for by using probabilistic distributions to define parameter values (e.g., sorption coefficients) and by carrying out sensitivity cases to examine impacts of changes to the chemical state of the geosphere, e.g., by setting sorption coefficients to fairly low values.

The chemical conditions in the geosphere are assumed to be time-independent for the one million year period of interest, as discussed under *Evolution of pore fluids (geosphere) [4.2.04.B]*.

FEP Screening

Include FEP in all scenarios.

FEP# 4.2.04.B   Evolution of pore fluids (geosphere)

<u>Description</u>

The evolution of groundwater composition in the geosphere is an ongoing process that occurs due to various mixing and water-rock interaction mechanisms (sorption, ion exchange, mineral precipitation/dissolution, etc.), as well as microbial activity. Events such as glaciation-deglaciation cycling, for instance, can also result in changes in groundwater chemistry by, for example, the ingress of oxygenated fresh water during a glacial advance.

Evolution of groundwater composition in the geosphere would occur in the absence of a repository. However, groundwater composition will be perturbed by the contents of, and heat generated by, the repository. The introduction of a deep geological repository may promote changes in the chemical evolution of the near-field (i.e., the repository and engineered barrier systems) groundwaters, and within the geosphere surrounding the repository; however, such changes are most likely to be temporary and would be expected to return to pre-repository conditions following repository closure.

Groundwater will evolve in response to: 1) ingress of different sources of mixing water, such as oxygenated surface water introduced during repository excavation; 2) microbial activity; 3) the presence of by-products of groundwater interactions with the container, buffer, backfill and other materials in the deep geological repository; 4) the introduction of pollutants during excavation; 5) the presence of redox couples, such as nitrogen compounds from explosives, dissolved organic carbon and dissolved manganese; 6) thermal-affected dissolution and precipitation of fracture-filling minerals; 7) hydrothermal alteration of primary rock minerals to clays; and 8) exposure to fresh rock surfaces in new fractures, such as may be found in the excavation damaged zone (EDZ). In a sedimentary shale-dominated environment, for example, the effects of heat on the argillaceous host minerals (e.g., clay alteration) and associated changes in porosity could be of significance.

A variety of subsequent reactions are possible as groundwater contacts the thermal field surrounding the repository and the engineered barriers and materials in the repository. For instance, fracture-filling minerals could be dissolved and replaced by other precipitants, affecting rock porosity, permeability and sorption capacity.

Analyses of the groundwater and its dissolved constituents (e.g., radioisotopes) may provide indications of its age (i.e., residence time in the bedrock) and state of thermodynamic equilibrium. For instance, high concentrations of tritium occur in groundwaters that have recently mixed with surface waters. Alternatively, isotopic analyses of some deep saline groundwaters from sedimentary environments (Wilson and Long 1993a, 1993b) indicate that the waters are very old. This has been demonstrated, for example, at the Bruce nuclear site (NWMO 2011), where porewater chemistry is indicative of diffusion-dominated solute transport at proposed repository depth.

<u>7CS Screening Analysis</u>

The 7CS repository is located at a hypothetical site in the sedimentary Michigan Basin in Ontario.

Changes to the chemical conditions in the shallow groundwater system will likely occur in

response to climate change (e.g., glaciation and global warming). However, these waters are expected to remain oxidizing and dilute. Hence, any changes are not expected to affect contaminant transport (i.e., sorption coefficients) and so are neglected in the 7CS.

Although chemical conditions in the near-surface would likely change, there is geological evidence that deep groundwaters in the Michigan Basin are old and, therefore, only slowly changing (NWMO 2011). This is supported by model calculations. The largest changes in groundwater composition are likely to occur during glaciation. However, paleohydrogeologic simulations (NWMO 2018, Section 2) indicate that glacial meltwaters only penetrate to the top of the Queenston formation (about 250 m below ground surface). More importantly, the glacial recharge that does penetrate below the shallow groundwater system (below ~215 m) is not expected to be oxygenated or influence redox conditions at the repository horizon (NWMO 2018, Section 2) (see also *Local glacial effects [1.3.05]).*

In the 7CS safety assessment, the critical group uses a 219 m well to capture water from the Guelph formation. The well, which is the only source of contaminants to the surface biosphere, essentially bypasses the shallow groundwater system. Thus, changes to the chemical conditions in the shallow groundwater system should not affect the results of the safety assessment calculations. For this reason, in the 7CS, the chemical conditions in the geosphere are assumed to be time-independent for the one million year period of interest.

In the Severe Erosion Scenario, a substantial fraction of the rock overlying the repository is assumed to be eroded over the one million year time frame of interest. For this scenario, the pore fluids in the geosphere, including at the repository horizon, could change with time. Similarly, the groundwater composition at the repository level could change with time for the Partially Sealed Repository and Repository Seals Failure Scenarios. For the latter scenario, the changes would depend on the severity of the failure (e.g., the hydraulic conductivity of the shaft seals). Consequently, changes to the groundwater chemistry likely would need to be taken into account in the safety assessment calculations for these scenarios.

FEP Screening

Include in the Severe Erosion, Partially Sealed Repository and Repository Seals Failure Scenarios. Screened out for the other scenarios because geosphere conditions at the repository level are assumed to be time-invariant.

FEP# 4.2.04.C   Salt exclusion (geosphere)

Description

Under permafrost conditions, ground temperature remains perennially below zero degrees Celsius and, as a consequence, groundwater may freeze. Typically, shallow groundwaters are relatively fresh, and therefore will freeze under such conditions. High salinity groundwaters, however, will not freeze until the appropriate sub-zero temperature is reached, which can be significantly lower than zero degrees Celsius. During slow freezing processes, dissolved components in groundwater may not become incorporated into the ice structure, but instead segregate into a separate phase, yielding what is referred to as salt exclusion. The development of this separate phase may result in:

1. formation of a saline water body moving ahead of an advancing freezing front,
2. isolation of brine pockets within the ice phase,
3. accumulation of salts on the grain-boundaries, or
4. crystallization of cryogenic (formed at sub-zero temperatures) minerals.

The formation of a saline water body ahead of the advancing permafrost, for example, would drive the saline front downward (predominantly by diffusion) as the permafrost deepens, which could result in temporarily increased salinity in the underlying non-frozen groundwater provided that the existing salinity and density gradients are large enough to allow for downward solute migration. Salt exclusion is affected by the following key variables: temperature, i.e., the onset of permafrost conditions in a glacial cycle; salinity of the groundwater, which affects the freezing point of the groundwater; and groundwater composition, which controls the nature of salts that can be excluded by the process (Miller and Marcos 2007).

7CS Screening Analysis

The 7CS repository is located at a hypothetical site in the Michigan Basin in Ontario. Glacial conditions are expected to occur at the repository site in the future. However, the Michigan Basin is at lower latitude where permafrost is estimated to reach a maximum depth of about 65 m. This limits the effect of salt exclusion.

The effect of salt exclusion is neglected in the 7CS because the salinity of the water in the salt exclusion zone is not expected to be higher than the present day salinity of the groundwater at repository depth (groundwater at repository depth has a TDS content of about 280 g/L). Although the saline water formed due to salt exclusion may sink downwards, it would not reach repository level.

FEP Screening

Screened out.

FEP# 4.2.04.D   Redox stability (geosphere)

Description

This FEP addresses the effects of oxygenated glacial meltwater infiltration on redox conditions in the geosphere.

An assessment of the long-term site geochemical stability requires knowledge/estimates of past glacial meltwater infiltration depths in order to determine the most likely maximum depths of infiltration during future glaciation-deglaciation scenarios. In particular, glacial meltwater infiltration in response to changes in the hydraulic head and pressure head gradients at ground surface could provide oxygenated, low salinity waters to depth. This could alter the groundwater geochemistry at repository depth as oxygenated waters may promote chemical reactions that would not occur under present-day (interglacial) conditions. In addition, microbial activity could be promoted due to the addition of oxygenated waters of lower salinity. This may have possible effects on processes such as 1) gas generation in the subsurface and 2) container degradation.

Typically, target environments for a deep geological repository in Canada would be characterized by geochemical indicators that suggest the groundwaters and porewaters are relatively old and, thereby, demonstrate a degree of stability and resistance to surface and sub-surface based perturbations (i.e., earthquakes, glaciation-deglaciation processes).

7CS Screening Analysis

The 7CS repository is located at a hypothetical site in the sedimentary Michigan Basin in Ontario. At the 7CS site, the largest changes to the repository system are likely to occur as a result of glaciation. However, paleohydrogeologic simulations (NWMO 2018, Chapter 2) indicate that glacial meltwaters would penetrate only to the top of the Queenston formation, i.e., about 250 mBGS (metres below ground surface), and so would not reach repository level. More importantly, the glacial recharge penetrating below the shallow groundwater system (> 215 mBGS) is not expected to be oxygenated or influence redox conditions at the repository horizon (NWMO 2018, Section 2) (see *Local glacial effects [1.3.05]).* Thus, after the oxygen present in the repository at closure is consumed and reducing conditions are established in the repository, redox conditions are not expected to change over the 1Ma time frame of interest.

FEP Screening

Screened out.

FEP# 4.2.04.E   Methane hydrate formation (geosphere)

<u>Description</u>

Methane hydrates, or methane ice (i.e., clathrates), are solid crystalline compounds of methane and water, having an approximate formula of $CH_4 \cdot nH_2O$, where n ≈ 5-7. Methane ice has a similar density and overall appearance to water ice.

Methane hydrates form under low-temperature, high-pressure conditions, both above and below the freezing point of water. Methane is trapped within hydrogen bonded water molecules and contributes to the structural stability of the hydrate due to its small molecular size. The hydrate lattice is stabilized by weak van der Waals forces. Methane hydrates can form only where the pressure is in excess of ~20 bars (corresponding to approximately 200 m depth) and where temperatures are less than 15 degrees Celsius.

Methane hydrates can form during glacial cycles when deep permafrost develops. The significance of methane hydrates is confined to: 1) the melting stage of the permafrost during deglaciation, or 2) the formation of warm-based ice sheets. The main issue surrounding methane hydrates, in the context of repository safety, is melting, which releases significant amounts of methane gas. It has been suggested that this process may affect the hydrogeological conditions, because the formation of gas may alter flow conditions in the bedrock (Miller and Marcos 2007).

Methane hydrate formation is affected by a number of key variables: temperature, i.e., formation of permafrost; hydrostatic pressure - methane hydrates form at pressures in excess of ~20 bars; groundwater composition, since hydrates can form only if the methane content exceeds its solubility (Miller and Marcos 2007); and groundwater and gas flow rates.

<u>7CS Screening Analysis</u>

The 7CS repository is located at a hypothetical site in the sedimentary Michigan Basin in Ontario. Glacial conditions are expected to occur at the repository site in the future. However, the Michigan Basin is at lower latitude, which constrains the depth of permafrost formation during glacial cycles (maximum depth of permafrost is about 65 m) and the potential of methane hydrate formation. Hence, formation of methane hydrates at the 7CS site is not likely and is neglected.

<u>FEP Screening</u>

Screened out.

FEP# 4.2.04.F   **Dissolution/karst formation**

Description

Dissolution chemistry refers to ongoing chemical reactions between groundwater and rock or fracture minerals, which lead to more or less continuous changes of the solid phases along groundwater flow paths and leads to the potential for increased groundwater flow and channelling. Karstification (rock corrosion leading to karst formation) is a chemical dissolution process by water in carbonate rocks (e.g., limestone, dolostone).

Soluble sedimentary rock, such as carbonates and evaporites, are deposited by precipitation processes and eroded principally by dissolution processes. At shallow depths, most of the permeability in such rocks is created by dissolution or karstification. These processes are a function of the flux of water through the rock and the saturation state of the water with respect to the dominant ions comprising the rock (Worthington 2011).

Karstification, where present in carbonate rock, can lead to the formation of continuous, large-aperture pathways through the rock (or aquifer), which may act as permeable conduits for advective transport. Groundwater flow velocities through these preferential pathways are enhanced in comparison to an equivalent porous medium or a discretely-fractured porous medium (Worthington 2011). Consequently, an understanding of karstification is important in assessing site-specific hydrogeological data collected as part of site characterization activities.

In order to accurately characterize system evolution, the influence that repository activities may have on groundwater chemistry and its evolution and, therefore, on groundwater flow dynamics, must be considered with respect to the dominant controls on the current groundwater chemistry. Mixing due to repository excavation activities, for example, could cause changes that promote mineral dissolution or mineral precipitation reactions, which could alter near-field geometry and groundwater flow conditions.

7CS Screening Analysis

In sedimentary environments, dissolution and karstification of carbonate rocks are relevant processes, particularly in the relatively shallow parts of the groundwater domain where weathering and erosion are more pronounced and advective flow is more likely to occur. The presence of karst at depth, for example, would imply an active (advection-dominant) groundwater regime.

The 7CS repository is located at a hypothetical site in the sedimentary Michigan Basin in Ontario. There is no evidence of an advection-dominant groundwater regime at the 7CS site (NWMO 2018, Section 2) and contaminant transport in the deep geosphere is diffusion controlled. Furthermore, NWMO (2011) notes that conditions are unsuitable for karst development in the intermediate and deep groundwater zones of the Michigan Basin in Ontario. Although paleokarst horizons do exist, their hydraulic conductivity does not appear to be significantly elevated and the horizons are not interconnected.

FEP Screening

Screened out.

FEP# 4.2.05   **Coupled THMC processes (geosphere)**

The FEPs cover the coupled thermal-hydraulic-mechanical-chemical processes that affect the host rock and the overall evolution of the geosphere over time as a result of these processes.

There are four subcategories under this category:

    4.2.05.A Self-sealing (geosphere)
    4.2.05.B Coupled hydraulic processes (geosphere)
    4.2.05.C Erosion and burial (geosphere)
    4.2.05.D Glaciation/deglaciation (geosphere)

FEP# 4.2.05.A   Self-sealing (geosphere)

Description

Self-sealing is a process that reduces the hydraulic transmissivity of the host rock by closure of newly formed or re-activated discontinuities. It can involve hydraulic and mechanical changes, but no structural change between both sides of the discontinuities, and typically occurs in rocks with high clay content such as clay shales and argillites. Two main processes contributing to self-sealing are: 1) coupled hydraulic processes and 2) geochemical processes. The first is linked to changes in the stress field and the second one to changes in the composition of the rock. The first process may occur in natural fractures by movements of these fracture planes (e.g., due to earthquakes, fault reactivation, uplift and subsidence). The latter one is controlled by moisture content and the composition of the groundwater and can have an effect on excavation damaged zone fractures (e.g., due to resaturation, swelling of bentonite backfill and creep).

7CS Screening Analysis

The 7CS repository is located at a hypothetical site in the sedimentary Michigan Basin in Ontario. The region is one of the most tectonically stable regions of the world, with low seismic activity. The reference geosphere has no active faults or discontinuities.

The properties of the geosphere at the 7CS repository site are assumed to be time-independent for the one million year period of interest. Although glaciation could increase the stresses in the host rock (see *Geomechanical processes (geosphere) [4.2.03]*), it is not expected that new fractures or faults would form (see *Fracture/fault reactivation [4.2.03.C]*). Thus, self-healing is not an issue in the 7CS and, in any case, its neglect would be conservative.

FEP Screening

Screened out.

FEP # 4.2.05.B   Coupled hydraulic processes (geosphere)

Description

This FEP concerns fluid flow driven by temperature, chemical or electrical gradients; rather than flow due to hydraulic pressure gradients. Fluid flow driven by these gradients are referred to as coupled ("off-diagonal") transport, and are called thermal, chemical and electrical osmosis, depending on the driving gradient. Fluid flow driven by hydraulic head gradients is called advection and is discussed under *Hydrogeological processes and conditions (geosphere) [4.2.02]*.

Chemical osmosis, for example, drives water to flow from zones of low salinity to zones of higher salinity, inducing an increase in fluid pressure in the zone with higher salt concentrations (Mazurek et al. 2003, 2009, 2011), potentially affecting geomechanical rock properties. Chemical osmosis has been proposed as a possible explanation for hydraulic overpressures observed in some argillaceous formations.

Coupled hydraulic processes are often negligible under normal engineering conditions. However, it is expected that advection will, in general, be quite low in the deep geosphere and, thus, these coupled processes could potentially affect groundwater flow in these materials.

7CS Screening Analysis

The 7CS repository is located at a hypothetical site in the sedimentary Michigan Basin in Ontario. Large disequilibrium hydraulic pressures have been measured in the deep geosphere of the Michigan Basin (NWMO 2011). The low total dissolved solids (TDS) gradient in this region, however, indicates that these disequilibrium pressures are not due to chemical osmosis (NWMO 2011, Sections 4.4 and 5.2). Therefore, fluid flow driven by chemical osmosis is not important in the 7CS and is neglected.

Thermal gradients in the near-field geosphere can be produced by the heat generated by the used fuel (see *Thermal processes and conditions (geosphere) [4.2.01]*) and by changes in surface temperatures due to glacial cycles. However, the thermal pulse due to radioactive heating will last a relatively short time compared to contaminant transport times to the surface. Further, 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. Therefore, fluid flow in response to thermal gradients is not a significant factor in the safety assessment for the 7CS and is neglected.

Finally, electrical osmosis is generally found to be unimportant even in the presence of artificially high potential gradients (SKB 2014) and is neglected in the 7CS.

FEP Screening

Screened out.

FEP# 4.2.05.C   Erosion and burial (geosphere)

Description

Weathering, transportation and deposition of materials at the earth's surface is controlled by a variety of dynamic effects, such as glaciation, water flow, soil creep, peat growth and aeolian processes (see *Regional erosion and sedimentation [1.2.07]*). These ongoing processes will actively alter and modify the surface environment, including the surface topography, which in turn would affect groundwater flow in the geosphere.

Rates of erosion and deposition vary considerably but are expected to peak during glacial retreat, as glacial outburst floods are discharged from the front of the ice sheet. During this period, the bedrock is expected to be eroded at a rate that will be primarily dependent upon its composition.

Sedimentation and deposition related to the glacial cycle will be primarily in the form of glacial moraines and eskers; large-scale landforms, such as fjords and valleys, may also be formed. In turn, eroded sediments may be transported long distances and deposited at a site, burying it to greater depth. During periods when the geosphere is overlain by an ice sheet, basal erosion resulting from 1) abrasion, 2) quarrying (plucking), and 3) mechanical erosion by meltwater (glacial streams) will be the primary erosive factors.

7CS Screening Analysis

The 7CS repository is located at a hypothetical site in the sedimentary Michigan Basin in Ontario. Hallet (2011) has reviewed currently available information for assessing the maximum amount of erosion likely to occur in the Michigan Basin. Based on his analysis, the Normal Evolution Scenario assumes that a small amount (tens of metres) of surface erosion occurs in the first one million years. This amount of surface erosion would have little effect on the calculated impacts due to (1) the extremely low permeability of the intermediate and deep rock formations, and (2) the deep depth (500 m below ground surface) of the 7CS repository. The small amount (tens of metres) of surface erosion will mainly affect the shallow groundwater regime. Erosion is therefore not explicitly modelled in the Normal Evolution Scenario. The effect of a much higher erosion rate is considered in the Severe Erosion Scenario.

