Fourth Case Study: Features, Events and Processes

NWMO TR-2012-14 **November 2012**

F. Garisto

Nuclear Waste Management Organization

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ABSTRACT

Title: **Fourth Case Study: Features, Events and Processes**
Report No.: **NWMO TR-2012-14**
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Company: Nuclear Waste Management Organization
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Abstract

The Fourth Case Study is a postclosure safety assessment of a deep geologic repository for used CANDU fuel at a hypothetical site in the Canadian Shield. It differs from the previous Third Case Study in that it considers a repository holding 4.6 million used fuel bundles (rather than 3.6 million), a revised repository design, a different repository depth (500 m rather than 670 m), and a hypothetical repository site with different characteristics.

The reference container has an outer copper shell for corrosion protection, an inner steel vessel for structural support, and a capacity to hold 360 used fuel bundles. The containers are placed with an in-floor placement design, whereas in-room placement or horizontal borehole placement was considered in the Third Case Study. The repository is located at the same hypothetical site as in the Third Case Study, but with different fracture and rock properties. The repository is placed at a depth of 500 m as a design assumption.

The safety assessment of a repository must consider a broad range of factors that could potentially affect the behaviour of the repository, contaminants arising from it and its 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. Thus, this report provides a structured and comprehensive list of possible FEPs relevant to the Fourth Case Study design and site. For each FEP, this report:

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

The development of a safety case for a site-specific safety assessment would proceed in stages from conceptual to detailed studies. The Fourth 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 Fourth Case Study is a postclosure safety assessment of a geological repository for used nuclear fuel. It is intended to illustrate NWMO's approach for assessing safety through an illustrative safety assessment for a deep geological repository at a hypothetical site in crystalline rock (NWMO 2012, Section 1).

The current study builds upon previous safety assessment studies that were completed by Atomic Energy of Canada Limited and Ontario Power Generation, including the Environmental Impact Statement (EIS) case study (Goodwin et al. 1994), the Second Case Study (SCS) (Goodwin et al. 1996) and the Third Case Study (Gierszewski et al. 2004, Garisto et al. 2005a). The level of detail is consistent with the pre-project stage and is not a full safety case. The Fourth Case Study postclosure safety assessment has been developed following regulatory guidance in CNSC G-320 (CNSC 2006).

The Fourth Case Study is similar to the Third Case Study (TCS) postclosure safety assessment in that the repository is located within the same hypothetical regional area of the Canadian Shield, but with different site properties. However, the Fourth Case Study considers a repository with 4.6 million used fuel bundles (rather than 3.6 million), a revised container design, a different repository design with in-floor container placement (rather than in-room or horizontal borehole placement), and a different repository depth (500 m rather than 670 m).

1.2 FOURTH CASE STUDY SCOPE

The postclosure safety of the repository system is assessed through consideration of a range of potential scenarios. Scenarios are postulated or assumed set of conditions or events that represent the possible future evolution of a repository and its surroundings (CNSC 2006). In the Fourth Case Study, both a Normal Evolution Scenario and Disruptive Event Scenarios are considered, where:

- 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 site and repository, and addresses the effects of anticipated extreme conditions, and in particular, 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 screening analyses of the features, events and processes (FEPs) presented in Section 3, as described in NWMO (2012, Section 6).

The scope of work for the Fourth Case Study has been limited to provide a demonstration of the approach to assessing safety, but the analysis is not as complete as would be required for a licensing submission for a real site. The following lists excluded areas of scope that might otherwise be included in a licensing submission, as further discussed in Section 7.2 of NWMO (2012):

- Variable Climate Analysis. The potential impacts of glaciation are discussed for the Normal Evolution Scenario, based on previous work. No new simulations of glaciation were done for the Fourth Case Study.
- Radiological Consequence Analysis. The consequence analysis for non-human biota is only performed for the Normal Evolution and All Containers Fail Scenarios.
- Non-Radiological Consequence Analysis. The effects of non-radiological releases from the repository are only evaluated for the Normal Evolution and All Containers Fail Scenarios.

1.3 REPORT OUTLINE

The present report supports the Fourth Case Study 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 colloid transport) that were considered in developing the models used in the quantitative analyses.

Specifically, not all potential features, events and processes ("FEPs") 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 features, events and processes are included or excluded in the quantitative analyses of the Fourth Case Study.

To provide a more comprehensive method for ensuring that all relevant factors are considered, and to provide a record of the reasoning, these factors have been collected into a structured format. This format follows the organization developed by the OECD Nuclear Energy Agency (NEA 2000) for characterizing system level features, events and processes.

Since the Third Case Study and Fourth Case Study sites and repository designs are very similar, the approach taken in the current study was to start with the FEP analyses for the Third Case Study (Garisto et al. 2004b). As expected, for most FEPs, the Third Case Study screening analysis remains valid, i.e., if the FEP is included (excluded) in the Third Case Study safety assessment then it is included (excluded) in the Fourth Case Study. However, some differences do arise due to the somewhat different scope of work in the two studies (e.g., the study of the impact of glaciation was not in the scope of work of the Third Case Study). More importantly, the FEP analyses were updated, as needed, to include more recent work and current thinking.

The report is organized as follows:

- **Section 2** provides a list of all Features, Events and Processes (FEPs) considered.
- **Section 3** examines each FEP in turn, provides a brief analysis with references, and concludes whether they should be specifically included or excluded in the quantitative analyses within the Fourth Case Study.
- **Appendix A** summarizes the history of this report, including the qualifications of the main contributors and reviewers.

2. FEP SUMMARY LIST

Features, events and processes are factors that can affect the performance and safety of a deep geologic repository. The FEPs list used for the Fourth Case Study follows the organisation of the international FEPs database developed by the OECD Nuclear Energy Agency (NEA 2000). All FEPs are organized under four main categories:

0. Assessment basis - defines the scope of the assessment;
1. External factors - describe factors outside the repository system;
2. Repository factors - describe features (properties) and processes associated with the repository and its surrounding geosphere and biosphere; and
3. Contaminant factors - describe the release, migration and impact of contaminants.

These FEPs are identical to those in the NEA database Version 1.2, with the following exceptions:

- NEA FEPs *0.08 Aims of the Assessment* and *0.09 Regulatory Requirements* have been moved up to the beginning of the Assessment Basis category, since they provide context for the analysis of the other Assessment Basis FEPs.
- NEA FEP *1.4.02 Motivation and Knowledge Issues* has been defined as *Deliberate Human Intrusion* here.
- NEA FEP *3.3.07 Non-radiological Toxicity/Effects* has been defined as *Chemical Toxicity Effects* here.

In a number of cases, we have divided a given NEA FEP into more specific sub-FEPs where we have found it 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 Chemically Toxic Contaminants*.

The assessment basis FEPs are listed in Table 2.1.

Table 2.1: Assessment Basis FEPs

0.0	**Assessment Basis**	
	0.0.01	Aims of the assessment
	0.0.02	Regulatory requirements and exclusions
	0.0.03	Impacts of concern
	0.0.04	Time scales of concern
	0.0.05	Spatial domain of concern
	0.0.06	Repository assumptions
	0.0.07	Future human action assumptions
	0.0.08	Future human behaviour (target group) assumptions
	0.0.09	Dose response assumptions

The repository 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 repository 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 2.2 and the Internal FEPs are listed in Table 2.3. There are more than 40 External FEPs and almost 80 Internal FEPs. As previously noted, some of the Internal FEPs are further subdivided as indicated in Table 2.3.

Table 2.2: External FEPs

1.1	**Repository Issues**	
	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	Repository design
	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 Processes and Effects**	
	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	Erosion and sedimentation
	1.2.08	Diagenesis
	1.2.09	Salt diapirism and dissolution
	1.2.10	Hydrological response to geological changes
1.3	**Climate Processes and Effects**	
	1.3.01	Global climate change
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	1.3.04	Periglacial effects
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	1.3.06	Warm climate effects (tropical and desert)
	1.3.07	Hydrological response to climate changes
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1.5	**Other External Factors**	
	1.5.01	Meteorite impact
	1.5.02	Species evolution
	1.5.03	Miscellaneous FEPs

Table 2.3: Internal FEPs Considered

2. REPOSITORY FACTORS			
2.1	Wastes and Engineered Features		
	2.1.01	Waste inventories	
		2.1.01.A	Inventory of radionuclides
		2.1.01.B	Inventory of chemically toxic contaminants
	2.1.02	Waste form materials and characteristics	
		2.1.02.A	Characteristics of used CANDU fuel (UO_2)
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		2.1.02.C	Characteristics of other waste forms
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		2.1.03.B	Fabrication and installation defects
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		2.1.03.D	General or uniform corrosion
		2.1.03.E	Mechanical degradation
		2.1.03.F	Localized corrosion
		2.1.03.G	Microbial-induced corrosion
		2.1.03.H	Internal corrosion processes
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		2.1.04.A	Repository layout
		2.1.04.B	Buffer characteristics and evolution
		2.1.04.C	Backfill characteristics and evolution
	2.1.05	Seals and grouts (cavern, tunnel, shaft)	
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		2.1.08.C	Evolution of hydraulic conditions
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		2.1.09.A	Water chemistry and evolution (repository)
		2.1.09.B	Hydrothermal alteration
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	2.2.11	Gas sources and effects (geosphere)	
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	2.3.06	Marine features	
	2.3.07	Atmosphere	
	2.3.08	Vegetation	
	2.3.09	Animal populations	
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	2.4.11	Leisure and other uses of the environment	
3. CONTAMINANT FACTORS			
3.1	Contaminant Characteristics		
	3.1.01	Radioactive decay and ingrowth	
	3.1.02	Chemical and organic toxin stability	
	3.1.03	Inorganic solids and solutes	
	3.1.04	Volatiles and potential for volatility	
	3.1.05	Organics and potential for organic forms	
	3.1.06	Noble gases	
3.2	Contaminant Release and Migration Factors		
	3.2.01	Dissolution, precipitation and crystallisation (contaminant)	
		3.2.01.A	Dissolution and precipitation (repository)
		3.2.01.B	Dissolution and precipitation (geosphere)
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3. FEP DESCRIPTION AND SCREENING ANALYSIS

3.1 OUTLINE

This section provides a description of each FEP, a brief screening analysis for each FEP, and lists the scenarios (if any) in which the FEP is included within the Fourth Case Study safety analyses.

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 generally means that there is a significant aspect of the FEP that should be specifically included in an identified scenario, usually as a parameter for one of the Fourth Case Study (FCS) 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.

The "include FEP" statement in the “FEP Screening” entry 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 FCS.

The Assessment Basis FEPs (see Table 2.1) define the scope of the safety assessment. They include factors related to regulatory requirements, definition of desired calculation end-points, and special requirements for a particular phase of assessment. As such, they would automatically be included in all scenarios of the Fourth Case Study. Consequently, the “FEP screening” entry is redundant for these FEPs and is not shown.

3.2 DISRUPTIVE SCENARIOS FOR THE FOURTH CASE STUDY

The long-term safety of the repository is based on the strength of the geosphere and engineered barriers (including the container and the shaft seals). Therefore, Disruptive Scenarios are typically based on circumstances in which these 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 Fourth Case Study (NWMO 2012):

- Inadvertent Human Intrusion;
- Shaft Seal Failure;
- Fracture Seal Failure;
- Poorly Sealed Borehole;
- Undetected Fault;
- Container Failure; and
- All Containers Fail.

A brief description of these disruptive scenarios follows.

The repository siting process will ensure that there are no known commercially viable natural resources at or below repository depth. Also, the repository has a small footprint (~6 km^2) and the repository is at a 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. Even this situation has a low probability of occurrence. Nevertheless, the possibility of inadvertent human intrusion into the repository by this method 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.

A second scenario by which the geosphere barrier can be bypassed is via the shafts (main, service and ventilation shafts). The shafts penetrate the geosphere, but are placed away from the waste panels and carefully sealed. The Shaft Seal Failure Scenario considers the possibility that the shaft seals are not fabricated or installed appropriately, or that the long-term performance of the shaft seals and shaft / repository excavation damage zones is poor due to unexpected physical, chemical and / or biological processes. While either situation could result in an enhanced permeability pathway to the surface, both are very unlikely due to quality control measures that will be applied during shaft seal closure and due to multiple durable material layers in the shaft.

A third scenario by which the geosphere barrier can be bypassed is via the fracture passing through the repository footprint (see Figure 3.1). The fracture extends from the repository to the surface and a repository access tunnel passes through the fracture. This tunnel and fracture are carefully sealed. The Fracture Seal Failure Scenario considers the possibility that the fracture seals are not fabricated or installed appropriately, or that the long-term performance of the fracture seals and tunnel / repository excavation damage zones is poor due to unexpected physical, chemical and / or biological processes. While either situation could result in an enhanced permeability pathway to the surface, both are very unlikely due to quality control measures that will be applied during fracture seal closure and the use of durable composite seals.

Another way in which the geosphere barrier can be bypassed is through the site characterization / monitoring boreholes. These boreholes are located in the vicinity of the repository down to and below repository depth. These boreholes will be appropriately sealed on completion of site investigation / monitoring activities so they will not have any effect on repository performance. However, if a deep borehole were not properly sealed or were to extensively degrade, then it could provide a small but relatively permeable pathway for the migration of contaminants from the repository horizon. The scenario is termed the Poorly Sealed Borehole Scenario. Such a situation is very unlikely due to the adoption of good engineering practice and quality control.

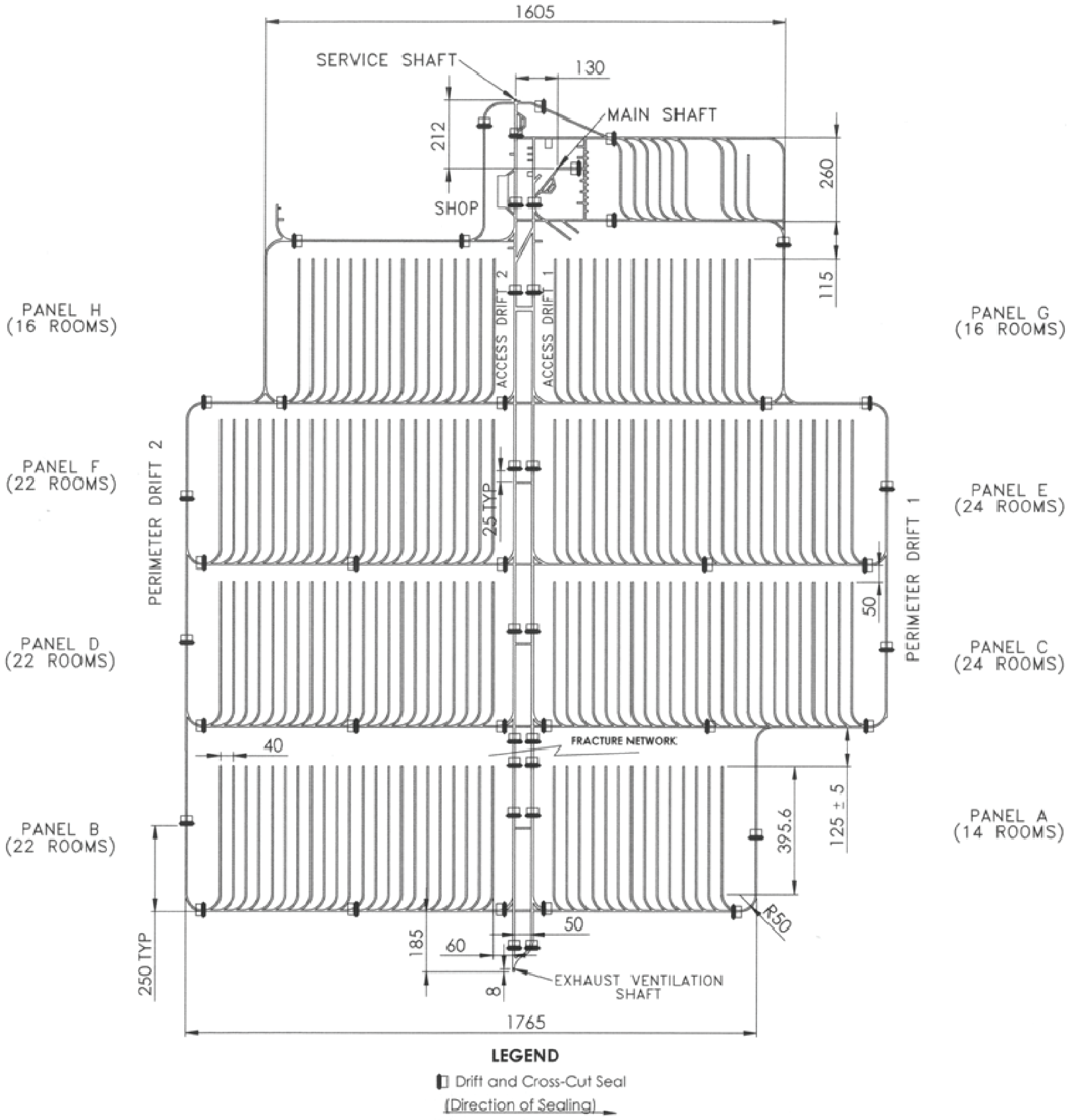
The fracture zone network at the hypothetical site is based on a geostatistical model that represents a Canadian Shield location consistent with surface lineaments. At a real site in crystalline rock, there could be some uncertainty in the fracture network and in the properties of the fractures, both now and in the future, as they may be affected by future glaciation or seismicity. Site characterization may not identify all existing significant fractures 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 displacement of an unknown 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.

Although the copper used fuel containers have been designed to have a functional life of not less than 100,000 years, they are expected to last much longer based on thermodynamic, experimental and natural analogue evidence that copper is stable for very long periods under deep geological repository conditions. However, there are several mechanisms by which a container could fail some time after it is installed in the repository. These container failures would be more extensive than the small undetected manufacturing/welding defects considered in the Normal Evolution Scenario. For the Fourth Case Study, the container failure mechanisms include, but are not limited to, the following:

1) a container has a manufacturing defect in the steel vessel that weakens it sufficiently that the container fails under the isostatic load imposed by an ice sheet passing over the repository site;
2) a container could be damaged by a sufficiently large shear load, resulting from a large seismic event that causes rock slippage along a local fracture intersecting a borehole (SKB 2011); and
3) if the buffer density is too low (e.g., poor installation), microbial films could form near the copper surface, aided by faster transport of nutrients through the buffer from the geosphere. Under such conditions, microbial corrosion could damage the copper container 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.

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 failure occurs long after repository closure. The probability of the Container Failure Scenario is low due to the quality assurance procedures in place to detect manufacturing defects in the steel vessels and dense bentonite blocks, to prevent installation errors and to exclude boreholes with “large” intersecting fractures. As well, the probability of large seismic events is low on the Canadian Shield.

The containers are designed to withstand an isostatic load of 45 MPa. With this design, the containers could withstand the sum of the hydraulic load due to a 3 km ice sheet (maximum load of 35 MPa for a 500 m deep repository, if the ice sheet is warm-based and the water table reaches the surface of the ice sheet) and a buffer swelling pressure of about 6 MPa. However, the design load of the container could be exceeded if, for example, the ice sheet thickness is greater than 3.5 km. Such an event could lead to multiple container failures and a significant increase in the contaminant releases from the repository and, hence, the calculated impacts. 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 first passage of an ice sheet over the site based on the reference glacial cycle used in Garisto et al. (2010). Note that the probability of such a scenario is low since the maximum ice sheet thickness at the repository site during the last glacial cycle was less than 3 km and the water table would not likely reach the surface of such a thick ice sheet, given the low atmospheric temperatures likely to be present at the time of peak ice sheet thickness (Garisto et al. 2010).



NOTES: Conceptual drawing only.
Seal locations are approximate.
Seal representations are not to scale.
Main Shaft to Service Shaft dimensions are centre-to-centre.

Figure 3.1: Plan view of underground 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.

0. ASSESSMENT BASIS

FEP # 0.0.00.0 Scope of main category 0.

Description

These are factors that define the scope of the safety or performance assessment. They include factors related to regulatory requirements, definition of desired calculation end-points, and special requirements for a particular phase of assessment. Decisions at this point will affect the phenomenological scope of a particular phase of assessment, i.e., what "physical factors" will be included.

There are ten sub-categories under Assessment basis:

0.01 Aims of the assessment
0.02 Regulatory requirements and exclusions
0.03 Impacts of concern
0.04 Time scales of concern
0.05 Spatial domain of concern
0.06 Repository assumptions
0.07 Future human action assumptions
0.08 Future human behaviour (target group) assumptions
0.09 Dose response assumptions

FEP #0.0.01 Aims of the assessment

Description

The purpose of the safety assessment. Examples include:
- to evaluate the feasibility of a concept,
- to help select a candidate site,
- to contribute to obtaining a construction license,
- to demonstrate compliance with regulatory criteria prior to decommissioning and closure,
- to contribute to public confidence,
- to contribute to confidence of policy makers and the scientific community,
- to guide research priorities, and
- to assist with system optimisation.

These are expected to change as the repository project proceeds. Clearly, the aims would be influenced by the requirements of the regulators and reviewers during a formal siting process (e.g., CEAA 1998).

FCS Screening Analysis

The main objective of the Fourth Case Study (FCS) is to provide an illustrative postclosure safety assessment for a used fuel repository in crystalline rock. This would be provided to the CNSC for a pre-project review to confirm that the conceptual design and safety assessment approach meets CNSC general expectations and that the illustrative postclosure safety assessment is consistent with CNSC Guide G-320 (CNSC 2006).

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”. The Fourth Case Study considers the Normal Evolution Scenario and various Disruptive Event Scenarios. Variant cases of these scenarios are also investigated. As the FCS is a limited assessment, it does not fully explore all scenarios. For example, the impact of glaciation is included in the FCS as part of the assessment of the Normal Evolution Scenario, but in a qualitative manner through reference to the work of Garisto et al. (2010) and Walsh and Avis (2010) for a similar case study.

In the FCS, radiological impacts on humans and non-human biota are evaluated, as required by G-320 (CNSC 2006). However, impacts on non-human biota are only calculated for the Normal Evolution and All Containers Fail Scenarios.

G-320 also indicates that the impacts on humans and non-human biota of releases of chemical toxic elements from the repository should also be evaluated. In the Fourth Case Study, these impacts are assessed only for the Normal Evolution and the All Containers Fail Scenarios.

The Fourth Case Study is based on a specific repository design and site concept. Since the site is hypothetical, the philosophy guiding the definition of its parameters is that the site should be feasible and conditionally acceptable. That is, it would meet reasonable technical siting criteria, such as those outlined in the NWMO site selection process and summarized in NWMO (2012, Section 1). The key attributes assumed for the hypothetical site are:

- The repository is located at a depth of 500 m;
- There is sufficient volume of rock at the site and depth to host the repository;
- Groundwater at repository depth has low salinity;

- Groundwater at repository depth provides a reducing environment;
- The host rock is capable of withstanding mechanical and thermal stresses;
- Seismic activity is low, consistent with general Canadian Shield conditions;
- Rates of land uplift, subsidence and erosion at the site are low enough that they will not adversely impact the isolation of the repository; and
- The host rock formations do not contain groundwater or economically exploitable natural resources at repository depth.

The analyses presented for the FCS provide a basic test of postclosure safety for this repository concept and assumed site, and provides a basis for future iterations in which progressively more topics can be addressed.

For a real candidate site, the results of this study would contribute to a larger "safety case" for the deep geologic repository at that site that would draw on other arguments regarding safety, notably geoscientific evidence from site characterization (e.g., the age of deep groundwaters), natural analogs and results from other international site studies.

FEP # 0.0.02 Regulatory requirements and exclusions

Description

The specific terms or conditions in national regulations related to safety assessment of a proposed repository.

The Canadian Nuclear Safety Commission (CNSC) is responsible for regulations that apply to the operation of nuclear facilities. The CNSC has regulatory documents pertaining to the long-term management of radioactive waste: P-290, G-320 and R-72.

A summary of some key points in these regulatory documents is provided below:

CNSC Policy P-290 (CNSC 2004) identifies the need for long-term management of radioactive waste and hazardous waste arising from licensed activities. The principles espoused by CNSC Policy P-290 that relate to long-term management are the following:

- The management of radioactive waste is commensurate with its radiological, chemical, and biological hazard to the health and safety of persons and the environment, and to national security;
- The assessment of future impacts of radioactive waste on the health and safety of persons and the environment encompasses the period of time when the maximum impact is predicted to occur; and
- The predicted impact on the health and safety of persons and the environment from the management of radioactive waste is no greater than the impact that is permissible in Canada at the time of the regulatory decision.

Key objectives for long-term management are containment and isolation of the waste, in accordance with the CNSC Guide G-320 (CNSC 2006). The guide states that: “containment can be achieved through a robust design based on multiple barriers providing defence-in-depth. Isolation is achieved through proper site selection and, when necessary, institutional controls to limit access and land use”.

CNSC Guide G-320 identifies expectations for “developing a long term safety case that includes a safety assessment complemented by various additional arguments based on:

1. Appropriate selection and application of assessment strategies;
2. Demonstration of system robustness;
3. The use of complementary indicators of safety; and
4. Any other evidence that is available to provide confidence in the long term safety of radioactive waste management.”

AECB document R-72 (AECB 1987) describes the general characteristics of a repository which should

a) isolate and retain radioactive substances to allow for more complete radioactive decay;
b) restrict the movement of those radionuclides which may escape from the repository, thus prolonging the time during which further radioactive decay can take place prior to their return to the biosphere; and
c) restrict human contact with the waste.

As well, "the disposal system and its components must be capable of accommodating disturbances due to natural phenomena likely to occur in the vicinity of the repository" and "the disposal should be passive; that is, it should be designed to minimize the obligation imposed

FCS Screening Analysis

The Fourth Case study is consistent with G-320 and P-290.

For the Normal Evolution Scenario and variants, the FCS compares calculated human dose rates to an annual individual effective dose rate of 0.3 mSv/a (NWMO 2012) and to the natural background dose rate. This radiological interim acceptance criterion is equal to the dose constraint recommended in ICRP 81 (ICRP 2000), which was the criterion used in the TCS.

For the Normal Evolution and All Containers Fail Scenarios, the Fourth Case Study also assesses the radiological impacts on non-human biota; and the impacts on humans and non-human biota of releases of chemical toxic elements from the repository. The former are assessed using calculated no-effect concentrations (Garisto et al. 2008) and the latter are assessed by comparing calculated contaminant concentrations in various biosphere media (e.g., surface water and soil) to chemical toxicity criteria, as described in Garisto et al. (2005b).

For Disruptive Event Scenarios, the interim acceptance criterion is: an annual individual effective adult dose rate of 1 mSv/a for credible chronic release scenarios. Acceptability of any scenario with calculated annual individual effective dose rates for chronic releases exceeding 1 mSv/a would be examined on a case-by-case basis taking into account the likelihood and nature of the exposure, uncertainty in the assessment and conservatism in the dose criterion. For the Inadvertent Human Intrusion Scenario, both the likelihood of exposure and the dose rate are reported; consequently, the radiological risk is also calculated.

With respect to natural background, the FCS also considers the following indicators:

- The Canadian average background dose rate to humans from natural sources (about 1.8 mSv/a, Grasty and LaMarre 2004),
- The natural background concentration of radionuclides in Canadian surface waters,
- The natural flux of radionuclides from the geosphere to the surface biosphere, and
- The natural erosion flux of chemical elements from granite into the surface biosphere.

FEP # 0.0.03 Impacts of concern

Description

This FEP identifies the possible consequences of the repository that are to be determined. These will depend on the Aim of the Assessment [0.0.01] and on Regulatory Requirements [0.0.02]. Also, any federal panel reviewing the environmental impact statement may establish their own guidelines.

Possible impacts include:
- radiological dose to individuals of a 'critical group';
- radiological risk to individuals of a 'critical group';
- population doses and risks;
- cumulative releases of radioactive material;
- chemical toxicity effects to the critical group and/or a population;
- radiological and chemical toxicity effects to the environment (plants and animals);
- effects on biodiversity and on rare, valued or endangered ecosystem species;
- modifications to the environment, such as distribution or concentration of radionuclides;
- contaminant fluxes into or through parts of the biosphere; and
- impact of uncertainties.

The impacts are expected to involve very low levels of exposure for a repository that functions as expected. However, there may be a need to consider the possibility of sudden increases in levels of exposure, perhaps leading to acute effects that may arise from situations where the repository is impaired by major disruptive processes and events such as human intrusion.

FCS Screening Analysis

In the FCS, impacts on humans and non-human biota of radionuclide and chemical toxic element releases from the repository are evaluated, as required by Regulatory Guide G-320 (CNSC 2006). The proposed interim acceptance criteria used in the FCS are described in NWMO (2012).

Previous studies have indicated that the most significant postclosure impacts are those associated with human groups living near the repository site (e.g., Garisto et al. 2004a, Goodwin et al. 1994). In keeping with the concept of a "critical group", we conservatively assume that people live near the site in the future, and have lifestyles that maximize their potential exposure doses while behaving in an otherwise reasonable manner.

Complementary indicators of safety are also examined. These indicators may be more useful on medium time frames (radiotoxicity concentration in surface waters) and very long time frames (radiotoxicity flux from the geosphere, erosion fluxes of chemical elements from granite) than, for example, the radiological dose rate (Becker et al. 2002, Garisto et al. 2005a).

This scope of the assessment is consistent with *Aims of the Assessment [0.0.01].* It is recognized that other impacts to the selected critical group and impacts to alternative critical groups would need to be evaluated for a formal safety assessment.

FEP # 0.0.04 Time scales of concern

Description

The time period over which the disposed wastes and repository may present some impact of concern, such as human health risk or environmental hazard, affects the time scale of the safety assessment.

Examples of time scales include:
- Duration of the preclosure period when the repository is in operation but not sealed;
- Period during which societal control and memory of the site is retained;
- Regulatory requirements for quantitative modelling;
- Time scale for significant climate changes, such as start of next ice age; and
- Time scale for radionuclides to decay to low levels, such as natural background radiation.

CNSC regulatory policy P-290 (CNSC 2004) requires that “the assessment of future impacts of radioactive waste on the health and safety of persons and the environment encompasses the period of time when the maximum impact is predicted to occur.”

Other authorities or review bodies might establish their own guidelines on this topic.

FCS Screening Analysis

Most of the initial radioactivity and associated hazards of used fuel are due to the fission products, which mostly 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.

Ultimately, since 98% of the used fuel is natural uranium, as radionuclides decay, the radioactivity in the repository will eventually become similar to that of a large uranium ore body such as is found in other locations on the Canadian Shield. This occurs on times scales of about one million years (see Figure 3.2).

Therefore, for the Fourth 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 timeframe for peak impact has been identified. It is recognized that estimating impacts becomes increasingly uncertain at long times.

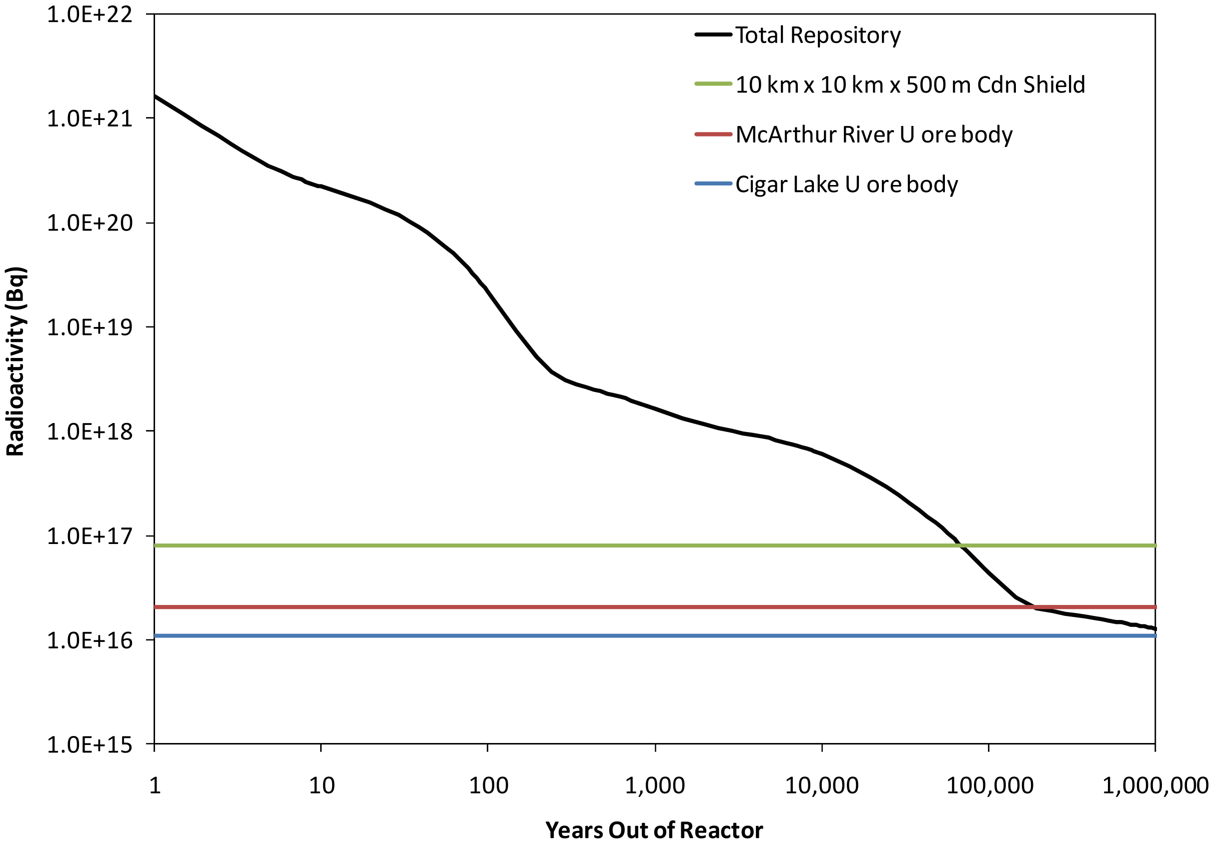


Figure 3.2: Time scale for radioactivity decay of used fuel in repository. The gamma-emitting fission products decay within about 500 years. The remaining fuel radioactivity becomes comparable to that of the granite in the surrounding watershed after about 10,000 to 100,000 years. On time scales of about 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.

FEP # 0.0.05 Spatial domain of concern

Description

The physical area over which the disposed wastes and repository may present some significant human health or environmental hazard.

This factor is related to other factors such as *Impacts of concern [0.0.03], Time scales of concern [0.0.04]* and *Future human behaviour (target group) assumptions [0.0.08]*. For instance, it may be inferred from G-320 (CNSC 2006) that the spatial domain of concern is local to the critical group and environmental receptors:

> “the development of scenarios should include identification of humans and environmental receptors that may be exposed to radioactive and hazardous substances”. Furthermore, “environmental protection is based on protecting populations of species, communities, and ecosystems.”

If the critical group is taken to be a self-sufficient rural household, then the domain of concern is likely localized near the repository site, and might be delineated by considerations such as the watershed catchment area near their household.

R-72 (AECB 1987) implies a larger domain; in particular that the general characteristics of a repository should:

> "(a) isolate and retain radioactive substances to allow for more complete radioactive decay; (b) restrict the movement of those radionuclides which may escape from the repository, thus prolonging the time during which further radioactive decay can take place prior to their return to the biosphere; and (c) restrict human contact with the waste."

Estimates of population dose also imply a larger physical area. That area might be limited to the watershed catchment area plus its downstream discharge areas, or it might infer the need for consideration of a global region.

Other authorities or review bodies might establish their own guidelines on this topic.

FCS Screening Analysis

The Fourth Case Study is a postclosure safety assessment of a deep geologic repository design at a hypothetical site on the Canadian Shield. The spatial domain that will be considered is the subregional watershed area (approximately 200 km^2) in which the repository is sited.

The study will specifically focus 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 nuclides 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.

FEP # 0.0.06 Repository assumptions

Description

The reference assumptions made about the construction, operation, closure and administration of the repository.

It is commonly assumed that the repository would be closed and sealed as specified in the engineering design, and that any deleterious events occurring earlier (such as repository flooding and placement-damaged containers) would have been corrected. Other assumptions may pertain to the period of monitoring and to the timing and schedule affecting the sealing of waste placement rooms, connecting drifts and shafts. Other assumptions might be inherent in the detailed information on the characteristics of the repository provided under *Wastes and Engineered features [2.1].*

Note that events or other factors that depart from these design basis assumptions are described elsewhere, such as under *Future Human Actions (active) [1.4].*

FCS Screening Analysis

The repository, including the containers, is assumed to be designed, built and sealed as described in NWMO (2012, Section 4). This includes a quality assurance program to ensure that the repository meets specifications.

The repository only contains used fuel bundles from present Canadian CANDU reactors. The repository will hold 4.6 million bundles, which is the present planned lifetime output from these reactors.

The repository is constructed, operated and closed according to the assumed schedule outlined in NWMO (2012, Section 4). Some key time lines are:
- used fuel bundles are at least 30-years old at 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 repository assumptions are described in the specific relevant sections.

FEP # 0.0.07 Future human action assumptions

Description

The reference assumptions concerning general boundary conditions on future human actions. These assumptions broadly define the future human society (such as hunter-gatherer or technologically advanced) and their actions that have a broad affect on the condition of their environment (such as contaminated by nuclear war).

G-320 (CNSC 2006) specifies that "the habits and characteristics that are assumed for the human critical group should be based on reasonably conservative and plausible assumptions that consider current lifestyles and available site-specific or region-specific information".

See also *Future human behaviour (target group) assumptions [0.08]*.

FCS Screening Analysis

It is assumed that future humans will largely resemble present day humans in terms of societal behaviour, capabilities and actions. This means that:

- There is no credit taken for advances in science and technology that might reduce the risk from the repository, e.g., no "cure for cancer" and no simple waste transmutation process.
- 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 current sense.
- 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.

FEP # 0.0.08 Future human behaviour (target group) assumptions

Description

The reference assumptions concerning the characteristics and behaviour of potentially exposed human individuals, communities or populations.

These assumptions may be based on regulatory requirements. For instance, G-320 (CNSC 2006) indicates that "the human receptors in a scenario may be based on the ICRP concept of a critical group for radiological protection of persons. It is reasonably assumed that the critical group for radiological protection will also be a conservative receptor for exposure to hazardous substances." Also, "the habits and characteristics that are assumed for the human critical group should be based on reasonably conservative and plausible assumptions that consider current lifestyles and available site-specific or region-specific information". Furthermore, "each scenario that is analyzed may have different critical groups for radiological protection".

Similar requirements are provided in other international regulations.

Assumptions on human behaviour also depend on the particular safety assessment scenario and the *Impacts of Concern [0.0.01].* A common assumption is to suppose that a rural self-sufficient household lives near the repository and uses a well for drinking water or irrigation.

Stakeholders other than the regulators may have a different set of reference assumptions (e.g., CEAA 1998).

FCS Screening Analysis

For dose assessment purposes, several reference groups of humans (i.e., critical groups) are considered in the Fourth Case Study. The characteristics of these critical groups (e.g., lifestyle and location) are conservatively selected so as to maximize calculated dose rates.

For the Normal Evolution Scenario, the human critical group depends on the climate (Garisto et al. 2010). For a temperate climate, the critical group is a self-sufficient farm household (with mix of dairy, meat and vegetable diet) living near the repository site and drawing water from a contaminated well or a lake. For a permafrost climate, periglacial conditions prevail and the critical group is a self-sufficient hunter group whose main diet consists of caribou meat. When a proglacial lake is present, the critical group is a self-sufficient fisher whose diet also consists mainly of caribou meat but also includes a large proportion of fish, taken from the proglacial lake. Humans do not reside near the repository when the site is covered by ice sheets; hence, calculated dose rates are assumed to be zero during these periods.

For the Inadvertent Human Intrusion Scenario, the reference human groups include (Medri 2012):

- a drill crew exposed to drill slurry spread around the drill rig and to a core section containing used fuel; and
- a resident at the site, exposed by living near and growing food on soil contaminated by drill slurry.

For the other disruptive event scenarios, the critical groups are the same as those used for the Normal Evolution Scenario, although only constant temperate climate simulations are carried out for the disruptive scenarios.

FEP # 0.0.09 Dose response assumptions

Description

The assumptions made to convert received dose to a measure of risk to an individual or population. This generally deals with humans but similar considerations might apply to other biota.

Related issues include sensitization, hormesis, synergistic effects, antagonism and threshold. Human and other biota may become sensitized to radiation exposure so that its effects are more severe. (The opposite effect, desensitization, is also possible.) This might involve the presence of other mutagens, which can cause genetic damage similar to radiation exposure. For example, if the DNA repair mechanism is overly stressed, more cancers and genetic effects than expected might result. Hormesis is a phenomenon which suggests low levels of radiation may have some beneficial effects, possibly from stimulated immune systems. Synergistic effects refer to the possibility that radiological impacts might be enhanced by the presence, for example, of chemically toxic material. Antagonism refers to the opposite effect, in which impacts are reduced by the presence of a second material. Another issue is the possibility that some responses may have a threshold below which there are no effects.

FCS Screening Analysis

The International Commission on Radiological Protection (ICRP) 2007 recommendations are considered to be the best estimate of dose response for humans (ICRP 2007) and replace the 1990 recommendations (ICRP 1991a). The new recommendations do not lead to changes in dose limits.

The recommendations are based on the Linear No-Threshold model, although account was taken of dose and dose-rate effects in their derivation.

1. The concentration of a radionuclide in an environmental medium is multiplied by a dose coefficient and other factors such as annual duration of exposure or amount of material ingested to obtain a dose equivalent in sieverts per year (Sv/a).

   Radiological exposures to humans are converted to dose rates using dose coefficients based on the 1990 ICRP recommendations, since dose coefficients based on the 2007 recommendations are not yet available. However, 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. The air inhalation dose coefficients are selected assuming that the radionuclides are present in the chemical form with the highest dose coefficient (Garisto 2002).

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).

1. EXTERNAL FACTORS

FEP # 1.0.00 Scope of main category 1.

Description

External factors are those with causes or origin outside the repository system domain. These factors include natural events and human decision 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 sub-categories of external factors are:
  1.1 Repository issues
  1.2 Geological processes and effects
  1.3 Climatic processes and effects
  1.4 Future human actions
  1.5 Other External Factors

1.1 Repository Issues

FEP # 1.1.00 Scope of sub-category 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 issues:

- 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 Repository design
- 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 waste

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.

See *Closure and repository sealing [1.1.04]* for discussion of boreholes, possibly drilled for site investigation purposes, that have been left open, improperly sealed or reopened for some reason.

FCS Screening Analysis

The Fourth Case Study is a postclosure safety assessment of a geologic repository for used fuel located at a hypothetical site. Since the site is hypothetical, there are no specific site data. Assumptions about the site characteristics will be made as follows:

- regional topography and surface water hydrological properties is based on the OPG Regional Groundwater Flow Model (Sykes et al. 2003);
- the location of fractures at the site is based on one of the possible realizations derived using the methodology developed by Srivastava (2002);
- measured geosphere property data from the AECL Whiteshell Research Area and Atikoken are used to develop a conservative geosphere permeability profile with depth; and
- other properties are selected consistent with conditions considered plausible for a Canadian Shield site that would be suitable for a repository (e.g., there are no identified commercially viable mineral resources at the site) (NWMO 2012, 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 no detrimental impact on safety.

FEP Screening

Include FEP in all scenarios.

FEP # 1.1.02 Excavation and construction

Description

Factors related to the excavation of shafts, tunnels, placement rooms, 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 undesirable situations such as localized stress concentrations that, for example, result in formation of an excavation damage zone. Other effects might be faulting, including through-going fractures that reach the surface, and settling or subsidence. These effects could subsequently be amplified by earthquakes and related events.
- Dewatering of the host and nearby rock would have significant changes in the 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.
- The excavation and construction process would likely introduce material foreign to the host rock, such as rock bolts, concrete, timbers, rail lines and shotcrete. Other foreign material could enter the open repository, such as 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.

FCS Screening Analysis

It is assumed for the Normal Evolution Scenario that the Fourth Case Study repository is constructed as designed (NWMO 2012, Section 4) under an appropriate quality assurance regime and with measures taken to limit the extent of the excavation damage zone (EDZ) around the repository and shaft.

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

- A controlled drill & blast excavation method is used, so the formation of an EDZ with enhanced permeability relative to the host rock is considered, as discussed under *Excavation Disturbed Zone [2.2.01]*;
- Minimal use of materials (e.g., rock bolts and grouting) for stabilization of openings;
- 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 in the Fourth Case Study analyses. However, other aspects of the excavation and construction methodology are not critical to the safety assessment.

The impact of poor construction of the shafts and tunnels, resulting in highly permeable EDZ zones around the shaft and fracture seals, is examined in the Shaft Seal Failure and Fracture Seal Failure Scenarios, respectively. The Container Failure Scenario examines the impact of extensive failure of a few containers, long after repository closure; due to, for example, a large shear load arising from rock movement, initiated by a large seismic event, along a local fracture crossing a borehole.

FEP Screening

Include FEP in all scenarios.

FEP # 1.1.03 Placement of wastes and backfill

Description

The placing of wastes (usually in containers) 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 placement room or might settle, and the void space might serve as a conduit for contaminant transport.

Several placement options are possible, and each will have different merits and shortcomings. For instance, placement in boreholes drilled into the floor of a room might reduce potential exposures during the operational phase, but this option might also lead to enhanced transport and exposures during the postclosure phase through creation of a substantial excavation damage zone in the rock web between boreholes, connection to intersecting fractures in the host rock, or establishment of contaminant flow pathways that avoid the backfill. Room-placement might avoid these undesirable processes, at the expense of increased exposures during the operational phase as well as creating a more difficult placement process.

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 repository resaturate and consequent effects on thermal and hydraulic gradients.

FCS Screening Analysis

In the Fourth Case Study, the in-floor container placement method is used with one row of containers along a placement room. 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 probability of manufacturing defects in the used fuel containers, some containers may be placed in the repository with small undetected defects in the copper shell. Consequently, as part of the Normal Evolution Scenario, it is assumed that some defective containers are present in the repository at the time of closure.

The repository design assumes that borehole locations that are found to intercept a local fracture would not be used. The Container Failure Scenario considers the case in which a few containers fail long after repository closure due to, for example, quality assurance failures that allow use of a borehole intersected by a local fracture; and undetected manufacturing defects in the steel vessel or dense bentonite blocks, as discussed in Section 3.2.

FEP Screening

Include FEP in all scenarios.

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 (see *Repository assumptions [0.04]*), or it may be necessary to examine the consequences of incomplete closure (perhaps as part of a study of disposal options). Incomplete closure could occur for a number of reasons; including disintegration of society, or lack of finances. Incomplete closure might involve leaving behind open shafts and placement rooms, or merely leaving behind open boreholes that have been forgotten.

It may also be necessary to consider the potential for degraded performance of shaft and borehole seals, particularly over the long time frames over which these seals contribute to safety (see *Seals and grouts (cavern, tunnel, shaft) [2.1.05]*).

FCS Screening Analysis

The reference schedule for the FCS repository includes 38-years of operation, 70 years of extended monitoring and 30 years of decommissioning and closure (see *Repository Assumptions [0.0.04]*). Thus, there would be a minimum of 135-years of repository records (and institutional control).

It is assumed that closure of the Fourth Case Study repository in 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 2012, Section 4) will also ensure proper closure.

The Normal Evolution Scenario represents reference assumptions on closure and degradation of the shaft and repository seals over time. The possibility of poorly sealed or degraded site investigation boreholes is considered in a Poorly Sealed Borehole Scenario. The possibility of degraded performance of the shaft or fracture seals, either due to improper placement of the seals or unexpected deterioration of the seals, is considered in the Shaft Seal Failure Scenario and Fracture Seal Failure Scenario, respectively. 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.

FEP Screening

Include FEP in all 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 *Deliberate and Inadvertent Human Intrusion [1.4.02]*).

FCS Screening Analysis

It is expected that the Fourth Case Study 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 include 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.

Consistent with international practice, it is assumed in this assessment that records and markers 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. These are a relatively well defined and could be represented by 'reference' fuel bundles. Variations in the assumed 'reference' fuel bundles might occur because the as-disposed bundles have different burnups, linear powers or cooling periods (i.e., out-of-reactor times) from the assumed reference fuel bundle.

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.

Examples of possible co-disposal wastes include:

- processed fuel wastes, possibly contained within a glass, bitumen, calcine or other solid matrix, or possibly in liquid or gaseous form;
- other types of non-standardised CANDU fuel bundles or non-CANDU fuel bundles, such as fuels used in research reactors, mixed-oxide (MOX) fuel bundles made from weapons-grade plutonium or from fertile thorium isotopes, bundles with unusual characteristics such as a non-collapsible sheath, bundles in which the fuel is uranium metal or a compound other than uranium dioxide, and fuels enriched in fissile isotopes of uranium, plutonium or thorium;
- decontamination waste and ion exchange resins;
- decommissioned reactor parts;
- low-level waste (LLW) and intermediate level waste (ILW);
- medical wastes; and
- special-purpose waste forms such as calcite containing carbon-14 and cement containing radioactive metals, laboratory wastes or solidified process wastes.

The waste allocations may also affect factors such as *Waste inventories [2.1.01], Waste form materials and characteristics [2.1.02]* and *Container materials and characteristics [2.1.03].*

FCS Screening Analysis

The scope of the Fourth Case Study is limited to CANDU used fuel bundles (see *Repository assumptions [0.0.06]*). The repository will hold 4.6 million bundles. There is no co-disposal involving other types of radioactive or chemically toxic wastes at the site.

For the purposes of calculating radionuclide inventories and other fuel bundle parameters, the reference fuel bundle for the FCS is the 37-element standard Bruce fuel bundle. Analysis indicates that 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) for typical burnups.

FEP Screening

Include FEP in all scenarios.

FEP # 1.1.07 Repository design

Description

Assumptions regarding the design of the repository including both the safety concept, i.e., the general features of design and how they are expected to lead to a satisfactory performance, and the more detailed engineering specification for excavation, construction and operation. A related issue is that the safety assessment may only analyze a subset of the total range of options. For instance, results from interim performance assessments, using data that becomes available from site investigation and construction, may contribute to decisions affecting design options and the selection of engineered barriers.

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 affected by the availability and cost of critical resources. The original design might be modified to accept material with inferior performance, or, conversely, the original design might not consider superior materials based on outdated information on costs and availability.
- The waste arisings in the final repository might be broadened to include co-disposal wastes (see *Waste allocation [1.1.06]*), leading to the use of alternative container designs and placement methods for wastes other than the reference CANDU fuel bundles.
- There may be significant differences between the conceptual design and the constructed version. For instance, the design might include 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 ground 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.

FCS Screening Analysis

The repository design concept is based on the in-floor container placement concept and is described in NWMO (2012, Section 4). The relevant repository parameters for the specific design considered in the Fourth Case Study are given in Garisto et al. (2012). It is expected that the design will become progressively more detailed with time, and that the safety assessment 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.

There may be specific regulations governing quality control procedures, objectives and criteria. These regulations, if enforced, could have an important direct role in safety assessments, and 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 *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 in a number of manners. For example, internal structural support might be supplied by a metallic insert or by particulate material, but the inserts might be defective or missing or the particulates might not sufficiently fill the void space. 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 (see *Container materials and characteristics [2.1.03]*).
- 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.
- Incomplete or inconsistent loading of containers with co-disposal wastes. Some of the previous issues could be of greater concern; for example, some potential co-disposal wastes will have significantly larger releases of decay heat.

FCS Screening Analysis

The FCS assumes that the repository is constructed, operated and closed according to the design basis, per *Repository assumptions [0.0.06]*. These 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 2012, Section 10).

Although substantial failure of the quality assurance is unlikely, the Fourth Case Study safety assessment assumes, even for the Normal Evolution Scenario, that some containers are placed in the repository with undetected defects in the copper shell of the container (based on the probability of manufacturing defects in the containers), leading to early release of radionuclides from the repository.

The possibility that engineered barriers do not perform as expected, as a result perhaps of poor placement or other issues related to quality control, is explored in disruptive scenarios. Thus, substantial quality assurance program failure is considered as a possible contributor to the Shaft Seal Failure, the Fracture Seal Failure, the Poorly Sealed Borehole and the Container Failure Scenarios.

FEP Screening

Include FEP in all scenarios. Assume that the quality control program fails to the extent that it does not detect seal placement errors for the Shaft Seal Failure, Fracture Seal Failure, and Poorly Sealed Borehole Scenarios; or manufacturing defects in the Container Failure Scenario.

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 activity and heat production from the wastes, material degradation, chemical and hydraulic changes during a prolonged open phase. There may also be implications on the loss of records and markers (see *Records and markers [1.1.05]*) and exposure to workers during prolonged periods before closure.

FCS Screening Analysis

The reference schedule for the FCS repository includes 38 years of operation, 70 years of extended monitoring and 30 years of decommissioning and closure (see *Repository assumptions [0.0.06]*).

FEP Screening

Include FEP in all scenarios.

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 *Records and markers [1.1.05].*

FCS Screening Analysis

For the Fourth Case Study, it is assumed that adequate administrative controls are in place to ensure closure of the facility. Thereafter, it is assumed that institutional controls (e.g., municipal land use controls), records or societal memory are sufficient to prevent inadvertent human intrusion for 300 years.

After this period, it is assumed that controls are no longer effective. The possibility of inadvertent intrusion into the repository after this period is considered in the Inadvertent Human Intrusion Scenario.

FEP Screening

Include FEP in all scenarios.

FEP # 1.1.11 Monitoring

Description

Monitoring that is carried out during operations or following closure of sections of or 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.

FCS Screening Analysis

For the Fourth Case Study, the repository will be monitored for about 70 years after all containers have been placed, as noted in *Repository assumptions [0.0.06].*

There is currently no specific monitoring plan; however, 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 will have no effect on the postclosure system.

However, to assess the possible negative effects from monitoring of the repository, the Poorly Sealed Borehole Scenario is considered in which it is assumed that a monitoring borehole is not properly sealed, potentially providing a pathway through the host rock.

FEP Screening

Include in the Poorly Sealed Borehole Scenario.

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.

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 backfilling [1.1.03]*);
- 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.

FCS Screening Analysis

Accidents and unplanned events are not included in the FCS as it is reasonable to assume that any deleterious effects would be remedied during the operation of the repository, and corrective actions will be taken so that performance is not impaired.

FEP Screening

Screened out.

FEP # 1.1.13 Retrieval of wastes

Description

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].*

FCS Screening Analysis

The Fourth Case Study repository design and operation has features that improve retrievability, notably the extended monitoring period during which time the access tunnels and shafts remain open. However, it is assumed for the purposes of the current assessment that there is no retrieval of waste after repository closure.

FEP Screening

Screened out.

1.2 Geological Processes and Effects

FEP # 1.2.00 Scope of sub-category 1.2

Description

Factors arising from the wider geological settings.