FEP Screening

Include FEP explicitly in the Severe Erosion Scenario.

FEP# 4.2.05.D   Glaciation/deglaciation (geosphere)

Description

An evaluation of thermo-hydro-mechanical-chemical coupled (THMC) processes associated with a glacial cycle involves modeling the interaction of groundwater flow and the thermo-hydro-mechanical processes associated with perennial ground freezing and thawing during periods of glaciation/deglaciation. Such models also consider water salinity, changes in pressure, and the evolution of stress fields in response to glacial loading.

The rapid growth and decay of perennially frozen ground has the potential to create large transient overpressures or suction pressures beneath a glacier; this may cause the water to be driven outwards as a consequence of the ice/water phase change induced by the glacier pressure gradient. The marginal wedge of perennially frozen ground acts a zone of reduced hydraulic conductivity so that the outward groundwater flux is forced to flow through a more restricted section. These circumstances tend to generate higher groundwater flow velocities and larger heads and head gradients than in a non-glacial perennially frozen zone. This phenomenon will be site-specific and dependent on the combined effects of the local stratigraphy and the nature of pre-existing structural anisotropies, such as fractures.

Fractured, or more porous, media would allow for greater penetration of glacial meltwater possibly during the period of glacial advance or retreat. This could significantly alter groundwater compositions at depth, notably concentrations of oxygen. In addition, high sub-glacial pressures and salinity may lower the melting point, and cool down the sub-glacial bed, so a thick sub-glacial permafrost zone may be sustained during the glacial stage.

Erosion is considered under *Erosion and burial (geosphere) [4.2.05.C]*.

7CS Screening Analysis

The 7CS repository is located at a hypothetical site in the sedimentary Michigan Basin in Ontario. It is assumed that there are no fractures or faults in the reference geosphere (NWMO 2018).

During the one million year time frame of interest, the repository site will be subjected to multiple glacial cycles (Peltier 2011) (see *Local glacial effects [1.3.05]*). Thus, glaciation is considered as part of the Normal Evolution Scenario. Glaciers are expected to modify the surface hydrology but not the bedrock hydrogeology (NWMO 2018, Section 2). Glaciation could also have a significant impact at the repository level by modifying the in situ stress field (see *Stress state evolution (geosphere) [4.2.03.B]*). These additional stresses have been taken into account in the design of the 7CS repository, including the used fuel containers.

The impact of hydro-mechanical coupling has been shown to be important during glaciation (Walsh and Avis 2010) and is included in the paleohydrogeologic simulations for the 7CS (NWMO 2018, Section 2).

FEP Screening

Include FEP in Normal Evolution Scenario.

FEP # 4.2.06   **Biological processes and conditions (geosphere)**

Description

This FEP concerns the biological and biochemical processes that affect the geosphere and its evolution with time. Changes in microbial community composition or microbial activity due to the excavation and long-term presence of the repository are included under this FEP.

The microbial species present in the subsurface are adapted to a wide range of carbon and energy sources. During the construction and operation phase of a repository, microbes would enter the deep geologic repository from the air and from human activities. A wide range of effects are possible due to the action of microbes that are already present in the geosphere, or that are introduced with repository materials. Microbial evolution, due to mutagenesis or natural evolution, is not expected to significantly impact geosphere processes; but, shifts in microbial community structure in response to evolving geochemical conditions is expected to occur.

Microbial processes play an important role in geochemical processes, including oxygen reduction, and are able to catalyze reactions that would not otherwise take place at low temperatures. Microbial processes will continue in the subsurface as long as carbon and energy sources are continually available. As such, microbial processes can affect Eh and pH, and contribute to the redox stability of deep groundwater. Microbial processes also play a role in gas evolution and can both consume and produce gases in the subsurface. Microbial communities are expected to be more diverse where biofilms form – for example, in an open fracture (Stroes-Gascoyne et al. 2000b) – and may have effects on groundwater flow and contaminant transport. Microorganisms can also biotransform contaminants, thereby affecting their transport properties (Humphreys et al. 2010; Sherwood Lollar 2011). In addition, organic microbial by-products could serve as ligands that could complex with, and enhance, heavy metal mobility.

7CS Screening Analysis

The 7CS repository is located at a hypothetical site in the sedimentary Michigan Basin in Ontario. It is assumed that there are no fractures or faults in the reference geosphere (NWMO 2018). The groundwater at repository depth is saline.

A variety of microorganisms will exist within the geosphere before repository construction. However, these will be more viable in the shallow groundwater zone where groundwaters are not saline. Microbial activity would be inhibited in the intermediate and deep groundwater zones where the salinity is high and water activities are low (NWMO 2018, Section 5). The most important potential effect of geosphere microbes is to modify the groundwater Eh and pH. Their specific contribution within the geosphere to this process is site-specific and is dealt with as one of several processes (organic and inorganic) that are involved in determining the chemistry of the far-field groundwater. The net effect of all of these processes is to determine the depth of the redox divide (i.e., the depth at which reducing conditions are achieved).

The presence of the repository will initially change the conditions in the near-field around the repository, making it hotter, drier, more oxygenated, and possibly adding some nutrients (Hallbeck 2010). This will affect which microbial species are initially active around the repository. However, re-establishment of normal conditions will occur eventually following repository closure, given the expected performance of the repository and shaft seals, as

temperatures decrease, and oxygen and nutrients introduced during construction and operation are consumed. Hence, the microbial populations will revert to their pre-construction levels.

Hence, biological processes in the geosphere are not explicitly modelled in the 7CS.

FEP Screening

Screened out.

FEP # 4.2.07   Gas processes (geosphere)

<u>Description</u>

This FEP describes processes associated with the generation of various gases in the host rock environment, as well as the migration of these gases.

There are four subcategories under this FEP:

    4.2.07.A Current gas state (geosphere)
    4.2.07.B Gas generation (geosphere)
    4.2.07.C Gas migration through porosity (geosphere)
    4.2.07.D Gas migration through pathway dilation (geosphere)

FEP# 4.2.07.A   Current gas state (geosphere)

Description

This FEP pertains to the presence of gases that are dissolved in groundwater and/or porewater or that are present in the geosphere as a distinct gas phase. Gas will be present in the geosphere from three sources: natural gases found in situ; gases that are generated from material within the repository; and gas present in the repository during operation that will become trapped upon closure. This FEP pertains only to naturally occurring gases.

Gases found naturally in the geosphere will exist either as a free gas phase, or in solution, dissolved within the groundwater. The solubility of geosphere gases will depend on both the pressure and temperature. Gases found naturally in the geosphere include methane, hydrogen, nitrogen, carbon dioxide, helium and trace amounts of other noble gases. (Helium, argon, and radon can be present in the geosphere as a result of radioactive decay.) Oxygen is typically only present in the upper 150 m of the subsurface, and is usually consumed by oxidation reactions with minerals and/or organic matter within the host rock.

Isotopic analyses of dissolved gases can be used to identify geochemical trends, which can be indicative of potential differences in groundwater systems at depth, as well as indicators for geosphere stability at depth.

Generation of gas in the geosphere is discussed under *Gas generation (geosphere) [4.2.07.B]*.

7CS Screening Analysis

The 7CS repository is located at a hypothetical site in the sedimentary Michigan Basin in Ontario. It is assumed that there are no fractures or faults in the reference geosphere (NWMO 2018).

Methane gas is found in the regional oil/gas fields 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 (NWMO 2011). However, it is assumed that there are no identified commercially viable mineral resources at or near the 7CS site.

Trace amounts of gas (in particular, methane, helium, radon and carbon dioxide) have been found throughout the intermediate and deep groundwater zones of the Michigan Basin. Both concentrations and isotopes of these trace gases can be helpful in assessing fluid origin and solute transport (NWMO 2011). For example, the measurements of methane isotope concentrations indicate that solute transport is diffusion dominated in the Ordovician formation (NWMO 2011, Section 4.6). It is anticipated that similar gas distributions and signatures would be observed at the repository site. (This would require verification during site characterization activities.)

Multiphase flow models show that the presence of a non-wetting gas phase can explain the under-pressures observed in the Ordovician formations (NWMO 2011, Section 5.4.9). Because it is assumed that there are no abnormal groundwater pressure distributions (i.e., under- or over-pressures) in the reference geosphere, free gas saturations at the 7CS repository site should be quite low. Thus, the expected trace quantities of naturally occurring gases (either

dissolved or in a distinct gas phase) at the 7CS site should not affect the evolution of the repository system and, so, naturally occurring gases are not explicitly included in the 7CS.

<u>FEP Screening</u>

Screened out.

FEP# 4.2.07.B   Gas generation (geosphere)

Description

This FEP covers the generation of gas in the geosphere and explicitly excludes gas generated within the repository. Gas generation in the geosphere is the natural result of changes in pressure, temperature and redox state, as well as microbial activities. However, the amount of gas generated as a result of these processes is not expected to be significant in the geosphere selected to host a repository, as measurable changes in geosphere conditions could potentially indicate a lack of stability and/or predictability of the environment. The generation of microbial gas (e.g., methane) at levels sufficient for natural resource potential would be cause for excluding the site from consideration as a host for deep geologic repository. Although thermogenic gases (i.e., methane) could have been generated in the geologic past, the generation of thermogenic gas within the geosphere would not be expected over the time frame relevant to safety of a repository.

See also *Current gas state (geosphere) [4.2.07.A]*.

7CS Screening Analysis

The 7CS repository is located at a hypothetical site in the sedimentary Michigan Basin in Ontario. It is assumed that there are no fractures or faults in the reference geosphere (NWMO 2018).

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 (NWMO 2011). However, it is assumed that there are no identified commercially viable mineral resources at or near the 7CS site, and that there is no significant generation of gas in the deep geosphere in the area of the repository (as is the case for other areas of the Michigan Basin).

FEP Screening

Screened out.

FEP# 4.2.07.C   Gas migration through porosity (geosphere)

Description

This FEP describes the migration of repository-generated gas through the geosphere, either as a dissolved gas diffusing in water or as a discrete phase. The migration of a gas can include:

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

The migration of a dissolved gas (Processes 1 and 2) can be described by the advection-dispersion equation (single-phase liquid flow). Dissolved gas transport will dominate as long as the gas generation rate is lower than the diffusive and advective flux of dissolved gas. If a separate gas phase is formed, gas migration will occur via two-phase flow (Processes 3 and 4). Two-phase flow is an advection process in which two separate phases (water as a wetting fluid and gas as a non-wetting fluid) flow at the same time through a poro-elastic geological medium. Two-phase flow can be described by the extended Darcy's law, in which the flow of each phase is determined by its respective pressure, density and viscosity.

In Process 5, gas migration occurs through dilated pores in the rock matrix. Evidence for microscopic dilation is the observation that gas permeability of the rock matrix is pressure-dependent. No macroscopic fractures are developed in this process, and the two fluids interact in a similar way as in Processes 3 and 4; thus, it can also be regarded as two-phase flow. Process 6 involves the creation of a macroscopic fracture where single-phase transport of gas occurs. Further discussion of Processes 5 and 6 can be found in *Gas migration through pathway dilation (geosphere) [4.2.07.D]*.

The amount of a gaseous compound that can dissolve in groundwater depends on the solubility of the gas in the groundwater, which in turn depends on the partial pressure of the gas and its temperature-dependent Henry's Law constant. In a closed system (a system with a limited total gas volume), the dissolved concentration also depends on the volume ratio of solution to total gas (Stumm and Morgan 1996).

7CS Screening Analysis

Potentially volatile radionuclides in the repository (such as C-14, Cl-36, Se-79, I-129 and Rn-222) may be transported out of the repository either as dissolved gases in groundwater or via two-phase flow. Transport of dissolved gaseous radionuclides is explicitly modelled in the 7CS.

In the 7CS, hydrogen gas would be generated in the repository by corrosion of the inner steel vessel of failed containers and corrosion of rock bolts. This hydrogen gas will either dissolve in groundwater or form a discrete gas phase. In the Normal Evolution Scenario, only a few

containers fail, so two-phase flow, even if it occurs, would not have a significant effect on the evolution of the repository system and so is neglected in this scenario. However, hydrogen gas dissolution and two-phase flow is taken into account in the analysis of the All Containers Fail Scenario, as the amount and rate of hydrogen gas generation is significant. The dissolution of gases is modelled in this scenario using Henry's Law constants.

Methane gas could in theory be formed in a repository by decay of organics in the clay-based sealing materials. However, in the 7CS, formation of methane gas in the repository is neglected because microbial activity is low (due to the high salinity of the groundwater); and the organic carbon in the clay materials has been stable for millions of years and, so, is probably recalcitrant.

<u>FEP Screening</u>

Include FEP in all scenarios.

FEP# 4.2.07.D   Gas migration through pathway dilation (geosphere)

Description

This FEP describes pore dilation, which occurs as a result of the gas pressure exceeding the normal stress in a pore. The gas pressure could exceed the normal stress in a pore if gas is generated in the repository at a rate greater than the rate through which the gas would flow/dissipate into the geosphere. Dilatancy of the pore volume results in an increased pore size.

When pore dilatancy cannot accommodate the increased gas pressure, fracturing (creation of secondary porosity) of the porous medium may occur. Fracturing occurs when the gas pressure exceeds the confining stress and strength of the rock. The fracturing that will occur due to gas pressure will only continue while the gas pressure exceeds the principal stress.

See also *Gas migration through porosity (geosphere) [4.2.07.C]*.

7CS Screening Analysis

This FEP concerns the migration of a gas phase through pore dilation, which increases the pore volume. In order for dilation to occur, the gas pressure that is exerted on the pore structure must exceed the strength of the rock and the confining stress.

In the 7CS, it is assumed that the repository is designed in such a way that the pressure of any gas generated in the repository would not exceed the strength of the rock. For the Normal Evolution Scenario, there are only 10 defective containers in the repository so the amount of gas generated is low (see *Gas sources and effects (container) [2.3.05]*) and gas pressures should not exceed the strength of the rock. For the All Containers Fail Scenario, a significant amount of hydrogen gas could form. However, scoping calculations using two-phase gas flow models, which include the effect of pore dilatancy, indicate that gas pressures in the repository would not exceed the target acceptance criterion, which is 80% of the lithostatic pressure (NWMO 2018, Section 8). Thus, fracturing of rock (i.e., pathway dilation) due to excessive gas pressures should not occur in this scenario.

FEP Screening

Include FEP in the All Containers Fail Scenario.

FEP # 4.2.08　　　　　**Erosion and sedimentation in fractures**

<u>Description</u>

Erosion and sedimentation in fractures involves the removal and deposition of mineral fillings in the fractures of crustal rocks. Dissolution and precipitation reactions in fracture systems are relatively fast in comparison with the weathering of the primary host minerals.

Erosion and sedimentation in fractures will largely depend on the presence and composition of the fracture-filling materials (e.g., quartz, gypsum and calcite); the action of groundwater or hydrothermal fluids moving through or near the fracture; and the evolution of crustal stress conditions. Erosion can occur by direct entrainment of filling grains (and ions) by fluids, or can be mediated by chemical reactions between the fluids and both the grain-supporting matrix and the fracture surfaces. Sedimentation occurs when the bearing force of the fluid is exceeded by other forces acting on the grains and ions, such as mechanical forces (e.g., gravity and friction) and molecular forces (ionic bonds, Van der Waals forces).

In both crystalline and sedimentary settings, single fracture openings are typically in the range of microns to centimetres, whereas their length and depth can range from microns to kilometres (e.g., McMurry and Ejeckam 2002). They are usually filled with quartz and/or calcite, and are associated with minerals such as zeolites, epidote, and clays (e.g., chlorite, illite, kaolinite). Additionally, sand- to clay-size grains frequently contribute to the filling of narrow fractures with larger apertures. On the other hand, breccia-filled fractures comprise rock fragments from previously fractured rocks, where the angular clasts are typically larger than pebble size, with a matrix of smaller grains and minerals, as found in single fractures.

Erosion and sedimentation in fractures may modify groundwater flow and contaminant transport pathways by changing the hydraulic conductivity of fractures. In crystalline environments, the primary mode of contaminant transport will be via advection through the pre-existing fracture network. A similar situation may exist in sedimentary environments; however, the effects of self-sealing and diagenesis can render fracture networks hydraulically irrelevant.

Paleohydrogeologic studies can elucidate the history of fracture evolution in terms of the complete regional tectonic history (e.g., Blyth et al. 2000; McMurry and Ejeckam 2002; Gascoyne 2004; Pisapia et al. 2011).

<u>7CS Screening Analysis</u>

The 7CS repository is located in a hypothetical site in the sedimentary Michigan Basin in Ontario. It is assumed that the reference geosphere does not contain any distinct fracture zones. However, a fault extending from repository depth to the surface is present in the geosphere of the Undetected Fault Scenario. As in other studies (NWMO 2012a, Geofirma 2011), it is expected that this fault would be assigned constant but conservative properties. Hence, erosion and sedimentation in fractures is not modelled in the 7CS.

<u>FEP Screening</u>

Screened out.

FEP # 4.2.09   Geological resources

<u>Description</u>

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

Deep resources include oil and gas, solid minerals, water and geothermal energy. Near-surface resources include deposits such as sand, gravel and clay. The repository and its contents may also be regarded as a geological resource; for example, copper containers could constitute an attractive economic source of copper, or the fissile isotopes might be desired for use in weapons or power generation. See also *Deliberate human intrusion [1.4.02], Drilling activities (human intrusion) [1.4.04]* and *Mining (human intrusion) [1.4.05]*.

<u>7CS Screening Analysis</u>

The 7CS repository is located at a hypothetical site in the sedimentary Michigan Basin in Ontario. The site description assumes that there are no significant natural resources near this site (NWMO 2018). This applies to both deep and surface resources. It is reasonable to expect that the site characterization program put into place at a repository site would confirm this.

See also *Deliberate human intrusion [1.4.02]* and *Drilling activities (human intrusion) [1.4.04]*.

<u>FEP Screening</u>

Screened out.

4.3 Contaminant Release and Transport (geosphere)

FEP # 4.3.00   Scope of subcategory 4.3

Description

Factors and processes related to contaminant transport in the geosphere, not including the excavation damaged zones.

There are nine subcategories under Contaminant Release and Transport (geosphere):

    4.3.01 Advection and dispersion (geosphere)
    4.3.02 Diffusion (geosphere)
    4.3.03 Matrix diffusion (geosphere)
    4.3.04 Dissolution and precipitation (geosphere)
    4.3.05 Speciation and solubility (geosphere)
    4.3.06 Sorption and desorption (geosphere)
    4.3.07 Colloid interaction and transport (geosphere)
    4.3.08 Gas-mediated transport of contaminants (geosphere)
    4.3.09 Coupled solute transport processes (geosphere)

FEP# 4.3.01   Advection and dispersion (geosphere)

<u>Description</u>

This FEP deals with the advection and dispersion of contaminants in groundwater within the geosphere. Advection is the process by which solutes are transported by the bulk motion of flowing groundwater. Dispersion (the spatial spreading of contaminants) is a mixing process associated with advection, and it occurs as a result of velocity differences during groundwater flow.