There are ten subcategories under geological processes and effects:

- 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 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

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

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

FCS Screening Analysis

The Fourth Case Study repository is assumed to be on the Canadian Shield, which is located in the interior of the large North American tectonic plate (see Figure 3.3). Tectonic activity is most likely to occur at the edges of the plate where rifts and subduction zones occur. The Shield is one of the most tectonically stable regions on the planet. The last volcanic eruptions in the Canadian Shield occurred more than a billion years ago while the tectonic provinces of the Canadian Shield were forming by accreting to the edges of what was then the plate margin.

If relative plate motions continue at present day rates, the Canadian Shield 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 Fourth Case Study.

See also *Seismicity (earthquakes) [1.2.03]* and *Volcanic and magmatic activity [1.2.04].*

FEP Screening

Screened out.

Figure 3.3: Location of the Canadian Shield. The top figure shows the extent of the Canadian Shield within Canada. The bottom figure shows the North American plate and its boundaries with the other major tectonic plates (from McMurry et al. 2003, adapted from U.S. Geological Survey map available at http://pubs.usgs.gov/gip/dynamic/slabs.html).

FEP # 1.2.02 Deformation (elastic, plastic or brittle)

Description

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

A fault is a large scale discontinuity or fracture in the Earth's crust accompanied by displacement of one side of the fracture relative to the other. Fractures may be caused by compressional or tensional forces in the Earth's crust. Such forces may result in the activation and extension of existing faults and, less likely, the generation of new faults, or they may result in creep during excavation of the repository. Void spaces could form or be closed by these forces. Rock might be extruded into existing void spaces. Compression forces could bring about these changes in a direct way, or they could be a factor in metamorphic changes to the rock. These processes could have a significant effect on groundwater flow and contaminant transport in the geosphere.

FCS Screening Analysis

The Fourth Case Study repository is assumed to be on the Canadian Shield, which is located in the interior of the large North American tectonic plate and is one of the most tectonically stable regions on the planet. Thus, deformation due to tectonic movement and orogeny is unlikely over the time scale of interest (see *Tectonic movement and orogeny [1.2.01]*).

However, over the next million years, deformation due to loading from ice-sheets is likely (see *Local glacial effects [1.3.05]*). The weight of the ice-sheets depresses the land underneath the ice sheet, which then slowly rebounds after the ice is removed. Much of the Canadian Shield outside of the Hudson Bay is still uplifting at about 5 mm/yr (Peltier 2002). This slow rate of change (depression or rebound), which occurs over a large area simultaneously, will not have a significant mechanical effect on the repository itself.

Local deformation due to glacial loading would increase rock stresses in the repository and could cause failure of roof and pillars in unsupported placement rooms and tunnels. However, the rooms and tunnels in the FCS repository are backfilled, so rockfall should not occur.

Based on observation of existing fractures in the Canadian Shield, it is expected that glacial-related deformation could cause movement along existing fractures, rather than creation of new fractures (McMurry et al. 2003). Therefore no new glacial-related fracture formation is considered in the Normal Evolution Scenario. However, all fractures included in the Fourth Case Study (see *Discontinuities and lineaments [2.2.04]*) are assumed to be open and permeable. This assumption accounts in part for the possible reactivation of fractures due to glacial-related deformation.

The effects of glaciation-related deformation on groundwater flow are discussed in *Hydrological response to geological changes [1.2.10]* and seismic reactivation of existing faults is discussed in *Seismicity (earthquakes) [1.2.03]*.

The impacts of assuming that the site characterization program has not identified all existing fracture zones at the repository site are explored in the Undetected Fault Scenario. The reactivation of such a closed fracture could be due to glacial-related deformation. The impact of a large seismic event that produces a shear load on the container, due to rock movement along a local fracture intersecting a borehole, is examined as part of the Container Failure Scenario.

FEP Screening

Include FEP in all scenarios.

This FEP is included by assuming that all identified fracture zones at the site are open and permeable. That is, any closed fractures at the site are conservatively assumed to have been activated, possibly due to glacial-related deformation.

FEP # 1.2.03 Seismicity (earthquakes)

Description

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

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

Observations have shown that the effects and magnitude of a seismic event are greater at the surface than underground. Thus the potential for damage of a repository may be less than expected for a given event.

FCS Screening Analysis

Since the FCS site is hypothetical, there is no specific information available on its seismicity. Rather, it is assumed that the site is a low-seismicity area. However, the following general observations can be made that would be consistent with a potential site in the Canadian Shield.

Active tectonic plate margins are the locus of most seismic and volcanic activity worldwide. In contrast, the Canadian Shield is located in the interior of the large North American tectonic plate, which is one of the most tectonically stable regions on the planet (see Figure 3.4).

During the past 500 years, few earthquakes of magnitude 5 or greater have been documented anywhere in the Canadian Shield except on the southeast edge of the Shield near the St. Lawrence Valley and in the far north. The seismic activity in and around the St. Lawrence Valley is associated with a structurally weak region of the crust that appears to be related to continuing strain and adjustment along large ancient faults that were created by rifting 600 million years ago during the early stages of formation of the Atlantic Ocean. The central portion of the Shield, in contrast, is almost devoid of seismic activity. It is designated as a region of low to negligible seismic hazard (Basham 1995).

Brief increases in seismic activity are assumed to occur with the release of vertical stresses as glaciers recede, but these periods are unlikely to last long (Atkinson and Martens 2007). In addition, the effect of earthquakes is much smaller at depth than at the surface (Power et al 1998, Backblom and Munier 2002).

An analysis conducted for an in-floor placement design by the Swedish program concluded that there would be no effect on the containers even if seismic activity resulted in shearing of up to 0.05 m in the rock across a container location (Raiko et al. 2010). Although there has been no analysis specific to the reference Canadian container, it is similar in design and dimensions to the SKB container, and is surrounded by a similar thickness of buffer. Thus, container failure due to such a shear load is assumed to be one of the mechanisms leading to failure of a few containers in the Container Failure Scenario. (Note that SKB estimates pessimistically that about 0.1 containers would fail due to shearing, over a million year timeframe, and include the Canister Failure due to Shear Load case as a disruptive scenario (SKB 2011)). Since seismic activity in portions of the Canadian Shield can be very low (Atkinson and McGuire 1993), as shown in Figure 3.4, the probability of such a failure mechanism is low at the repository site.

Seismic reactivation of existing faults is a remote possibility as it would require a very large event to occur right at the repository site. However, seismic activity may increase as ice-sheet retreat from the site. Since glaciation is considered as part of the Normal Evolution Scenario, the potential effects of seismic activity need to be assessed. This is done in the FCS by assuming, for all scenarios, that all identified fractures at the site are open and permeable, and by considering the possibility of a new active fault through the Undetected Fault Scenario.

A severe seismic event is considered as the potential cause for the activation of the fault in the Undetected Fault Scenario, and degradation of the shaft and fracture seals in the Shaft Seal Failure and Fracture Seal Failure Scenarios, respectively.

FEP Screening

Include FEP in all scenarios. This FEP is included by assuming that all identified fracture zones at the site are open and permeable. That is, any closed fractures at the site are conservatively assumed to have been activated by seismicity (and glacial-related deformation).

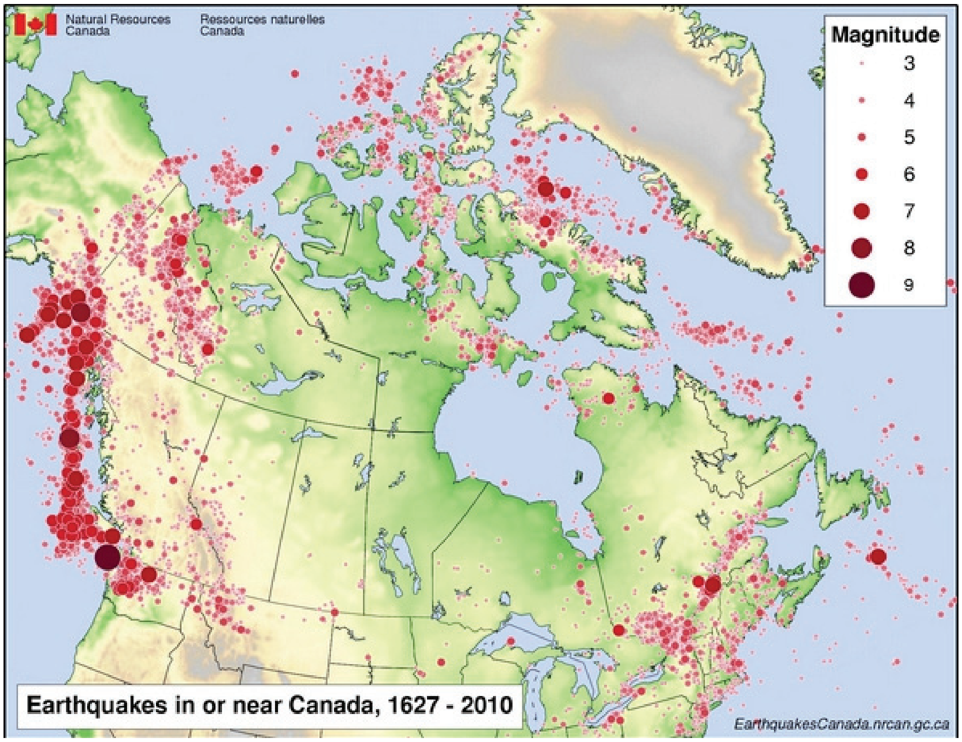


Figure 3.4: Major earthquakes in Canada since 1627 (obtained from Natural Resource Canada website http://earthquakescanada.nrcan.gc.ca/historic-historique/caneqmap-eng.php).

FEP # 1.2.04 Volcanic and magmatic activity

Description

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

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

Effects on the geosphere could include activation, creation and sealing of faults, changes in topography, changes in rock stress, deformation of rock and changes to groundwater composition and temperatures. Effects on the repository could include indirect changes in temperature, groundwater flow or groundwater chemistry, or direct disruption by intersection of repository rooms by a magmatic dike. A volcano that intersects the repository and that also reaches the earth's surface may give rise to dispersion of wastes in a plume of volcanic ash.

FCS Screening Analysis

Active tectonic plate margins, including rifts and subduction zones, are the locus of most seismic and volcanic activity worldwide. In contrast, the Canadian Shield, the site of the hypothetical FCS repository, is located in the interior of the large North American tectonic plate, which is one of the most tectonically stable regions on the planet.

Volcanic activity in the interior of the Canadian Shield is very unlikely for at least another 20 million years, because the Canadian Shield is part of a vast, stable cratonic region where the earth's heat flux is low (Perry et al. 2010). The last volcanic eruptions in the Canadian Shield occurred more than a billion years ago, while the tectonic provinces of the Canadian Shield were forming by accreting to the edges of what was then the plate margin (Wheeler 1995).

The most recent volcanic activity in Ontario was related to the Great Meteor (or New England) hotspot in the upper mantle. About 130-180 million years ago, this hotspot was beneath present-day Ontario, where it created the kimberlites found in the James Bay Lowlands and other parts of Ontario (Heaman and Kjarsgaard 2000). Because of movement of the North American Plate, this hotspot is currently below the North Atlantic Ocean.

Based on present relative plate motions, volcanic activity may develop again in approximately 20 million years. At that time, the southwestern edge of the Canadian Shield may pass over a hot spot that is currently associated with volcanic eruptions and fumaroles in the Snake River Plain and Yellowstone area of the western U.S. (Wood and Kienle 1990, Müller et al. 1993).

Therefore volcanic and magmatic activity is not included in the Fourth Case Study because they are outside of the timeframe of interest.

FEP Screening

Screened out.

FEP # 1.2.05 Metamorphism

Description

The processes by which rocks are changed by the action of heat (typically at temperatures greater than 200°C) and pressure (usually at depths of several kilometres) beneath the Earth's surface or in the vicinity of *Volcanic and magmatic activity [1.2.04].*

The past metamorphic history of a host rock may be important to understanding its present- day characteristics and future evolution. Ongoing metamorphism can activate, create or seal faults; change topography and rock stress; deform rock structures; and alter groundwater composition and temperatures. Metamorphism can also alter the mineralogical and physical properties of rock; for instance, shale is composed of thin layers of fine-grained sediment, most of which is clay minerals, and can be altered by metamorphism to slate, a more compact and harder rock.

FCS Screening Analysis

The (hypothetical) Fourth Case Study repository site is on the Canadian Shield and the repository is in granitic rock (at a depth of 500 m) with the bedrock exposed near the surface. There are no significant sedimentary layers in the area. No volcanic activity is expected for tens of millions of years (see *Volcanic and magmatic activity [1.2.04]*). Therefore there is neither particularly susceptible rock, nor the temperatures and pressures needed for metamorphism to occur in the host rock over the 1 million year time frame of the Fourth Case Study.

FEP Screening

Screened out.

FEP # 1.2.06 Hydrothermal activity

Description

Processes associated with high temperature groundwaters, including buoyancy (density-driven groundwater flow) and alteration of minerals in the rocks through which the high temperature groundwater flows. These processes are often complex and strongly coupled; for example mineral alteration could involve fracture infilling which decreases groundwater flow and produces more saline groundwaters, resulting in formation of a new set of mineral alteration reactions, and so forth.

Groundwater temperature is determined by the large-scale geological and hydrogeological properties of the rock, such as the location of geothermal heat sources, thermal conductivity, location of recharge and discharge areas and hydraulic conductivity. Some specific consequences are described elsewhere; for instance evolution of the buffer, backfill and seals are described under Buffer and backfill materials and characteristics [2.1.04] and *Seals and grouts (cavern, tunnel, shaft) [2.1.05]*. More general effects are described under *Thermal processes and conditions (repository and geosphere) [2.1.11 and 2.2.10]*.

FCS Screening Analysis

The Fourth Case Study repository is assumed to be located on the Canadian Shield. The heat flux is low across the Canadian Shield (Perry et al. 2010). Therefore, geosphere driven hydrothermal processes act too slowly to be of concern over the 1 million year time frame of the Fourth Case Study.

FEP Screening

Screened out.

FEP # 1.2.07 Erosion and sedimentation

Description

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

This factor is concerned with processes (such as glaciation or massive river erosion such as caused the Grand Canyon) which could result in localized incisions that remove large volumes of rock from a small area or broader ranging actions that remove large volumes of surface soil and rock from a widespread area. It also includes subsequent deposition of the eroded material on lake bottoms and in river deltas. Related processes are discussed under *Erosion and Deposition [2.3.12],* and related glaciation effects under *Local Glacial Effects [1.3.05]*.

FCS Screening Analysis

The Fourth Case Study repository is assumed to be located on the Canadian Shield.

The erosion rate from wind and water on the Canadian Shield is less than 2 metres per 100,000 years (Merrett and Gillespie 1983), and would have negligible influence on a deep repository.

More significant is the potential erosion or deposition due to repeated cycles of glaciation. The hypothetical repository site is relatively flat and the surface is primarily granite bedrock. This is in part due to the ice sheet erosion that has already occurred over the past million years and that has removed easily erodible material.

White (1972) estimated that repeated cycles of erosion by ice sheets followed by slightly greater isostatic uplift of the most deeply eroded areas removed between 20 and 35 m of rock per 100,000 years from the Canadian Shield over the past million years. However, Sugden (1976) disputes the work of White and suggests that glacial erosion has removed no more than a few tens of metres of material from the Shield area of Northern Hemisphere during the Pleistocene (2.6 million years before the present), i.e., about 1 m per 100,000 years. This is in agreement with the work of Passe (2004) who estimated that only about 1 m of material is eroded during a glacial cycle (range 0.2 to 4 m). At this rate, glacial erosion is not significant over a million years.

Thus, erosion is not considered as a factor in the geosphere model for the FCS over the one million year time frame of interest.

Although there could be significant sediment deposits as a result of glaciers, these could be removed during subsequent glacial cycle. Since such deposits would likely provide further isolation for a repository, it is conservative to neglect them. Therefore, the FCS will not consider any significant sediment layers deposited by glaciation.

FEP Screening

Screened out.

FEP # 1.2.08 Diagenesis

Description

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

FCS Screening Analysis

The hypothetical repository site is assumed to consist of plutonic rock extending close to the surface, as is typical of the central portion of the Canadian Shield. No significant changes to these rock properties are expected given their mineralogy and the limited temperature and pressure at the repository.

Although glaciation may result in deposition of sedimentary material at the site surface, these are equally likely to be removed on the next glaciation cycle. In any event, such surface layers would not be subjected to the significant pressures or temperatures needed to promote consolidation over the relevant time scale.

Thus, diagenesis is expected to be insignificant at the Fourth Case Study repository site over the 1 million year time frame of interest and is, therefore, not considered.

FEP Screening

Screened out.

FEP # 1.2.09 Salt diapirism and dissolution

Description

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

FCS Screening Analysis

The Fourth Case Study repository is assumed to be sited in the plutonic rock of the Canadian Shield. Therefore, this FEP is not relevant to the Fourth Case Study.

FEP Screening

Screened out.

FEP # 1.2.10 Hydrological response to geological changes

Description

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

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

FCS Screening Analysis

At the FCS hypothetical repository site, the only geologically significant process expected to occur on a 1 million year time frame is glaciation (see *Deformation (elastic, plastic or brittle) [1.2.02]*).

Glaciation is likely to have an important effect on the groundwater flow field at the site, particularly during ice-sheet advance and retreat. In the FCS, the effects of glaciation on groundwater flow as well as on the impacts of the repository are discussed as part of the Normal Evolution Scenario.

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

FEP Screening

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

1.3 Climatic Processes and Effects

FEP # 1.3.00 Scope of sub-category 1.3

Description

Factors related to global climate change and consequent regional effects.

There are nine subcategories under climatic processes and effects:

- 1.3.01 Global climate change
- 1.3.02 Local and regional 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 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

The global climate and its evolution in time.

Climate is characterized by a range of factors, but notably temperature and precipitation. Global climate change would likely lead to local changes around a repository (see *Local and regional climate change [1.3.02]*) and, hence, could affect the performance of the repository.

One important possible climate change is the onset of a new ice age (see Figure 3.5). The last million years have been characterized by glacial and interglacial cycling with a period of about 100,000 years, and it is plausible that these will continue. The global climate could also move to global warming, possibly caused by elevated levels of greenhouse gases in the atmosphere; extended winters caused by dust generated by nuclear war, volcanoes or meteorite impacts; or other large-scale changes that might be attributed to changes in ocean current patterns, changes in the extent of snow and vegetation cover on the earth's surface, and changes in the degree of cloud cover in the atmosphere.

FCS Screening Analysis

Currently, the global climate is warming. Current estimates suggest there will be an increase in the global average temperature, accompanied by a rise in sea levels, an increase in extreme weather, and changes in precipitation patterns (IPCC 2007). The potential effects of global warming are considered further under *Local and Regional climate change [1.3.02].*

In the long term, the most significant global climate change would be the re-occurence of glacial cycles, following the pattern of the past one million years with glacial cycles roughly every 120,000 years. These 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 (e.g., Berger and Loutre 2002), the basic solar insolation variations will continue and, therefore, it is prudent for the FCS safety assessment to assume that glaciation will resume in the long-term.

Glaciation could have a large effect on the repository system (see *Local glacial effects [1.3.05]*), although changes at the repository level are more muted because of the depth of the repository. Hence, the impacts of glaciation on repository performance are included as part of the Normal Evolution Scenario. The potential effects are discussed under *Local glacial effects [1.3.05].*

FEP Screening

Include FEP in Normal Evolution Scenario.

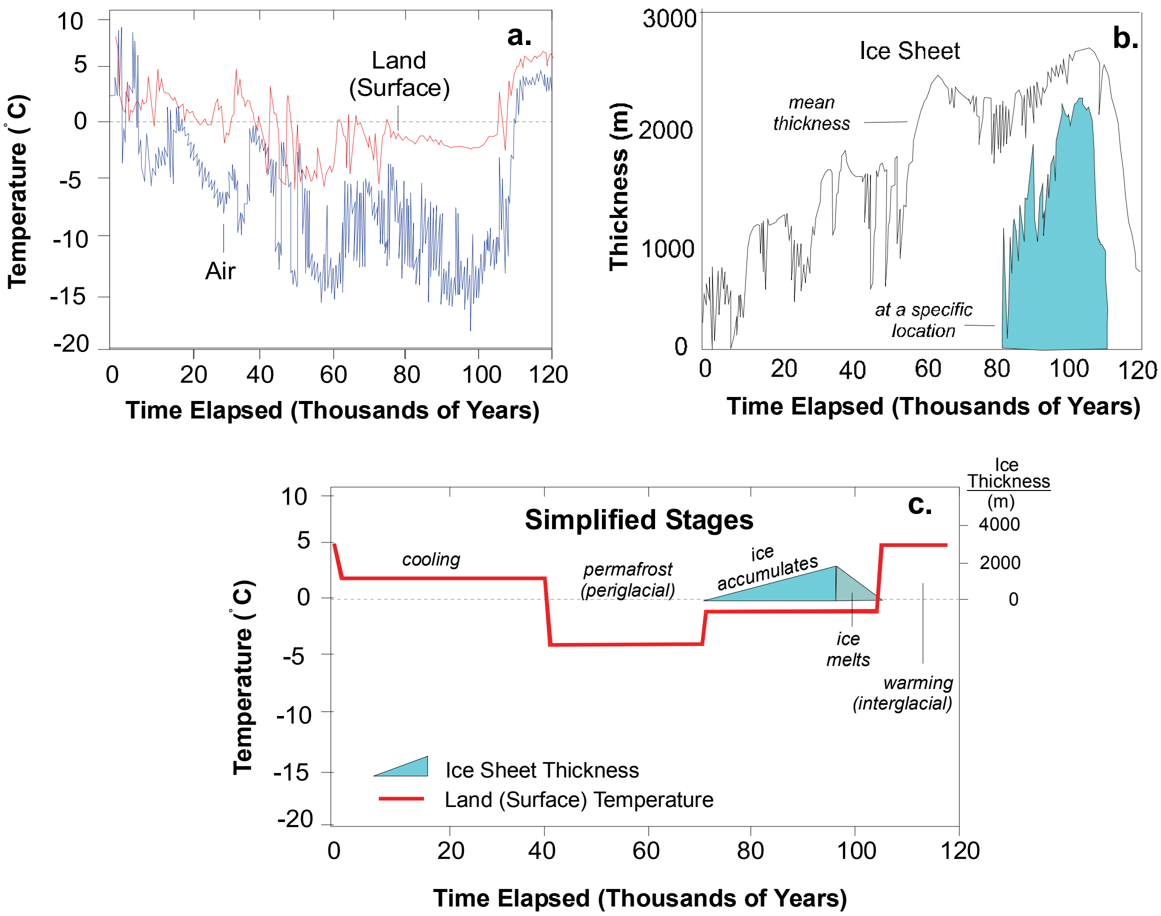


Figure 3.5: The main stages of glacial cycles (from McMurry et al. 2003)

(a) Calculated average temperatures for the air above and the land surface below the Laurentide ice sheet during the last major glaciation (adapted from Marshall and Clarke 1999).

(b) Calculated average thickness of the Laurentide ice sheet as a whole (adapted from Marshall and Clarke 1999) and the modelled thickness (shaded area) at one particular location in the ice sheet (Peltier 2002).

(c) Five simplified stages of a glacial episode, as interpreted from modelling by Peltier (2002, 2006). The time axis starts from the end of the interglacial period. Historically, these have lasted about 10,000 to 20,000 years.

FEP # 1.3.02 Local and regional climate change

Description

The climate at a repository site, on a local or regional scale, and its evolution in time. Broad climate types include tropical, dry, temperate, continental, polar and alpine. Climate is characterized by a range of factors, but most notably temperature and precipitation.

Changes to the local climate can be
- a long lasting response to variations in *Global climate change [1.3.01]*,
- regional climate fluctuations lasting a few years in response to processes such as El Nino, and
- normal fluctuations caused by seasonal and even daily variations in weather.

Climate change can occur as smooth or abrupt gradations from one climate state to the next. The processes that occur during the change between these states may also be important.

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

FCS Screening Analysis

Regional climate changes are potentially important for the repository system, especially in the surface and near-surface 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.

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 FCS 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].* Thus, in the FCS, the effects of glaciation are discussed as part of the Normal Evolution Scenario.

FEP Screening

Include FEP in the Normal Evolution Scenario.

FEP # 1.3.03 Sea level change

Description

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 rebound movement of the land mass associated with glacial unloading or rebound (see also *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 change in proximity to oceanic sources.

FCS Screening Analysis

The FCS will not consider the effects of sea level change because the location of the hypothetical repository is assumed to be hundreds of kilometers from the nearest ocean.

FEP Screening

Screened out.

FEP # 1.3.04 Periglacial effects

Description

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

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

The onset or retreat of glaciation will lead to a change to or from periglacial conditions. These will be accompanied by changes in drainage and watershed systems, which will affect groundwater flow, and changes in the plant, animal and human communities, which will affect exposure pathways.

FCS Screening Analysis

In the FCS, the effects of glaciation are considered in the Normal Evolution Scenario. A reference glacial cycle is considered (Garisto et al. 2010) which includes extensive periods of cold but ice-sheet-free environments in which permafrost is formed. During these periods, the climate is not suitable for farming and the critical group living near the repository is assumed to have characteristics similar to those of a self-sufficient hunter whose main food source is caribou meat.

The maximum extent of permafrost depth at the FCS hypothetical site is assumed to be a few hundred meters - i.e., less than repository depth - as is typical of permafrost over much of the southern Canadian Shield. Formation and disappearance of permafrost affects the groundwater flow regime since the permafrost layer has a very low hydraulic conductivity (Walsh and Avis 2010).

FEP Screening

Include FEP in Normal Evolution Scenario.

FEP # 1.3.05 Local glacial effects

Description

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

The presence of an ice sheet will change hydraulic heads directly, possibly imposing an additional head equivalent to the height of the ice sheet. During and after the glaciation, the surface topography will likely change, and new underground fractures might form or old fractures might open or close. Consequently the groundwater flow paths may change. The presence of permafrost around the ice sheet will also extend its affects on groundwater flow.

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

The pressure of the ice mass on the landscape will cause a wide-spread depression of the regional crustal plate. Isostatic rebound will occur after the ice sheet retreats. The weight of the ice sheet will change the stress fields around the glacier. In particular, the advance or retreat of the ice sheet may be accompanied by reactivation of faults and fractures, and the occurrence of earthquakes (see *Seismicity [1.2.03]*).

The glaciers may cause deep flooding with oxygenated water, possibly during the period of glacial advance or retreat. The process could significantly alter groundwater compositions at depth, notably concentrations of oxygen or other electrochemical oxidants.

Glaciation would also bring about massive changes to the biosphere. For instance, the presence of a nearby ice sheet would likely promote formation of a tundra climate and biosphere. Another important change would be the characteristics of humans living nearby.

FCS Screening Analysis

As identified in *Local and Regional Climate Change [1.3.02],* the repository site is assumed to be affected by future glaciation, and in particular will be covered periodically with ice sheets over the next million years. The effects of ice sheets within the region of the repository are discussed in the FCS for the Normal Evolution Scenario.

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

The ice-sheets may cause the introduction of oxygenated fresh water, possibly during the period of ice-sheet advance or retreat when head gradients are largest, potentially altering groundwater compositions. However, field evidence from the Canadian Shield at the Whiteshell Research Area indicates that oxygenated waters have not penetrated below about 50 m from the surface (Gascoyne et al. 2004, McMurry and Ejeckam 2002) although glacial meltwaters may have penetrated down to 350 m or so (Zhang and Frape 2002, Garisto et al. 2010). This arises because the oxygen in the meltwater is consumed by reaction with, for example, ferrous minerals in the rock (Spiessl et al. 2009). Part of the site selection process would favour sites where there is evidence that past glaciations have not altered the groundwater at repository level.