Groundwater in the geosphere can move due to the effects of thermal buoyancy, hydraulic heads (gravity), and density differences. Groundwater can move through the connected pores in the medium and the interstitial spaces between mineral grains (porous flow) or through fractures in the rock (fracture flow), which have high permeabilities compared to the host rock.

Contaminants may be transported in moving groundwater as dissolved species, particulates and colloids. Dissolved contaminants will be transported at a rate equal to the average linear groundwater velocity, although the concentration of contaminants can be reduced through dispersion and dilution processes, or due to sorption onto exposed mineral surfaces. Dispersion acts to delay and reduce the peak breakthrough concentration of contaminants because contaminants become spread through a larger volume of rock and water, and thus become potentially available for sorption on larger surface areas.

Advection and dispersion in the geosphere will be affected by a number of variables: fracture geometry, spatial distribution, interconnectivity, and transmissivity; hydraulic gradients and groundwater pressure (head), which may change in time in response to environmental effects (e.g., glaciation); groundwater composition (salinity); and temperature (Miller and Marcos 2007).

An important characteristic of saturated groundwater flow in fractured rock is that the flow rate is strongly heterogeneous on all scales. At large scales (tens of metres or more), flow is concentrated in a small number of flowing features, e.g., fracture zones. On smaller scales (cm), flow within a fracture is often channeled through interconnected void spaces in between any fracture filling minerals. In addition, there are many water filled void spaces that are not interconnected, in which water is effectively stagnant and diffusion becomes the dominant transport mechanism.

The relative significance of advective versus diffusive transport is often discussed in terms of the Peclet number, P, which is defined by the equation:

$$P = v L / D$$

where v is a measure of the advective velocity, L is the transport path length, and D is a measure of diffusive transport. Advective transport is more important than diffusion when P is greater than about 10, and diffusive transport is more important for P values less than 1.0.

7CS Screening Analysis

Transport of contaminants through the geosphere by advection and dispersion is explicitly modelled in the 7CS. However, at the 7CS repository site, advection and dispersion are less important than diffusion in the intermediate and deep groundwater zones (depths > 215 m) because of the low hydraulic conductivities of the geosphere layers in these zones.

FEP Screening

Include FEP in all scenarios.

FEP# 4.3.02   **Diffusion (geosphere)**

Description

This FEP concerns the diffusion of contaminants in the geosphere.

Diffusion refers to the movement of ions, molecules and/or colloids primarily as a result of concentrations gradients. Diffusion is independent of fluid movement. Diffusion causes spreading of contaminants from regions of high concentration to regions of low concentration.

There are two principal types of diffusion to consider in the geosphere: molecular diffusion and surface diffusion. Surface diffusion applies to solutes that are weakly bound near the surface of mineral grains by electrostatic forces and diffuse parallel to the mineral surface. The very narrow layer of water (a few nm) at the interface between minerals and porewater, where solutes may be electrostatically bonded, is referred to as the electric double layer (EDL). Water in the EDL is distinct from the bulk aqueous solution that occurs outside the EDL. Molecular diffusion occurs outside the EDL within the bulk solution. Porous bedrock systems may contain multiple fluid phases (e.g., oil, water and gas) and molecular diffusion occurs in each.

7CS Screening Analysis

Transport of dissolved contaminants in the geosphere by diffusion is explicitly modelled in the 7CS.

At the 7CS repository site, diffusion is the dominant mechanism for solute transport in the deep low permeability geosphere formations. Surface diffusion is not explicitly included in the 7CS models; but, it is implicitly included since the diffusion coefficients used in the safety assessment are based on measured values.

FEP Screening

Include FEP in all scenarios.

FEP # 4.3.03   Matrix diffusion (geosphere)

Description

The migration of contaminants, by molecular diffusion, into and out of the stagnant water in the geosphere.

Of particular interest is matrix diffusion, which involves (molecular) diffusion of dissolved contaminants and particulates between a conductive feature (e.g., a fracture zone) and the stagnant water in the adjacent intact rock mass. Stagnant water can be present, for example, in the pore spaces or in the non-conducting small-scale fractures of the intact 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 while the water in the remaining pore space is stagnant.

The net effect of matrix diffusion could be a reduction in the concentrations of dissolved contaminants or particulates in the moving groundwater, and a delay in their transport to the surface. Conversely, dissolved salts in the stagnant water of the host rock can diffuse into the conductive fractures. See also discussion under other FEPs in *Contaminant release and transport (geosphere) [4.3]*.

7CS Screening Analysis

The 7CS repository is located at a hypothetical site in the sedimentary Michigan Basin in Ontario. The reference geosphere does not contain any distinct fracture zones. Although small-scale fractures and joints are likely present in the shallow groundwater zone, the scale of these features is such that, at the scale of the contaminant transport pathways, their effects are subsumed within the measured hydraulic conductivities, and groundwater flow (and contaminant transport) can be treated as taking place in an equivalent porous medium. Thus, as there are no fractures, matrix diffusion is not relevant for those scenarios that use the reference geosphere.

A fault extending from repository depth to the surface is present in the geosphere of the Undetected Fault Scenario. However, even for this scenario, matrix diffusion is neglected because it would be conservative for contaminants that are sorbed in the geosphere (Garisto et al. 2001).

Thus, matrix diffusion is not considered in the 7CS.

FEP Screening

Screened out.

FEP # 4.3.04   **Dissolution and precipitation (geosphere)**

Description

This FEP discusses the influence of the dissolution and precipitation of contaminants in the geosphere on contaminant transport. Precipitation reactions generally act to retard contaminant transport.

Contaminants moving through the geosphere could be subjected to precipitation and dissolution at different points along their flow paths, caused by changes in the physico-chemical conditions such as temperature, groundwater chemistry (Eh, pH, etc.), mineralogy (primary minerals and rock alteration products) or microbial activity. Changing flow rates may have an influence also, especially in the case of kinetically hindered reactions. These conditions may change with time (see also *Chemical processes and conditions (geosphere) [4.2.04]*) and, for example, previously precipitated contaminants could redissolve.

7CS Screening Analysis

In the 7CS, the highest concentrations of contaminants occur in failed containers, where precipitation of contaminants is modelled. As dissolved contaminants move away from the failed containers and into the geosphere, their concentrations should decrease substantially as a result of dilution by groundwater or porewater. Therefore, contaminant concentrations in the geosphere should not exceed the solubility of the contaminant, assuming the groundwater chemical conditions are similar in the geosphere and in the failed container. Some changes in hydrogeochemistry could be anticipated, for example, due to high pH leachates from degrading cement structures. However, such changes in groundwater chemistry are expected to be localized to a small zone in close proximity to the interface between the engineered sealing materials and the host rock due to the extremely low permeability of the host rock; and the changes in groundwater chemistry such as pH will be buffered by the water-rock interactions. Hence, precipitation (and redissolution) of contaminants in the geosphere is not modelled in the 7CS. This is expected to be a conservative approximation because contaminant concentrations and, hence, calculated impacts, should decrease if precipitation occurs.

FEP Screening

Screened out.

FEP # 4.3.05   Speciation and solubility (geosphere)

Description

This FEP describes the influence of speciation and solubility of contaminants in the geosphere as it relates to contaminant transport. Speciation is the distribution and form of an element among defined chemical species (i.e., the types and concentrations of one element among its various chemical forms in an aqueous solution). The solubility of a solute is the maximum quantity of the solute that dissolves in a given amount of solvent or solution at a specified temperature.

The speciation of contaminants in porewater and groundwater is an important factor influencing the behaviour and transport of contaminants in the geosphere. It can be affected by the properties of the groundwater and porewater (notably pH, redox, salinity, and concentration of complexing agents), as well as the temperature and pressure. For example, complexing agents (organics such as humic and fulvic acids; inorganic ions such as fluoride and nitrate anions; etc.) could chemically bind with a contaminant to form another stable species.

Groundwater compositions will vary at different locations in the geosphere. For instance, shallow groundwaters typically have a composition similar to fresh oxidizing meteoric water, but deep groundwaters can be more saline than seawater and reducing. Groundwater compositions could be affected also by the presence of specific minerals; for instance, minerals containing iron or sulphur can have a strong influence on the electrochemical potential of groundwater. The redox state of the groundwater will significantly affect the aqueous speciation of redox sensitive elements such as Se, Tc and actinides.

The speciation of contaminants, which is influenced strongly by the groundwater composition, will affect their solubilities. The formation of stable aqueous species, e.g., by binding with complexing agents in the groundwater, will increase solubility limits, promoting the dissolution and transport of contaminants. Conversely, a decrease in the stability of aqueous species will lead to precipitation and decreased transport of contaminants (see *Dissolution and precipitation (geosphere) [4.3.04]*).

The speciation and solubility of contaminants will also affect their sorption properties. In the presence of strong complexing agents, the formation of stable aqueous species will decrease the sorption of contaminants (see also *Sorption and desorption (geosphere) [4.3.06]*).

7CS Screening Analysis

The speciation and solubility of contaminants in the geosphere is not explicitly modelled in the 7CS. Neglect of solubility limits in the geosphere should be reasonable, as discussed under *Dissolution and precipitation (geosphere) [4.3.04]*.

Chemical speciation in the geosphere is, however, implicitly taken into account in the selection of the geosphere contaminant sorption coefficients (and their uncertainty range) because these sorption values, which are influenced by chemical speciation, are obtained from experiments that include the relevant groundwater, minerals and pH/T/Eh conditions.

<u>FEP Screening</u>

Screened out.

FEP # 4.3.06   **Sorption and desorption (geosphere)**

Description

This FEP describes the sorption and desorption of contaminants in the geosphere as it relates to contaminant transport. Sorption describes the physico-chemical interaction of a dissolved species with a solid phase, by which dissolved species are removed from solution and bind to the solid surface. Desorption is the opposite process.

Sorption of contaminants in the geosphere depends on factors such as the properties of the contaminant (valance state, hydrolysis and complexation constants), dissolved contaminant concentration, the properties of sorbing minerals (mineralogical compositions and mineral surface characteristics), groundwater chemistry (pH, Eh, salinity, and concentrations of complexing agents, such as carbonate, and humic and fulvic substances), and temperature.

Sorption and desorption in the geosphere may delay contaminant transport, especially for long flow paths in which groundwater velocities are low. Sorption can take place on: 1) the surface of fractures, 2) fracture infillings, 3) the pores of rock matrix in crystalline rocks and 4) the surface of pores in sedimentary rocks.

Sorption is often described by a simple distribution coefficient (K_d), which assumes that sorption is reversible, and reaches equilibrium rapidly. In the transport modelling, it is assumed that K_d is independent of variations in water chemistry or mineralogy along the flow path, the solid-water ratio or concentrations of other species. More sophisticated approaches involve the use of sorption isotherms or surface complexation models.

7CS Screening Analysis

In the 7CS, sorption and desorption of contaminants in the geosphere are modelled assuming a linear sorption isotherm characterized by a K_d value.

Irreversible sorption is not modelled. This is expected to be a conservative assumption.

Sorption properties are considered to be constant in time. This is reasonable because, after the geosphere has saturated and reducing conditions are attained in the repository, the sorption characteristics of the deep rock formations are not expected to change significantly over the million year time frame of interest, as discussed in *Chemical processes and conditions (geosphere) [4.2.04]*). Some changes in hydrogeochemistry could be anticipated, for example, due to high pH leachates from degrading cement structures. However, such changes in groundwater chemistry are anticipated to be localized to in close proximity to the interface between the engineered sealing materials and the host rock due to the extremely low permeability of the host rock; and the changes in groundwater chemistry such as pH will be buffered by the water-rock interactions. Conditions in fractures, especially near the surface, may vary with time, but transport in these features is sufficiently fast that sorption is not likely to be a significant factor.

FEP Screening

Include FEP in all scenarios.

FEP# 4.3.07   **Colloid interaction and transport (geosphere)**

Description

This FEP describes the formation and transport of colloids in the geosphere, their interaction with contaminants and their influence on contaminant transport. Colloids are small organic or inorganic particles in the nanometre to micrometre size range, small enough to form long-lasting suspensions in a liquid phase.

Colloids are unstable thermodynamically and exist because of the slow kinetics of their agglomeration into solids (called coagulation or flocculation). The stability of colloids is influenced by a wide range of factors, such as pH, redox potential, particle size distribution, chemical composition of the groundwater (e.g., major cations) and surface chemistry of colloids. Colloid stability generally decreases as ionic strength (salinity) increases.

Several classes of colloids can be defined. Contaminants may, themselves, be colloids (also called intrinsic colloids), such as polymeric plutonium. Contaminants may also be sorbed onto other naturally occurring colloids (also called pseudo-colloids), which may have:

  - an inorganic base such as mineral fragments and clay;
  - an organic base such as humin (insoluble humic substances such as plant residues); or
  - a microbial base such as bacteria.

In crystalline rocks, common forms of inorganic colloids are phyllosilicates (e.g., mica, clay minerals) or silica, iron oxides and hydroxides. In argillaceous formations, common forms of inorganic colloids are clay minerals (kaolinite, illite and mixed-layer illite/smectite), quartz/silica, calcite and iron oxide.

Organic colloids may comprise small fragments of degrading organic material (or dead individual microorganisms) or organic macromolecules, such as humic and fulvic acids. Organic materials can form coatings on inorganic colloids, which may make them more stable and potentially more mobile. Metal ions, and radionuclides of higher oxidation state, are often preferentially associated with humic colloids.

Colloids occur naturally in groundwaters and surface waters. They could enter the repository with groundwater, be introduced with backfill material such as crushed granite, or be produced in the repository as rock flour from the use of explosives or drilling. 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 activities.

Colloids may influence contaminant transport by serving as a mobile carrier of otherwise highly-sorbing (and, therefore, potentially immobile) contaminants. This means that colloids can increase the apparent groundwater concentration of low solubility contaminants. Colloid transport may be affected by 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 and fractures that are too small to permit ingress, and thereby affecting the hydraulic conductivity of the fractures.

7CS Screening Analysis

In order for colloid-facilitated transport to be important, there are three criteria that must be satisfied: (1) sufficient colloids must be available to compete with immobile surfaces for contaminants; (2) contaminants must associate essentially irreversibly with the colloids; and (3) the colloids must be able to move through the groundwater to uncontaminated areas (Ryan and Elimelech 1996).

The 7CS repository is located at a hypothetical site in the sedimentary Michigan Basin in Ontario. Natural colloid concentrations in argillaceous clays are relatively low. For example, natural colloid concentrations in Opalinus Clay at Mont Terri range from 0.000002 to 0.6 mg/L. These concentrations are thought to be low due to the high salinity of the groundwaters (Voegelin and Kretzschmar 2002).

Colloid transport is not expected to be important in the 7CS geosphere because: (1) the reference geosphere does not contain any fracture zones, making colloid transport difficult; (2) groundwaters are saline in the intermediate and deep groundwater zones, making colloids unstable and colloid concentrations low; and (3) transport is diffusion dominated in the deep geosphere (depth > 215 m), which makes colloid transport difficult. Hence, colloid transport in the geosphere is not included in the 7CS system model.

Irreversible sorption of contaminates onto colloids is not presently modelled.

FEP Screening

Screened out.

FEP # 4.3.08   Gas-mediated transport of contaminants (geosphere)

Description

The transport of contaminants in gas or vapour phase, or as fine particulate or aerosols suspended in gas or vapour, in the geosphere.

Contaminant gases may be generated from the wastes, e.g., C-14 as carbon dioxide or methane, and transported in the gas phase through the repository and geosphere. Contaminant gases, aerosols or particulates may also be transported along with other non-toxic gases. Alternatively, gas pressures could be sufficiently high to form an unsaturated phase where two-phase flow is important, or to expel contaminants dissolved in groundwater from parts of the repository and geosphere.

See also *Gas processes (geosphere) [4.2.07], Volatiles and potential for volatility [6.1.04]* and *Noble gases [6.1.06].*

7CS Screening Analysis

In the Normal Evolution Scenario of the 7CS, low but non-zero gas production in the repository is expected after saturation of the repository. The copper coated used fuel containers are corrosion resistant, but gas could be generated from corrosion of the steel in breached containers, from corrosion of residual iron in the repository (i.e., rock bolts), and from trace organics in the seal materials. However, the rate of gas production is sufficiently low that two-phase gas flow in the geosphere is not expected to occur (see also *Gas-mediated transport of contaminants (waste package) [2.4.05]*). Hence, gas-mediated transport of contaminants is not important in the Normal Evolution Scenario.

However, for the All Containers Fail Scenario, the rate of hydrogen production would be much higher. Therefore the effects of gas generation need to be considered in this scenario, including an analysis of the dose consequences of gas-mediated transport of radionuclides from the repository to the biosphere (NWMO 2018, Section 7).

FEP Screening

Include FEP in the All Containers Fail Scenario.

FEP # 4.3.09   **Coupled solute transport processes (geosphere)**

Description

In principle, dissolved contaminant transport can be driven by temperature, hydraulic, chemical and/or electrical gradients. Solute transport due to a concentration gradient, which is called diffusion, and solute transport with a moving fluid, which is called advection, are covered under other FEPs in *Contaminant release and transport (geosphere)* [4.3].

Solute transport driven by the other gradients are referred to as coupled ("off-diagonal") transport, and are called thermal diffusion or Soret effect (thermal gradient), hyperfiltration (hydraulic gradient) and electrophoresis (electrical gradient), depending on the driving gradient.

Because these processes depend on different gradients than those driving diffusion or advection, they might contribute to solute transport if diffusive and advective transport rates are low.

7CS Screening Analysis

An analysis of the effects of coupled processes and their implications for solute transport has been provided by Soler (2001) for the Swiss Opalinus Clay Project. This study concluded that only thermal osmosis (fluid flow driven by a temperature gradient) might be important for fluid (and solute) transport. However, when mass conservation calculations were done with 2-D and 3-D models, the result showed no significant effect on time scales of 1000 years or more, in part because temperature gradients would have dropped considerably by then.

In the 7CS, peak thermal gradients occur during the period when the repository is saturating. However, during this time, all containers are intact and so there are no releases of contaminants from the repository. Most container failures occur after thermal gradients have dropped considerably in the geosphere, so thermal diffusion or thermal osmosis should not contribute significantly to solute transport.

Therefore, coupled solute transport processes in the geosphere are considered to have a small effect and are not included in the 7CS.

FEP Screening

Screened out.

5. BIOSPHERE FACTORS

FEP # 5.0.00   Scope of main category 5.

<u>Description</u>

The biosphere factors include the features and processes that occur within the surface environment or biosphere (e.g., near-surface aquifers and sediments), including human activities, and how these features and processes might change over long periods of time.

The four subcategories under Biosphere Factors are:

      5.1 Surface environment
      5.2 Human behaviour
      5.3 Contaminant release and transport (biosphere)
      5.4 Exposure factors

5.1 Surface Environment

FEP # 5.1.00.   Scope of subcategory 5.1

<u>Description</u>

The features and processes within the surface environment or biosphere, including near-surface aquifers and sediments, but excluding human activities. It includes a description of how these features and processes might change over long periods of time.