For the FCS site, paleohydrogeologic simulations (NWMO 2012, Chapter 2) indicate that glacial meltwaters would reach the repository level, with tracer meltwater concentrations ranging between 5% and 45% within the rock matrix at the repository horizon; although, significantly higher meltwater concentrations occurred within the discrete higher permeability fracture zones. (Note that composite seals are used to isolate the fracture passing through the repository footprint from the repository, as shown in Figure 3.1.) However, the glacial recharge penetrating below the shallow groundwater system (i.e., below 150 m depth) is not expected to be oxygenated or influence redox conditions at the repository horizon (NWMO 2012, Section 2.3.5.3).

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 reference used fuel container. Similarly, the potential geomechanical effects from the ice-sheet loading on the repository and shaft would need to be taken into account for the specific site conditions. However, the repository and shafts would be backfilled, and it is assumed that the repository would be generally aligned favourably with the normal rock stresses at a real site such that there would be little effect from ice-sheet loads.

Local glacial effects, due to passage of an ice sheet over the site that is thicker than the design basis ice sheet thickness, are assumed to be the cause of container failures in the All Containers Fail Scenario. The probability of such an event is low since the design basis ice sheet thickness is intended to represent the maximum for the site location, and since the water table in the middle of a large ice sheet is not likely to be near the surface of the ice sheet given the low atmospheric temperatures during the time of peak ice sheet thickness.

Glaciation would bring about significant changes to the biosphere. Erosional processes associated with glacial movement and glacial meltwaters can change local topography but such changes are neglected in the FCS (see *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.

Local glacial effects are considered a potential cause of the All Containers Fail Scenario.

FEP # 1.3.06 Warm climate effects (tropical and desert)

Description

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

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

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

FCS Screening Analysis

The development of tropical/warm-desert conditions on the Canadian Shield is unlikely over the one million year time frame of interest due to its northerly latitude and the dominance of glacial cycling. There is no evidence of tropical or hot desert conditions over the past Quaternary period. The current period of global warming is also not expected to result in a temperature rise sufficiently extreme to induce tropical or hot desert conditions. Therefore warm climate effects are not included in the Fourth Case Study.

FEP Screening

Screened out.

FEP # 1.3.07 Hydrological response to climate change

Description

Related to changes in hydrology and hydrogeology in response to climate change in a region, excluding glaciation.

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, extent of soil saturation, surface runoff, changes in sediment load characteristics and groundwater recharge. Vegetation and human actions may modify these responses. Potential effects include climate-induced evolution of surface water bodies, such as the formation of lakes and rivers, or their loss by sedimentation and infilling, river course meander and long-lasting flooding or drying of low lying areas,

Other effects, e.g., due to glaciation, 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 on the repository system are described under *Hydrological processes and conditions (repository and geosphere) [2.1.08 and 2.2.07], Surface water bodies [2.3.04]* and *Hydrological regime and water balance (near-surface) [2.3.11].*

FCS Screening Analysis

The effects of hydrological response to climate change other than glaciation are not included in the Fourth Case Study.

The deep groundwater flow conditions in the rocks of the Canadian Shield would not be significantly altered by a climatic change to wetter or drier conditions (within the expected normal range of variation) and so are assumed to be independent of climatic conditions. Specifically, the water table in the Canadian Shield in general is within a few meters of ground surface and is maintained at that level by only a small influx of the total annual precipitation. If the climate becomes wetter, water table levels would remain relatively unchanged although more surface water flows would result. Similarly, annual precipitation rates would have to decrease to a very small percentage of present day levels to cause a significant decrease in the water table levels in the Canadian Shield.

The FCS does consider the effects of normal climate variation on irrigation rates (see *Meteorology [2.3.10]*).

FEP Screening

Screened out.

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.

FCS Screening Analysis

The current ecosystem in the vicinity of the FCS site is assumed to be boreal forest, consistent with much of the Canadian Shield.

As long as the climate remains generally temperate as a result of global warming, the overall nature of the ecosystem is expected to remain broadly similar to the present. The ecosystem would likely evolve towards a temperate deciduous forest or mixed-wood basis.

Major ecological changes would result from glacial cycling. In particular, during periglacial periods, the ecosystem would be tundra. The FCS qualitatively considers ecological response to glaciation as part of the Normal Evolution Scenario, as was done in Garisto et al. (2010).

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 changes.

Climate affects the abundance and availability of natural resources such as water and the types of crops that can be grown. It also affects the activities and needs of humans; for instance a colder climate would likely increase the time spent indoors and heating fuel needs, which may in turn influence air quality and inhalation doses. The more extreme a climate, the greater the extent of human control over these resources is necessary 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.

FCS Screening Analysis

The characteristics of potential human critical groups will change as a result of climate change. Global warming in the next millennium can be expected to have some impact on human behaviour. More significant impacts are expected as the climate cools in the longer term 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 such as is practiced 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 be re-established in the area.

The FCS considers human response to climate changes resulting from glaciation as part of the Normal Evolution Scenario. Based on Garisto et al. (2010), three critical groups are defined: a self-sufficient farmer who resides during periods of temperate climate, a self-sufficient hunter who resides during periods of permafrost and a self-sufficient fisher who resides 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 sub-category 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 [2.4].*

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. See also *Future human action assumptions [0.0.05].*

Examples of such activities include the following.

- The greenhouse effect. Man-made emissions of gases such as carbon dioxide and methane have been implicated as factors in global warming. Concerns exist that the continued emission of such gases could lead to massive climate change; for instance the Canadian Shield might experience a warmer and drier climate. This effect could act to delay or even prevent the next glaciation cycle.
- Industrial chemicals such as chlorofluorocarbon compounds may lead to the destruction of the earth's ozone layer. An impaired ozone layer could have direct effects on humans or ecological systems. Moreover, there may be a subsequent effect on climate.
- 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.
- 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.

FCS Screening Analysis

In the near-term, human induced global warming may cause temperature and precipitation changes whose impacts can be locally important; for example, there could be changes in precipitation rates and, hence, stream and river flows. 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 (see *Global climate change [1.3.01]*).

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 which is 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 *Un-intrusive site investigation [1.4.03], Drilling activities (human intrusion) [1.4.04], Mining and other underground activities (human intrusion) [1.4.05], Surface environment, human activities [1.4.06]* and *Water management (wells, reservoirs, dams) [1.4.07].*

FCS Screening Analysis

Deliberate human intrusion is not included in the Fourth Case Study. It is assumed that any society wishing to recover such materials would have the technology to understand and avoid the hazards, i.e., they are responsible for their actions. Malicious acts are not included either, except that it is noted that the depth of the repository would be a significant deterrent to malicious intrusion.

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.

Such 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.

FCS Screening Analysis

Non-intrusive site investigations for any purpose are not considered because they would not have any effect on the repository or contaminants.

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 activity in the vicinity of the repository, performed without knowledge of the repository. This category includes exploratory boreholes drilled in association with mining but not *Mining (human intrusion) [1.4.05].*

Another important drilling activity, for water-supply wells, is discussed 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;
- production of geothermal energy;
- injection of liquid wastes and other fluids;
- underground nuclear testing; 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.

FCS 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 deep 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 assumed at the hypothetical site.

Since it is assumed that the host rock does not have significant 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.

Nonetheless, because of the long time frames of interest, it is possible that institutional controls, markers and societal memory would have lapsed. Thus, the Fourth Case Study considers an Inadvertent Human Intrusion Scenario in which an exploratory borehole drilled from the surface is assumed to pass through a repository container and brings 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.

FEP Screening

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

Reasons for mining and related activities include:

- recovery of nearby natural resources such as minerals 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 material 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, and 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.

FCS Screening Analysis

The Fourth Case Study does not consider the effects of mining activities. Mining into or near the repository is unlikely because the site selection process would favour host rocks that are of no economic interest (and the plutonic hosts rocks of interest fall into this category for the most part). Furthermore, the repository depth (500 m) is well below what would be of interest from a rock quarry viewpoint. Also deep mining activities would typically be preceded by exploratory boreholes to verify the nature of the rock. The effects of boreholes are included as discussed in *Drilling Activities [1.4.04].*

FEP Screening

Screened out.

FEP # 1.4.06 Surface environment, human activities

Description

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;
- introduction of pollutants such as road salt and herbicides (which may alter contaminant movement patterns and exposure pathways); and
- major earthmoving projects, such as construction of dikes and dams (which could alter the landscape, and change groundwater recharge and discharge locations).

FCS Screening Analysis

The depth of the repository 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 are considered in all scenarios, and less than the impacts of intruding directly into the repository via an exploration borehole which is considered in the Inadvertent Human Intrusion Scenario.

FEP Screening

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, lakes or drainage systems for hydroelectric generation, irrigation, flood control etc., could alter the landscape and expose subsoil, overburden or bedrock, and change groundwater flow regimes such as recharge and discharge locations.

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

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

- Surface water sources 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 [2.4.05.C]*. Further consideration of irrigation water is discussed under *Rural and agricultural land and water use [2.4.09]* and *Urban and industrial land and water use [2.4.10].*

FCS Screening Analysis

There is present-day shallow groundwater pumping and use for domestic and agricultural purposes on the Canadian Shield. Therefore, the use of a water extraction well is considered in the Fourth Case Study after institutional controls are no longer effective.

The development of hydroelectric projects would not likely have large effects. The regional area around the FCS hypothetical site has low topographic relief, so that any dams in the area would have low hydraulic head structures (typically less than 20 m) and these would have little effect on groundwater flows at repository depths.

FEP Screening

Include a 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.

FCS Screening Analysis

As noted in *Future human action assumptions [0.0.07]*, the FCS 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 FCS will specifically assume that adequate institutions will exist for at least 300 years following repository closure. The possibility of loss of institutional control eventually allowing inadvertent intrusion in the repository will be considered in the FCS. 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 on or near the site.

FEP Screening

Include FEP in all scenarios.

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

FCS Screening Analysis

The effects of possible future developments in technology are not included in the Fourth Case Study (see also *Future human action assumptions [0.0.07]*). Consistent with the recommendations of the International Commission on Radiological Protection (ICRP 2000) and CNSC Guide G-320 (CNSC 2006), it is assumed that future humans will largely resemble present-day humans in terms of habits and characteristics.

As noted in the FEP Description above, a lower level of technology might make it less likely that intrusion could be technically achieved. A higher level of technology might make intrusion more likely but as well might imply increased knowledge of the risks and how to control them. For example, we do not consider factors that might result in retrieval and better disposal of the wastes, or technologies that might better allow for monitoring or repair of the containers.

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 that was not performing to the standards required, had been disrupted by some natural event or process, or had been inadvertently or deliberately damaged 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.

FCS Screening Analysis

The 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 level and any necessary remedial operations can be undertaken with a fair degree of control to ensure that they do not have a detrimental impact on repository safety. Following closure, it is assumed that, even if there were to be remedial actions, their effects on the repository would be assessed at the time of remediation to ensure that they did not detrimentally affect repository safety.

FEP Screening

Screened out.

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].*

FCS Screening Analysis

Events of this type are not considered because no known non-nuclear explosive device could breach or otherwise seriously affect the rock, groundwater, seals or containers in a closed repository at a depth of 500 m in a granite pluton. The impacts to the critical group from the effects of a nuclear bomb exploding near a repository site would likely outweigh any additional impacts arising from the repository, over both short and long time frames.

FEP Screening

Screened out.

1.5 Other External Factors

FEP # 1.5.00 Scope of sub-category 1.5

Description

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

There are three subcategories:

- 1.5.01 Meteorite impact
- 1.5.02 Species evolution
- 1.5.03 Miscellaneous 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.

FCS 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 located in the Canadian Shield, similar to the depth and size of the FCS repository.

   Wuschke et al. (1995) (see also Goodwin et al. 1994, p.637) estimated that the probability of a significant meteor impact at or near the repository is 1.4×10^{-11} per year, see Figure 3.6. Their calculations were based on the assessment that the smallest (and hence most likely) meteor to have a significant effect on the repository would produce an impact crater that would redistribute the rock to the level of the repository (see Figure 3.7), and fracture rock to a depth of 2.7 km. (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 that another ~2 km of shattered rock underlies the crater floor, using the meteorite crater data in Grieve and Robertson (1984)). Although Wuschke et al. (1995) used meteorite probability versus size data from the 1980s, results from a more recent survey are very similar (Brown et al. 2002).

   Wuschke et al. (1995) found the radiological risk from this meteorite impact scenario to be very small, largely because the probability of a meteor impact of sufficient magnitude to affect the repository was low, even though 100% of the radionuclides in the repository are released to the biosphere. At longer times, the cumulative probability of an impact increases but radioactive decay reduces the consequences.

2. As noted above, in their base case, Wuschke et al. (1995) consider a meteorite producing a crater of 3.6 km in diameter, whose zone of redistributed rock extends just to vault depth (i.e., 500 m). A meteorite larger that this would produce a larger volume of redistributed rock and would eject some of the waste from the vault, providing greater dilution of the vault contents. Wuschke et al. (1995) argue that the risk from such a large meteorite impact would be smaller than for the base case meteor because the probability of a larger meteorite impact is lower and because radionuclide concentrations in the biosphere would be lower due to the greater dispersal of the waste.

3. Finally, Wuschke et al. (1996) considered the case in which a meteorite produces a crater whose zone of fractured rock extends to repository depth. 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 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.

4. Wuschke et al. (1995) considered the risk of large but very unlikely meteorites. Conversely, the consequences of a "likely" meteor can 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 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 FCS repository. Most debris is far too small to have an impact. Large structures such as the International Space Station are not very massive (about 300 Mg), nor very dense and would impact with generally lower velocities than meteors. For comparison, a 10 m diameter meteor would be about 200 Mg.

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

FEP Screening

Screened out.

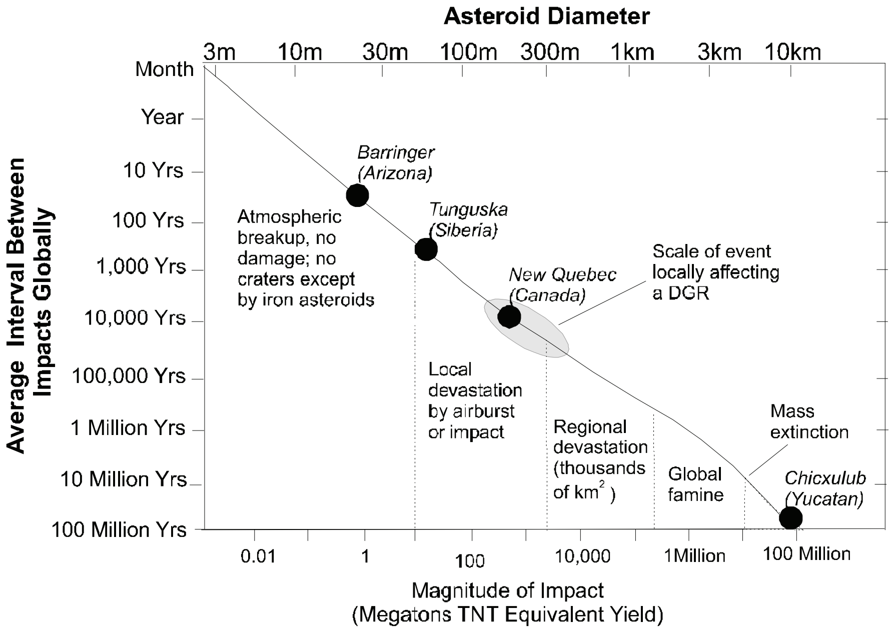


Figure 3.6: Estimated frequency and severity of meteorite impacts on the Earth as a whole (adapted from Morrison et al. 1994). Shaded region on curve indicates the approximate magnitude of events that would produce a crater and shattered rock to a depth of 500 to 1000 m. For any given meteor impact, 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..

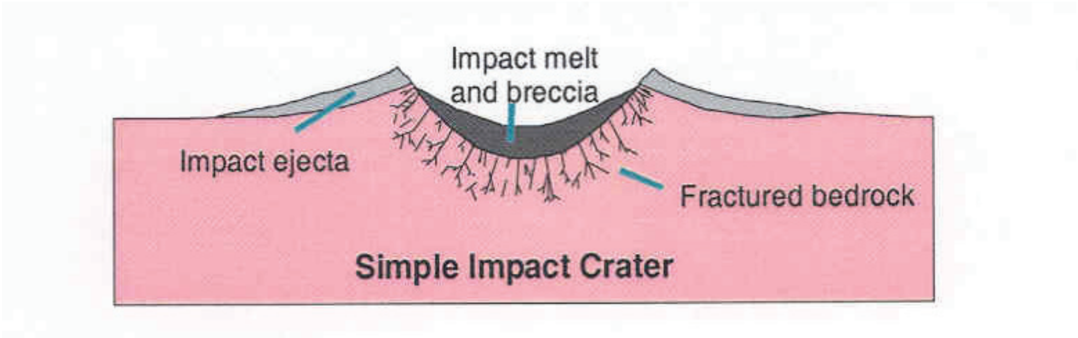


Figure 3.7: Cross-section of a simple meteorite impact crater (from McMurry et al. 2003). In the base case of Wuschke et al. (1995), the bottom of the melt and breccia layer is approximately at repository level, i.e., 500 m below the original surface, and the rock below the repository level is fractured by the meteorite impact.

FEP # 1.5.02 Species evolution

Description

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

Over the times 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.

FCS Screening Analysis

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.

Consistent with the recommendations of ICRP Publication 81 (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.

It is likely that some microbial adaptation would occur, but unlikely that it would lead to dramatically new species since the main materials present in the repository are also present in natural settings (uranium, iron, copper, 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.

FEP Screening

Screened out.

FEP # 1.5.03 Miscellaneous FEPs

Description

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

FCS Screening Analysis

Consideration of the following unusual factors is excluded in the Fourth Case Study 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.

(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. 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 since this occurs very slowly, about 1^{o} per million years.

FEP Screening

Screened out.

2. REPOSITORY FACTORS

FEP # 2.0.00 Scope of main category 2.

Description

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

The four sub-categories under repository system domain are:

- 2.1 Wastes and engineered features
- 2.2 Geological environment
- 2.3 Surface environment
- 2.4 Human behaviour

2.1 Wastes and Engineered Features

FEP # 2.1.00 Scope of sub-category 2.1

Description

Features and processes within the waste and engineered components of the repository, as they exist at the time of placement and considering changes that could occur over long periods of time. Waste and engineered components are also referred to collectively as and ‘repository’ below.

There are 14 subcategories under Wastes and Engineered Features:

2.1.01 Waste inventories
2.1.02 Waste form materials and characteristics
2.1.03 Container materials and characteristics
2.1.04 Buffer and backfill materials and characteristics
2.1.05 Seals and grouts (cavern, tunnel, shaft)
2.1.06 Other engineered features
2.1.07 Mechanical processes and conditions (repository)
2.1.08 Hydrological processes and conditions (repository)
2.1.09 Chemical processes and conditions (repository)
2.1.10 Biological processes and conditions (repository)
2.1.11 Thermal processes and conditions (repository)
2.1.12 Gas sources and effects (repository)
2.1.13 Radiation effects (repository)
2.1.14 Nuclear criticality.

FEP # 2.1.01 Waste inventories

Description

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 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) from CANDU power plants; and
- introduced with the engineered barriers, such as large volumes of iron, copper and organics, as well as materials that might be introduced inadvertently such as diesel oil.

A repository may also be used for the co-disposal of various radioactive and chemically toxic wastes; some potential examples are noted under *Waste allocation [1.1.06].* A related consideration is the potential hazard of mined rock (tailings) produced when excavating the repository. This topic might be included in a preclosure assessment but may require evaluation of potential long-term impacts.

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.

Estimates of 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 large range around the average; that is, some bundles may have very low or very high discharge burnups. Radionuclide inventories will be time dependent (see *Radioactive Decay and Ingrowth [3.1.01]*).

The presence of impurities in used CANDU fuel bundles may also be of concern. For instance, there are several possible sources of inventories for Cl-36 in irradiated CANDU fuel, but the most important is thought to be neutron activation of stable Cl-35 which is present as an impurity. There are other possibilities where activation of impurities and transmutation may give rise to significant quantities of hazardous radionuclides. In fact, most radionuclides of concern in Zircaloy arise from neutron activation of elemental impurities in the alloy.

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

FCS Screening Analysis

For the FCS, it is assumed that only CANDU fuel bundles are placed in the repository (see *Repository assumptions [0.0.06]*).

The initial radionuclide inventories in the UO_2 and the Zircaloy cladding are included. The values are based on 30 year cooled fuel with a burnup of 220 MWh/kg U and a power rating of 455 kW/bundle (Tait et al. 2000; Tait and Hanna 2001). These inventories include radionuclides generated by neutron activation of impurities in the fuel or Zircaloy sheaths. In the Fourth Case Study, uncertainties in the inventories are also considered.

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 that in the UO_2 fuel itself and need not be considered separately.

After placement, 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 for further significant changes 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.

Estimates of 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 large range around the average; that is, some bundles may have very low or very high discharge burnups. These inventories could include both stable and radioactive isotopes, and total inventories will be time dependent for many elements (see *Radioactive decay and ingrowth [3.1.01]* and *Chemical and organic toxin stability [3.1.02]*). 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-shell containers).

FCS Screening Analysis

For the FCS, only CANDU fuel bundles are placed in the repository (see *Repository Assumptions [0.0.06]*).

The inventories of chemically toxic elements in the UO_2 and the Zircaloy cladding of CANDU fuel bundles are described in Tait et al. (2000) and Tait and Hanna (2001). The inventories for 30 year old used fuel are used in the FCS.

The FCS discusses 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. This is done by comparing the calculated concentrations of these elements in various biosphere media with criteria for protection of humans and biota from non-radiological impacts provided in NWMO (2012).

FEP Screening

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

FEP # 2.1.02 Waste form materials and characteristics

Description

The physical, chemical and biological characteristics of the waste forms at the time of placement, and evolution of these properties with time. This category includes processes that are relevant specifically as waste degradation processes, rather than processes that contribute to the general evolution of the near field.

The waste form will usually be conditioned prior to placement 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 placement, and will change in response to the conditions within the repository. A process of particular interest is the contaminant source term, or the characteristics of release of a contaminant from its waste matrix, such as congruent or instant release controlled by electrochemical dissolution or leaching. (By definition, leaching is the release of a contaminant without matrix dissolution whereas dissolution is the release as the host matrix dissolves.)

The following specific factors are discussed under separate entries:

- 2.1.02A Characteristics of used CANDU fuel (UO_2)
- 2.1.02B Characteristics of Zircaloy cladding
- 2.1.02C Characteristics of other waste forms
- 2.1.02D Used fuel dissolution
- 2.1.02E Zircaloy cladding dissolution.

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.

Current information indicates that radionuclides and chemically toxic elements are not distributed uniformly in the UO_2 matrix or on its surface. 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 surfaces, diffusion of gaseous and volatile nuclides to grain boundaries and to cooler regions (typically gaps between fuel pellets and between a fuel pellet and its Zircaloy cladding), and formation of "epsilon" phases of rare earth metals. 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_4O_9, U_3O_8 and to UO_3) and selective leaching.

Corrosion/dissolution of the UO_2 fuel is discussed in *Used fuel dissolution [2.1.02.D].*

FCS Screening Analysis

The FCS considers used CANDU 37-element fuel bundles with a nominal burnup of 220 MWh/kg U and a minimum cooling time of 30 years (see *Inventory of radionuclides [2.1.01.A]*). The (unirradiated) standard 37-element bundle is 495 mm long with a 102 mm diameter, and contains 21.8 kg of UO_2 and 2.2 kg of Zircaloy (Tait et al. 2000). Variation between other bundle types used in Canadian CANDUs is not considered 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 (less than 1%) of CANDU fuel in-reactor and the anticipated conditions during storage and transport.

The used fuel is a stable solid ceramic material. The key fuel characteristics for postclosure assessment are defined below (largely from McMurry et al. 2003).

The used fuel is composed of sintered UO_2 pellets with a typical diameter of about 12 mm. The material has a density of 97% theoretical, a nominal irradiated grain size of 10-50 μm, and an oxygen/uranium ratio of about 2.001 unirradiated. Although some pellet cracking will have occurred during irradiation, the fuel pellets are expected to be largely intact at the time of placement. Irradiation will have resulted in some movement of porosity and gas, resulting in bubble formation both within the grains and on the grain boundaries, and in the formation of "epsilon particles" consisting of small particles of Tc, Mo and other metals. About 2% of the mass of the unirradiated fuel has been converted to new nuclides - 98% of the fuel is unchanged. More than 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 bundle is important, since the location affects the rate of release of the radionuclides if the container is breached and groundwater contacts the fuel (see *Used fuel dissolution [2.1.02.D]*).

Other important characteristics are the mass of UO_2 within a container and the effective surface area of the used fuel. Parameters describing these important characteristics are included in the FCS models.

FEP Screening

Include FEP in all scenarios.

FEP # 2.1.02.B Characteristics of Zircaloy cladding

Description

The properties of Zircaloy cladding, notably as they affects release of radionuclides and chemically toxic elements.

One characteristic is the physical/chemical state of the cladding, which includes the properties of Zircaloy cladding 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) are released instantly when water contacts the fuel. The mechanisms by which Zircaloy dissolves/corrodes, releasing radionuclides within the Zircaloy cladding itself, is discussed separately under *Zircaloy cladding dissolution [2.1.02.E].*

The Zircaloy cladding 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.

FCS Screening Analysis

The FCS models include parameters describing the properties of the Zircaloy cladding.

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

The inventory of activation products within the cladding after irradiation, including from chemical impurities, is given in Tait et al. (2000). Radionuclides and chemical impurities are assumed to be uniformly distributed within the Zircaloy metal cladding because it is thin compared to neutron path lengths. However, some radionuclides such as C-14 may be more concentrated in the zirconium oxide layer on the surface of the cladding. Evolution of the cladding and release of radionuclides is discussed separately under *Zircaloy cladding dissolution [2.1.02.E].*

The Zircaloy cladding is covered in a protective oxide coating. This makes it slow to corrode in water, or to react with UO_2. Most of the cladding will therefore maintain some mechanical integrity for very long times, preventing water in the container from contacting the fuel. However, the possibility of failure of the cladding due to stress corrosion cracking or delayed hydride cracking may be plausible at longer times and after groundwater enters the container. (Note that less than 1% of CANDU fuel is initially defected.) Rather than estimating this failure process in detail and, therefore, providing an estimate of how much fuel protection is provided by the cladding, the FCS neglects the presence of the Zircaloy cladding as a barrier to the corrosion of UO_2 fuel and to the release of contaminants from the 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 Characteristics of other waste forms

Description

The properties of other waste forms found in the repository, notably as they affect releases of radionuclides and chemically toxic elements within these materials.

A wide range of possible release processes exist for different waste forms. For instance, vitrified waste forms may be subject to leaching, recrystallization and cracking. Some waste forms might be thermodynamically stable and undergo slow dissolution (such as calcite) and others might transform to stable phases (such as cement altering to stable silicates after an initial period of rapid leaching). Some waste forms, such as bitumen, might be unstable and relatively reactive.

FCS Screening Analysis

In the FCS, it is assumed that only CANDU used fuel is placed in the repository. Thus, it is not necessary to define the characteristics of other waste forms.

FEP Screening

Screened out.

FEP # 2.1.02.D Used fuel dissolution

Description

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

Analyses over several decades indicate that radionuclide releases from used UO_2 fuel can be described by a fast and a slow mechanism: instant release and congruent release.

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. 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 and natural organics). 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 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.

Other possibilities to consider are mechanical breakdown, phase changes (such as UO_2 transforming to U_4O_9, U_3O_8 and to UO_3) and selective leaching.

FCS Screening Analysis

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. Some of the radionuclides are able to move under hot reactor conditions, and accumulate at grain boundaries or fuel void spaces (e.g., fuel sheath gap).