There are thirteen subcategories under Surface Environment:

    5.1.01 Topography and morphology
    5.1.02 Soil and sediment
    5.1.03 Near-surface aquifers and water-bearing features
    5.1.04 Surface water bodies
    5.1.05 Coastal features
    5.1.06 Marine features
    5.1.07 Atmosphere
    5.1.08 Meteorology
    5.1.08 Hydrological regime and water balance
    5.1.10 Erosion and deposition (biosphere)
    5.1.11 Ecological systems
    5.1.12 Vegetation
    5.1.13 Animal Populations

FEP # 5.1.01   Topography and morphology

Description

The relief or shape of the land (and water) surface.

Surface types include plains, hills, valleys, outcrops, channels and canyons. Changes covered within this category are limited to short term processes, such as river erosion, that could occur over a few centuries.

Topography is important because it defines surface water flows, the location of groundwater recharge and discharge locations, and the magnitude of hydraulic heads that drive local and regional groundwater flows.

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

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

7CS Screening Analysis

Topography is explicitly included in the 7CS. The topography provides a surface boundary condition for hydraulic heads, which in turn affect groundwater flow. The surface topography is considered as part of the geosphere groundwater flow model, on a regional (18,000 km²) flow scale and on the subregional (1,600 km²) flow and the main (186 km²) and detailed (88 km²) transport model scales (see, for example, Figure 3-11). The topography also defines the surface water bodies and groundwater discharge zones, which are used to define reference locations for critical groups and the characteristics of local water supplies.

The hypothetical repository site is located in the Michigan Basin in Ontario. This region is geologically stable (see *Geological factors [1.2]*) with no mountain building occurring in the region, only gradual (glacial) erosion. The current topography at the hypothetical repository site is relatively flat. Since this topography is in part the result of multiple past glaciations, it is expected that this topography will be maintained during subsequent ice-sheet advances and retreats; i.e., large topographic differences are unlikely to be created (see also *Regional erosion and sedimentation [1.2.07]*). Although the exact future topography is not known, as per present conditions, it is expected to be sufficient to drive water through the shallow groundwater zone but not to significantly influence flow in the low-permeability intermediate and deep groundwater zones. For these reasons, the topography is assumed to be time-independent in the 7CS safety assessment calculations.

FEP Screening

Include FEP in all scenarios.
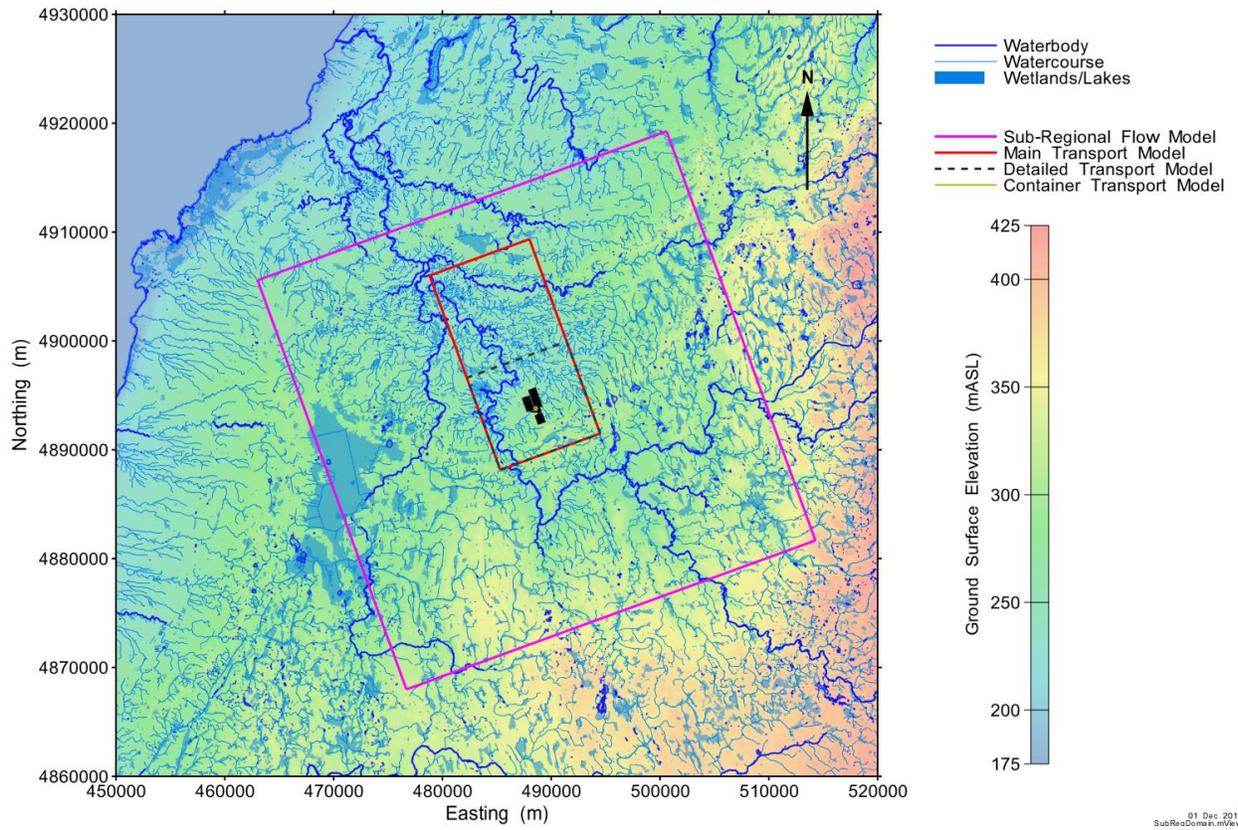
Figure 3-11: Subregional Flow, Main Transport and Detailed Transport Model Domains

FEP # 5.1.02   Soil and sediment

<u>Description</u>

The soils and sediments that lie over the rock of the geosphere.

There are three subcategories under this FEP:

      5.1.02.A Surface soils
      5.1.02.B Overburden
      5.1.02.C Aquatic sediments

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

FEP # 5.1.02.A   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 0.2-0.3 m is the active surface soil region which contains the bulk of the plant roots, as well as being the region most directly affected by agricultural practices, such as plowing.

The soil type, such as loam, sand, clay and organic, can be roughly characterized by parameters such as particle-size distribution and organic matter content. These will have different physical and chemical properties (e.g., erosion rates, water percolation rates, pH, organic content), different land management properties (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.

Another physical property is the distance between the soil surface and the water table, which can vary from centimetres to metres and which can change rapidly in response to surface water infiltration and runoff. The soil profile with depth may have distinct geochemical and structural layers. For example, there may be an organic litter layer on top followed by a mixed layer with decaying organic matter. The next layer, particularly on the Canadian Shield, may be an eluviated (a nutrient-poor leached-horizon) layer. The lowest layer is usually very similar to the parent geologic material.

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 transport (biosphere) [5.3]*).

The properties (including existence) of soils will evolve because of natural weathering processes that include: hydration and dehydration, freeze-thaw cycles, dissolution and leaching, oxidation, acid hydrolysis and complexation. For instance, a podzolic soil is formed in temperate areas with high rainfall and granite parent material; this soil type tends to be acidic with iron and aluminium oxides, clays, alkalis and alkaline earth metals leached from surface to deeper horizons. Soils evolve also 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 affect local ecosystems and the net consequence to groundwater and contaminant movement. These processes may also affect how the critical group uses the soils.

7CS Screening Analysis

Surface soils are explicitly modelled in the 7CS. Surface soils are used to grow plants for human and animal foods (garden and forage field), to grow trees to provide wood for building and heating fuel (woodlot), and to obtain peat for heating fuel (peat lot).

A simple soil compartment model is used to calculate contaminant concentrations in surface soils. The effects of irrigation, leaching, radioactive decay, radioactive ingrowth, groundwater discharge, precipitation, surface runoff, etc. are included in the calculation of soil concentrations. A compartment model is particularly appropriate for agricultural soils because they are plowed

regularly and are therefore well-mixed.

A clay-type soil is assumed to exist at the 7CS repository site. The soil type, in theory, may change over time. However, the change would occur slowly. For the 7CS, the soil type will be constant for any simulation, but the importance of soil evolution will be approximately evaluated by considering the effects of four soil types: sand, clay, loam or organic, in the probabilistic calculations.

FEP Screening

Include FEP in all scenarios.

FEP # 5.1.02.B   Overburden

Description

The unconsolidated rock, clay, sand and soils that overlie 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 [5.1.02.C]*).

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

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

7CS Screening Analysis

Overlying sediments or overburden are explicitly included in the 7CS groundwater flow models. An overburden layer is present for terrestrial areas and a sediment layer is present under lakes and rivers. The total thickness of the overburden varies from place to place. Because contaminants can be absorbed in the overburden, it affects the concentrations of contaminants in groundwater discharging into the biosphere.

FEP Screening

Include FEP in all scenarios.

FEP # 5.1.02.C   **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 overburden sediments when, for instance, a river changes its course or a lake dries up. They are often dredged for use as soil conditioners.

Aquatic sediments can play an important role in contaminant transport through sorption processes (see *Sorption and desorption (biosphere) [5.3.03]* and *Colloid interaction and transport (biosphere) [5.3.04]*). Sorption onto sediments can remove contaminants from the aqueous environment, but, in the process, contribute to exposure routes involving contaminated sediments such as through emergent plants like wild rice, or the transformation of lake beds to agricultural land (see, for instance, *Surface environment, human activities [1.4.06]*).

7CS Screening Analysis

Aquatic sediments (at the bottom of rivers and lakes) will be explicitly included in the 7CS. Two types of sediments are treated in the biosphere model – mixed sediments and compacted sediments.

Compacted sediments are treated as part of the geosphere model and can affect the groundwater flow field in the geosphere near surface water bodies as well as contaminant concentrations in groundwater discharging into surface water bodies.

Mixed sediments are treated as part of the biosphere model. Suspended particulates in the lake are deposited into the mixed sediment compartment. In the contaminant transport calculations, it is assumed that contaminants in the groundwater discharging into the lake are not sorbed by the mixed sediments. This approximation is conservative for the calculation of contaminant concentrations in lake water but not for the calculation of contaminant concentrations in the mixed sediments.

In probabilistic simulations, sediments can sometimes be used as soil by the critical group. This soil consists of a mixture of mixed sediments and compacted sediments, with the mixed sediments being a small fraction of the total mass. Thus, underestimation of contaminant concentrations in mixed sediments (see above) will have a relatively small effect on calculated dose rates.

FEP Screening

Include FEP in all scenarios.

FEP # 5.1.03   **Near-surface aquifers and water-bearing features**

<u>Description</u>

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

<u>7CS Screening Analysis</u>

At the 7CS site, groundwater flows westward through the shallow groundwater zone, which includes the Guelph Formation, to discharge into a major lake. Layers of sand and gravel constitute local aquifers whereas the till layers comprise aquitards (i.e., they restrict groundwater flow).

The aquifers in the area of the repository are used for water abstraction. In the 7CS, well water used by the critical group is extracted from the Guelph Formation. This is conservative because contaminant concentrations would be higher in the Guelph Formation than in an overlying aquifer.

<u>FEP Screening</u>

Include FEP in all scenarios.

FEP # 5.1.04   **Surface water bodies**

Description

The characteristics of surface water bodies such as rivers, lakes, wetlands and springs. Particulates that deposit from surface water bodies are discussed under *Aquatic sediments [5.1.02.C].*

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

Other considerations are provided under:

    5.1.04.A Wetlands
    5.1.04.B Lakes and rivers
    5.1.04.C Springs and discharge zones

FEP # 5.1.04.A   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) are common to the Canadian Shield and are typically an intermediate state of lake infilling, a local consequence of beaver activity, or the outcome of periodic flooding of low lying areas. They 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 be drained to provide agricultural land (see *Surface environment, human activities [1.4.06]*) and mined for peat which is then used as a fuel or soil supplement.

7CS Screening Analysis

There are no wetlands in the Site-Scale and Repository-Scale groundwater models that are used in the safety assessment calculations for the 7CS. Furthermore, the Regional-Scale groundwater model does not explicitly include wetlands. Thus, wetlands are not included in the 7CS.

FEP Screening

Screened out.

FEP # 5.1.04.B   Lakes and rivers

Description

The properties of surface water bodies 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:

-   Mixing refers to the dispersal of contaminants through the water body to form homogeneous concentrations. 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 as 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.
-   Flushing refers to the net rate of water flow and generally has seasonal variations. It is usually associated with dilution and dispersion of materials (including contaminants), but reconcentration is possible in hot dry environments where evaporation dominates.
-   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 [5.1.02.C]*.
-   Surface water pH may be a concern in regions (e.g., the Canadian Shield) where most lakes are poorly buffered. These lakes tend to be readily affected by acidic sources (such as acid rain) which make them less productive. Surface water pH can also influence contaminants through the availability of suspended particles and the reaction of contaminants.

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

Surface water bodies and springs can involve a variety of contaminant transport mechanisms and exposure pathways, such as transfer to fish, ingestion of drinking water by humans and other organisms, and water immersion. These issues are discussed further under *Contaminant release and transport (biosphere) [5.3]* and *Exposure factors [5.4]*.

7CS Screening Analysis

At the 7CS repository site, contaminated groundwater from the repository discharges into surface water bodies. These water features are explicitly included in the 7CS biosphere model. Furthermore, for the purposes of the safety assessment, a reference surface water body that could be used by the critical group as a source of drinking and irrigation water is identified. In

the 7CS, a series of rivers close to the repository site are selected to be the potential source of water for the critical group. These rivers are within the discharge zone for groundwater originating near the repository (NWMO 2018, Section 7).

The model used to calculate radionuclide (or contaminant) concentrations in surface water includes radionuclide mass losses due to (net) sediment deposition, radioactive decay, water outflow and volatilization; and radionuclide mass inputs due to groundwater discharge into the water body, and radioactive ingrowth. (Resuspension of sediments is implicitly modelled by using the net sediment deposition rate in the model.) (See also *Aquatic sediments [2.3.02.C]*.) Each surface water body is assumed to be well-mixed, and the water flow rate through it is dependent on the precipitation and runoff (see *Meteorology [2.3.10]*).

In the 7CS, surface water bodies, as with other biosphere features, are assumed to have time-independent properties in any given simulation. Hence, the potential evolution of the surface water bodies are neglected. However, a range of parameter values are used for probabilistic analyses, thereby providing some indication of the influence of temporal changes to surface water properties.

It should be noted that in those scenarios that use a well as the source of water for the critical group the calculated impacts are independent of the properties of the surface water bodies. For cases in which there is no well a surface water body is used as the water source, then contaminants may discharge directly to the surface water bodies in addition to other indirect pathways.

FEP Screening

Include FEP in all scenarios.

FEP # 5.1.04.C   Springs and discharge zones

Description

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

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

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

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

7CS Screening Analysis

Groundwater discharge zones are required to explicitly link the geosphere to the biosphere and are, therefore, explicitly modelled in the 7CS. Discharge zones usually underlie a water body (wetland, lake, river), but can also underlie terrestrial areas (e.g., areas where the water table is below the surface and the land is suitable for agriculture). The 7CS model allows for discharges to both aquatic and terrestrial areas.

Given the relatively shallow topography of the 7CS repository site, drinking water is most likely to come from a well or a lake, rather than a spring. In the 7CS, the critical group uses water from a deep well. For conservatism, this well is located such that it intercepts the contaminated groundwater plume from the repository. Contaminant concentrations in a surface spring would be lower than in well water because, as it moves upward, the contaminated groundwater plume is diluted by clean water infiltrating from the surface. Thus, surface springs are not considered as possible water sources for the critical group in the 7CS.

FEP Screening

Include FEP in all scenarios.

FEP # 5.1.05   Coastal features

Description

The characteristics of coasts and the near-shore of fresh and marine water bodies. 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 for 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.

7CS Screening Analysis

Coastal features are not included in the 7CS safety assessment models because the hypothetical repository site is located inland.

Note that although the Regional-Scale groundwater flow model includes large lakes, coastal features, *per se,* are not explicitly included in the model.

FEP Screening

Screened out.

FEP # 5.1.06   Marine features

<u>Description</u>

The characteristics of seas and oceans, including the sea bed. 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.

<u>7CS Screening Analysis</u>

Marine features are not included in the 7CS. The repository in the 7CS is assumed to be sited in Ontario, far from seas and oceans. Therefore, there is no need to include marine features in the 7CS.

<u>FEP Screening</u>

Screened out.

FEP # 5.1.07   Atmosphere

Description

The characteristics of the atmosphere. 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.

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

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

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

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

The atmosphere has significant dilution potential. For instance, wind is a major environmental force in the transport of contaminants through the atmosphere, by processes of advection, dispersion and diffusion. Wind could also have indirect effects on the behaviour and transport of contaminants through processes such as evapotranspiration, fires, and deposition onto soil and vegetation. The wind attributes are discussed under *Meteorology [5.1.08].*

<u>7CS Screening Analysis</u>

The atmosphere is included in the 7CS.

Atmospheric processes that are explicitly modelled 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).

Both indoor and outdoor air concentrations are modelled (see *Contaminated environmental media [5.4.02]*).

<u>FEP Screening</u>

Include FEP in all scenarios

FEP # 5.1.08   Meteorology

Description

The characteristics of weather and climate.

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

Daily and seasonal variations can have a wide influence. For example, these variations affect irrigation requirements for agricultural crops, habitat for animal populations, the source of drinking water and the accumulation and rapid expulsion of contaminants under snow and ice covers. The variability in meteorology 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.

7CS Screening Analysis

Meteorology is included in the 7CS. For example, explicit account is taken of the effective precipitation rate and average wind speed in, for example, the calculation of the atmospheric deposition rate, soil leaching rate, and atmospheric dispersion. Implicit account is taken of meteorology through the use of (Southern) Ontario specific values for parameters dependent on meteorological conditions (e.g., temperature, rain fall rate, snow fall, etc.), including plant yields, vegetation type, etc.

Meteorological parameters are defined by probabilistic distributions, thereby ensuring that the natural variability in meteorology is taken into account in probabilistic simulations. For a given simulation, however, meteorological parameters are constant, so potential effects due to the natural (short-term) temporal variations in meteorology are not included.

The probability distribution functions defining the meteorological parameter values reflect current-day conditions. These distributions would change if there were long-term changes to the climate in Southern Ontario (due to, for example, global warming or glaciation).

In the 7CS, a discussion of the influence of glaciation is included as part of the Normal Evolution Scenario. Meteorological parameters vary with the glacial cycle, e.g., conditions become drier than current day conditions during periods of permafrost.

FEP Screening

Include FEP in all scenarios.

FEP # 5.1.09   Hydrological regime and water balance

Description

The near-surface hydrology at a watershed scale, including soil water balance.

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

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

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

Changes to the hydrological regime could induce changes in the behaviour of the critical group as well. 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.

7CS Screening Analysis

The near-surface hydrology is explicitly included in the 7CS. Specifically, water flows through local rivers and lakes, if present, are calculated in terms of the runoff and the watershed surface area; the precipitation rate is used in the calculation of the wet deposition rate to soil and plants and contaminant leach rates from soils; and irrigation rates are inversely correlated to the precipitation rate.

In the groundwater flow models used in the 7CS, the near-surface groundwater system is predominantly driven by local subregional-scale topographic changes. Meteoric water recharges the groundwater system by infiltration from topographic highs and flows near the surface before discharging into surface waters or wetlands associated with local topographic lows.

For constant climate conditions, the near-surface hydrology is assumed constant throughout the simulation period. The natural variability in the hydrological regime is described by using probabilistic density functions (PDFs) to define the associated parameter values. The PDFs do not include extreme events or long-term climate change (due to, for example, global warming or glaciation). In the 7CS, a qualitative discussion of the influence of glaciation is included as part of the Normal Evolution Scenario. The hydrological regime and water balance vary with the glacial cycle (NWMO 2018, Section 2; Garisto et al. 2010).

In the 7CS, it is assumed that all contaminants discharged into the local environment (i.e., via a well or at discharge zones) are also discharged into a local river (which could be used as a

water source by the critical group). Although this overestimates the mass of contaminants in the biosphere, it is a conservative approach that avoids the need to account for the details of contaminant transfer to the river from runoff and other upstream surface water bodies.

FEP Screening

Include FEP in all scenarios.

FEP # 5.1.10   **Erosion and deposition (biosphere)**

Description

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

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

7CS Screening Analysis

The 7CS repository is located at a hypothetical site in the sedimentary Michigan Basin in Ontario. Hallet (2011) has reviewed glacial erosion rates for the Michigan Basin. Based on his results, the Normal Evolution Scenario of the 7CS assumes that a small amount (tens of metres) of surface erosion occurs in the first one million years. This amount of erosion would not affect calculated impacts due to the low permeability of the intermediate and deep rock layers and so erosion is not explicitly modelled in the Normal Evolution Scenario.

The effects of higher erosion rates are considered in the Severe Erosion Scenario.

FEP Screening

Include FEP in the Severe Erosion Scenario.

FEP # 5.1.11   Ecological systems

Description

The relations between populations of animals, plants and microbes.

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 members 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);
- cometabolism or the biodegradation of synthetic or hazardous waste materials as a concurrent process with normal metabolic processes;
- bioconcentration, which refers to the ability of an organism to concentrate nutrients and chemicals from its environment, usually from water or soil;
- bioaccumulation, which refers to the tendency of an organism to continue to bioconcentrate throughout its lifetime;
- biomagnification, which refers to the occurrence of nutrients and chemicals at successively higher concentrations with increasing trophic level in the food web;
- recycling, which refers to the reuse of organic material and nutrients;
- biological feedback, which has 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 which 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 [5.2]*). The main issue is whether or not, and how, these changes might influence contaminant transport and exposure routes.

Finally, the effects of a repository on ecosystems should be considered with respect to possible changes to local conditions – groundwater flows, salinity and temperature. For instance, a repository sited in an environmentally sensitive area might have relatively minor impacts overall, but at the same time could have significant impacts on a local endangered species.

7CS Screening Analysis

Ecological systems are included in the 7CS.

The ecosystems of the surface environment provide the background within which contaminant migration may occur, should such contaminants be released into the biosphere. These include natural (forest, wetland, aquatic) and man-made (agricultural) ecosystems. Contaminants may migrate through these systems, e.g., via root uptake into vegetation (bioconcentration) and subsequent movement through the food chain.

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

It should be noted that in terms of glaciation, which is qualitatively discussed in the 7CS as part of the Normal Evolution Scenario, the ecological systems present near the repository site change as the climate changes during the glacial cycle. This change affects the types of plants and animals that can live near the repository site. In the safety assessment for the Normal Evolution Scenario, these changes are taken into account by changing the characteristics of the critical groups, animals and plants living near repository site during the different periods of the glacial cycle.

FEP Screening

Include FEP in all scenarios.

FEP # 5.1.12   Vegetation

<u>Description</u>

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

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 depends on factors such as contaminant properties, soil type, plant species and the stage of the plant's growth cycle.

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

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

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

<u>7CS Screening Analysis</u>

Vegetation (e.g., garden and forage field plants) is included in the 7CS. It is used as food (by humans and animals) and for fuel and building materials (trees).

Contaminant concentrations in plants are affected by uptake of contaminants from soil, atmospheric deposition, deposition of irrigation water, washout of deposited material and plant yields. In the 7CS, plant properties are assumed to be time invariant.

In the 7CS, glaciation is included as part of the Normal Evolution Scenario. The nature of the plants growing near the repository site changes during glaciation. During permafrost periods, for example, farming is not viable and the critical group diet could consist mainly of caribou meat (Garisto et al. 2010). Caribou are assumed to eat mainly lichens, which have very different properties from vascular plants. Such differences are taken into account in the assessment of the Normal Evolution Scenario.

<u>FEP Screening</u>

Include FEP in all scenarios.

FEP # 5.1.13   Animal populations

Description

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

A large range of characteristics is possible and many could affect contaminant transport and exposure routes. Of particular importance are the animals (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.
- Contaminants levels can increase when moving up the food chain (biomagnification).
- Miscellaneous characteristics could be important. Examples include animal grooming and fighting that may lead to external contamination.

The effects of the repository on animals should be considered with respect to possible changes to local conditions such as moisture levels, groundwater flows, salinity and temperature. Potential impacts should 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.

7CS Screening Analysis

Ingestion of contaminated animal produce is a potentially important exposure pathway for humans, so animal populations are included in the 7CS. For temperate climates, the critical group is a self-sufficient farm household (see *Diet and liquid intake [5.2.03]*) that uses animal products. Domesticated food animals (beef and dairy cows, poultry) and fish are explicitly included in the 7CS. Animal characteristics are assumed to be time-independent throughout a single simulation, although their properties are treated as varying within a range.

A qualitative discussion of the influence of glaciation is included in the 7CS for the Normal Evolution Scenario. Animal populations at the repository site would vary with climate (Garisto et al. 2010); so, for example, domesticated farm animals are present during periods of temperate climate, whereas caribou are present during periods of periglacial climate.

In the 7CS, impacts of the repository on non-human biota are determined for the Normal Evolution and All Containers Fail Scenarios. The potential impacts of radionuclides on non-human biota are determined using the approach described in Medri and Bird (2015). The impact of potentially chemically toxic elements on humans and non-human biota are determined by comparison of chemical element concentrations in various biosphere media to selected acceptance criteria (NWMO 2018, Section 7).

FEP Screening

Include FEP in all scenarios.

5.2 Human Behaviour

FEP # 5.2.00   Scope of subcategory 5.2

Description

The general habits and characteristics of the potentially affected individuals or populations, i.e., critical groups, including how these habits and characteristics might change over long periods of time but subject to the human activities described under *Future human actions [1.4]*).

There are eleven subcategories under Human Behaviour:

    5.2.01 Human characteristics (physiology, metabolism)
    5.2.02 Age, gender and ethnicity
    5.2.03 Diet and liquid intake
    5.2.04 Human habits (excluding diet)
    5.2.05 Community characteristics
    5.2.06 Food and water processing and preparation
    5.2.07 Dwellings
    5.2.08 Wild and natural land and water use
    5.2.09 Rural and agricultural land and water use
    5.2.10 Urban and industrial land and water use
    5.2.11 Leisure and other uses of the environment.

FEP # 5.2.01   Human characteristics (physiology, metabolism)

<u>Description</u>

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 toxins 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 an aboriginal group, might have a genetic tendency towards certain features that may affect their susceptibility to contaminants. Variability is discussed under *Age, gender and ethnicity [5.2.02].*

<u>7CS Screening Analysis</u>

Generally, the 7CS does not directly include characteristics related to the internal workings of the human body (e.g., physiology and metabolism). Rather, these characteristics are implicitly included through the selected values of, for example, the radiological dose coefficients, which are derived based on a knowledge of human physiology and metabolism, human energy requirements (and corresponding food ingestion rates), human water ingestion rates and human breathing rates.

However, the specific activity models used in the 7CS for H-3, Cl-36, C-14, and I-129 require specific physiological information on the H, Cl and C content of the human body, and the iodine content of the human thyroid.

The 7CS uses reference man (ICRP 1991a) as representative of the dose impacts that would be seen for a wide range of human characteristics.

<u>FEP Screening</u>

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

FEP # 5.2.02   Age, gender and ethnicity

Description

Susceptibility to radioactive and chemically toxic material varies in relation to age, sex and reproductive status. Children and infants, although similar to adults, often have characteristic differences (e.g. respiratory rates, food types, ingestion of soil), which may lead to different exposure characteristics.

7CS Screening Analysis

In the 7CS, radiological doses to a reference adult human are calculated. Dose rates to infants or children may be more limiting in some particular circumstances. However, the adult dose rate is a reasonable indicator of repository safety for a prospective assessment because the variations in dose rates are not expected to be large, and because dose rates are likely to be low but chronic and, therefore, represent a lifetime exposure.

Differences in dose rate due to gender are discussed by Whillans (2006). 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." The approach recommended by ICRP (ICRP 2007) for prospective risk assessment is to base the estimates on gender-averaged values of the parameters. However, gender-averaged dose coefficients are not yet available.

Ethnicity is not a relevant factor in the 7CS – the ICRP dose models to not include ethnic variations.

FEP Screening

Screened out.

FEP # 5.2.03   **Diet and liquid intake**

Description

The intake of food and water by individual humans, and the compositions and origin of intake.

The diet of humans can vary greatly, both qualitatively and quantitatively. Potential food types include grains, legumes, cultivated and wild fruit and berries, juices from wild and cultivated fruits, domestic animals, products of domestic animals (such as milk, yogurt, 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.)

The total amount of food consumed can also vary with factors such as age and extent 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 should 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.

There may be a need to consider several particular diets. These are described under:

     5.2.03.A Farming diet
     5.2.03.B Hunter/gatherer diet
     5.2.03.C Other diets

where the two main categories are for a farming household and a hunter/gatherer lifestyle. An aboriginal diet, for example, may be of particular relevance for a repository located on the Canadian Shield. Depending on the lifestyle, it might be sufficiently covered within the reference farming and hunter/gatherer diets, or may require a third community-specific diet.

FEP # 5.2.03.A   Farming diet

<u>Description</u>

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 (and potentially contaminated) soil, as well as domesticated animals and fish. Water would come from wells or lakes.

The type of farming household can vary from self-sufficient to an "industrial" or monoculture operation.

<u>7CS Screening Analysis</u>

The diet and liquid intakes of the human exposure group, as well as the source of these foodstuffs, are explicitly included in the 7CS. Only adult radiological dose rates are calculated in the 7CS (see *Age, gender and ethnicity [5.2.02]*), and, hence, the human diet and fluid intakes are those for adults.

Of the various plausible critical group lifestyles (Zach et al. 1996), it is expected that doses to a self-sufficient farm group would be the highest because such a group is assumed to reside and grow their food in areas where contaminant concentrations are expected to be highest, particularly if they use a well and irrigate their crops.

The 7CS includes a self-sufficient farming household as the reference human critical group during temperate periods, when farming is viable. For this group, the human diet and liquid intake are specified through the ingestion rates of five different food types (meat, milk, poultry/eggs, plants and fish) and the ingestion rate of water.

During temperate periods (when farming is viable), the source of drinking and irrigation water is a well in the Reference Case. The alternative case in which the source of water is a surface water body (i.e., a lake) would lead to lower dose rates because of greater dilution.

<u>FEP Screening</u>

Include FEP in all scenarios.

FEP # 5.2.03.B   Hunter/gatherer diet

Description

The food and water ingested by persons living a hunter/gatherer lifestyle. This could be representative of some aboriginal communities, for example.

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 lakes; and a high percentage of their time may be spent outdoors.

7CS Screening Analysis

In the 7CS, the critical group is a self-sufficient farmer during temperate periods.

However, a qualitative discussion of the influence of glaciation is included as part of the Normal Evolution Scenario. The critical group would vary with the climate. Based on Garisto et al. (2010), for example, the critical group could be a self-sufficient hunter during permafrost periods and a self-sufficient fisher during proglacial lake periods. The hunter diet consists mostly of caribou meat, supplemented with wild foods and fish. The fisher eats mostly caribou and fish, but also some plants. The self-sufficient farmer receives the highest dose rate in Garisto et al. (2010) because this group uses water from a well, whereas the other groups use lake water.

FEP Screening

Include FEP in the Normal Evolution Scenario.

FEP # 5.2.03.C   Other diets

<u>Description</u>

Other diets that cannot be adequately represented by a farming household diet or a hunter/gatherer diet.

Possibilities could include:

-   a reference diet that might be established by the regulators to reflect the characteristics of some hypothetical 'reference' person such as the ICRP reference man;
-   vegetarian diet;
-   actual diets corresponding to specific communities (aboriginal or other) that live in the vicinity of a proposed repository; and
-   urban household.

<u>7CS Screening Analysis</u>

Zach et al. (1996) considered several alternative diet/lifestyles, including several vegetarian lifestyles as well as specific diets that emphasized meat, poultry/eggs, dairy and fish. For meat/dairy diets, calculated median dose rates were about 50-fold lower than for the Reference Case simulation (in which the critical group diet consisted of both plant and animal foods); for vegetarian diets, dose rates were 2 to 3 times higher.

The BIOMASS Theme 1 results (IAEA 2003) for a reference biosphere considered Arable Farmer, Livestock Farmer, Horticulture, Gamekeeper, Fisherman and Villager diet/lifestyles. The calculated peak dose rates only varied within a factor of 3.

These results indicate that diet is a factor affecting calculated dose rates, but variation between critical groups would likely be within a factor of 3. Therefore, although specific alternative diet/lifestyles may be considered as part of a siting-based assessment, other diets are not considered within the 7CS scope of work.

<u>FEP Screening</u>

Screened out.

FEP # 5.2.04   **Human habits (excluding diet)**

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 which could increase external exposure;
-   keeping of pets which could become externally contaminated through a variety of pathways and increase external exposure when handled by humans;
-   smoking, which can increase inhalation exposure to radionuclides taken up by tobacco plants from contaminated soil or through leaf deposition;
-   agricultural practices, such as plowing, cultivation and harvesting, which can create dust and lead to inhalation and external exposure;
-   dwelling location, such as underground or partially buried, or on bodies of water; and
-   use of physical resources such as peat, wood, stone and water.

Other examples are discussed in *Community characteristics [5.2.05]*, and *Leisure and other uses of the environment [5.2.11]*.

7CS Screening Analysis

The habits (excluding diet) of the exposure group are explicitly included in the 7CS.

The particular habits accounted for include:

-   time spent indoors
-   time spent outdoors
-   time spent immersed in water (bathing or swimming)
-   water source (well or lake), see also under *Water sources [5.2.05.C]*
-   agricultural practices, if any (e.g., irrigation and plowing)
-   food storage practices (related to food holdup times)
-   heating fuel source (wood or peat)
-   dwelling characteristics.

FEP Screening

Include FEP in all scenarios.

FEP # 5.2.05   **Community characteristics**

<u>Description</u>

The characteristics, behaviour and lifestyle of groups of humans that might be affected by the repository.

Some of the more important characteristics are discussed separately under:

    5.2.05.A Community type
    5.2.05.B Community location
    5.2.05.C Water source

FEP # 5.2.05.A   Community type

Description

The general nature and size of the community, and, in particular, their degree of self-sufficiency.

Communities found in southern Ontario range from rural farm households to larger towns that support heavy industries. One relevant classification scheme might be based on the degree of self-sufficiency of members of the community, such as the following.

- A hunter/gatherer 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.
- 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 may practise intensive farming (including factory farms, fish farms, monoculture intensive crops, greenhouses and hydroponics), but may also use external resources for some of their food, water, etc.
- An urban community may rely mostly on resources imported from beyond the local area.

Some characteristics may lead to unique exposure pathways; for instance, plowing of contaminated agricultural land may be an important inhalation and external exposure pathway.

7CS Screening Analysis

The general nature of the potentially exposed community and their degree of self-sufficiency is included in the 7CS (Garisto et al. 2005c).

For the 7CS, the dose rates received by a self-sufficient household are calculated. Self-sufficient communities, that rely mostly on local resources for food, water, house heating fuels, etc., are expected to receive higher dose rates than communities that are not self-sufficient. A household rather than a community is considered so that the associated water and land requirements are less and more likely to fully capture any released contaminants. Large communities draw on larger supply ranges, which would include uncontaminated food and water sources, leading to lower dose rates.

The nature and characteristics of each community are assumed to be time-independent, although different communities may exist during the different climate periods of a glacial cycle (Garisto et al. 2010). Because the selected community type is expected to be conservative, the use of a constant end-point provides a consistent indication of the effects of the repository over long time scales.

FEP Screening

Include FEP in all scenarios.

FEP # 5.2.05.B   Community location

<u>Description</u>

The location of the community relative to areas that may be contaminated by the effects of the repository.

A community most at risk might be situated on the discharge area of deep groundwaters that have become contaminated by the repository. This location has the potential for the greatest impacts because dilution effects occurring in the biosphere are small. All exposure pathways could be affected.

Alternatively, significant impacts might be experienced by a community situated at a downstream location, where contaminants from multiple groundwater discharge areas converge and contaminants accumulate. This location also has the potential for the greatest impacts because the community could be exposed to a greater mass of contaminants and the accumulation process (in lake sediment for instance) could largely defeat contaminant dilution effects.

<u>7CS Screening Analysis</u>

In the 7CS, it is assumed that the exposed community resides near the repository site, where a well (used by the self-sufficient farming household during temperate periods) can intersect the contaminant plume from the repository (see also *Water source [5.2.05.C]*) and capture a large fraction of the contaminants released from the repository.

Dose rates to groups living "downstream" of the repository site should be lower than for groups living near the repository, because contaminants would be diluted as they travel to "downstream" locations.

<u>FEP Screening</u>

Include FEP in all scenarios.

FEP # 5.2.05.C   **Water source**

<u>Description</u>

The origin of water used by the critical group for domestic purposes, including drinking, and to meet irrigation demands.

Humans require water for domestic use, including drinking, cooking, washing and bathing. They may also require water to irrigate gardens and large agricultural fields used for crops and forage, to provide drinking water for livestock and to serve other purposes such as supply and maintenance of water for fish hatcheries or process water for industry. Potential water sources include lakes, rivers, streams, wells and springs; although bottled spring water might be imported principally for drinking purposes. Note that different sources might be used for different purposes; for instance, water used for domestic purposes might be obtained 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 occupation of the community, and additional volumes and sources might be required for a growing community.

The different water 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 their source of water.

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

See also the related discussions under:
 - *Water management (wells, reservoirs, dams) [1.4.07]* which includes more considerations on water-supply wells;
 - *Near-surface aquifers and water-bearing features [5.1.03]* and *Surface water bodies [5.1.04]* which are also concerned with water sources; and
 - other uses of water (and land) discussed under *Rural and agricultural land and water use [5.2.09]* and *Urban and industrial land and water use [5.2.10].*

<u>7CS Screening Analysis</u>

The water source for the potentially most exposed persons (i.e., the critical group) is included in the 7CS.

In the 7CS, the critical group during temperate periods (a self-sufficient farm household) takes its drinking and domestic water (including irrigation water for the garden) from a deep well (about 220 m) in the Guelph Formation. This well captures essentially all the contaminants entering the Guelph Formation from the repository. Evidence from previous safety assessments indicates that average dose rates are much lower if the water source for the critical group is a local surface water body (e.g., a lake) rather than a well.