In the FCS, the radionuclide inventory located at grain boundaries and void spaces is assumed to be released instantly from the fuel as soon as groundwater contacts the fuel. This assumption is conservative since it ignores the likelihood that releases from grain boundaries, which are controlled by the corrosion/dissolution properties of the grain boundaries, would be delayed under reducing conditions. The (much larger) fraction of the radionuclide inventories located within the UO_2 grains is released congruently as the used fuel dissolves. This is because diffusion of atoms within solid grains is very slow at the temperatures in a repository.

In the FCS, the used fuel dissolution rate (Garisto et al. 2012, Appendix E) depends on the strength of the alpha, beta and gamma radiation fields and the fuel surface area. After decay of the alpha field at long times, chemical processes control the rate of fuel dissolution.

FEP Screening

Include FEP in all scenarios.

FEP # 2.1.02.E Zircaloy cladding dissolution

Description

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

Most radionuclides in Zircaloy are expected to be uniformly present due to 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. The radionuclides in the bulk metal would be released by congruent dissolution of the Zircaloy. Another release mechanism might involve the selective leaching of some nuclides or pitting/crevice corrosion in the presence of radiolytically-decomposed saline groundwaters (particularly if early container failure allows cladding contact with groundwater while radiation doses are high).

FCS Screening Analysis

In the FCS, most radionuclides in the Zircaloy cladding are released congruently as the Zircaloy cladding dissolves. For some radionuclides, e.g., C-14, a fraction of the radionuclide inventory in the cladding is released rapidly after water contacts the fuel (Garisto et al. 2012).

Zircaloy is a very corrosion resistant alloy (Shoesmith and Zagidulin 2010). A solubility limited dissolution model is used to calculate the rate of Zircaloy dissolution. In this model, the Zircaloy is assumed to dissolve quickly enough to maintain the aqueous concentration of zirconium in a breached container at its solubility limit. The dissolution rate is then limited by the rate of transport of dissolved zirconium out of the container.

FEP Screening

Include FEP in all scenarios.

FEP # 2.1.03 Container materials and characteristics

Description

The physical, chemical and biological characteristics of the containers at the time of placement, and their evolution in 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 characteristics and its degradation processes are discussed under:

- 2.1.03A Container design characteristics
- 2.1.03B Fabrication and installation defects
- 2.1.03C Stress corrosion cracking
- 2.1.03D General or uniform corrosion
- 2.1.03E Mechanical degradation
- 2.1.03F Localized corrosion
- 2.1.03G Microbial-induced corrosion
- 2.1.03H Internal corrosion processes.

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. Material aspects are also discussed under *Container Materials and Characteristics [2.1.03]*.

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 container. It may also be an important consideration for criticality concerns.
- The construction method may influence failure rates associated with fabrication defects (see *Fabrication and Installation Defects [2.1.03B]*).
- Design options that use a different material to provide internal support might lead to additional corrosion processes (see *Internal Corrosion Processes [2.1.03.F]*).
- 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]*).

FCS Screening Analysis

Only one container design is considered in the FCS, since the only wasteform considered is used CANDU fuel.

The FCS container consists of an outer corrosion-barrier oxygen-free phosphorous-doped copper vessel and an inner load-bearing carbon steel vessel (see Figure 3.8). The outer copper shell gives the container a long corrosion-free life, while the inner steel vessel provides the mechanical support, even under glacial loads. This design also makes the radiation fields low outside the container.

The outer copper vessel has a welded top lid and is 1.25 m diameter by 3.9 m long, with a wall thickness of 25 mm. The steel vessel has a bolted top lid with a wall thickness of at least 90 mm.

The container can hold 360 fuel bundles (6 layers of 60 bundles); so 12,778 containers are needed to hold 4.6 million fuel bundles.

The (empty) inner steel vessel has an inside volume of 2.5 m^3. The filled container has an internal void volume of 1.58 m^3 that is initially filled with inert gas.

A full container weighs about 26.7 Mg, of which 6.9 Mg is U.

The container is designed to withstand an isostatic external pressure loading of 45 MPa, as described in *Mechanical degradation [2.1.03.E].* More details on the design are provided in Garisto et al. (2012) and its references.

FEP Screening

Include FEP in all scenarios.

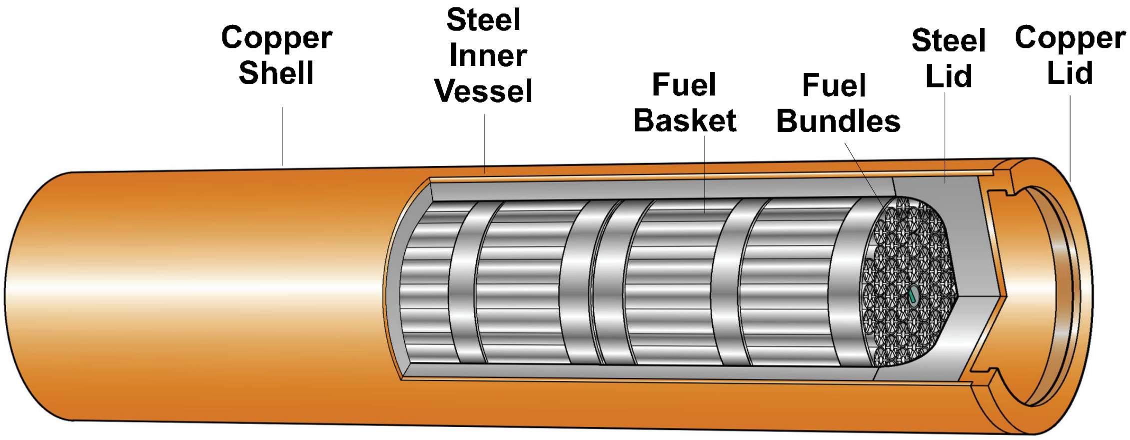


Figure 3.8: Cutaway illustration of container showing copper outer shell with welded copper lid with handling lugs, steel inner vessel and steel inner baskets holding used fuel.

FEP # 2.1.03.B Fabrication and installation defects

Description

The presence of defects in 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, leading to the growth of a small defect to a more substantial opening.

FCS Screening Analysis

The container design is robust with a significant margin of safety for normal mechanical loads. The possibility of fabrication defects that significantly reduce mechanical strength are considered very low, as is the possibility that handling will introduce defects. The primary concern is the integrity of the copper shell corrosion barrier. This is not a load bearing component, and has a significant margin of safety for corrosion. The most significant concern is considered to be the presence of an undetected through-wall penetration defects arising during the fabrication or top-lid closure welding processes.

The most likely location for the defect will be in the lid weld region. The fabrication process for the copper shell will involve a series of inspections that will be designed to reduce the possibility of weld defects to very low levels. The probability of an undetected through-wall defect has been estimated as 0.001-0.0001/container, based on experience with other nuclear components (Maak et al. 2001). This is consistent with weld trials on 50-mm copper shell containers that estimated a frequency of 10-20 mm defects as around one per thousand, and > 20 mm as negligible (SKB 2011). In the FCS, with 12,778 containers with a 25-mm copper shell, this means that statistically about 3 containers might be placed with through-wall defects. In the SKB repository with 6,000 containers, none have through-wall defects (SKB 2011).

The size of the defect will affect the rate at which water can enter the failed container, and at which gases (e.g., H_2 from iron corrosion) and contaminants can escape from the container. The area of the defect is included in the models for contaminant release and transport.

The dimensions of the defect could grow with time, particularly as corrosion of the inner steel vessel results in an expanding volume of corrosion products. On the other hand, the defect itself could be filled with corrosion products, so that its effective area for transport is reduced.

For the FCS, based on the expected low weld defect rate, it is assumed that a small fraction of containers placed in the repository have undetected full penetration defects in the copper shell. It is also assumed that the defect area remains constant in time, but a range of areas is considered that represent the uncertainty in the size of an undetected defect. Other modelling (e.g., Third Case Study, Garisto et al. 2004a) has indicated that the exact dimensions of the defect is not critical to the safety assessment results because the transport of contaminants out of the container is also constrained by their rate of transport of through the surrounding buffer. That is, for sufficiently large defects, the mass transport resistance in the buffer controls the rate of release of contaminants out of the container.

The possibility of undetected defects during manufacture of the steel vessels, leading to collapse of a few containers during glaciation, is considered in the Container Failure Scenario. As well, the possibility that the mechanical load on the containers in the repository exceeds the design load, due to, for example, passage of an ice sheet over the repository site that is thicker than the design basis ice sheet thickness, is examined in the All Containers Fail Scenario.

FEP Screening

Include FEP in all scenarios.

FEP # 2.1.03.C Stress corrosion cracking

Description

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

Stress corrosion cracking, or hydride embrittlement and cracking, may mechanically weaken the container and promote subsequent failure or other corrosion mechanisms. The process might be accelerated if hydrogen is attracted to and accumulates at a defect or crack site. Metals such as copper might be susceptible to stress corrosion cracking in nitrate-rich aqueous solutions. This could be an important issue if groundwaters near the repository contain nitrogen residues from blasting.

FCS Screening Analysis

Stress corrosion cracking of the copper shell is not considered to be a viable failure mechanism since the various factors (oxidants, tensile stress and stress corrosion agents) necessary for crack initiation and propagation are not expected to be operative simultaneously under repository environment (NWMO 2012; 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 FCS.

FEP Screening

Screened out.

FEP # 2.1.03.D General or uniform corrosion

Description

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) environment. 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 variables such as groundwater composition. For instance, the presence of sulphides in groundwater will likely promote the corrosion rates of copper alloys.

FCS Screening Analysis

The FCS container shells are constructed from an oxygen-free low-phosphorous copper. The uniform corrosion rate of such copper is low under the expected repository conditions and would not affect the integrity of the container, with uniform corrosion depths of the order of tens of micrometers after 1 million years (NWMO 2012, King et al. 2010) compared to a copper shell thickness of 25 mm.

Hultquist and co-workers (Hultquist et al. 2009; Szakálos et al. 2007) have suggested that oxidation of copper by pure water is possible. However, the scientific validity of their proposal is still being debated in the literature (King et al. 2010 and references therein). Nevertheless, assuming that oxidation of copper by water can occur under repository conditions, using the measured equilibrium partial pressure of H_2 for this reaction (Hultquist et al. 2009), and neglecting other sources of H_2, it is conservatively estimated that the corrosion of copper by water would continue at a rate at which H_2 could be transported away from the copper surface, i.e., a rate of a few nm/year (King 2010). At this rate, the uniform corrosion depth is less than a few mm in 1 million years.

Thus, uniform corrosion can be neglected on the time scale of interest for the FCS.

FEP Screening

Screened out.

FEP # 2.1.03.E Mechanical degradation

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 expansion. 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 glass beads, poured lead or other materials to provide internal support. These materials may compact, shrink or otherwise fail to perform their expected function and lead to container collapse.

FCS Screening Analysis

The FCS container consists of an outer copper shell and an inner carbon steel vessel. The load-bearing capacity is provided by the inner (~ 90-mm thick) carbon steel vessel.

The outer copper vessel is expected to be subjected to creep deformation in a deep geological repository. Creep of the copper will stop once the copper vessel has collapsed onto the steel vessel since the creep deformation of the steel vessel is expected to be extremely small under repository conditions (Dutton 2006). For a 25-mm-thick copper vessel, the maximum gap between the copper vessel and the steel vessel is 1 mm, which limits the extent of the creep deformation to below the allowable limit of 10% (Saiedfar and Maak 2002). A tight fit-up between the steel and copper vessels is required for the copper/steel dual vessel used fuel container. .

The steel vessel is designed to withstand a normal hydrostatic pressure and buffer swelling load of 15 MPa at 120°C, and an additional hydrostatic pressure of 30 MPa at 50°C corresponding to the maximum hydrostatic pressure head associated with a 3 km thick ice sheet (Saiedfar and Maak 2002). The mechanical loads are likely to be less than these design values. This provides margin for handling off-normal loads. Therefore, mechanical failure is not expected to be important over a one million year period (see also McMurry et al. 2003). Mechanical degradation due to manufacturing defects is considered under *Fabrication and installation defects [2.1.03.B].*

Processes that would lead to mechanical degradation of the steel are also not significant for this timeframe. The generation rate of gases from radioactive decay is insignificant and the lack of water or oxygen access to the interior of the container prevents any significant formation of rust or other reaction products (McMurry et al. 2003).

For a container with a full penetration defect, corrosion of the inner steel vessel will occur after groundwater enters the container, as discussed under *Internal corrosion processes [2.1.03.H]*.

In this case, the container would likely degrade and collapse under the hydrostatic loads on a time scale of less than 100,000 years (McMurry et al. 2004). This collapse is not modelled in the FCS for the reasons outlined under *Internal corrosion processes [2.1.03.H].*

The possibility that the mechanical load on the containers in the repository exceeds the design load (due to, for example, passage of an ice sheet over the repository site that is thicker than design basis ice sheet), causing failure of the containers, is examined in the All Containers Fail Scenario.

The possibility that a large seismic event causes container failure due to the shear stress on the container resulting from rock movement along a local fracture intersecting the borehole is considered in the Container Failure Scenario.

FEP Screening

Include FEP in the All Containers Fail and Container Failure Scenarios.

FEP # 2.1.03.F Localized corrosion

Description
The localised formation of cavities in a metal surface caused by nonuniform 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 or in a closure weld. These sites may concentrate chloride ions and hydrogen ions (or atomic hydrogen which could promote stress-induced cracking (see *Stress corrosion cracking [2.1.03.C]*) which initiate or accelerate corrosion.

One concern is that the localized effects may lead to failure long before more uniform corrosion processes. Another possibility is the formation of weaknesses in the container, which then contribute to mechanical failure (see *Mechanical degradation [2.1.03.E]*).

FCS Screening Analysis

The FCS container shells are constructed from oxygen-free low-phosphorous copper. Pitting, crevice corrosion and under-deposit corrosion are not expected to be important over time frames up to 1 million years after closure (NWMO 2012, King et al. 2010).

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 in a repository (King et al. 2010).

Pitting of copper is observed in various environments, and in particular 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 2012, King et al. 2010).

The FCS copper shell is sufficiently thick to protect against localized corrosion for the one million year assessment period (King et al. 2010).

FEP Screening

Screened out.

FEP # 2.1.03.G 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 anoxic 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.

FCS Screening Analysis

Microbial-induced corrosion of copper has been observed under various environmental conditions. However, there is substantial experimental evidence indicating that microbial activity and, hence, microbial-induced corrosion can be greatly limited under the conditions imposed by the dense bentonite sealing materials surrounding the copper containers in the FCS design. Specifically, the microbial activity near the copper shell 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 2012, King et al. 2010).

Although microbial activity near the container surface is unlikely, it will likely be occurring within the host rock and, in particular, at the buffer-host rock interface. Side products from microbial activity could include sulphides produced from sulphate reduction in buffer or groundwater, which can cause copper corrosion. In this case, the rate of copper corrosion would be limited by the rate of sulphide generation at the rock, and its transport by diffusion across the buffer to the container surface (King et al. 2010). The FCS copper shell is sufficiently thick to protect against this microbial-induced corrosion for the one million year assessment period of interest (King et al. 2010).

As noted above, microbial-induced corrosion is effectively prevented by use of high density bentonite around the container. However, defects in the manufacture or installation of the dense bentonite blocks around the container could lower the density of the buffer around the container. If the buffer density is sufficiently low, it would not prevent microbial activity near the container and, further, would allow transport of nutrients through the buffer, possibly leading to microbial-induced corrosion of the container. Thus, microbial-induced corrosion is considered to be one mechanism by which containers fail in the Container Failure Scenario.

FEP Screening

Include FEP in the Container Failure Scenario.

FEP # 2.1.03.H 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 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 breach.

FCS Screening Analysis

Unless the container fails, there is an insufficient mass of corrosion agents within the container (i.e., water, O_2, N_2) to cause significant internal corrosion of container (note that container is backfilled with He gas) (McMurry et al. 2003).

If the copper shell barrier has been breached, groundwater can enter the container, leading in particular to corrosion of the internal steel components. These processes are described in general terms in McMurry et al. (2004). For example, corrosion of the steel will produce hydrogen gas that can slow down the rate of groundwater ingress into the container and delay further corrosion (e.g., SKB 1999a). Contaminant release from a failed container would then be delayed due to the time needed for formation of a continuous water pathway through the defect, and transport could be delayed due to sorption on the iron rust.

Rather than modelling the internal processes in detail, the FCS uses a simplified model. This model considers the initial geometry with the internal void volume and a defined defect, but neglects internal sorption and diffusion, and assumes fast saturation of the container interior. It is expected to be a conservative model for radionuclide releases from the container, at least initially after container failure.

Therefore, internal corrosion of the container is not modelled in the FCS. Note that the corrosion of the UO_2 and Zircaloy are described separately under *Waste form materials and characteristics [2.1.02].*

FEP Screening

Screened out.

FEP # 2.1.04 Buffer and backfill materials and characteristics

Description

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

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

- Buffer refers to the material immediately surrounding a waste container, if its primary role is to modify the hydraulic and chemical conditions near the container (e.g., preventing water flow and retarding contaminant transport).
- Backfill refers to the material primarily used as a filler for 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. (In some concepts involving intermediate level and low level waste, the term backfill describes the material placed between waste containers, whose primary role is to act as a physical and chemical barrier to contaminant transport.)
- Buffer and backfill materials may include clays and cement, and mixtures of these with aggregates such as silica sand or crushed rock.

The materials and characteristics are discussed further under:

2.1.04A Repository layout
2.1.04B Buffer characteristics and evolution
2.1.04C Backfill characteristics and evolution.

Some relevant processes are described under *Hydrothermal alteration [2.1.09.B], Biological processes and conditions (repository) [2.1.10] (microbial processes), Mechanical processes and conditions (repository) [2.1.2.07] (swelling pressures), Sorption and desorption (contaminant) [3.2.03]*, and *Colloid interactions and transport (contaminant) [3.2.04].*

FEP # 2.1.04.A Repository layout

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.

On the large scale, layout refers to the siting of 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, at different levels, or ramped between more than one level.

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

Repository layout will also specify the particular materials to be used.

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.

On the large scale, repository layout will affect the distance between placed containers and nearby fracture zones. In some designs, an placement room may straddle a fracture zone with bulkheads and seals used to provide isolation between containers and the fracture zone. At the room scale, positioning of the repository contents can also have a strong influence on performance.

FCS Screening Analysis

The FCS room layout (see Figure 3.9) is based on containers placed vertically in the in-floor configuration and surrounded by a 100% bentonite buffer layer (SNC Lavalin 2011, Garisto et al. 2012).

The access tunnels and placement rooms are mainly filled with dense backfill blocks (a 5:25:70% bentonite:clay:aggregate mixture) blocks, with gaps filled with light backfill pellets (50:50% bentonite:granite sand mixture). A concrete bulkhead isolates each placement room from the access tunnel. The shafts are sealed primarily with a 70:30% bentonite:silica sand mixture; concrete is used at the base of the shaft and other places for mechanical support, and asphalt or high-density buffer may be used in places for seal redundancy.

The FCS 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 - the design assumes that 10% of the borehole locations would intercept a local fracture and not be useable.

However, minor variations in the placement room layout (e.g., exact proportion of dense or light backfill, room lengths) 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 room locations will need to be considered explicitly in the FCS since the release pathways and surface discharge points may vary depending on where any failed containers occur in the repository.

FEP Screening

Include FEP in all scenarios.

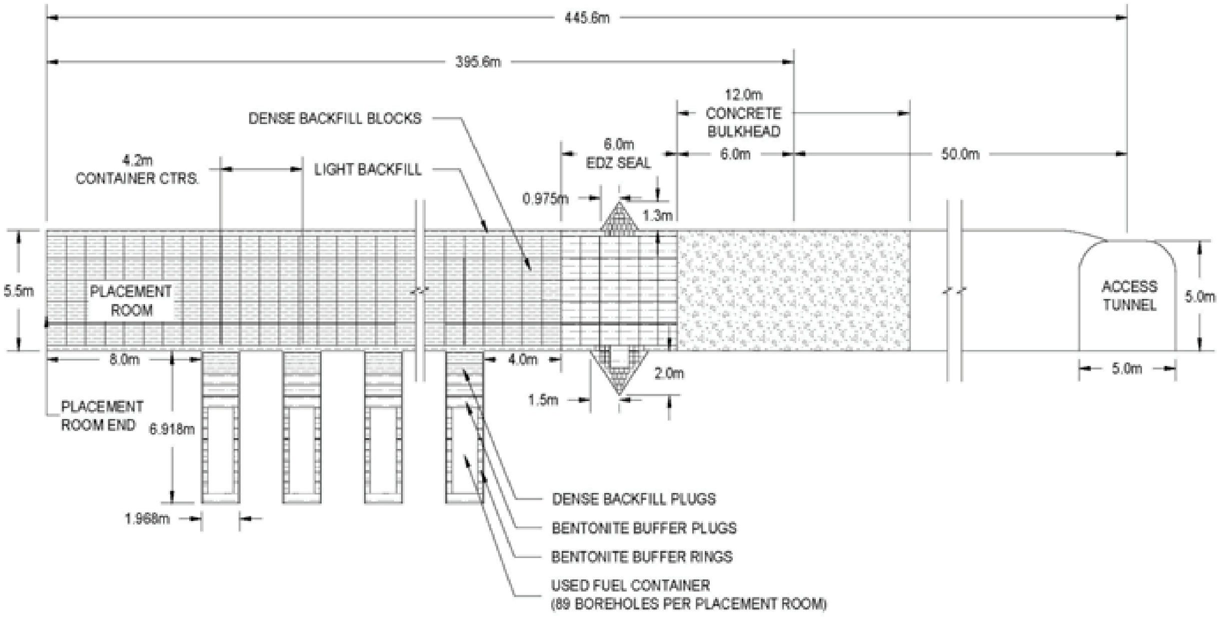


Figure 3.9: Placement room layout

FEP # 2.1.04.B Buffer characteristics and evolution

Description

Properties of the buffer and their evolution with time. This factor 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 (or backfill) to improve performance or safety. 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 movement include composition, density, hydraulic conductivity and porosity (see also *Sorption and desorption (contaminant) [3.2.03]*). The properties may not be uniform; for instance, the 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 formation of a moving redox front (possibly complicated by radiolysis products), loss of soluble material and accumulation of insoluble salts, silica cementation, alteration of bentonite to kaolinite or illite or zeolite, and a reduction in swelling and self-healing capacity or sorption properties if calcium-rich waters replace sodium in bentonite or if incoming groundwaters are highly saline. The specific issue of hydrothermal alteration of the buffer is addressed under *Hydrothermal alteration [2.1.09.B].* The initial and evolving conditions could also have different implications on the growth of microbes. This is addressed under *Biological processes and conditions (repository) [2.1.10].*

The properties of the gap backfill will also change with time. The conditions in this layer adjacent to the container could be of particular relevance for the growth of microbes, particularly as biofilms on the container. This issue is addressed under *Biological processes and conditions (repository) [2.1.10].*

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

FCS Screening Analysis

The containers in the FCS are surrounded by rings of highly compacted 100% bentonite, with the gaps next to the container and borehole walls filled with 100% bentonite pebbles (Garisto et al. 2012). The saturated buffer layer is essentially impermeable to groundwater flow since the dense bentonite would have a very low permeability.

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 will saturate the buffer. During this process, the buffer will swell and gaps or cracks in the buffer will self-seal and maintain a hydraulic conductivity and diffusivity similar to that of intact material (Graham et al. 1997). There will be some equilibration of density among the various buffer components as the pressures are equalized. The time scale for saturation may be several hundred years in sparsely fractured rock. Non-volatile contaminants would not be released from any failed containers prior to this period, because no pathway would exist whereby they could leave the container. A "time delay" is included in the FCS models to represent this saturation period, during which there would be no contaminant releases from defective containers.

After this period, the buffer properties can be considered homogenous, with no cracks. The gaps between the container and buffer, and between buffer layers, will have been filled by the swelling buffer material. The buffer is dense enough that its swelling capacity will not be significantly affected by the low groundwater salinity around the FCS repository (about 10 g/L).

A summary of buffer properties and stability is provided in Pusch (2001). Important buffer parameters are its effective thickness, porosity, and contaminant diffusivity and capacity factors. These are included in the FCS models for contaminant transport. Transport properties will depend on temperature. There will be an initial temperature rise in the buffer to about 100°C within ~30 years, and then the temperature will decrease slowly back to ambient temperature over 10,000-100,000 years. In the FCS, the temperature of the buffer is assumed to remain at 70°C throughout the assessment period.

Physical/chemical evolution of the buffer (after saturation) is judged to be an insignificant factor in the FCS over 1 million years because the alteration of bentonite is very slow under the conditions in the repository, notably the low groundwater flow rates, low temperature and low groundwater concentrations of potassium (McMurry et al. 2004) (see also *Hydrothermal alteration [2.109A]*). This is illustrated in Table 3.1 using the model of Huang et al. (1993).

Small changes to the buffer porewater chemistry would occur over this time, e.g., due to dissolution of the minor mineral components in the buffer. The water content would slowly modify towards the surrounding host rock porewater. These changes would, however, not affect the buffer transport properties (Arcos et al. 2006, 2000). (See also *Chemical processes and conditions (repository) [2.1.09]*). Thus, evolution of the buffer parameters with time is neglected in the FCS.

Buffer material can erode in the presence of freshwater because clay particles lose their cohesiveness 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 (SKB 2011). However, this is an issue only if glacial meltwater can penetrate to repository level, and if there is a local fracture that allows buffer particles to move away from the container borehole. Although calculations indicate that glacial meltwaters could reach the repository horizon at the FCS site (NWMO 2012, Chapter 2), the maximum concentration of glacial meltwater is about 50%. This dilution is insufficient to cause buffer erosion, given the salinity of groundwater at depth.

The evolution of biological processes within the buffer is discussed in *Biological processes and conditions (repository) [2.1.10].*

Defects in the manufacture or installation of the dense bentonite blocks around the container – leading to a low density buffer around the container, which allows microbial activity near the container and transport of nutrients through the buffer, could result in microbial-induced corrosion of the container. This is considered as one possible mechanism by which containers could fail in the Container Failure Scenario.

FEP Screening

Include FEP in all scenarios.

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. carried out their experiments at high temperatures (> 250°C); therefore, in applying their results to the FCS repository it is implicitly assumed that the extrapolation to lower temperatures is valid.

The porewater K^+ concentration and temperature are conservatively taken to be 20 mg/L or $5.1\text{x}10^{-4}$ mol/L (McMurry 2004) and 70°C (Guo 2009). It is clear that smectite illitization will be of very minor importance (due mainly to the low temperature of the system) and will not adversely affect bentonite swelling. At 70°C, approximately 0.19% of the smectite initially present is lost over 1 Ma.

FEP # 2.1.04.C 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 movement include composition, density, hydraulic conductivity and porosity (see also *Sorption and Desorption [3.2.03]*). 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 specific issue of hydrothermal alteration of the backfill is addressed under *Hydrothermal alteration [2.1.09.B].* The influx of groundwater will saturate the backfill, lower its temperature and expose it to groundwater. For instance, evolution of backfill could result in formation of a moving redox front (possibly complicated by radiolysis products), 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. The evolving conditions could also have different implications on the growth of microbes. Local erosion of the backfill may occur if groundwater velocities are sufficiently high.

FCS Screening Analysis

Placement rooms and tunnels are backfilled with blocks of dense backfill of 5 wt% bentonite, 25 wt% glacial clay and 70% crushed granite aggregate (Garisto et al. 2012), with gaps around the dense backfill blocks filled with pellets of light backfill (50 wt% crushed granite and 50% bentonite).