In the 7CS, the effect of glaciation on the calculated impacts of the repository is qualitatively assessed for the Normal Evolution Scenario. Critical group characteristics vary during a glacial

cycle, including the water source. For example, in the glaciation study of Garisto et al. (2010), the water source is a well for the self-sufficient farmer and a surface water body for the self-sufficient hunter or fisher (see also *Lakes and rivers [5.1.04.B]*).

The fate of contaminants in waste water from the household is not modelled explicitly in the 7CS. Such contaminants would likely end up in surface water bodies (streams, lakes, etc.) and be diluted by the water flowing through such bodies, reducing their potential impact on humans.

<u>FEP Screening</u>

Include FEP in all scenarios.

FEP # 5.2.06   Food and water processing and preparation

Description

The treatment of food stuffs and water between raw origin and consumption.

Once a crop is harvested or an animal slaughtered, it may be subject to a variety of storage, processing and preparation activities prior to human or livestock consumption, changing the contaminant distribution and content in the product. For example, any delay processes between harvesting and ingestion will allow for losses caused by radioactive decay. Other examples include:

-   stored crops could become contaminated (or decontaminated) by seepage or flooding of 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.

7CS Screening Analysis

Contaminants in water and foods are usually lost as a result of processing and preparation. In the 7CS, such losses are neglected in the calculation of exposure dose rates. This makes the calculated 7CS dose rates conservative.

The 7CS does, however, account for the effect of radioactive decay between the time food is harvested and the time it is consumed. Because these holdup times are generally small, this only affects radionuclides with short half-lives.

FEP Screening

Screened out.

FEP # 5.2.07   Dwellings

Description

The characteristics of the houses or other structures or shelter in which humans spend time.

Factors that may affect the occupants' exposure modes and levels include:

- the dwelling location, which may be particularly important for impacts from radon (see *Radon and radon daughter exposure [5.4.08]*) or exposure to contaminated gases (see *Gas-mediated transport of contaminants [5.3.08]*);
- materials used in construction such as wood, stone and ashes, especially for those materials that tend to accumulate contaminants;
- design elements for improved energy efficiency and air tightness and size, which could have a strong influence on air exchange rate and indoor concentrations of contaminants;
- heating source, such as wood, peat and biogas (generated from plant materials, feces and refuse, or from trapping natural 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;
- 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;
- 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. Other external exposure pathways as well as ingestion exposure could also be influenced.

7CS Screening Analysis

The characteristics of the house or shelter used by the critical group are included in the 7CS.

The following characteristics of the house/shelter can be explicitly specified:

- the building materials used to construct the house, which, if contaminated by radionuclides, expose inhabitants to external radiation doses;
- the type of heating fuel used by the household;
- the building size, as specified by building height and width;
- the building air infiltration rate, i.e., the number of air exchanges per hour;
- the introduction of potentially contaminated water into the house, resulting in release of contaminants into indoor air; and
- the number of people residing in the house.

FEP Screening

Include FEP in all scenarios.

FEP # 5.2.08   Wild and natural land and water use

Description

The use of natural or semi-natural tracts of land and water such as forest, bush and lakes.

Special foodstuffs and resources may be gathered from natural land and water which may lead to significant modes of exposure. Examples include picking of wild blueberries in season as a supplement to normal diet (see also *Diet and liquid intake [5.2.03]*, notably *Hunter/gatherer diet [5.2.03.B]*), fishing (see also *Human habits (excluding diet) [5.2.04]*), and gathering of peat and wood for household heating (see also *Dwellings [5.2.07]*).

Other examples of wild and natural land and water use are discussed elsewhere under *Community characteristics [5.2.05]*, *Surface environment, human activities [1.4.06]* and *Water management (wells, reservoirs, dams) [1.4.07]*.

7CS Screening Analysis

The use of wild (or natural) land and water is included in the 7CS. The extent of such land and water use depends on the characteristics of the critical group.

For the critical group living during temperate periods (a self-sufficient farm household), the use of natural land and water is limited. The group takes its water from a well and produces most of the food it consumes. However, a natural woodlot is used to obtain wood for fuel or construction material, fish are obtained from a surface water body, peat may be burned for heating, rock may be used for construction, and lake sediment may be used for growing food.

The critical groups living during the non-temperate periods of a glacial cycle (Garisto et al. 2010), in contrast, use wild foods (caribou, fish, berries, etc.) and water from a surface water body. In the 7CS, the effects of glaciation are discussed as part of the Normal Evolution Scenario.

FEP Screening

Include FEP in all scenarios.

FEP # 5.2.09   Rural and agricultural land and water use

Description

The use of land and water for agriculture, fisheries, game ranching and similar practices.

An important set of processes are those related to agricultural practices which can affect the land form, hydrology and natural ecology, and which can also have direct effects on key elements of local food chains. Examples of such agricultural practices include:

- irrigation of gardens and fields, whether from a well or nearby surface water source;
- supply of water and local feed for domestic animals;
- draining of wetlands for farming use;
- growth of a range of crops or intensive monoculture crops; and
- use of intensive farming practices such as greenhouses or hydroponics.

Other agricultural practices, possibly having lesser impact, include:

- the use of crop fertilizers (chemicals, manure, fish meal, minerals, ashes and sewage sludge) and soil conditioners (peat moss, leaf litter or lake sediments);
- the use of herbicides, pesticides, fungicides and related products;
- recycling, particularly of organic materials in, for example, soil conditioners; and
- outdoor spraying of water to cool buildings and control dust.

Fish hatcheries and fish farming could expose fish to contaminated water, sediments and feed. Game ranching of indigenous (bison, elk) and imported (ostrich, llama) animals could affect dose impacts because many wild animals have much leaner meat or use different foods than domestic animals; also, game animals tend to be older when slaughtered. In addition, there are markets for products such as antlers and gall bladders that could represent new exposure pathways.

In considering rural and agricultural use of land and water, the duration of the use may need to be considered because 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 leaving the land fallow for an extended period.

7CS Screening Analysis

The use of land and water for agriculture is included in the 7CS. The extent of such land and water use depends on the characteristics of the critical group.

In the constant temperate climate simulations, the reference critical group is a self-sufficient farm household that uses a well. The rural and agricultural land and water practices followed by such a group potentially could include the following:

- raising poultry, beef cattle and milk cows on local land;
- growing all food needed by the household and its animals;
- irrigating gardens with well water;
- irrigating forage fields with lake water;
- using wood from a woodlot for heating and as building material;

- taking fish from a local lake;
- using wetlands for farming; and
- using lake sediments as soil.

<u>FEP Screening</u>

Include FEP in all scenarios.

FEP # 5.2.10   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.

One important consideration concerns industrial and urban water use. 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 cause substantial 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. Other considerations include inhalation and air immersion exposure, which could become more important because of vehicle traffic on dusty roads and the use of heating fuels and chemicals.

Another important 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 that could have significant impacts. For example, urban areas are often covered with impermeable surfaces which could focus deep groundwater discharges to undesirable areas, and often sewage effluent is concentrated and released at single points of discharge.

Other examples of urban and industrial land and water use are discussed under *Community characteristics [5.2.05], Surface environment, human activities [1.4.06]* and *Water management (wells, reservoirs, dams) [1.4.07]*.

7CS Screening Analysis

In the 7CS, for conservatism, dose rates are calculated for the critical group that is most exposed to contaminants released from the repository, primarily the self-sufficient farm household. They reside near the repository site, where exposure to contaminants released from the repository is expected to be highest.

Urban residents and industrial workers would be less exposed to contaminants discharged from the repository because, for example, the food and water they consume would likely come from uncontaminated sources (i.e., a supermarket with different food sources and municipal water supply). Therefore, urban and industrial land and water use is not included in the 7CS.

FEP Screening

Screened out.

FEP # 5.2.11   Leisure and other uses of the 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, mountains and wilderness areas for hiking, cross-country skiing and camping activities, caves for spelunking. Other leisure activities, such as hockey, curling, baseball and golf, might use local resources, while reading, watching television and resting might occur mostly in the residence of the critical group. Many of these activities might influence which exposure pathways have significant impacts, such as the likelihood and magnitude of external exposure to contaminated ground or inhalation exposure to contaminated air. The ratio of time spent indoors and outdoors, and hence the importance of different exposure routes, will depend on climate and the characteristics and interests of the critical group.

7CS Screening Analysis

In the 7CS, for conservatism, dose rates are calculated for the critical group that is most exposed to contaminants released from the repository, primarily the self-sufficient farm household. They reside near the repository site, where exposure to contaminants released from the repository is expected to be highest.

The leisure activities of the critical group are not explicitly included in the 7CS because they are not likely to significantly affect exposure doses. (For a self-sufficient farm household that grows its own food, gardening is not a leisure activity.) Account is, however, taken for the ratio of the time spent indoors and outdoors, and the time immersed in water (either bathing or swimming).

FEP Screening

Screened out.

5.3 Contaminant Release and Transport (biosphere)

FEP # 5.3.00   **Scope of subcategory 5.3**

Description

Factors and processes related to contaminant releases into the biosphere and contaminant transport within the biosphere.

There are twelve subcategories under Contaminant Release and Transport (biosphere):

     5.3.01 Dissolution and precipitation (biosphere)
     5.3.02 Speciation and solubility (biosphere)
     5.3.03 Sorption and desorption (biosphere)
     5.3.04 Colloid interaction and transport (biosphere)
     5.3.05 Biologically-mediated processes, excluding transport (biosphere)
     5.3.06 Water-mediated transport of contaminants (biosphere)
     5.3.07 Solid-mediated transport of contaminants (biosphere)
     5.3.08 Gas-mediated transport of contaminants (biosphere)
     5.3.09 Atmospheric transport of contaminants (biosphere)
     5.3.10 Biologically-mediated transport of contaminants (biosphere)
     5.3.11 Human action mediated transport of contaminants (biosphere)
     5.3.12 Foodchains and uptake of contaminants

FEP # 5.3.01   Dissolution and precipitation (biosphere)

Description

Dissolution and precipitation processes occurring in the surface and near-surface environment accessed by animals and plants.

Contaminants entering the biosphere from the geosphere will likely encounter quite different chemical and physical conditions, such as atmospheric concentrations of oxygen and carbon dioxide in water. These conditions may lead to precipitation at the biosphere-geosphere interface. Contaminants moving through the biosphere could be subjected to precipitation or dissolution as a result of different local conditions, or by active microbial processes. These reactions can take place in surface water and porewater 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 doses. Chemical precipitation in the soil rooting zones is usually negatively correlated with uptake by plant roots (i.e., larger solubilities correspond to greater uptake). However, precipitation in the rooting zone also immobilises contaminants, leaving them in place where they could eventually be accessed by plants, and thus may result in larger transfers over time. See also the related discussion under *Speciation and solubility (biosphere) [5.3.02]* and *Sorption and desorption (biosphere) [5.3.03].*

These processes can change in response to processes such as daily and seasonal changes in meteoric precipitation, climate change, and land change use.

7CS Screening Analysis

Precipitation (and redissolution) of contaminants in the biosphere is not explicitly modelled in the 7CS.

Many biosphere transfer parameter values used in the 7CS (notably plant concentration factors, soil K_d values) are based on field or laboratory experiments, and do not distinguish between the physical form of the element other than its physical location (e.g., attached to solid, in porewater, in tissue). Thus dissolution or precipitation occurring under these conditions would be effectively included in the parameter values, and implicitly included in subsequent analysis.

FEP Screening

Screened out, but implicitly included in the parameter values for subsequent analysis.

FEP # 5.3.02   Speciation and solubility (biosphere)

Description

Speciation and solubility processes occurring in the accessible environment. Speciation refers to the chemical forms or species of an element dissolved in water. The solubility of an element is the maximum (or saturated) concentration that can exist in the water and is dependent on the element, temperature, pressure, and water composition. An element may also be present in water as particulates; see *Colloid interactions and transport (biosphere) [5.3.04]*.

Important parameters that could influence the chemical speciation and solubility of some elements are the electrochemical potential (Eh), pH and carbonate concentration of the water (soil porewater or surface water). Waters near the surface are expected to be oxidizing but reducing conditions could prevail in aquatic sediments or deeper soils. Soil porewater composition could change with depth as fresh meteoric water containing carbonic acid undergoes chemical reactions as the water moves down through the soil profile.

Speciation of contaminants in near-surface and surface waters of the biosphere could be very important because of:

  -    the relatively large concentrations of oxygen and carbon dioxide that are dissolved in rain water and that exist in the soil porewater,
  -    organic complexes leached from decomposition products of vegetation and other organic matter,
  -    the high concentrations of humates and fulvates normally found in soils, and
  -    organic compounds and detritus produced by microbial processes.

Chemical species in the biosphere (organics such as humic and fulvic acids; inorganic ions such as chloride and nitrate, etc.) could act as complexing agents that chemically bond with a contaminant to form another stable species. The formation of new species in the biosphere can increase (or decrease) the solubility of the complexed element and can modify transport properties, for instance, by forming a neutral or anionic complex that is less likely to sorb.

The composition of waters in the biosphere, including their dependence on location (and depth) and their evolution with time, will affect contaminant speciation and solubility. 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. High solubilities increase the mobility of contaminants, but low solubilities 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 *Dissolution and precipitation (biosphere) [5.3.01]*.

7CS Screening Analysis

Contaminant speciation and solubility in the biosphere are not explicitly modelled in the 7CS.

Neglect of solubility limits in the biosphere should be reasonable because of the likely low contaminant concentrations in the biosphere due to dispersion and dilution of contaminants as they move towards the surface (see also *Dissolution and precipitation (biosphere) [5.3.01]*).

Because biosphere contaminant parameter values (e.g., soil K_d values, plant/soil concentration ratios, volatility) are based on field or laboratory experiments, chemical speciation and solubility effects could have influenced the measured experimental data. Thus, such effects are likely implicitly included in the 7CS.

FEP Screening

Screened out.

FEP # 5.3.03   **Sorption and desorption (biosphere)**

Description

Sorption and desorption processes occurring in the accessible environment including weathered overburden and subsoil, and sediments under surface water bodies. Sorption describes the physicochemical interactions of a dissolved species with a solid phase to remove the species from solution. Desorption is the opposite process.

Sorption and desorption are often described by a simple partition coefficient (K_d), 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.

Factors that affect sorption include the solid and liquid composition, the form of the species in solution (see *Speciation and solubility (biosphere) [5.3.02]*), accessible porosity in the solid and the presence of colloids (see *Colloid interactions and transport (biosphere) [5.3.04]* and *Biologically mediated processes, excluding transport (biosphere) [5.3.05])*.

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 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.

7CS Screening Analysis

In the 7CS, sorption and desorption of contaminants in the overburden, sediment and soil are modelled explicitly assuming a linear sorption isotherm characterized by a K_d value.

FEP Screening

Include FEP in all scenarios.

FEP # 5.3.04   Colloid interaction and transport (biosphere)

Description

The formation and transport of colloids, and their interaction with contaminants in the accessible environment. 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.

Several classes of colloids can be defined. Contaminants may themselves be colloids, such as polymeric plutonium. Contaminants may also be sorbed onto other naturally occurring colloids which may have

  - an inorganic base such as mineral fragments and clay,
  - an organic base such as humin (insoluble humic substances such as plant residues), or
  - a microbial base such as bacteria.

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

Colloids may influence contaminant transport by serving as a mobile carrier of otherwise highly-sorbing (and, therefore, potentially immobile) contaminants.

Colloids are common in the biosphere where agitation by surface waters may form colloids from soil, sediment and organic detritus. For instance, seasonal variations in the flow of a river may cause erosion of river banks and some of the eroded material could form suspended particulates and colloids. Contaminants sorbed on this material can become important components of aquatic food chains, or it can be transported readily and possibly be concentrated in deltas or spawning grounds.

7CS Screening Analysis

In the biosphere, colloids (or suspended particles) may contribute significantly to contaminant movement (in soils, rivers, etc.), in part because of the higher porosity of biosphere media and the presence of organic materials. For example, the international review of the US Yucca Mountain Project's biosphere model noted that "…migration of radionuclides in the soil is dominated by the migration of radionuclides that are bound to very small particles…especially for radionuclides that are strongly bound to soil." (IAEA 2001). However, data for parameters such as sorption coefficients (K_d) and transfer factors are usually derived from experiments under conditions in which contaminants may be present in colloidal and/or dissolved form. Therefore, the effect of colloids is implicitly included in these biosphere data. For these reasons, colloidal interactions and transport in the biosphere are not explicitly modelled in the 7CS.

It should be noted that, in the 7CS, contaminant movement into the biosphere is dominated by human action mediated transport (see *Human action mediated transport of contaminants (biosphere) [5.3.11]*), including well water extraction, irrigation of the garden plot, and crop harvesting. Irrigation water is generally the main source of contaminants to the local biosphere (in particular, the garden soil). In this case, there is no difference in the transfer of contaminants whether dissolved or as colloids.

<u>FEP Screening</u>

Screened out.

FEP # 5.3.05   Biologically-mediated processes, excluding transport (biosphere)

Description

The biological processes that can affect the form (species) or related properties of contaminants. Transport related processes are discussed under *Biological-mediated transport of contaminants (biosphere) [5.3.10]*.

Biological-mediated processes that could affect contaminant properties include the following.

-   The action of anaerobic bacteria could modify groundwater composition, affecting the pH and Eh and subsequently increasing or decreasing contaminant sorption and solubility. Changes to Eh would be most important for redox-sensitive elements such as technetium and plutonium.
-   Micro-organisms might metabolize or serve directly as organic complexing agents which can change solubilities and sorption properties for many elements, including iodine and many heavy metals (see *Speciation and solubility (biosphere) [5.3.02]*).
-   Bacteria and microbes may chemically transform contaminants and thereby change their sorption and solubility properties. Properties that lead to increased mobility would promote transport, while the reverse effect could cause zones of accumulation – this could increase or decrease plant uptake, depending on the species and complexes formed and the time frame.
-   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 was sloughed off (see also *Foodchains and uptake of contaminants [5.3.12]*).

7CS Screening Analysis

Biologically mediated processes (excluding transport) are not explicitly modelled in the 7CS. Rather, it is assumed that the effects of such processes, if important, are implicitly included by using parameter values from field experiments under natural conditions.

FEP Screening

Screened out, but implicitly included by using parameter values from field experiments under natural conditions.

FEP # 5.3.06   Water-mediated transport of contaminants (biosphere)

Description

Transport of radionuclides and chemical contaminants in groundwater and surface water of the accessible environment.

Contaminants released from a repository would likely enter the biosphere through discharge of deep groundwater into a lake or river; their fate, and environmental and human impact would be largely affected by subsequent transport processes. These processes include advection, diffusion and dispersion (see *Surface water bodies [5.1.04]* and *Near-surface aquifers and water-bearing features [5.1.03]*). Contaminant removal by flushing, degassing and sedimentation can then transfer contaminants to other parts of the biosphere, including deep ocean sediments where they may be effectively removed from the accessible environment for geologic times. Another water-mediated process is the direct transfer of contaminants from surface water, and surface water sediments, to fish and other aquatic biota.

Contaminant transport in the biosphere can also occur in near-surface water, including soil and sediment pore water. Contaminant transport by advection, diffusion and dispersion in soil porewater would be affected by characteristics such as soil texture, mineralogy, and porewater pH and composition (see also *Soil and sediment [5.1.02]*). Contaminants may move up and down the soil profile through capillary rise and leaching as well. Capillary rise involves the drawing up of soil water, above the water table, in continuous pores of the soil until the suction gradient upward is balanced by the gravitational pull downward. It is a key process in soil solute transport; for example, contaminants dissolved in soil water can be transported upward with capillary rise. Leaching involves the selective removal of contaminants bound to soil particles, and their subsequent transport down to the water table or laterally with runoff water. Leaching is generally associated with meteoric precipitation or irrigation, where water is supplied at the top of the soil profile.

Other factors to consider, including evolution of components of the biosphere, are discussed under *Surface Environment [5.1]*.

7CS Screening Analysis

Transport of contaminants in surface waters and the near-surface groundwater flow system is explicitly modelled in the 7CS. Water-mediated transport processes include, for example, advection, diffusion and dispersion, flushing and soil leaching. Water mediated transport of contaminants to humans (via drinking water) and non-human biota (fish) are included in the 7CS.

FEP Screening

Include FEP in all scenarios.

FEP # 5.3.07   Solid-mediated transport of contaminants (biosphere)

<u>Description</u>

The transport of contaminants in large-scale solid phase movement.

The processes of most interest are large scale erosion processes which are described throughout *External factors [1.]*, such as *Regional erosion and sedimentation [1.2.07], Volcanic and magmatic activity [1.2.04]* and *Periglacial effects [1.3.04].* However, smaller scale processes can occur, such as the downward movement of soil particles in time, as soil formation proceeds. Evidence of this is found in column studies where the density of lower horizons can increase due to particle migration following disturbance in the surface soil layers. In the aquatic environment, a similar process occurs on a horizontal plane and results in silting in of river deltas and harbours.

Transport of solids by human activities is included in *Human action mediated transport of contaminants (biosphere) [5.3.11].*

<u>7CS Screening Analysis</u>

The 7CS does not model the transport of contaminants (in the biosphere) due to the large-scale movement of solid materials (e.g., wind or water erosion) even during glaciation (see *Erosion and deposition (biosphere) [5.1.10]*). Dose rates to the most exposed individuals, who reside near the site of the repository, are calculated in the 7CS. By neglecting losses due to, for example, erosion, contaminants would remain within the local environment near the repository and so calculated impacts would be conservative.

<u>FEP Screening</u>

Screened out.

FEP # 5.3.08   Gas-mediated transport of contaminants (biosphere)

Description

The transport of contaminants in gas or vapour phase, or as fine particulate or aerosols suspended in gas or vapour, but excluding *Atmospheric transport of contaminants (biosphere) [5.3.09]*.

Contaminant gases may be generated from the wastes, e.g., C-14 as carbon dioxide or methane, and transported as dissolved gases through the repository and geosphere, and into the surface. Dissolved gases can also come out of solution within the shallow geosphere (where pressures are lower) and enter the biosphere as gases.

Alternatively, gas pressures in the repository (from corrosion of metals and decomposition of organics) could be sufficiently high to form an unsaturated phase where two-phase flow is important. Contaminant gases, aerosols or particulates may be transported with these non-toxic gases through the repository and geosphere, and into 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 [5.2.07]*. See also *Volatiles and Potential for Volatility [6.1.04], Noble Gases [6.1.06]* and *Radon and Radon Daughter Exposure [5.4.08]*.

7CS Screening Analysis

In the Normal Evolution Scenario of the 7CS, after saturation of the repository, low but non-zero gas production in the repository is expected. Although the copper containers are corrosion resistant, gas could be generated from corrosion of the carbon steel in failed containers, from corrosion of residual iron in the repository (i.e., rock bolts) and from organics in the seal materials. However, it is not expected that the amount of gas generated would be sufficient for two-phase flow to occur in the geosphere and for gas-mediated transport from the repository to the surface (see discussion under *Gas-mediated transport of contaminants (waste package) [2.4.05]*).

For the All Containers Fail Scenario, however, the rate of hydrogen gas production is sufficiently high that two-phase gas flow from the repository to the surface could occur, likely along the excavation damaged zone of the repository and shafts (NWMO 2018, Section 8). This gas could carry gaseous contaminants such as C-14 into the biosphere. Thus, gas-mediated transport of contaminants is taken into account in this scenario.

Gas-mediated transport within the surface biosphere is included in all cases. In this case, contaminants are brought to surface through groundwater, and become airborne through processes including release from lake surfaces, release into air during domestic water use, and forest fires. These air releases can then be transported via air and cause exposure.

FEP Screening

Include FEP in all scenarios with respect to gas-mediated transport of contaminants with surface (atmosphere). Gas-mediated transport of contaminants from the repository to the surface is only modelled in the All Containers Fail Scenario.

FEP # 5.3.09   Atmospheric transport of contaminants (biosphere)

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, and suspension of dusts due to wind erosion, plowing or fires (forest, agricultural and from house heating). Contaminants may also enter the indoor atmosphere from use of contaminated water in showers and air humidifiers and 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.

One important consideration, however, is that atmospheric transport can provide exposure pathways whereby contaminants move from limited discharge locations to locations where they could have a wider or more serious impact. In particular, atmospheric processes could lead to contaminant deposition onto gardens, forage fields and forests. The fallout from the nuclear accident at Chernobyl is an example in which radioactive contamination was spread hundreds of kilometres to affect remote communities in northern Sweden. See also the discussion of wet and dry deposition and related topics under *Atmosphere [5.1.07]*.

7CS Screening Analysis

Atmospheric transport (advection and dispersion) of contaminants is explicitly modelled in the 7CS. This includes the atmospheric transport and dispersion of: gases volatilized from soil and surface water bodies, aerosols generated at the interface of the atmosphere and surface water bodies, dust particles suspended from soils, and smoke from fires. The atmospheric deposition of contaminants onto soil and plants is also modelled. In this way, the critical group is exposed to radionuclides and other contaminants via the air inhalation and air immersion pathways.

FEP Screening

Include FEP in all scenarios.

FEP # 5.3.10   **Biologically-mediated transport of contaminants (biosphere)**

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 *Biologically-mediated processes, excluding transport (biosphere) [5.3.05]*.

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 take up contaminants deposited on their leaves as well. 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 *Biologically-mediated processes, excluding transport (biosphere) [5.3.05]*). More direct effects include:

-   formation of biofilms that restrict or plug groundwater flow and contaminant transport, and
-   decomposition reactions of bacteria and microbes that leach or otherwise release contaminants that have been taken up by soils, plants and animals.

This later effect is part of the larger process of natural recycling. Microorganisms have a strong influence on environmental 'cycles of matter', affecting the movement and transport of elements such as carbon, nitrogen and oxygen (and contaminants) through the biosphere, geosphere, hydrosphere, atmosphere and anthrosphere.

Some transport related effects of plants and animals are discussed under *Surface environment [5.1]*. See also factors such as bioconcentration, bioaccumulation and biomagnification, as discussed under *Ecological systems [5.1.11]*.

7CS Screening Analysis

Some biologically-mediated contaminant transport processes are explicitly modelled in the 7CS, including:

    (1) bioturbation in soils,
    (2) uptake of contaminants from soils by plants,
    (3) uptake of contaminants from soil, water, and plants by animals, and
    (4) uptake of contaminants from soil, water, and plant and animal foodstuffs by humans.

Some biologically-mediated transport processes are only implicitly modelled, including:

    (1) recycling of contaminants in animal droppings,
    (2) recycling of contaminants in falling leaves, and
    (3) translocation of contaminants from plant surfaces to internal plant parts.

These latter processes are implicitly treated by use of conservative models. For example, contaminants are not 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; i.e., 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.

FEP # 5.3.11   Human action mediated transport of contaminants (biosphere)

Description

The transport of 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 itself or contaminated overburden or sediments from lakes, rivers and estuaries. These actions result in the transport of contaminated rock, soil or water to the accessible environment. Large-scale activities, such as dam construction, may result in the movement of large volumes of contaminated solid material from one part of the biosphere to another, and to the diversion of groundwater flow regimes that affect discharge locations of contaminated water. Smaller scale and often seasonal activities, such as plowing, which results 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 collected 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 [1.4]* and *Human behaviour [5.2]*.

7CS Screening Analysis

Transport of contaminants by human action is explicitly modelled in the 7CS. In particular, the critical group extracts water from a well and uses well water to irrigate a garden plot. These are important processes by which contaminants enter the biosphere. Other explicitly modelled processes are the use of wood or peat for fuel.

In the Inadvertent Human Intrusion Scenario, the consequences of moving used fuel to the surface as a result of drilling are modelled.

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 plowed. The assumption that contaminants are not depleted from the soil by plant uptake could imply that humans recycle their waste to the soil (i.e., use compost piles).

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.

FEP # 5.3.12   **Foodchains and uptake of contaminants**

<u>Description</u>

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 systems [5.1.11],* include:

-   biotransformation or metabolism which involves catabolism (breaking down of more complex molecules), anabolism (building up of life molecules from simpler materials) and cometabolism (biodegradation of synthetic or hazardous waste materials concurrently with catabolism);
-   bioconcentration, which refers to the ability of an organism to concentrate contaminants from its environment, usually from water or soil;
-   bioaccumulation, which refers to the tendency of an organism to continue to bioconcentrate contaminants throughout its lifetime;
-   biomagnification, which refers to the occurrence of contaminants at successively higher concentrations with increasing trophic level in the food web;
-   biological interim storage, which refers to temporary holdback of contaminants;
-   recycling, which refers to the reuse of contaminants; and
-   biological feedback, which has 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 contaminants through 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 and water.

Microorganisms also form part of the human food chain, directly with foods such as yogurt and indirectly through processes such as fermentation.

The complexity of possible routes is caused, in part, by the fact that both domestic and wild plants and animals might serve as a source 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 in the same species;
-   may include plants, fruits, water and other animals (by scavengers and predators); and
-   may include food supplements, man-made and natural salt licks; 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>7CS Screening Analysis</u>

The human food chain is modelled in the 7CS. This includes the following human ingestion exposure pathways:

- Soil to humans
- Soil to plant to humans
- Soil to plants to animals to humans
- Soil to animals to humans
- Water to humans
- Water to plants to humans
- Water to soil to plants to humans
- Water to animals to humans
- Air to plants to humans
- Air to animals to humans
- Air to plants to animals to humans.

The transfers implied by these exposure pathways are treated using linear steady-state transfer factors in the 7CS biosphere model. These transfer factors are based on empirical data and, hence, implicitly include the effects of biological processes such as bioconcentration and bioaccumulation.

<u>FEP Screening</u>

Include FEP in all scenarios.

5.4 Exposure Factors

FEP # 5.4.00   Scope of subcategory 5.4

<u>Description</u>

The processes and conditions that directly affect the dose to potentially affected humans or biota from the presence of contaminants in the surrounding environment.

There are eight subcategories under Exposure Factors:

     5.4.01 Contaminated drinking water and foodstuffs
     5.4.02 Contaminated environmental media
     5.4.03 Other contaminated materials
     5.4.04 Exposure modes
     5.4.05 Dosimetry
     5.4.06 Radiological toxicity effects
     5.4.07 Chemical toxicity effects
     5.4.08 Radon and radon daughter exposure

FEP # 5.4.01   Contaminated drinking water and foodstuffs

Description

The presence of contaminants in drinking water, foodstuffs and other items that may be consumed by humans.

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 and intermediaries. However, factors such as bioconcentration, bioaccumulation and biomagnification can elevate concentrations of some contaminants in foodstuffs and may result in significant exposure to particular contaminants.

See also the related discussion under *Foodchains and uptake of contaminants [5.3.12]* and throughout *Human behaviour [5.2],* particularly under *Diet and liquid intake [5.2.03].*

7CS Screening Analysis

Exposure to contaminated drinking water and foodstuffs is explicitly included in the 7CS. Foodstuffs include fish, plants, and meat and milk products. Related exposure factors include the drinking water ingestion rate, the food ingestion rates of the various food types (meat, plants, milk, poultry, and fish) and the total human energy requirement. The food ingestion rates are prorated, if needed, so that the total human energy intake equals the total human energy requirement.

FEP Screening

Include FEP in all scenarios.

FEP # 5.4.02   Contaminated environmental media

<u>Description</u>

The presence of contaminants in environmental media including soil, water, and air.

Contaminant concentrations in environmental media will be important in assessing the impact on biota, and humans (via both the ingestion and external exposure pathways). 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 of 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 grassfires. The discussions under *Surface environment [5.1]* describe features and processes that could contribute to contamination of environmental media and the discussions under *Contaminant release and transport (biosphere) [5.3]* provide more specific detail on how contaminants from the repository (including mine wastes excavated from construction of the repository) could move though and enter different compartments of the accessible environment. The accessible environment of concern is discussed under *Human behaviour [5.2]* and *Exposure modes [5.4.04]*.

Some media might attain higher concentrations than their surroundings because of natural processes such as bioaccumulation or evaporation of water. 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 (biosphere) [5.3.11]*).

<u>7CS Screening Analysis</u>

Contaminant concentrations in environmental media are explicitly calculated by the 7CS safety assessment models. The environmental media included in the 7CS are: indoor and outdoor air, well water, soil, plants and non-human biota.

<u>FEP Screening</u>

Include FEP in all scenarios.

FEP # 5.4.03   **Other contaminated materials**

Description

The presence of 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;
- peat, charcoal and biogas (from plant materials, feces and refuse, or from trapping natural methane, from garbage disposal sites, bogs and sediments) for use in house heating; and
- water used in showers and humidifiers and in cooling or washing.

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.

Direct consumption exposure through foods and water is explicitly treated elsewhere, see *Foodchains and uptake of contaminants [5.3.12]*.

7CS Screening Analysis

In the 7CS, exposure to the following "other contaminated materials" is explicitly modelled:
- direct gamma dose from building materials made from wood and soil;
- release to air from heating fuels such as peat and wood; and
- release to air from water used in showers and bathing.

FEP Screening

Include FEP in all scenarios.

FEP # 5.4.04   Exposure modes

<u>Description</u>

The exposure of humans and biota to 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 chemically toxic species differ in their ability to affect organisms.

-   Radiotoxic materials can lead to impacts through internal or external exposure.
-   Chemically toxic species impacts require direct contact, including internal exposure or through skin (surface) contact.

There are two subcategories under this FEP:

    5.4.04.A Exposure of humans
    5.4.04.B Exposure of biota other than humans.

FEP # 5.4.04.A   Exposure of humans

Description

The important internal and external exposure modes affecting humans are:

-   ingestion (internal) exposure from drinking and eating contaminated water, food, soil and dust;
-   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 moisturizers. In the specific case of tritiated water vapour, skin sorption could be more important than inhalation;
-   inhalation (internal) exposure from inhaling gaseous and particulate contaminants; and
-   external exposure from irradiation by radionuclides deposited on, or present on, the ground (groundshine), buildings, vegetation, animals, rocks and other objects, and as a result of immersion in contaminated water bodies and air.

The exposure pathways listed above need not be explicitly modelled to determine potential impacts on humans. For example, the impact of human exposure to chemically toxic species can be determined by comparison of contaminant concentrations in the biosphere to selected chemical toxicity concentration criteria. If the ratio of a contaminant concentration to the corresponding toxicity criterion is less than one then the exposure to that concentration in the biosphere would be considered non-detrimental to humans. In this case, the concentration criteria would have been based on the appropriate exposure modes.

7CS Screening Analysis

Human exposures to internal and external radiation doses are explicitly modelled in the 7CS. Internal exposure is from ingestion of soil, water and food stuffs, and inhalation of dust and air. External exposure is from exposure to contaminated media outside the body. The external human exposure pathways modelled in the 7CS include: air immersion, ground exposure, water immersion and building material exposure.

Human exposures to chemically toxic elements are evaluated for the Normal Evolution and the All Containers Fail Scenarios. A food chain model is not used to determine the impact on humans of potentially chemically toxic elements released from the repository. Rather, as was done in Garisto et al. (2005b), concentrations of chemically toxic elements in various biosphere compartments (e.g., soil and surface water) are compared to selected chemical toxicity criteria.

FEP Screening

Include FEP in all scenarios.

FEP # 5.4.04.B   Exposure of biota other than humans

Description

Exposure modes affecting biota other than humans.

Biota can be divided into two broad groups:

-   domesticated and cultivated species, which may have relatively well known properties, including information on diet and contaminant transfer processes; and
-   wild and indigenous species, whose characteristics may be less well understood.

The latter group may be of most concern for a remote disposal site because the most contaminated areas could be wetlands and surroundings that constitute a habitat for coniferous trees, fruit-bearing bushes and trees, lichens, annual and perennial vegetation, mammals with long life spans (moose, bear, and deer) or short life spans (voles, mice), many species of birds (seed-eating, insectivorous, aquatic-based and raptorial), and a large number of aquatic plants, amphibians, fish, invertebrates and other species. The properties of these biota 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 fish may experience relatively unique impacts involving external exposure to contaminated lake sediment.

The exposure pathways would be similar to those for humans - inhalation, ingestion, external contamination or irradiation. However, the relative importance of these pathways would depend on the particular species. For example,

-   Absorption through skin may be an important pathway;
-   Burrowing animals are more directly exposed externally and internally to contaminated soils and sediments;
-   Aquatic plants take up contaminants from the water column and the atmosphere (emergent plants), or from the water as well as the sediments (submergent plants).

These exposure pathways need not be explicitly modelled to determine potential impacts on non-human biota. For example, the impact of exposure to chemically toxic species can be determined by comparison of contaminant concentrations in various biosphere compartments to selected chemical toxicity concentration criteria that are based on the appropriate exposure pathways. If the ratio of a contaminant concentration to the corresponding toxicity criterion is less than one then the exposure to that concentration in the biosphere would be considered non-detrimental to the non-human biota.

7CS Screening Analysis

In the 7CS, radiological impacts on non-human biota of radionuclide releases from the repository are assessed for the Normal Evolution and All Containers Fail Scenarios. This is carried out using the approach described by Medri and Bird (2015).

In the 7CS, the impacts on non-human biota of chemically toxic elements released from the repository are estimated for the Normal Evolution and All Containers Fail Scenarios. The chemical toxicity criteria used in the 7CS are protective of both humans and non-human biota (NWMO 2018).

<u>FEP Screening</u>

Include FEP in the Normal Evolution Scenario and All Containers Fail Scenario.

FEP # 5.4.05   Dosimetry

<u>Description</u>

Dosimetry describes the dependence between radiation or chemical toxicity effect(s) and the amount of radiation or chemical agent in the organs, tissues or the whole body. Different species will have different dosimetry.

Doses depend on factors that include:

-   form of exposure, e.g., internal or external exposure;
-   metabolism of the radioelement and physicochemical form if inhaled or ingested;
-   residence time in the tissue or organ,
-   energy and type of radioactive emissions of the radionuclide; and
-   the age at time of exposure and the lifetime commitment to the exposure.