A summary of backfill properties and stability is provided in Pusch (2001). Oscarson and Dixon (1989) summarize the clay compositions that could be used in Canada.

Evolution of the backfill parameters with time, including the potential for erosion, is judged to be an insignificant factor in the FCS under the expected physical and chemical conditions in the repository, and hence is not modelled for the same reasons as discussed in *Buffer characteristics and evolution [2.1.04.B]*. The specific issues of hydrothermal alteration and microbe growth are addressed in *Hydrothermal alteration [2.1.09.B]* and *Biological processes and conditions (repository) [2.1.10]*, respectively.

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

FEP Screening

Include FEP in all scenarios.

FEP # 2.1.05 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 placement 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 disturbed zone [2.2.01]*). 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 *Chemical processes and conditions (repository) [2.1.09]* 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 placement rooms so that contaminants could readily move throughout the repository and exit at some location where transport to the accessible environment is most favourable.

FCS Screening Analysis

The FCS repository includes a combination of bulkheads, seals and backfill with the repository access tunnels and shafts. The shaft, for example, would be sealed with a combination of 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 limit water movement to diffusion control within the sealing materials.

In the Normal Evolution Scenario of the FCS, these 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 [2.1.04.B].* The degradation of the concrete will be slow because of the low groundwater flow.

In the FCS, the impacts of significant degradation of shaft seals, fracture seals and borehole seals (relative to their design specifications) are investigated in the Shaft Seal Failure Scenario, the Fracture Seal Failure Scenario, and Poorly Sealed Borehole Scenario, respectively.

FEP Screening

Include in all scenarios. The effects of significantly degraded seals are investigated the Shaft Seal Failure, Fracture Seal Failure and Poorly Sealed Borehole Scenarios.

FEP # 2.1.06 Other engineered features

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 railway line may be used to move containers from a shaft to an 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) [2.1.09]).*

Features used to stabilize openings may not be effective over long time frames (see *Mechanical processes and conditions (repository) [2.1.07]*).

FCS Screening Analysis

The possible effects associated with this factor are not explicitly modelled in the FCS because all engineering features would be chosen during the repository design stage to avoid any significant adverse effects.

The placement borehole would not use additional engineering materials other than the buffer and container already described. Concrete flooring and any cabling or ducting would be removed from placement rooms after containers have been placed. The room bulkhead seal would be placed far enough from the first container, and also based on a low-pH concrete formulation, to minimize effects of the alkaline plume on the container.

Rockbolts 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 crystalline rock these would not be present in significant enough amounts to affect the postclosure performance.

FEP Screening

Screened out.

FEP # 2.1.07 Mechanical processes and conditions (repository)

Description

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

This factor is discussed further under:

2.1.07A Buffer and backfill swelling
2.1.07B Formation and healing of cracks
2.1.07C Collapse of repository openings
2.1.07D Evolution of stresses in the near-field
2.1.07E Buffer and backfill creep.

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) [2.1.08]*), faulty placement or settling of containers (see *Placement of wastes and backfilling [1.1.03]*) and the effects of earthquakes (see *Seismicity (earthquakes) [1.2.03]*). See also related issues under *Mechanical processes and conditions (geosphere) [2.2.06].*

FEP # 2.1.07.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 return back to the repository and saturate these materials. Since 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 likely 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 the time when full saturation occurs, 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.

FCS 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 the buffer and backfill are generally described in Pusch (2001), and also in Dixon (2000). The effect of the low porewater salinity in the FCS host rock would have minor effect on swelling. The FCS assumes that the buffer and backfill swell as per their design basis.

The swelling of the buffer would provide a load on the container. As designed, this would cause the copper shell to creep onto the inner steel vessel, the load bearing component of the container. The container is designed specifically to accommodate these loads.

Since saturation of the buffer and backfill is non-uniform, differential swelling pressures may exist causing displacement of some material and movement of the containers. However, these effects are expected to be minor. Furthermore, non-uniformity in the swelling pressures would be short-lived, i.e., until the buffer and backfill are completely saturated. Possible non-uniform loads would be considered as part of the container design basis. Non-uniformities in buffer density remaining after saturation would be minor, and are not explicitly modelled in the FCS safety assessment.

The swelling properties of bentonite clays can change with time due to illitization or similar chemical processes (Johnson et al. 1994). This is not important at the FCS site over one million years as discussed under *Hydrothermal alteration [2.1.09.B].*

FEP Screening

Included in all scenarios.

FEP # 2.1.07.B Formation and healing of cracks

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 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 (see *Buffer and backfill materials and characteristics [2.1.04]* for discussions related to evolution of the buffer and backfill).

FCS Screening Analysis

Gaps will be present in the buffer, backfill and seals during the saturation phase, but there is no groundwater access to the containers at this time and so contaminant transport out of the container does not occur during this time.

After saturation, these gaps would be closed by the swelling of the bentonite clay component in the buffer and backfill, if sufficient bentonite material is present. A design requirement for the FCS repository is that a sufficient amount of swelling clay be included in the system to provide this capacity (Baumgartner et al. 1996). Experiments (Oscarson et al. 1996; Oscarson et al. 1990) indicate that the sealing process takes place quickly, once water is present along the crack. Therefore the FCS does not consider cracks within the buffer and backfill clay-based seals.

Cracks in concrete, grouting and the host rock (e.g., EDZ) might fill due to geochemical processes, but this process is not included in the FCS.

FEP Screening

Screened out.

FEP # 2.1.07.C Collapse of repository openings

Description

The collapse of tunnels and boreholes, including cave-ins, roof settling and rock bursts.

These processes and events may occur for reasons that include inadequate support provided by seals and backfill, stress relief of fractured or damaged rock, and failure over long times of rock bolts and other supports. Potential effects include damage to the containers, buffer, backfill and seals, and undesirable changes to groundwater and contaminant transport.

FCS Screening Analysis

Collapse of repository openings cannot occur after closure of the repository, because all openings are filled with buffer and backfill materials. These materials also exert a significant swelling pressure on the surrounding rock, which would fill any small gaps which may exist along the backfill/wall interface after filling.

FEP Screening

Screened out.

FEP # 2.1.07.D Evolution of stresses in the near-field

Description

The evolution of stresses in the near-field from swelling, thermal expansion and volume changes.

Stress concentrations might be highest near the rock webs between placement boreholes, tunnels etc., with the cumulative effects of multiple openings having interacting effects. Stress relief processes could lead to further damage to the EDZ (see *Excavation disturbed zone [2.2.01]*), collapse of repository openings (see *Collapse of repository openings [2.1.07.C]*), damage to repository contents, and undesirable changes to groundwater and contaminant transport pathways.

Stresses may also evolve from external factors, such as glacial loading (see *Local glacial effects [1.3.05]*) and earthquakes (see *Seismicity (earthquakes) [1.2.03]*).

FCS Screening Analysis

Stress fields and stress concentrations will be considered as part of the repository design for a specific site (e.g., Borgesson and Hernelind 1999).

Near-field stresses will evolve during the initial thermal heating and repository saturation processes. Since the container is designed for these loads, no damage to the container is expected.

The formation of a thermally damaged zone within the rock web between in-floor containers, which is larger than that due to excavation alone, is included in the FCS assessment. Since the temperature rise occurs early after placement, this thermal damaged zone is assumed present from the beginning rather than evolving with time.

After the saturation of the repository, significant changes in stresses would only occur as a result of seismic activity or glaciation. Although the Canadian Shield is a low seismic area, seismic activity is possible over long time frames (see *Seismicity (earthquakes) [1.2.03]*). However, earthquakes are in general a transient load. Local stress changes would require significant shifting or shearing of the rock; the changed stresses could be important if this shearing intercepted a container borehole or a seal (see *Seismicity (earthquakes) [1.2.03]*). The FCS assumes the repository siting and container design would make container failure due to rock shear unlikely. Nevertheless, container failure due to a shear load, caused by movement of rock along a local fracture intercepting a borehole, is one potential mechanism responsible for the Container Failure Scenario.

Glaciation is expected on 100,000 year time frames and so estimates of the stresses at the repository level from glaciation have been considered in the container and repository design. These changing stresses could lead to changes in hydraulic conditions through, for example, hydro-mechanical coupling (see *Mechanical processes and conditions (geosphere) [2.2.06]*).

The consequences of the passage of an ice sheet over the repository that is thicker than the design basis ice sheet, which causes the isostatic load on the containers to exceed their design load, is considered in the All Containers Fail Scenario. Further, the consequences of a large seismic event that causes rock movement along a local fracture intersecting a borehole, leading to container failure, is examined in the Container Failure Scenario.

FEP Screening

Include in all scenarios, since the thermally damaged zone is included in the modelling.

FEP # 2.1.07.E Buffer and backfill creep

Description

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.

FCS Screening Analysis

The effects of buffer and backfill creep are expected to be minor. For example, detailed studies for a similar sized SKB container indicated movement on the order of a couple of millimeters in 1 million years (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.

FEP Screening

Screened out.

FEP # 2.1.08 Hydrological processes and conditions (repository)

Description

The hydrological and hydrogeological processes that affect the wastes, containers, seals and other engineered features, and the overall hydrological evolution of the near-field with time. This includes the hydraulic influences on wastes, containers and repository components by the surrounding geology. The movement of contaminants is described in *Water-mediated Transport of Contaminants (repository) [3.2.07.A].*

This factor is discussed further under:

- 2.1.08.A Desaturation and resaturation of the repository
- 2.1.08.B Groundwater movement
- 2.1.08.C Evolution of hydraulic conditions
- 2.1.08.D Other coupled hydraulic processes.

These processes affect each other, and are also affected by other factors, such as the formation of cracks in the buffer (see *Mechanical processes and conditions (repository) [2.1.07], Excavation disturbed zone [2.2.01],* and the effects of earthquakes (*Seismicity (earthquakes) [1.2.03]*). See also related issues under *Hydrological processes and conditions (geosphere) [2.2.07].*

FEP # 2.1.08.A Desaturation and resaturation of the repository

Description

The establishment of unsaturated conditions near the repository during the excavation and operation phases, and their return to saturated conditions.

During excavation and operation, groundwater will seep into the repository from the surrounding rock and be pumped away, creating an unsaturated zone near the repository. This unsaturated zone may also affect the water table near the surface.

Following closure, saturated conditions will eventually be re-established. However, this may take a long time if ingress of water is restricted because of low host rock permeabilities or effective seals, and will likely vary at different locations within the repository. In sparsely-saturated rock, high near-field porewater pressures from the repository heating could change the flow field and affect the 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 (and the buffer and backfill) may never attain their original moisture contents because of hysteresis.

FCS Screening Analysis

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). However, the fundamental property of interest to the Fourth Case Study is how long this process takes, since the time period prior to complete resaturation of the repository is not expected to be detrimental to container or sealing material performance (McMurry et al. 2003) and since release of non-gaseous contaminants from a defective container cannot occur until after resaturation of the repository.

In the Second Case Study (Goodwin et al. 1996), saturation of the entire repository was assumed to occur at the instant of repository closure, although bounding estimates indicated that resaturation could take up to several centuries. One consequence was that in some simulations there were large impacts from Sr-90, which has a half-life of 29 years. Subsequent analyses showed that a resaturation time of only 100 years would substantially reduce dose contributions from Sr-90.

Moreover, modelling work suggests that it could take tens of thousands of years, well after the repository has saturated, before the container is flooded with water and contaminants are released from a defective container (McMurry et al. 2004, Bond et al. 1997).

Therefore, the FCS includes a time delay to represent the saturation period, during which contaminant releases do not occur. In this limited sense, desaturation and resaturation of the repository is accounted for in the FCS.

FEP Screening

Include FEP in all scenarios.

FEP # 2.1.08.B Groundwater movement

Description

Factors influencing the movement of groundwater in the near field.

Groundwater movement through the repository will be influenced by advection and diffusion through the various media. Unsaturated conditions could persist for long periods of time so that gas transport or two-phase flow may be possible. Groundwater might preferentially move around the repository because the EDZ acts as a 'hydraulic cage' (see *Excavation disturbed zone [2.2.01]*), or it might be shunted through the repository which acts 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 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 would also be affected by the onset of glaciation and significant degradation of repository seals.

The movement of groundwater is a concern because it may lead to the subsequent transport of dissolved or suspended contaminants. However, contaminants can also move by diffusion in stagnant water. Further discussion of contaminant transport is provided under *Contaminant release and migration factors [3.2].*

FCS Screening Analysis

The FCS explicitly accounts for groundwater flow in the near field since it can influence contaminant transport. Only the groundwater flow field following repository saturation is needed because contaminant releases from a defective container can only occur after repository saturation. Thus, the possibility of two-phase flow is not included in the FCS (see also *Gas sources and effects (repository) [2.1.12]*).

Groundwater flow through the backfill and excavation disturbed zone (EDZ) is modelled in the FCS (flow through the buffer is neglected because of its low permeability).

FEP Screening

Include FEP in all scenarios.

FEP # 2.1.08.C Evolution of hydraulic conditions

Description

Changes in the hydraulic conditions (apart from the resaturation transient).

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 groundwater, including saline waters, 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. 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 opening such as the repository tunnels and shafts.

FCS Screening Analysis

The repository seals and low permeability host rock would limit groundwater flows within the near-field. Due to the durable crystalline rock mineralogy, low salinity porewater and low temperatures, no significant precipitation of secondary minerals is expected. The peak temperature of around 100^{o}C at container surfaces is not sufficient to drive significant flows within this low-permeability system. Some degradation of concrete seals will occur with time; thus, degraded concrete properties are used in the FCS groundwater modelling.

Large earthquakes are unlikely, but could cause movement along existing fractures. However, the repository is sited to avoid the larger fracture zones that are more likely to move and it is assumed that all identified fractures at the site are permeable.

Thus, for the constant climate simulations carried out in the FCS, 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 variant cases with different boundary conditions or properties. For example, the effects of a higher and lower permeability geosphere are examined in the FCS.

Since glaciation is expected to occur in the future, in the FCS, the effect of glaciation is considered within the Normal Evolution Scenario. During glaciation, the groundwater flow field is transient and changes significantly at surface during advance and retreat of the ice sheets (Walsh and Avis 2010). Groundwater flow can also be influenced by the hydraulic pressure gradients generated by the weight of ice sheets over the repository site, i.e., by hydromechanical coupling (Walsh and Avis 2010).

Disruptive scenarios are assessed under constant temperate climate conditions, so there is no external driver for change in hydraulic conditions. Furthermore, degraded parameters that affect hydraulic conditions in the disruptive scenarios are assumed to occur at time of closure. For example, in the Shaft Seal Failure Scenario, the shaft seal permeability is conservatively set much higher than the design value from the time of repository closure so there is no change in the hydraulic conditions with time.

FEP Screening

Include FEP in the Normal Evolution Scenario

FEP # 2.1.08.D Coupled hydraulic processes

Description

Fluid flow driven by temperature, chemical or electrical gradients, rather than 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 [2.1.08.B]* and *Evolution of hydraulic conditions [2.1.08.C].*

These coupled transport flow processes are often negligible under normal engineering conditions. However, it is expected that the advective flow will, in general, be quite low in the engineered barriers of a repository, and so these coupled processes could dominate the flow of water in these materials.

FCS Screening Analysis

An analysis of the effects of coupled processes and their implications for solute transport has been provided in the context of the Opalinus Clay formation (Soler 2001), which is under consideration as the possible site of a deep geologic repository in Switzerland (NAGRA 2002).

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

Soler (2001) concluded that only thermal osmosis might be important to fluid (and solute) transport. But 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 would have dropped considerably by then. It was considered possible that coupled processes might be important 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 Fourth Case Study.

FEP Screening

Screened out.

FEP # 2.1.09 Chemical processes and conditions (repository)

Description

The chemical and geochemical processes that affect the wastes, containers, seals and other engineered features, and the overall chemical evolution of near field with time. This includes the effects of chemical and geochemical influences on wastes, containers and repository components by the surrounding geology.

Many repository-related chemical processes are explicitly accounted for under other FEPS:

- dissolution of the UO_2 fuel and Zircaloy cladding - see *Waste forms material and characteristics [2.1.02]*
- corrosion of the container - see *Container material and characteristics [2.1.03]*
- precipitation of radionuclides - see *Dissolution, precipitation and crystallisation [3.2.01]* and *Speciation and solubility (contaminant) [3.2.02]*
- sorption of radionuclides - see *Sorption and desorption (contaminant) [3.2.03].*

Under this category, we specifically consider the following topics:

2.1.09A Water chemistry and evolution (repository)
2.1.09B Hydrothermal alteration
2.1.09C Other chemical processes.

It should be noted that chemical and geochemical processes in the repository occur concurrently and are often interrelated - see *Chemical processes and conditions (geosphere) [2.2.08].*

FEP # 2.1.09.A Water chemistry and evolution (repository)

Description

Groundwater chemistry conditions within the repository, and their evolution with time. 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 and over times 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.

The evolution of groundwater may never reach a final equilibrium state because of intrusion by various sources of groundwater that include water introduced during construction and operation, migration of saline water and injection of oxygenated surface water following a glacial retreat.

FCS Screening Analysis

The porewater composition in the repository, including the electrochemical potential and pH, is important in determining the solubility of certain elements (notably U, Pu, Tc and Am). The modification of the groundwater as it passes through the buffer/backfill is the most important aspect to include in the Fourth Case Study.

The general electrochemical redox state - i.e., reducing or oxidizing - can be an important parameter for transport properties (notably sorption). For the FCS, it is expected that the repository will be initially oxidizing due to trapped air from the placement operations, but will return to the natural reducing state on the same time scale as the saturation process (McMurry et al. 2003). 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 buffering capacity of the rock (and microbes within the rock). Even glaciation is not expected to change the redox conditions - this would be considered as part of the siting process. Since radionuclide transport is only important after saturation, FCS properties can simply be based on assuming "reducing" conditions.

The water eventually 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 and ion exchange of the Na in the sodium bentonite clay with the Ca cations in the groundwater. This process is expected to be take tens of thousands of years (McMurry et al. 2003). This time-dependent process is not explicitly modelled in the FCS.

Instead, solubilities within the container were calculated for a range of cases bounded by the groundwater equilibrated with bentonite buffer and carbon steel, and for groundwater alone (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. In the past, this variability in the groundwater composition has been found to have little influence on calculated dose rates (Garisto et al. 2004a, 2005a; Goodwin et al. 1994, 1996).

FEP Screening

Include FEP in all scenarios.

FEP # 2.1.09.B Hydrothermal alteration

Description

Alteration of the buffer and backfill clay components due to chemical interactions with the 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 the drying of the buffer. These precipitates may serve to block or line conduits and prevent expansion of the buffer and backfill. Calcite and gypsum are other common minerals that are relatively 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 materials and characteristics [2.1.04]*, and under *Seals and grouts (cavern, tunnel, shaft) [2.1.05].*

FCS Screening Analysis

Hydrothermal alteration of the clay materials in the FCS repository (i.e., buffer and backfill) is not likely because the maximum temperatures in the repository are relatively low (temperatures on the surface of the container are, by design, less than 100°C) and the reference groundwater (consistent with plausible Canadian Shield groundwaters) does not contain high concentrations of reactive species, notably K cations (McMurry et al. 2003; Pusch 2001; Johnson et al. 1994, Section 3.3.1). Therefore, hydrothermal alteration is not included in the FCS. See Table 3.1 in *Buffer characteristics and evolution [2.1.04.B].*

FEP Screening

Screened out.

FEP # 2.1.09.C Other chemical processes

Description

Other chemical processes not otherwise considered. These can include:

(1) Migration of salts and dissolved contaminants may be enhanced near the container and elsewhere in the repository because of the formation of chemical concentration gradients. Such gradients could be caused by temperature changes, radiolysis (changing local redox conditions), different electrochemical potentials between various materials in the repository or between distant ore bodies and the material in the repository, and ingress of saline groundwater. Possible effects include altered dissolution rates of the waste matrices and dissolution and precipitation of chemical compounds with subsequent opening or plugging of pores.

(2) A 'geochemical pump' could form, in which a sequence of geochemical reactions act to move material from one place to another. For example, uranium might be dissolved at the surface of the used fuel and precipitated somewhere in the buffer or backfill.

FCS Screening Analysis

The following chemical processes are expected to be either insignificant or could be conservatively ignored in the FCS:

- The chemical evolution of the buffer leading to substantial filling of pores in the buffer with precipitants, which then prevent contaminant movement.
- The corrosion of the carbon steel inner vessel, resulting in the production of iron oxides, that strongly absorb some radionuclides, and H_2 gas that could inhibit corrosion of the fuel (Shoesmith 2008).
- Irreversible sorption of contaminants on iron rust or buffer and backfill materials.

"Pumping" of uranium is not relevant for the FCS since the UO_2 dissolution rate is calculated using a kinetic model. The solubility limited dissolution rate is only reached at very long times

FEP Screening

Screened out.

FEP # 2.1.10 Biological processes and conditions (repository)

Description

The biological and biochemical processes that affect the wastes, containers, seals and other engineered features, and the overall biological or biochemical evolution of near-field with time. This includes the effects of biological and biochemical influences on wastes, containers and repository components by the surrounding geology.

Organic material is likely to be naturally occurring in the engineered barriers, notably in the clay used in the buffer and backfill, and will 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 [2.1.03.G].* Other specific concerns are:

- 2.1.10A Biological processes (repository)
- 2.1.10B Complexation by organics (repository materials)
- 2.1.10C Biological effects on groundwater movement.

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 near field and in the surrounding geosphere (see *Biological processes and conditions (geosphere) [2.2.09]*).

FEP # 2.1.10.A Biological processes (repository)

Description

Biological activity in the repository and their 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 oxygen content, electrochemical potential and pH. Natural viruses may also be present and influence microbial populations.

Microbial production of organic complexing agents is covered in *Complexation by organics [2.1.10.B].*

Microbial effects on container corrosion are covered in *Microbial-induced corrosion [2.1.03.G].*

FCS Screening Analysis

The microbial population within the repository will vary after placement 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, particularly near the container because of the low water activity associated with the presence of dense bentonite.

Microbes within the backfill and near-field rock will contribute to the porewater chemistry via oxygen consumption and the development of redox conditions; however that process is expected to occur relatively quickly after closure and is not explicitly modelled in the FCS.

FEP Screening

Screened out.

FEP # 2.1.10.B Complexation by organics (repository materials)

Description

The formation of stable complexes with organics found in natural groundwaters and with organic byproducts from biological activity, including methane, humates and fulvates.

These stable complexes could change the properties of the buffer, or promote corrosion of the container or other metals through effects on solubilities and transport rates.

Another important effect, complexation of contaminants affecting solubility and transport, is discussed under *Complexing agent effects (contaminant) [3.2.05].*

FCS Screening Analysis

This factor is not expected to be important in the FCS because of the low levels of complexing organics in the buffer/backfill.

Microbial activity could be a source of complexing agents within the backfill region and host rock. These complexing agents could make some radionuclides more mobile by decreasing element sorption coefficients. This is not expected to be significant, but is bounded by the analysis of low sorption variant cases to the Normal Evolution Scenario. Microbes can also be a source of contaminant sorption; this is conservatively neglected.

FEP Screening

Screened out.

FEP # 2.1.10.C Biological effects on groundwater movement

Description

The influence of biological processes on groundwater movement in the repository.

The growth of microscopic organisms may result in the formation of reactive biofilms at interfaces, such as on the walls of the repository and container. Other biologically mediated processes may alter the composition of the engineered barriers; for instance, microbes may consume compounds and minerals containing redox-sensitive elements such as sulphur and iron. The consequent changes to the porosity and permeability of material in the repository (pore plugging) could influence the rate and volume of groundwater movement.

FCS Screening Analysis

The effect of biological processes on groundwater movement is not included in the FCS because these effects, if any, are expected to be small. Further, 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 the engineered barriers and, thus, it is conservative to neglect such effects.

FEP Screening

Screened out.

FEP # 2.1.11 Thermal processes and conditions (repository)

Description

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. This includes the effects of changes in condition, e.g., temperature, caused by radioactive decay heat, conduction and convection.

This category is divided into:

2.1.11.A Thermal conduction and convection
2.1.11.B Coupled heat transfer processes

These processes affect the temperature conditions within the repository. The effects of temperature on the other processes are covered within the discussion of those processes.

FEP # 2.1.11.A Thermal conduction and convection

Description

Heat transfer due to gradients in temperature caused by heat conduction or groundwater flow, and the overall thermal evolution of the near-field with time.

Ambient temperatures in the repository will be determined by natural geothermal gradients. However, elevated temperatures will occur because of the heat production from radioactive decay. 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 several thousands of years. The temperature rise might be non-uniform, caused by the uneven distribution of fuels with higher heat generation in the containers, by variations in thermal properties of the material placed in the repository (including gaps), by variable rates of resaturation, and by the rock thermal conductivity.

Some effects of elevated temperatures are discussed elsewhere. For instance, in the repository and near field, elevated temperatures could:

- redistribute the moisture in the buffer and backfill, possibly leading to localized formation of cracks, particularly in an extended period of unsaturated conditions (see *Buffer and backfill materials and characteristics [2.1.04]*);
- affect groundwater movement (see thermal buoyancy effects under *Hydrothermal activity [1.2.06]* and resaturation effects under *Hydrological processes and conditions (repository) [2.1.08]*);
- affect stress evolution and concentration (see *Mechanical processes and conditions (repository) [2.1.07]*); and
- change the rates and nature of chemical reactions including corrosion of the container and evolution of the buffer and backfill (see *Container materials and characteristics [2.1.03]* and *Chemical processes and conditions (repository) [2.1.09]*).

Elevated temperatures could also have subtle effects on the surface environment; see, for example, *Vegetation [2.3.08].*

Another specific issue of interest is the generation of steam, if the temperature in the repository exceeds 100°C, possibly only at localized areas. Steam might increase cracking of buffer and backfill materials, modify groundwater circulation patterns and 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 the unsaturated zone. A geological percolator might form, where water boils, condenses and drains back to be boiled again.

FCS Screening Analysis

Heat is generated in a used fuel repository by radioactive decay. For the FCS, the initial thermal power of a container is about 1330 W, based on 360 bundles at a burnup of 220 MWh/kgU and 30 years after discharge.

The design of the FCS repository (including container spacing, placement room spacing and placement room shape) is based on the results of thermal modelling calculations (SNC-Lavalin 2011, Guo 2009). The selected design ensures that the maximum temperature at the container surfaces is less than 100°C. (This prevents steam formation.) The temperature will reach a maximum within about 30 years, then drop somewhat within about 100 years and then hold to a relatively steady profile for tens of thousands of years based on a rough balance between decay heat and thermal conduction (SNC-Lavalin 2011, Guo 2009). Temperatures will then return to ambient conditions (~11°C) by 100,000 years.

The heating of the rock may affect the extent of the rock damage zone near the containers, as discussed in *Excavation disturbed zone [2.2.01]*.

For the postclosure safety assessment, the initial peak temperature transient is neglected, but the increased local heating is considered. Specifically, the FCS postclosure safety assessment assumes that the temperature in the highly compacted bentonite layer around the container is constant at 70°C, which is representative of the quasi-steady-state thermal conditions of the repository within the first 10,000 years after repository closure. The material property values such as diffusion coefficients are chosen to be consistent with this higher temperature. In contrast, the properties of the backfill, which is further from the containers, are based on the ambient long-term temperature.

The temperature in the host rock surrounding the repository are typically about 40^{o}C for tens of thousands of years within a few hundred meters of the repository. The thermal effects on the host rock are discussed in *Geological Environment [2.2],* and in particular *Thermal processes and conditions [2.2.10]*.

FEP Screening

Included in all scenarios.