Special considerations pertaining to radioactive material is the decay of a parent radionuclide (or precursor) to its daughter radionuclide (or progeny), as described below.

1.   The precursor and progeny can have substantially different chemical and physical properties. These differences can affect the movement of contaminants through an organism.
2.   The precursor and progeny can have quite different toxicity properties. One important example of these effects is discussed in *Radon and Radon Daughter Exposure [5.4.08]*.

Many radionuclides have an Annual Derived Limit (ADL) for intake by human workers, which represents a level above which there could be an unacceptable risk of harmful effects (ICRP 1991b).

Similar comments apply to chemical toxic effects, except that chemical and biochemical disruption of cell functions, not radioactive emissions, affects the tissues of the body. Chemical toxics can have a wide variety of effects on biota, and the dose response of an organism is often reported as intake levels such as the No Observed Adverse Effect Level, the lowest intake observed to produce lethal effects in a population, or the level which would have lethal effects to 50 percent of the population (LD50). The chemical form of a compound plays an important role in determining whether or not, and how, the toxic component interacts with cells and tissues. A very large number of chemical compounds exist but suitable quantitative dosimetry data may be sparse.

<u>7CS Screening Analysis</u>

In the 7CS, radiological impacts on humans and non-humans are calculated. Also, the impacts of chemically toxic elements on human and non-humans are evaluated for the Normal Evolution and All Containers Fail Scenarios.

Radiation dosimetry is included in the 7CS by use of adult (whole body effective) internal and external dose coefficients based on the recommendations of the ICRP (ICRP 1991a).

The internal dose coefficients (ingestion and air inhalation) are taken from ICRP72 (ICRP 1996). The external air immersion, water immersion and ground exposure dose coefficients are taken from Eckerman and Leggett (1996). The external building exposure coefficients are calculated

as described in Gobien et al. (2018).

Whole body effective dose coefficients are calculated taking into account, for example, the radiation energies and types emitted by the radionuclides, the half-life of the radionuclide, the residence time of the radionuclide in the body, the organs affected by the radionuclide, tissue weighting factors, radiation weighting factors, etc. The calculated dose rates will include the effects of decay chains, either by explicitly modelling the chains or by including the contribution from the daughters in the dose coefficient for the parent (e.g., Gobien and Garisto 2012).

In the 7CS, non-human radiological doses from internal and external exposure are calculated using the approach described by Medri and Bird (2015).

The potential impacts on humans and non-human biota of chemically toxic elements released from the repository are evaluated for the Normal Evolution and All Containers Fail Scenarios. The potential impacts are determined by comparing concentrations of chemical toxic elements in various biosphere compartments to criteria for chemical toxicity effects (NWMO 2018).

FEP Screening

Include FEP in all scenarios.

FEP # 5.4.06   **Radiological toxicity effects**

<u>Description</u>

The effects of radiation on humans and other organisms.

Radiation effects can be classified in several different ways:
- somatic or genetic, occurring in the exposed individual or in the offspring of the exposed individual, respectively; and
- stochastic or nonstochastic, where the probability of the effect is a function of dose received) or the severity of the effect is a function of dose received and no effect may be observed below some threshold, respectively.

At high exposure levels, radiation can kill cells outright, leading 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, because of mutations that may lead to cancer or, if the reproductive cells are affected, hereditary effects that may be detrimental 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 brain development and mental capacity.

If 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 [5.4.07]*.

<u>7CS Screening Analysis</u>

In the 7CS, radiological impacts on humans and non-humans are calculated.

Human dose rates and / or risks are calculated as follows:

1. The concentration of a radionuclide in an environmental medium is multiplied by a dose coefficient and other factors, e.g., annual duration of exposure or amount of material ingested, to obtain a dose equivalent in Sieverts per year (Sv/a).

   In the 7CS, radiological exposures to humans are converted to dose rates using dose coefficients based on the 1990 ICRP recommendations (ICRP 1991a) because, at present, dose coefficients based on the 2007 recommendations (ICRP 2007) are not available. However, the new recommendations do not lead to changes in dose limits and are based on the Linear No-Threshold model (see Figure 3-12). Hence, dose coefficients are not expected to change substantially (Wrixon 2008).

   Human internal and external dose coefficients are from ICRP 72 (ICRP 1996) and Eckerman and Leggett (1996), respectively, which are based on the 1990 ICRP recommendations. The air inhalation dose coefficients are determined by selecting the chemical species that lead(s) to the highest dose (Gobien and Garisto 2012).

2. The total dose to an individual is the sum of the dose equivalents from all radionuclides and all exposure routes for a given exposure scenario.

3. This total dose may be multiplied by a risk or dose-to-risk conversion factor, which converts the total dose into a specified health effect. The factor 0.057/Sv may be used for converting a human dose rate to a risk of serious health effects, including fatal cancers, detriment from non-fatal cancers, and serious genetic effects (ICRP 2007).

Human dose rates are compared to the criterion for radiological protection of persons (ICRP 2007). For dose rates below this level, it is expected that the risk of radiological toxicity from both stochastic and deterministic effects are negligible.

In the 7CS, radiological impacts on non-humans are evaluated for the Normal Evolution and All Containers Fail Scenarios. Non-human radiological doses are calculated in the 7CS using the approach described in Medri and Bird (2015) and are compared to the criterion for radiological protection of non-human biota (NWMO 2018, Section 7).

FEP Screening

Include FEP in all scenarios.

Models for the Health Risks from Exposure to Low Levels of Ionizing Radiation

Risk (excess cancers)

Approximate lowest dose where excess cancer has been observed

100 mSv

Dose (above background)

- ·········· Hypersensitivity
- ———— LNT
- — — — Threshold
- = = = Hormesis
- ● Epidemiological data
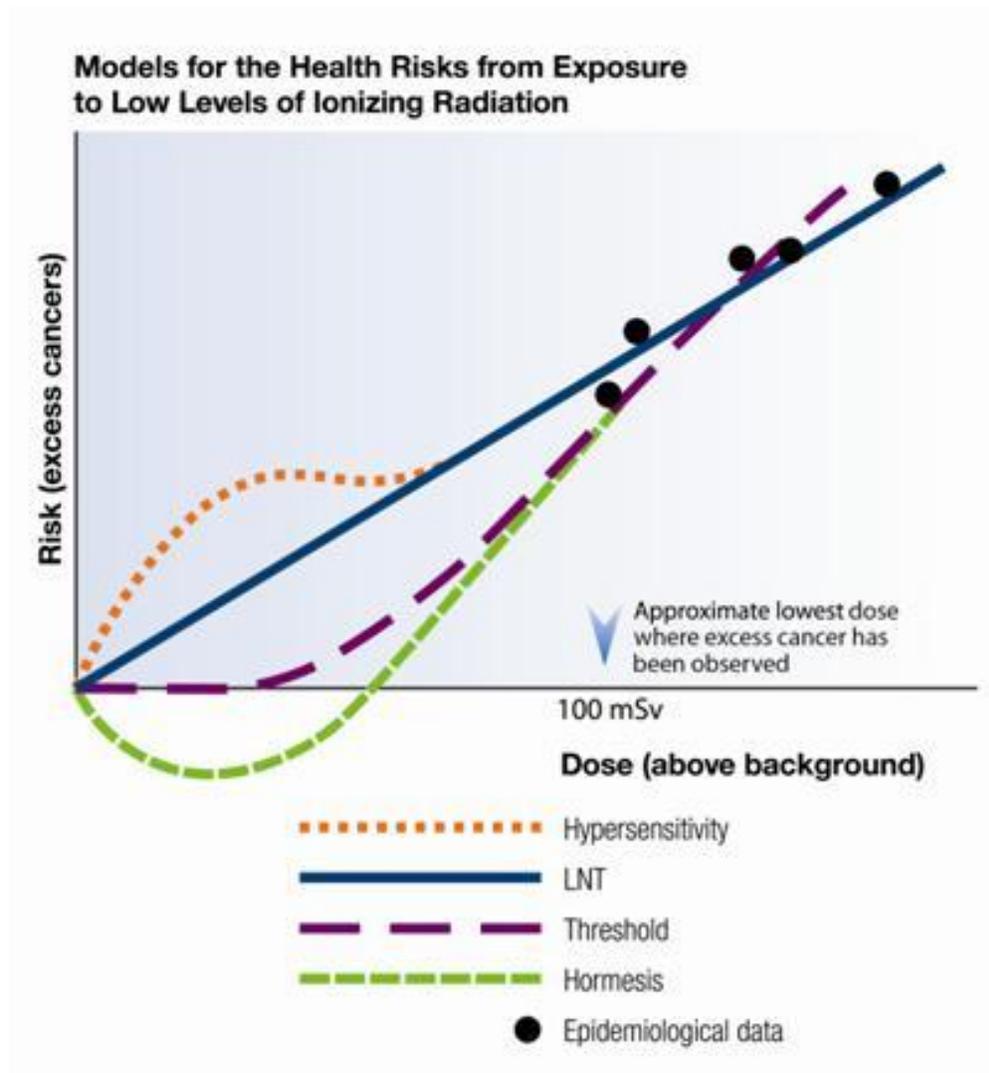
Note: Taken from CNSC website, http://www.nuclearsafety.gc.ca/eng/pdfs/reading-room/healthstudies/Fact-Sheet-Linear-Non-Threshold-Model-2013.pdf**, accessed November 2017**

Figure 3-12: Health Risk from Low Levels of Radiation Showing the Reference Linear-No-Threshold (LNT) Model and Others as Well as the Limit of Epidemiological Data

FEP # 5.4.07   Chemical toxicity effects

Description

The effects of chemically toxic species on humans and other organisms.

Some elements in nuclear fuel waste can be chemically toxic to humans and other organisms, including plants. Some radionuclides may also be chemically toxic, for instance:

-   naturally occurring uranium is a heavy metal and as such is chemically toxic;
-   Tc-99 may be more chemically toxic than radiotoxic (Coffey et al. 1984, Gerber et al. 1989); and
-   I-129 may be more chemically toxic than radiotoxic to non-human biota.

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, leading to subsequent disruption of food chains that may affect other biota. Detrimental impacts can be found for most elements, but health and environmental impacts from arsenic, cadmium, chromium, lead, mercury and selenium are among those that have received the greatest attention. See also *Radiological toxicity effects [5.4.06]*.

Another issue of concern is synergistic effects (and its opposite, antagonistic effects) or the combined effects of two or more radiotoxic or chemotoxic species on human and other organisms. Two or more toxic substances may interact with each other, or interact jointly with an organism, to produce biological effects that can be different in extent and kind than 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 an organism. In addition, an inactive substance may enhance the action of an active substance (potentiation) or an active substance may decrease the effect of another active substance (antagonism). Some effects, such as hormesis, i.e., the beneficial effect of a toxic at low dose rates, may be beneficial.

7CS Screening Analysis

In the 7CS, the impacts on humans and non-human biota of releases of potentially chemical toxic elements from the repository are assessed for the Normal Evolution and All Containers Fail Scenarios. The impacts are assessed by comparing concentrations of potentially chemically toxic elements in biosphere compartments to the selected criteria for chemical toxicity effects (NWMO 2018), as described in Garisto et al. (2005b).

The issue of synergistic effects is not considered in the 7CS.

FEP Screening

Include FEP in the Normal Evolution and All Containers Fail Scenarios.

FEP # 5.4.08   Radon and radon daughter exposure

Description

Radon and radon daughter exposure is considered separately to exposure to other radionuclides because the behaviour of radon and its daughters, and their modes of exposure, are somewhat unique.

Radon-222 is mobile (see *Noble gases [6.1.06]*) and can readily enter different components of the biosphere. It has a short half-life (about 4 days), as does its immediate daughters, Po-218, Pb-214, Bi-214 and Po-214 (the next decay product, Pb-210 has a half-life of 21 years). The consequence is that exposure to Rn-222 almost always implies exposure to its short-lived daughters 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 thought to be inhalation of radon daughters attached to dust particles, which then deposit in the respiratory system. This particular exposure mode is thought to be a large (and in some cases the largest) component of dose to humans received from natural background sources of radiation, and is thought to arise primarily from infiltration of Rn-222 into human dwellings.

7CS Screening Analysis

The dose rate from exposure to Rn-222 calculated in the 7CS includes doses from radon daughters due to the decay of U-238 from the used fuel. 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 nuclides (UNSCEAR 2000, Gobien and Garisto 2012).

FEP Screening

Include FEP in all scenarios.

6. CONTAMINANT FACTORS

FEP # 6.0.00   **Scope of main category 6.**

<u>Description</u>

Factors describing the characteristics of contaminants placed in the repository. Contaminants include radionuclides and potentially chemically toxic elements.

There is one category under Contaminant Factors:

   6.1 Contaminant characteristics

6.1 Contaminant Characteristics

FEP # 6.1.00   Scope of subcategory 6.1

<u>Description</u>

The characteristics of the radionuclides and other contaminant species that might be considered in a postclosure safety assessment.

There are six subcategories under Contaminant Characteristics:

      6.1.01 Radioactive decay and ingrowth
      6.1.02 Chemical and organic toxin stability
      6.1.03 Inorganic solids and solutes
      6.1.04 Volatiles and potential for volatility
      6.1.05 Organics and potential for organic forms
      6.1.06 Noble gases

FEP # 6.1.01 Radioactive decay and ingrowth

<u>Description</u>

Radioactive decay is the spontaneous disintegration 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 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.

The decay rate of a radioactive isotope is inversely related to the decay half-life. Half-lives can range from fractions of a second to billions of years. Half-life and decay rate are not sensitive to temperature, pressure, chemical reactions, magnetic fields or other physical conditions within a repository. Atomic nuclides can be converted into other nuclides by processes involving bombardment with neutrons, intense particles, or very high-energy photons. These latter processes are generally collectively referred to as "transmutation".

The inventories of radionuclides of potential concern are described in *Waste inventories [2.1.01]*.

<u>7CS Screening Analysis</u>

Radioactive decay and ingrowth is explicitly accounted for in the 7CS throughout the modelled system, including the repository, geosphere and biosphere.

<u>FEP Screening</u>

Include FEP in all scenarios.

FEP # 6.1.02   **Chemical and organic toxin stability**

<u>Description</u>

The ability of a toxic chemical element or compound, including toxic organic compounds, to resist changes which 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.

The inventories of chemical substances of potential concern are described in *Waste inventories [2.1.01].*

<u>7CS Screening Analysis</u>

In the 7CS, the potential impacts on humans and non-human biota of releases of potentially chemically toxic elements from the repository are evaluated for the Normal Evolution and All Containers Fail Scenarios using the approach described in Garisto et al. (2005b). The chemical form of the element is generally not taken into account with respect to transport of the element through the geosphere or biosphere, but for purposes of the assessment it is assumed that the element is in a relatively simple stable form.

<u>FEP Screening</u>

Include FEP in the Normal Evolution and All Containers Fail Scenarios.

FEP # 6.1.03   Inorganic solids and solutes

<u>Description</u>

The characteristics of other contaminants or constituent inorganic solids and solutes that may be of concern.

Contaminants of concern 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, Zr-93 will have the sorption and precipitation characteristics of zirconium. The most abundant isotope in used fuel, U-238, is an inorganic element. Also, most minerals in the geosphere and substances introduced into the repository are inorganic compounds.

The inventories of substances of potential concern are described in *Waste inventories [2.1.01].*

<u>7CS Screening Analysis</u>

The inventories of substances of potential concern are described in *Waste inventories [2.1.01].*

In the 7CS, the transport of inorganic contaminants is included in the modelling of the repository, geosphere and biosphere.

<u>FEP Screening</u>

Include FEP in all scenarios.

FEP # 6.1.04   Volatiles and potential for volatility

Description

The characteristics of 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 *Noble gases [6.1.06]*) or may form volatile compounds, such as C-14 incorporated into carbon dioxide or methane, I-129 forming iodine gas, and tritium (H-3) incorporated into hydrogen gas or water vapour. Similar comments apply to the stable isotopes of these and other elements.

Gaseous and volatile species may be transported in the gas phase if the volume and pressure of the gas is sufficiently high. Gaseous and volatile species might also be transported as dissolved species in groundwater, but subsequently released as gases upon discharge into the biosphere. For instance, carbon dioxide is highly soluble in groundwater, and often appears as bubbles near a discharge area. See also *Gas sources and effects (repository) [3.2.06]* and *Gas processes (geosphere) [4.2.07]*.

7CS Screening Analysis

The potential for certain radionuclides to volatilize, for example, C-14, I-129 and Rn-222, is taken into account in the biosphere model.

The amounts of volatile or semi-volatile contaminants released from the fuel in a defected container should be sufficiently low that a gas phase does not form (i.e., the vapour pressure of the dissolved element does not exceed the hydraulic pressure) and so these contaminants should dissolve in and move through and with the groundwater.

However, a hydrogen gas phase might form by corrosion of the steel in failed containers. In this case volatile or semi-volatile contaminants could be transported in the gas phase. In the 7CS Normal Evolution Scenario, formation of such a hydrogen gas phase in the repository or geosphere is not modelled, as discussed under *Gas sources and effects (repository) [3.2.06]* and *Gas processes (geosphere) [4.2.07]*, because only a small amount of hydrogen gas is generated when there are only 10 breached containers in the repository. However, in the All Containers Fail Scenario, the formation of a gas phase in the repository is considered as is the gas phase transport of volatile and semi-volatile radionuclides from the repository to the surface (NWMO 2018, Section 8).

FEP Screening

Include FEP in all scenarios.

FEP # 6.1.05   Organics and potential for organic forms

Description

The characteristics of contaminants that can be incorporated into organic species under repository or surface environment conditions. This process is likely to be mediated by biological processes.

This category includes organic compounds containing 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 other inorganic mercury compounds and are more likely to contaminate aquatic biota. See also *Biological processes and conditions (repository) [3.2.05], Biological processes and conditions (geosphere) [4.2.06]* and *Ecological systems [5.1.11].*

7CS Screening Analysis

The chemical form of contaminants, including formation of organic forms, is not explicitly modelled in the 7CS. Transport properties and transfer factors are generally empirically based. Thus, the effect of chemical speciation is implicitly accounted for in the selection of associated parameter values, e.g., soil sorption coefficients, which are often derived from field values and reflect typical speciation.

FEP Screening

Screened out, but implicitly included in transport properties.

FEP # 6.1.06.   Noble gases

<u>Description</u>

The characteristics of the noble gases: helium, neon, argon, krypton, xenon and radon (He, Ne, Ar, Kr, Xe and Rn).

Because these elements are chemically inert, they are largely unaffected by sorption, will not precipitate, and will move with little delay through various transport media. One isotope of special concern is Rn-222, the decay product of Ra-226. The behaviours of Rn-222 and its daughters are unique and can lead to different modes of exposure to humans, as described under *Radon and radon daughter exposure [5.4.08].*

<u>7CS Screening Analysis</u>

The characteristics of the radionuclides of the noble gases Kr, Ar and Rn are explicitly accounted for in the 7CS. The radionuclides of the other noble gases are relatively short lived (with no long-lived parents or daughters) and are, therefore, neglected because they do not contribute to the calculated postclosure radiological dose rates.

<u>FEP Screening</u>

Include FEP in all scenarios.

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