FEP # 2.1.11.B Coupled heat transfer processes

Description

Heat transfer by all gradients except 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 (density or concentration gradients) or Peltier effect (electrical gradient). Heat transfer due to temperature gradients is discussed under *Thermal conduction and convection [2.1.11A].*

Coupled transport processes could contribute to the heat transfer in the engineered barriers of a repository, especially if the thermal gradients and advective flow rates are low enough. Suitable conditions might occur in the engineered barriers on a 1000-10000 year time scale when the buffer is saturated and temperatures are fairly steady.

FCS Screening Analysis

An analysis of the effects of coupled processes and the implications for heat transport has been done (Soler 2001) in the context of the Swiss Opalinus Clay Project - a safety assessment of a deep geologic repository sited in the Opalinus Clay layer (NAGRA 2002). The coupled processes for heat transport were thermal filtration (hydraulic gradient), Dufour effect (chemical gradient) and 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 Canadian concept.

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 are considered to be a small effect and are not included in the Fourth Case Study.

FEP Screening

Screened out.

FEP # 2.1.12 Gas sources and effects (repository)

Description

Factors within and around the wastes, containers and engineered features 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 and container inserts. It may also be produced by radiation effects, including helium as a product of radioactive decay and gases produced by radiolysis (see *Radiation effects (repository) [2.1.13]*) and as byproducts of microbial activity. Potential gases include hydrogen, oxygen, 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 [3.2.09]*). 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 to damage the repository.

Gas sources and effects are also coupled with other processes occurring in the repository; some specific effects are noted under *Container materials and characteristics [2.1.03]* and *Other engineered features [2.1.06].*

FCS Screening Analysis

The main sources of gas in the repository would be the initially trapped air, and the formation of H_2 as a result of corrosion of iron components left within the repository or exposed steel as a result of container failures. (The primary exposed metal within the repository will be copper, which is considered stable under reducing repository conditions.) Gases are also produced by radioactive decay (helium, argon, and krypton) and by microbial processes (methane). However, gases generated by radioactive decay would only be released into the repository from defective containers.

The amounts of gases generated in a repository are small in practical terms, and the rate of gas production is also comparatively low. For example, only a few containers are expected to fail initially, and the amount of iron structural components is expected to be minimized by design and repository location. At the groundwater pressures that occur at repository depths, the actual volume of these gases is small.

A gas fire or explosion can only occur if a flammable gas mixture (e.g., H_2/O_2 mixture) forms and there is a source of ignition. There is no credible source of ignition in a sealed and backfilled repository, and oxygen would be consumed by various natural processes.

The effect of gas generation is likely to be most significant only in the context of confined spaces. Analyses reported in SR97 indicate a positive benefit can be expected from the H_2 gas generated from the corrosion of the iron insert in a defective container due to prevention of groundwater contact with used fuel (SKB 1999a) and the decrease in the fuel dissolution rate (Shoesmith 2008, Rollin et al. 2001). Neglecting formation of this H_2 gas would be conservative.

Experiments on gas transport through clay-based sealing materials indicate that dense saturated clay will retain the gas to pressures on the order of the swelling pressure. Gas breakthrough occurs at sufficiently high pressures, likely through the formation of multiple small cracks through the material. However, the gas pathways close up again after the passage of the gas and have no effect on the permeability of the buffer to water (Harrington and Horseman 2003).

In the All Containers Fail Scenario, the amount of hydrogen gas generated is significantly higher than in the Normal Evolution Scenario. However, scoping calculations indicate that gas pressure in the repository would not build up to significant levels (i.e., the pressure remains much lower than the lithostatic pressure) because the gas can move through the FCS geosphere (NWMO 2012).

Therefore, the FCS does not include the effects of gas formation on contaminant migration or other processes in the repository.

FEP Screening

Screened out.

FEP # 2.1.13 Radiation effects (repository)

Description

The effects of the radiation emitted from the wastes on the waste form, containers, seals and other engineered features, and on the groundwater in the repository.

The following specific factors are discussed under separate entries:

- 2.1.13A Radiation effects - wasteform
- 2.1.13B Radiation effects - container
- 2.1.13C Radiation effects - sealing materials.

FEP # 2.1.13.A Radiation effects - wasteform

Description

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

Radiation is generated by radioactive decay of the radionuclides present in the waste form (i.e., used fuel). In addition, radioactive decay generates decay products (e.g., He gas and radionuclide progeny). This radiation (particularly alpha radiation) and re-coil particles 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 changing the fraction of radionuclides in the grain boundaries, thereby making it easier for radionuclides to be released from the waste form.

Another potentially important effect of radiation is radiolysis of water, which refers to the decomposition of water and its dissolved components by alpha, beta and gamma 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 alpha and beta 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 effectively 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 (due to formation of reactive radicals) and possibly the solubility of contaminants that are released from the wasteform.

FCS Screening Analysis

The FCS 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. See *Used fuel dissolution [2.1.02.D].*

The ongoing radioactive decay of the used fuel will also give rise to formation of decay products and irradiation damage of the used fuel matrix. The changes in radionuclide inventories with time are modelled explicitly (see *Inventory of radionuclides [2.1.01.A]*).

Irradiation damage to the used fuel matrix would be primarily caused by alpha-decay, because high-energy alpha particles and recoil atoms can cause atomic displacements. However, given the temperatures 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 (Ferry et al. 2008, Desgranges et al. 2003). Thus, this effect is not included in the FCS, and the instant release fractions (see *Inventory of radionuclides [2.1.01.A]*) derived from data for post-discharge fuels are used in the safety assessment calculations.

FEP Screening

Include FEP in all scenarios.

FEP # 2.1.13.B Radiation effects - container

Description

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

Examples of possible effects are container overpressurization due to helium gas production from the decay of the actinides in 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 and generate large concentrations of reactive compounds. These changes could lead to enhanced corrosion of the containers.

FCS Screening Analysis

The container is exposed to gamma and neutron radiation from the used fuel. Gamma radiation is mainly from short-lived 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 sufficiently large (> 1.5 MeV) then an electron/positron pair can form in the metal.) Thus, 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 self-shielding by the container itself (~ 0.05 Gy/h, Hanna and Arguner 2001). The gamma radiation leaving the container interacts with water and/or air outside the container. Radiolysis of H_2O (liquid or vapour) and air produces small quantities of O_2 and other oxidants. After 500 years, the residual radiation field would be very low because most of the remaining radioactivity would be from alpha emission of long-lived actinides. Alpha particles would not penetrate beyond the fuel cladding. Calculations indicate that the total thickness of copper affected by radiolytic oxidants would not exceed tens of micrometers (SKB 2011). Thus, damage to container materials from radiolysis will be negligible.

The neutron flux, predominantly fast neutrons with $E > 0.3$ MeV, from a used fuel container varies from about $2\times10^{6}\ n\cdot m^{-2}\cdot s^{-1}$ for 30 year fuel to $2\times10^{4}\ n\cdot m^{-2}\cdot s^{-1}$ after one million years (Tait et al. 2000). Over a one million year timeframe, the total neutron fluence experienced by the container material would be less than $10^{19}\ n\cdot m^{-2}$. Defect formation from fast neutrons would require a neutron fluence of about $10^{20}\ n\cdot m^{-2}$ in copper and iron at 70 - 80°C to result in significant hardening (Fabritsiev and Pokrovsky 2002, Eldrup et al. 2002), with thermal neutrons having a more pronounced impact at low fluencies (Fabritsiev and Pokrovsky 2002). Consequently, it is unlikely that the container metals would be significantly affected by radiation, even after as much as a million years of exposure to used fuel.

Helium is generated in the fuel by alpha decay. The amount of helium in the fuel increases with time. After 10 million years, the fuel contains about 0.082 mol/kg U (Tait et al. 2000). If all this helium is released from the fuel into the void volume of the container (1.58 m^3), the pressure in the container would increase by about 1 MPa at 70°C, using the ideal gas law. This pressurization would not affect the lifetime of the container, given that the steel vessel is designed to withstand an isostatic load much larger than 1 MPa.

FEP Screening

Screened out.

FEP # 2.1.13.C Radiation effects - sealing materials

Description

The effects of irradiation 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 effective electrochemical potential (Eh) and pH, and result in chemical changes to the bentonite materials 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.

FCS Screening Analysis

The gamma radiation fields (alpha and beta radiation cannot pass through the container) on the outside surface of the containers are low, i.e., on the order of 0.05 Gy/hr at placement (Hanna and Arguner 2001). Allowing for decay of most gamma emitters within 500 years, the cumulative dose to clay near the container would be about 0.2 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 thermally-induced mineral transformations of some species, 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 explicitly modelled in the FCS.

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} alpha/g (Pusch 2001, p.110). However, conservative calculations for the SKB KBS-3 container indicated that the possible affected buffer zone would be small and would have no overall effect on its performance (Pusch 2001, p.110). Since the amount of alpha-emitting nuclides within a FCS container is within a factor of 2 of that in the SKB KBS-3 container, we also expect this process to be unimportant for the FCS and so it is not modelled.

FEP Screening

Screened out.

FEP # 2.1.14 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-abundance 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.

FCS Screening Analysis

The FCS considers only used natural-enriched CANDU UO_2 fuel, which starts with a fissile material content of 0.7% and is depleted as a result of reactor irradiation. Such fuel cannot become critical without the presence of heavy water, as in a CANDU reactor. The uranium in used fuel, with a burnup 220 MWh/kgU, contains about 0.17% U-235 and 0.001% U-233 (Tait et al. 2000). This could not become critical even if there was physical separation of uranium.

Physical separation and concentration of Pu-239 would be required for criticality, which depends upon the likelihood of such separation occurring by natural processes without concomitant poisons also being included. There is about 18 kg of Pu-239 in a single container (360 bundles, 220 MWh/kgU burnup), along with smaller amount of other non-fissile Pu (Tait et al. 2000). This amount drops below the 5-kg subcritical limit for Pu-239 solid metal (CNSC 2010) in about 100,000 years.

Formation of a critical mass is not expected to be an issue for the FCS because it was not found to be an issue in the following studies:

- Calculations for used CANDU fuel in the EIS/SCS containers, with similar fuel and residual fissile content per kgU, but 1/5 as much fuel per container as in the FCS (McCamis 1992; Johnson et al. 1994).
- Calculations for used PWR fuel in the SKB KBS-3 container, with higher residual fissile content per kgU, but 1/3 as much fuel per container as in the FCS (SKB 1999b).
- Calculations for various waste containers for the US Yucca Mountain Project, including fuel with higher residual fissile content per kgU and also greater amounts of fuel per container than FCS, but different repository conditions (Rechard et al. 2003).

FEP Screening

Screened out.

2.2 Geological Environment

FEP # 2.2.00 Scope of sub-category 2.2

Description

The features and processes within the geological environment include hydrogeological, geomechanical and geochemical features and processes, 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 13 subcategories describing FEPs in the geological environment:

2.2.01	Excavation disturbed zone
2.2.02	Host rock
2.2.03	Other geological units
2.2.04	Discontinuities and lineaments (geosphere)
2.2.05	Contaminant transport path characteristics (geosphere)
2.2.06	Mechanical processes and conditions (geosphere)
2.2.07	Hydrological processes and conditions (geosphere)
2.2.08	Chemical processes and conditions (geosphere)
2.2.09	Biological processes and conditions (geosphere)
2.2.10	Thermal processes and conditions (geosphere)
2.2.11	Gas sources and effects (geosphere)
2.2.12	Undetected features (geosphere)
2.2.13	Geological resources.

FEP # 2.2.01 Excavation disturbed zone

Description

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

The EDZ is formed as a consequence of the repository excavation, and its extent and properties depend on factors such as the nature of the host rock, the excavation method, and the location and effectiveness of seals and grouts around the rooms and tunnels. Although it is not a physically separate entity from the host rock, the EDZ could comprise a layer of rock 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 [2.1.07.C]*).

The EDZ may affect groundwater flow and contaminant transport by providing a more permeable pathway than the host rock or buffer/backfill. The EDZ might comprise a number of hydraulically isolated areas, or it might comprise a web of damaged rock that interconnects all repository openings. The EDZ might be most extensive in particular parts of the repository, such as along the top of repository rooms or between boreholes in the in-floor placement option. The EDZ might also extend sufficiently far 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 in the EDZ. If it is sufficiently large, the EDZ could act like a hydraulic cage, decreasing groundwater velocities within the repository.

Contaminant movement would also be affected. 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. Moreover, the EDZ might also act 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 porewaters, the EDZ may accumulate salts derived from 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 these salts to redissolve, giving an initial repository-water composition that is more saline than the ambient groundwater. This may have a bearing on the chemical stability of 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 open. After saturation of the EDZ, the higher repository temperatures could promote hydrothermal interactions, causing mineral alteration, and perhaps fracture formation or fracture infilling. In particular, the EDZ thickness could increase. Other properties such as permeability could be affected by hydrothermal reactions in the EDZ, by intrusion into the EDZ of backfill, and by seismic events. Stress relief cracking or degradation of seals could extend and hydraulically connect isolated EDZ regions.

FCS Screening Analysis

Studies of the EDZ in tunnels in sparsely fractured rock excavated by controlled-blast technique relevant for the assumed FCS geosphere have indicated the presence of the EDZ as a thin inner (0.3 m) and outer (1 m) layer around the room, and 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 thermo-mechanical analysis of Guo (2009) also indicates that a relatively large thermally damaged zone (TDZ) would form in the tunnel floors between the boreholes. The thickness of the TDZ is about 0.24 m near the borehole and decreases to 0.02 m at the mid-point between two boreholes.

Analyses of the near-field region for other repository studies have found that the EDZ contributes to flow and transport, but is not a critical factor, e.g., detailed hydrological modelling in Chan et al. (1999), and SCS parameter sensitivity analyses in Goodwin et al. (1996, p.61).

Therefore, for the FCS, the EDZ, including the TDZ, should be included in the groundwater flow and transport models. The EDZ can be cautiously assumed to be fully hydraulically connected axially along rooms. However, the seals at the room ends will provide a hydraulic break.

Some precipitation of secondary phases such as calcite and gypsum, which dissolve from the clay-based materials, at the EDZ/backfill interface is likely; the main effect of these however would be to reduce the hydraulic conductivity of the EDZ until they redissolve. Thereafter, the properties of the EDZ are unlikely to change with time. The FCS will conservatively ignore this reduced conductivity period and use constant EDZ properties. These should, however, be assigned a range of values to investigate the sensitivity of calculated results to EDZ properties.

The effects of the small amounts of salt that could accumulate at the EDZ interface on the large volume of backfill and buffer is considered insignificant.

FEP Screening

Include FEP in all scenarios.

FEP # 2.2.02 Host rock

Description

The characteristics of the rock matrix in which the repository is sited, including its evolution in time. This does not include the excavation disturbed zone (see *Excavation disturbed zone [2.2.01]*).

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

Uncertainties in these properties are an important issue. For instance, rock properties measured in the laboratory may be significantly different from in situ values due to stress relief cracking after drilling. More generally, the rock characterization around a repository may be incomplete or inaccurate. Finally, some underlying assumptions may be unsupported or not transferable from one rock domain to another. For instance, observations of near-surface rock may suggest that highly fractured rock 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.

Properties of the host rock could change with time, starting from an initial state that may be somewhat unsaturated and possibly contaminated with atmospheric air and contaminants introduced into the repository. The properties may change with temperature.

FCS Screening Analysis

In the FCS, the repository is located 500 m underground in a large volume of granite. The granite is represented by several layers, each of which is characterized by properties relevant to flow (e.g., permeability, porosity) and relevant to transport (e.g., dispersivity, sorption). The variation in permeability between the layers will be represented by a reference permeability profile decreasing with depth.

Note that the Regional Groundwater Flow Study (Sykes et al. 2003) compared a layered uniform model with a layered but spatially inhomogeneous model, and concluded that the groundwater flow was not substantially different in sparsely fractured rock typical of the Canadian Shield. This was because of the strong influence of surface topography on the groundwater flow.

A specific fracture network and specific values for the flow and transport related properties (e.g., porosity and sorption) are assumed, see *Discontinuities and lineaments (geosphere) [2.2.04]*. Potential changes to fractures are also addressed in *Discontinuities and lineaments [2.2.04].*

The Canadian Shield granite is old and stable, and it is not expected that the characteristics of the host rock would change over time except possibly for fracture properties (see *Discontinuities and lineaments [2.2.04]*) or near the repository itself (see *Excavation disturbed zone [2.2.01]*).

Thus, in the FCS, 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 host rock transport properties (e.g., sorption), but not flow properties, are represented by a range in property values that encompasses their uncertainty. See *Contaminant transport path characteristics [2.2.05].*

FEP Screening

Include FEP in all scenarios.

FEP # 2.2.03 Other geological units

Description

The characteristics of rocks other than the host rock, as they may evolve with time. Geological units are separate rock structures and types that make up the region in which the repository is located. This does not include overburdens, i.e., soils and sediments overlying the bedrock, which are discussed in *Soil and sediment [2.3.02].*

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

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

FCS Screening Analysis

For the FCS hypothetical geosphere, there are no geological units other than the granite host rock within the ~200 km^2 subregional watershed area.

Geological units further away are beyond the groundwater model flow boundaries and do not impact the conditions at the site.

Overburden and soils are included, but discussed under *Soil and sediment* [2.3.02].

FEP Screening

Screened out.

FEP # 2.2.04 Discontinuities and lineaments (geosphere)

Description

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

Some of these features might form preferential groundwater and contaminant transport pathways, reducing the effectiveness of some portion of the geosphere (as a barrier) or focussing contaminant releases into the biosphere at particular discharge points. Other features (such as intrusive dykes) might provide information on the potential for future magmatic or seismic activity.

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

FCS Screening Analysis

The Fourth Case Study hypothetical site is situated in a subregional watershed area of ~200 km². 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.

Since the site is hypothetical, a reference set of fractures was defined using a geostatistical process (Srivastava 2002) that matches surface lineaments with relevant statistics for fracture sizes, shape and depth profiles. The reference fractures are illustrated in Figure 3.10. These are explicitly modelled as conducting features, with defined fracture material flow (e.g., porosity) and transport (e.g., sorption) properties. (Smaller fractures are considered as part of the effective properties of the host rock.) Flow properties are assumed constant, but assigned conservatively large values. Transport properties consider a range encompassing natural variability.

At a real site, there would be some uncertainties in the fracture set (location, length, orientation, permeability), which would have to be addressed in the safety assessment. Evaluating the impact of this uncertainty could include repeating parts of the safety analyses for alternative fracture sets. Within the present case study, the implications of fracture uncertainty are addressed by assuming all fractures are permeable and by considering alternative locations of the fracture passing through the repository footprint (see Figure 3.1), which is the main transport pathway to the surface, relative to the failed containers.

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 or extension of these fractures.

Based on the geological age of the Canadian Shield and its history, including multiple glaciations, it is assumed that fractures at the FCS are old and stable, and will not significantly grow, nor will new fractures form over the one million year assessment period. (The actual age of fractures at a real site would need to be assessed.) It is possible, however, that presently closed fractures could be reactivated (McMurry et al. 2003) by glacial-related deformation and/or seismic activity. Since, in the FCS, all known fractures at the repository site are assumed to be open and permeable, the fracture network at the site is assumed to be unaffected by glaciation and seismicity.

It is also possible that not all discontinuities at the site, including fractures, have been identified. The impact of an undetected transmissive vertical fault, extending from below the repository level into the shallow groundwater system, is examined in the Undetected Fault Scenario. Such a fault would affect the characteristics of the host rock and could provide a contaminant pathway that bypasses the deep groundwater system.

FEP Screening

Include FEP in all scenarios.

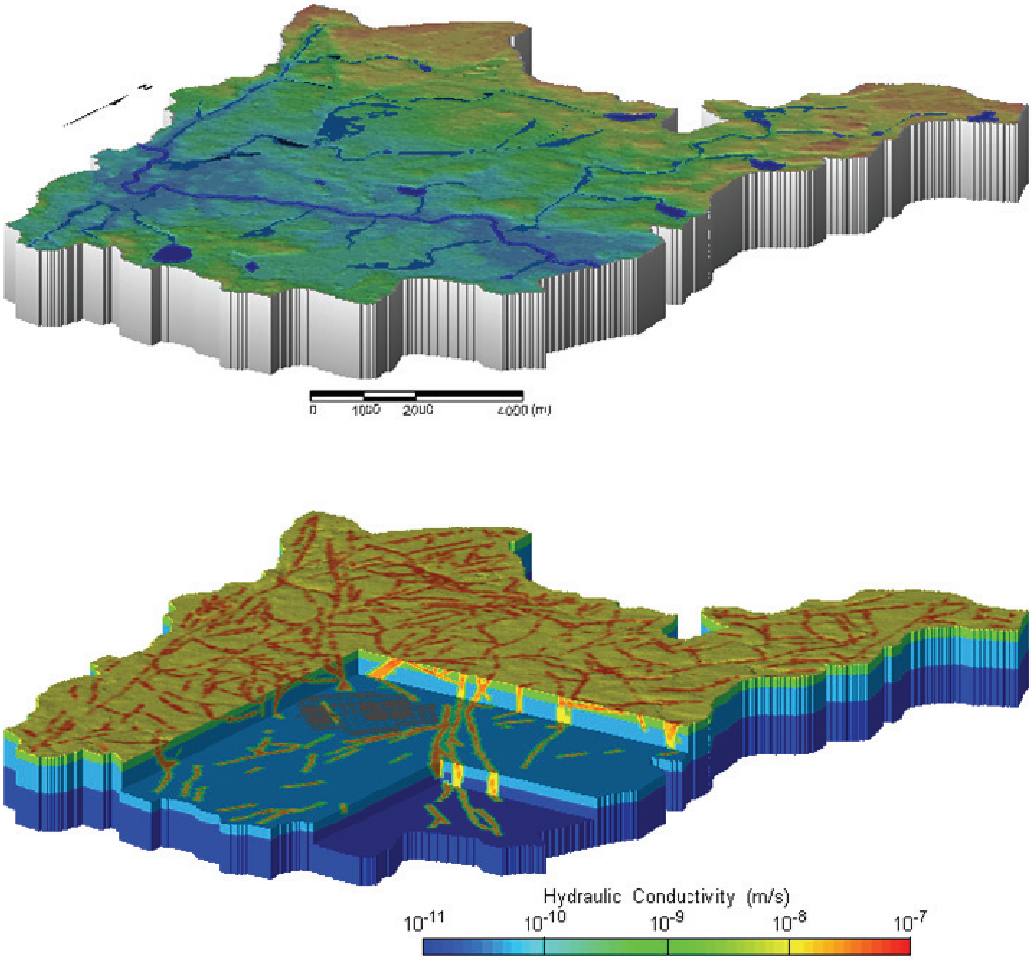


Figure 3.10: Perspective view of 200 km^2 subregional area. Top figure shows surface water features and topology. Bottom figure shows fracture network and surface lineaments, as equivalent porous media, and location of repository.

FEP # 2.2.05 Contaminant transport path characteristics (geosphere)

Description

Characteristics of the main pathways for contaminant transport through the geosphere.

These characteristics include hydraulic conductivity, porosity, tortuosity and interconnectivity. Groundwater and contaminant transport through rocks may occur by processes that include the following, depending on the characteristics of the rock:

2.2.05A Advection and dispersion
2.2.05B Diffusion
2.2.05C Matrix diffusion.

The relative significance of advective versus diffusive transport is often discussed in terms of the Peclet number, P, which is equal to

$$P = v L / D$$

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 for values of P greater than about 10, and diffusive transport for values less than 1.

Related issues are discussed under *Hydrological processes and conditions (geosphere) [2.2.07].* Another closely related subject, the location of discharge zones, is discussed under *Topography and morphology [2.3.01].* Finally, other contaminant-specific processes are discussed under *Contaminant release and migration factors [3.2].*

FEP # 2.2.05.A Advection and dispersion

Description

Processes involving groundwater movement through fractures and host rock under the influence of a pressure or thermal gradient.

Groundwater in the geosphere can move because of the effects of thermal buoyancy, hydraulic heads (gravity) and density differences. The groundwater can move through the pores in the medium and the interstitial spaces between small grains of materials (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. Variations in groundwater velocity and pathways cause dispersion, i.e., the spatial spreading of contaminants during advective transport.

FCS Screening Analysis

The processes of advection and dispersion (in the geosphere) are included in the FCS through the use of the advection-dispersion equation with sorption.

The parameters needed include diffusivity, sorption coefficient, porosity, tortuosity, groundwater velocity, dispersivity, and dimensions. For constant climate simulations, transport properties are assumed to be time-independent, although a range of values is considered as part of probabilistic and sensitivity analyses. However, for glaciation, which is considered in the Reference Case of the Normal Evolution Scenario, groundwater flow is transient due to the advance and retreat of the ice sheets.

The groundwater flow calculations in the FCS assume that the temperature of the buffer is constant at 70°C but also assume that the rock around the repository is at ambient temperature, i.e., the effect of repository heating of the rock in the vicinity of the repository is neglected. The neglect of repository heating of the host rock on groundwater flow is considered reasonable for the reasons outlined below.

Studies of the effect of repository heating on groundwater flow were carried out for the EIS study (Davison et al. 1994) and the SCS (Stanchell et al. 1996). In the EIS study, the hydraulic conductivity of the rock around the repository was low (10^{-12} m/s) and repository heating increased the groundwater velocity in the sparsely fractured rock by up to an order of magnitude. However, particle tracking calculations indicated that the minimum travel time to the biosphere decreased by less than 1% because the transport times through the fractured rock were orders of magnitude longer than the duration of the velocity perturbation caused by repository heating. In the SCS, in contrast, the hydraulic conductivity of the rock around the repository was relatively high (10^{-10} m/s) and repository heating reduced the minimum travel time to the biosphere by about 17% for rock with an effective porosity of 0.004, i.e., from 3100 years to 2570 years.

In the Fourth Case Study, the hydraulic conductivity of the intact rock is $4\text{x}10^{-11}$ (m/s) for the Reference Case of the Normal Evolution Scenario, which is between the values used in the EIS study and SCS. Hence, the impacts of repository heating on the transport times to the surface biosphere should be less than the 17% observed in the SCS. Moreover, for the Reference

Case, it is found that for the nonsorbing radionuclide I-129, which is the dominant contributor to the total dose rate, the time of the peak I-129 flux to the surface is 100,000 years. The thermal transient is much shorter than 100,000 years, suggesting that the effect of repository heating on the contaminant transport times to the surface should be small. For these reasons, the groundwater flow calculations in the FCS neglect the effect of repository heating of the host rock on the groundwater flow field.

See also *Evolution of hydraulic conditions [2.1.08.C]* and *Thermal conduction and convection [2.1.11.A]*.

FEP Screening

Include FEP in all scenarios.

FEP # 2.2.05.B Diffusion

Description

The migration of contaminants in the geosphere caused by molecular motion (i.e., diffusion).

Molecular diffusion can occur in moving or stagnant groundwater. Although water molecules themselves can diffuse, the diffusion of dissolved species and particulates (including contaminants) is of most concern here. Diffusive transport is driven by thermal, concentration or chemical potential gradients and can be in any direction relative to advective flow of groundwater. Diffusion can be the most important transport mechanism in situations where groundwater flow is very slow.

See also *Matrix diffusion [2.2.05.C].*

FCS Screening Analysis

Transport of dissolved contaminants in the geosphere by ordinary diffusion (i.e., driven by concentration gradients) is included in the FCS. Diffusion is important in intact geosphere zones where there are no fractures and the groundwater velocity is very low. In this case, the tortuosity and (transport) porosity of the geosphere zone are important parameters.

Diffusive transport due to gradients other than concentration gradients is not modelled in the FCS. These coupled processes are expected to be unimportant in the geosphere as is the case for transport in the repository (see *Coupled hydraulic processes [2.1.08.D]*).

FEP Screening

Include FEP in all scenarios.

FEP # 2.2.05.C Matrix diffusion

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 fracture (or other relatively conductive zones) 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 *Water-mediated transport of contaminants [3.2.07]* and *Sorption and desorption (contaminant) [3.2.03].*

FCS Screening Analysis

The reference FCS case will not explicitly consider matrix diffusion in the geosphere. Instead, nuclide transport in the geosphere will be modelled using an equivalent-porous-medium representation of the host rock. The sensitivity studies carried out in the Third Case Study using the dual-continuum FRAC3DVS model (Garisto et al. 2004a) indicate that use of the equivalent-porous medium representation provides a suitable description of nuclide transport in the geosphere.

Neglecting matrix diffusion in the FCS geosphere is not expected to significantly affect the calculated total dose rates, which will likely be dominated by radionuclides such as I-129 for which matrix diffusion effects are small (Garisto et al. 2001). Furthermore, neglect of matrix diffusion would be conservative for radionuclides that are adsorbed in the geosphere (Garisto et al. 2001).

FEP Screening

Screened out.

FEP # 2.2.06 Mechanical processes and conditions (geosphere)

Description

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

External regional effects are discussed in *Seismicity (earthquakes) [1.2.03]* and *Local glacial effects [1.3.05].* Effects on the repository itself, such as collapse of openings, are discussed under *Mechanical processes and conditions (repository) [2.1.07].*

Excavation of a deep repository will result in removal of substantial volumes of host rock. The process will last several decades before placement of the backfill and closure of all underground openings. The excavation process will create stresses across the repository. Seismic events may magnify these stresses. The stresses could lead to fracture formation or changes in porosity (and therefore permeability). Another possible effect is subsidence of the surface environment.

One important result would be the influence on groundwater movement and contaminant transport. The excavation-induced fractures may form a high-permeability conduit connecting an placement room to a fracture zone leading to the surface. The nature of these fractures might also be different from naturally occurring fractures, such as in the chemical reactivity of exposed mineral surfaces.

There may be coupling between the thermal, hydraulic and mechanical processes. For example, after the containers have been placed, the heat generated by the used fuel will change the temperatures around the repository, causing thermal expansion and related stresses. Of particular importance, during glaciation, is hydro-mechanical coupling, which refers to physical interaction between hydraulic and mechanical processes. Hydro-mechanical coupling due to glacial loads can lead to hydraulic head gradient changes and, hence, fluid flow changes.

Hydro-mechanical coupling includes two basic direct phenomena (Wang 2000): (1) a solid-to-fluid coupling that occurs when a change in applied stress produces a change in fluid pressure or fluid mass (and, hence, fluid flow) , and (2) a fluid-to-solid coupling that occurs when a change in fluid pressure or fluid mass produces a change in the volume of the porous medium. Note that the reduction in pore volume leads to a reduction in the cross-sectional area and a reduction in fluid flow capacity, and a reduction of pore volume may result in a stiffer material.

FCS Screening Analysis

For the Fourth Case Study, 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]*). This was the case at the AECL Underground Research Laboratory, and is expected to be typical of Canadian Shield sparsely-fractured rock assuming that the repository is appropriately aligned with the principal stresses. Scoping design calculations for a Third Case Study repository at 1000 m depth (i.e., higher natural rock stresses than at the 500 m depth of the FCS repository) indicated that the post-excavation stresses, including thermal stresses, are acceptable. Therefore, there is likely to be no significant fractures created, no significant changes in porosity, and (because the rooms are backfilled) no subsidence.

While the 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 (geosphere) [2.2.04]*.

The coupled thermal-mechanical analysis of rock behaviour carried out by Guo (2009) was used as the basis for selecting the appropriate container spacing, placement room spacing and placement room shape for the Fourth Case Study repository. The stability of the rock mass was evaluated using the Hoek and Brown empirical failure criterion. The calculations showed that excavation of placement rooms would not cause any significant failure in the rock surrounding the placement room, although some localized damage would occur at the roof of the placement room. In comparison to an elliptical-shaped room, the localized damage is more sever in a circular-shaped room. The thickness of the damage zone is estimated to be less than 0.13 m at the roof of the placement room.

In addition, Guo (2009) showed that a large thermally damaged zone exists between the container in-floor boreholes (see *Excavation disturbed zone [2.2.01*]). This thermally damaged zone is explicitly included in the detailed FRAC3DVS groundwater modelling calculations.

The impact of hydro-mechanical coupling has been shown to be important during glaciation (Walsh and Avis 2010). Hence, hydro-mechanical coupling is implicitly included in the qualitative discussion of glaciation effects in the Normal Evolution Scenario.

FEP Screening

Include in all scenarios (since analysis forms basis of repository design).

FEP # 2.2.07 Hydrological processes and conditions (geosphere)

Description

The hydrological and hydrogeological processes that affect the host rock and other rock units, and the overall evolution of conditions with time. This includes the effects of changes in condition, e.g., hydraulic head, due to the excavation, construction and the long-term presence of the repository. A related subject, the location of discharge zones, is discussed under *Topography and morphology [2.3.01].*

Hydrogeological processes include the movement of water through the relevant geological formations in the repository region and their controlling factors. Understanding these processes requires knowledge of the recharge and discharge zones, the groundwater flow pathways, the degree and extent of water saturation, and factors that may drive the flow, including hydraulic heads (gravity) and density effects caused by salinity and temperature gradients. It also requires knowledge of the interactions between regional and local flow systems under various boundary conditions and of seasonal and annual cycles of water tables in rocks of the Canadian Shield rocks.

The existing hydrological and hydrogeological processes and conditions that affect the host rock and other rock units will evolve in time because of natural changes (in climate for instance) and because of the excavation and continued presence of the repository. The ambient groundwater flow conditions in the undisturbed geosphere will likely be saturated flow driven largely by hydraulic heads with some influence from geothermal gradients and density effects. These flows will evolve naturally in time because of long-term variations in the water table. The ambient conditions will change substantially near the repository because of the creation of a zone of unsaturated rock, the presence of a large thermal source and, possibly, the introduction of surface water into the repository environment. Other processes influencing the long-term evolution of the hydrogeological regime include failure of borehole and shaft seals. Potential processes and effects include channelling of groundwater flow within existing and induced fracture zones, which may promote formation of voids through erosion and cavitation; precipitation or dissolution of minerals which could plug or open pores and fractures; the ingress of surface water containing oxygen and other contaminants to the rock and fracture surfaces at depth, and the creation of new discharge zones for deep groundwater.

One important consideration is the existence of conditions that are apparently unusual or anomalous, inasmuch as they may be indicators of potentially important processes and features. Some hydrogeological observations might be regarded as unusual or atypical (or perhaps faulty) and have an incomplete or inadequate explanation. Better characterization of some such conditions could lead to an understanding of processes that may have important influences on the performance of a repository system. Examples include the following.

- Studies of plutons in the Canadian Shield over the past few decades have shown the wide spread occurrence of highly saline waters at depth. The existence of these waters may imply that deep groundwaters have remained stagnant for very long time frames. The finding of dilute groundwater at these depths, therefore, may be considered to be anomalous and warrant investigation.
- The presence of unexpectedly high or low groundwater pressures in rock at depth in the Whiteshell Research Area may imply that its groundwater flow comprises a relatively fast component (fracture flow) driven by topographic gradients and a slow transient component (matrix flow) driven by relict (geological) pressure gradients.

FCS Screening Analysis

The main geosphere hydrological processes and conditions related to groundwater flow are included in the Fourth Case Study, specifically: host rock and fracture permeability, hydraulic heads driven by surface topography and the effects of a water supply well. The major fractures are explicitly included in the hydrological model.

These processes and conditions are assumed to be time-independent. Since the FCS site is assumed to be in a stable geological environment, the largest likely changes would arise from glaciation. In the FCS, the effect of glaciation is quantitatively discussed as part of the Reference Case of the Normal Evolution Scenario. During glaciation, the groundwater flow field is transient because of the advance and retreat of ice-sheets over the site (Walsh and Avis 2010). The large changes to the groundwater flow field during ice sheet advance and retreat affects contaminant migration and consequently the calculated doses to the critical group (Garisto et al. 2010).

The transient hydrogeological conditions, between the time of repository closure and the time at which the repository becomes saturated, are not modelled within the FCS. During this saturation period, nuclides cannot be released from the repository through the groundwater pathway.

The FCS explicitly considers the effects of uncertainty in the geosphere permeability profile through evaluation of alternative cases, and in the effects of varying well demand on the groundwater flow.

At present, the model used in the FCS to calculate the groundwater flow field does not include the effects of variable-density, i.e., salinity. However, this is expected to be a small effect due to the low salinities in the FCS geosphere at repository depth. Generally, increasing salinity with depth is favorable to the stability of the groundwater system.

FEP Screening

Include FEP in all scenarios.

FEP # 2.2.08 Chemical processes and conditions (geosphere)

Description

The chemical and geochemical processes that affect the host rock and other rock units, and the overall evolution of conditions with time. This includes the effects of changes in conditions, e.g., Eh, pH and the dissolution and precipitation of minerals, associated with the excavation and long-term presence of the repository.

The hydrochemical regime requires knowledge of the groundwater chemistry including dominant species, element solubilities, concentrations of complexants, 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 could be in thermodynamic equilibrium or near-equilibrium with minerals encountered in the groundwater flow path. Surface waters containing dissolved carbon dioxide and oxygen will react with feldspars and other minerals in granite to yield groundwaters that are typically slightly alkaline and relatively rich in silica and the cations, calcium and sodium, and the main anionic species, bicarbonate and sulphate. The redox conditions are expected to be reducing and controlled by the presence of iron-bearing minerals such as chlorite. Other alteration products, often found as fracture infillings, include clays such as kaolinite and illite, quartz, iron oxides and hydroxides, calcite and gypsum. Deeper groundwaters contain no free oxygen, less bicarbonate, but more dissolved salts, especially calcium and sodium chlorides.

Alternative groundwater compositions could occur for reasons that include: different sources of recharge water caused, for instance, by deep ingress of oxygenated fresh water during a glacial retreat ; the introduction of pollutants during excavation; exposure to fresh rock surfaces in new fractures such as might be found in the EDZ; high local concentrations of reactive minerals such as pyrite; the presence of redox couples such as nitrogen compounds from explosives, dissolved organic carbon and dissolved manganese; and effects of microbial activity.

A variety of subsequent reactions are possible as this groundwater contacts the thermal field surrounding the repository and the material in the repository. For instance, fracture-filling minerals could be dissolved and replaced by other precipitants, affecting rock porosity, permeability and sorption. A specific example is dissolution of silica from quartz-rich granite minerals such as feldspar when subjected to slightly elevated temperatures over long times, followed by the migration and precipitation of fresh quartz crystals at cooler locations. Grain size effects and partial dissolution of micas and feldspars could be important factors in the selective enlargement of fractures and channels in rock.

Evolution of groundwater composition in the geosphere is an ongoing process which would occur in the absence of a repository. However, groundwater composition will certainly be perturbed by the contents of and heat generated by the repository. Groundwater will evolve in response to: ingress of different sources of mixing water, including oxygenated surface water introduced during events such as repository excavation; byproducts of groundwater interactions with the container, buffer, backfill and other material in the repository; thermal-affected dissolution and precipitation of fracture-filling minerals; and hydrothermal alteration of primary rock minerals to clays.

Groundwater may also evolve because of the effects of radiation emitted from the repository on the surrounding rock. Direct damage to rock structure is unlikely, but some effects could occur through chemical reactions involving reactive products from radiolysis. See also *Radiation effects (repository) [2.1.13].*

Analyses of the groundwater and its dissolved salts 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 analysis of some deep saline groundwaters from the Canadian Shield has indicated that they are very old, implying very low flow rates at repository depths.

FCS Screening Analysis

The main chemical conditions in the geosphere that affect groundwater transport of contaminants are included in the FCS, specifically: redox boundary, mineral composition, and groundwater composition. The main chemical processes included are contaminant sorption and solubility. The effect of these conditions on sorption is discussed further in *Sorption and desorption (contaminant) [3.2.03].*

The chemical conditions in the geosphere are assumed to be time-independent for the one million year period of interest. Although the chemical conditions in the near-surface would likely change, there is geological evidence that deep groundwaters in the Canadian Shield can be old and therefore only slowly changing (Gascoyne 2000, 2004; McMurry et al. 2003). At the FCS site, the largest changes are likely to occur during glaciation. However, paleohydrogeologic simulations (NWMO 2012, Chapter 2) indicate that glacial meltwaters concentrations would range between 5% and 45% within the rock matrix at the repository horizon; although, higher meltwater concentrations occurred within the discrete higher permeability fracture zones. This dilution should not significantly affect material properties. More importantly, the glacial recharge penetrating below the shallow groundwater system (i.e., below 150 m depth) is not expected to be oxygenated or influence redox conditions at the repository horizon (NWMO 2012, Section 2.3.5.3) (see *Local glacial effects [1.3.05]).*

The fracture model conservatively assumes that fractures remain open and relatively porous, and so the details of possible chemistry occurring within the fracture are not modelled.

Variability or uncertainty in the chemical conditions is accounted for by use of probabilistic distributions to define the associated parameter values.

FEP Screening

Include FEP in all scenarios.

FEP # 2.2.09 Biological processes and conditions (geosphere)

Description

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

A wide range of effects is possible from the action of microbes that are natural to the geosphere, or that are introduced with repository materials. For instance, anaerobic microbes could modify the groundwater Eh and pH. Organic byproducts might serve as ligands that could complex with and enhance the mobility of heavy metals (e.g., methylation). Biofilms might form in fractures, and reduce permeabilities or change sorption capabilities. Other potential effects on the transport of contaminants are discussed under *Biologically mediated processes, excluding transport (contaminant) [3.2.06].*

FCS Screening Analysis

A variety of microorganisms will exist within the geosphere. 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. This will affect which microbial species are initially active around the repository, but re-establishment of normal conditions will eventually occur, given the expected performance of repository and shaft seals, as temperatures decrease, and oxygen and nutrients are consumed.

The potentially most important effect of geosphere microbes is to modify the groundwater Eh and pH. Their specific contribution within the geosphere to this process will not be modelled in the FCS, as they are one of several processes (organic plus inorganic) that are involved in determining the chemistry of the far-field groundwater. Rather, the net effect of all these processes is partially included through the selection of the depth of the redox divide, i.e., the depth at which reducing conditions are achieved. (The geosphere K_d values for redox sensitive elements depend on the depth of the redox divide.)

Potential effects of biological processes and conditions on contaminant transport are discussed under *Biologically mediated processes, excluding transport (contaminant) [3.2.06],* and *Biologically-mediated transport of contaminants [3.2.11].*

FEP Screening

Screened out.

FEP # 2.2.10 Thermal processes and conditions (geosphere)

Description

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

Geothermal regime refers to sources of geological heat, the distribution of heat by conduction and transport (convection) in fluids, and the resulting thermal field or gradient. The consequent effects could have mechanical, hydraulic, chemical and biological implications (see subcategories [2.2.05] to [2.2.09]). For instance, thermal expansion could lead to formation of fractures and cracks in the rock or fracture displacement; thermal buoyancy could drive groundwater movement and form convection cells in permeable zones; groundwaters would be more reactive and tend to evolve in a thermal gradient; and the growth and activity of microbes might be promoted.

FCS Screening Analysis

Temperatures within the geosphere are determined by thermal analyses (Guo 2009). These show that the temperature in the geosphere increases to a maximum by about 10,000 years after closure of the repository and then returns to ambient (~11°C) within 100,000 years. The temperature increases most in the centre of the repository and least at the corners of the repository. The maximum rock temperature at the borehole surface is less than 65^{o}C, and the temperature of most of the rock mass, except near the containers, is less than 42^{o}C.

In the FCS, the geosphere around the repository is mainly unaffected by this thermal plume, as discussed in *Mechanical processes and conditions (geosphere) [2.2.06]*, except for the thermal effect on the near-field rock which is covered in *Excavation disturbed zone [2.2.01].*

The effects of the temperature increase on groundwater flow and solute transport are not expected to be important based on the discussion in *Advection and dispersion [2.2.05.A]*. Furthermore, the initial thermal peak during the initial heat up phase and until repository saturation is not included because groundwater transport of contaminants cannot occur during this period.

FEP Screening

Screened out.

FEP # 2.2.11 Gas sources and effects (geosphere)

Description

The natural sources of gases within the geosphere, and the effect of natural and repository produced gas on the geosphere.

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

Gases could dissolve in and affect the composition of groundwater. For instance, dissolution of carbon dioxide tends to lower groundwater pH and dissolution of methane will affect Eh. Gases could be transported with groundwater, or they could accumulate in the geosphere and form an unsaturated area. Unsaturated or two-phase flow might then become important, and gases could be released as bursts of bubbles that force a passage through the rock and fractures. Some gases such as hydrogen and methane are flammable and even explosive if mixed with oxygen, and could damage or alter the properties of the geosphere. Groundwaters containing large quantities of dissolved gas might exhibit extensive degassing (characterized by fizzing and bubbling) at points along the flow path where pressures are low, notably at discharge locations at the surface environment.

FCS Screening Analysis

Although there will be some gas generated within the geosphere, gas generated within the repository is likely to be more important, both because of the total amount generated and because of its generation and, hence, concentration within a smaller volume. However, as noted under *Gas sources and effects (repository) [2.1.12],* the formation of significant amounts of gases such as H_2 in the repository is limited for all scenarios except the All Containers Fail Scenario.

After these gases have reached the geosphere, the permeability of crystalline fractured rock, although low, is generally expected to be sufficient that the gas can escape through the geosphere and will not cause a problem, even for the All Containers Fail Scenario (NWMO 2012, Rodwell et al. 1999). Therefore, the analysis of the movement of this gas out of the repository and through the geosphere is not considered further in the FCS.

The presence of H_2, the primary gas released from the repository, will tend to promote the desired reducing conditions in the near-field geosphere. Therefore, any further effect on the groundwater chemistry is not considered.

FEP Screening

Screened out.

FEP # 2.2.12 Undetected features (geosphere)

Description

Natural or man-made features within the geosphere which are not detected during the site investigation, or even during excavation and operation of the repository.

Examples of possible features are faults, fracture zones, induced fractures caused by excavation, inhomogeneities, unexpected splays or branching of known fractures, brine pockets and old boreholes and mine workings. These features could play a significant role in the transport of groundwater to and from the repository. See also related factors in *Future human actions [1.4]*, such as *Drilling activities (human intrusion) [1.4.04].*

FCS Screening Analysis

For a real site, it is expected that through measurements of known fracture zones, and through remote-detection techniques applied around the repository itself, it would be unlikely that an undetected large-scale feature could exist within approximately 25 m or the repository. However, it is recognized that the information available at a real repository site may be ambiguous, and that there could be undetected geosphere features. However, for the FCS Normal Evolution Scenario, it is assumed that the reference geosphere model adequately describes the main features of importance for radionuclide transport (see *Discontinuities and lineaments [2.2.04]*).

The effect of an undetected fracture is examined as part of the Undetected Fault Scenario.

FEP Screening

Include in the Undetected Fault Scenario.

FEP # 2.2.13 Geological resources

Description

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].*

FCS Screening Analysis

The FCS uses a hypothetical site. The site description assumes that there are no significant geological resources near this site. This applies to both deep and surface resources. It is reasonable to expect that the site characterization program put into place at the repository would confirm this.

See also *Deliberate human intrusion [1.4.02]* and *Drilling activities (human intrusion) [1.4.04].*

FEP Screening

Screened out.

2.3 Surface Environment

FEP # 2.3.00 Scope of sub-category 2.3

Description

The features and processes within the surface environment, including near-surface aquifers and sediments, but excluding human activities. It includes description of how these features and processes might change over long periods of time.

There are 13 subcategories describing FEPs for the surface environment:

- 2.3.01 Topography and morphology
- 2.3.02 Soil and sediment
- 2.3.03 Near surface aquifers
- 2.3.04 Surface water bodies
- 2.3.05 Coastal features
- 2.3.06 Marine features
- 2.3.07 Atmosphere
- 2.3.08 Vegetation
- 2.3.09 Animal populations
- 2.3.10 Meteorology
- 2.3.11 Hydrological regime and water balance
- 2.3.12 Erosion and deposition
- 2.3.13 Ecological systems.

FEP # 2.3.01 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. Features such as slope or depression affect the amounts of moisture and soil that are retained locally, which in turn influences plant and animal communities.

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

FCS Screening Analysis

Topography is explicitly included in the FCS. This 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 both a regional (5700 km^2 scale) and on the subregional (~200 km^2) and site (4 km^2) scales (see, for example, Figure 3.11).

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

In the FCS, the biosphere topography is assumed to be time-independent. As noted in *Tectonic movement and orogeny [1.2.01]*, there is no mountain building occurring on the Canadian Shield over the next one million years.

FEP Screening

Include FEP in all scenarios.

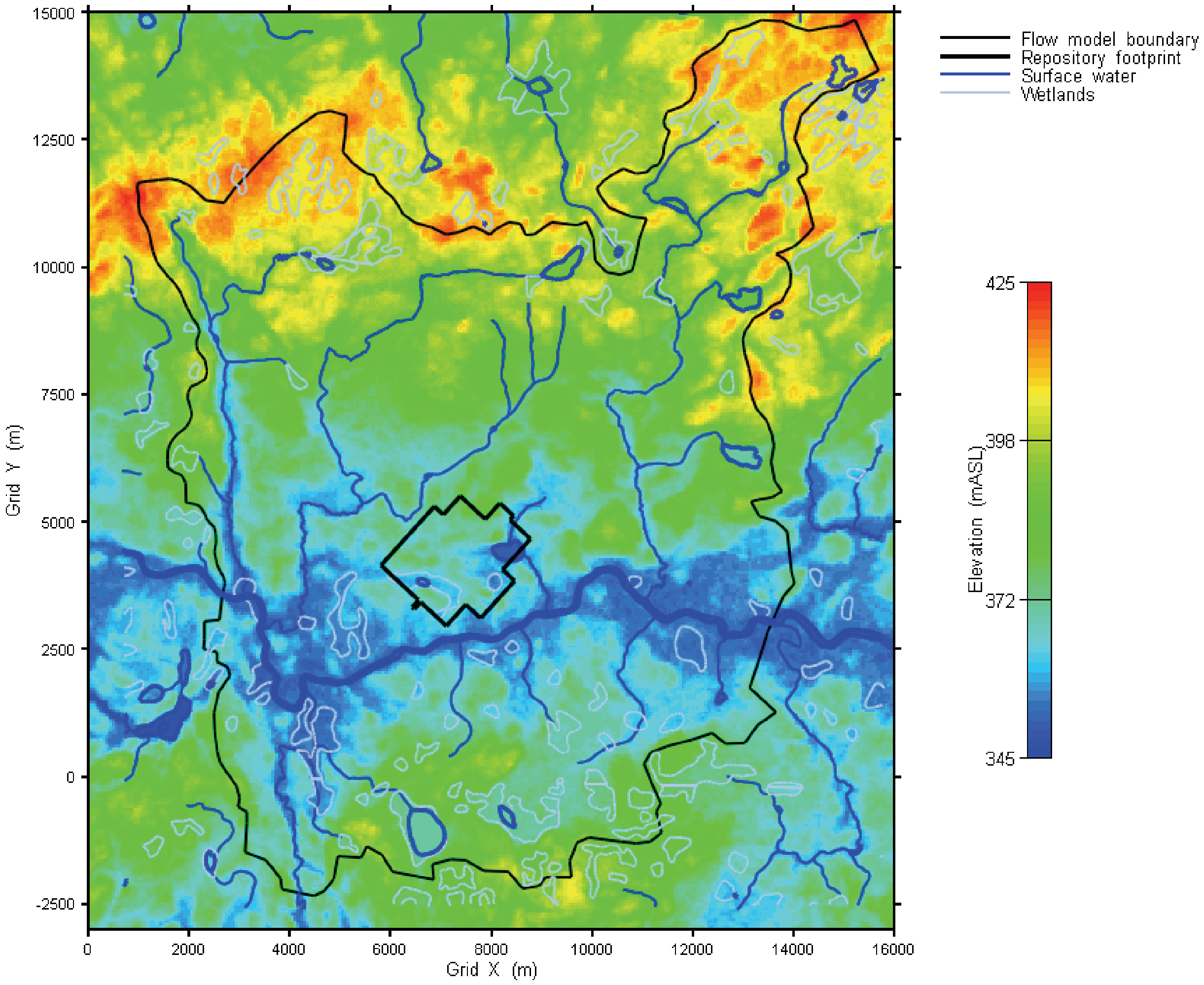


Figure 3.11: The hypothetical subregional surface topography, indicating major lakes and rivers and repository location. The topography is relatively flat.

FEP # 2.3.02 Soil and sediment

Description

The soils and sediments that lie over the rock of the geosphere.

Further discussion of soils and sediments is provided under three categories:

2.3.02A Surface soils
2.3.02B Overburden
2.3.02C 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 # 2.3.02.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 meters 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 is the region most directly affected by agricultural practices such as ploughing.

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 down to 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 porewaters is dependent on various soil properties, and contaminant redistribution can lead to a number of different exposure pathways (see further discussion under *Contaminant release and migration factors [3.2]*).

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

FCS Screening Analysis

Surface soils will be explicitly modelled in the FCS. 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).

Simple soil compartment models are 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 therefore are well-mixed.

In the FCS, two soil models are used. A shallow soil model is used when the depth of the water table is less than 0.5 m from the surface and an upland soil model is used when the depth of the water table is more than 0.5 m from the surface.

The soil type at the site may change over time. However, the change would be slow. For the FCS, 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: clay, loam, silt or organic, in the probabilistic calculations.

FEP Screening

Include in all scenarios.

FEP # 2.3.02.B Overburden

Description

The unconsolidated rock, clay, sand and soils that overly the rock of the geosphere, but not including the surface soils. This category includes similar material that may be found under surface water bodies, but not sediments formed by the deposition of particulates from surface water (see *Aquatic sediments [2.3.02.C]*).

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

The overburden layer on the Canadian Shield is generally fully saturated. It may serve as a pathway for contaminated groundwater flows from the geosphere and as a source of diluting contaminant-free water. Overburden with a high clay content can be relatively impermeable, and groundwater flow might be restricted or confined to channels and fractures. A localized discharge from 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 in the same way that soils evolve. However, changes may also be driven by hydrothermal reactions with groundwater. Human activities such as dredging and excavation can affect the overburden.

FCS Screening Analysis

Overlying sediments or overburden are explicitly included in the FCS groundwater flow model. An overburden is assumed for terrestrial areas, and a sediment layer under lakes and rivers. Since radionuclides can be absorbed in the overburden, it affects the concentrations of radionuclides in the groundwater discharging into the biosphere.

FEP Screening

Include in all scenarios.

FEP # 2.3.02.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 compact sediments may eventually form surface soil and overburden sediments when, for instance, a river changes its course or a lake dries up. They are often dredged for use as soil conditioners.

Aquatic sediments can play an important role in contaminant transport through sorption processes (see *Sorption and Desorption [3.2.03]* and *Colloids [3.2.04]*). Contaminant sorption onto sediments can remove contaminants from the aqueous environment, but in the process contribute to exposure routes involving contaminated sediments such as through emergent plants like wild rice, or the transformation of lake beds to agricultural land (see, for instance, *Surface environment, human activities [1.4.06]*).

FCS Screening Analysis

Aquatic sediments will be explicitly included in the FCS. 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 a lake as well as the contaminant concentrations in the groundwater discharging into the lake from the repository.

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, the underestimation of contaminant concentrations in mixed sediments (see above) will have a relatively small effect on the calculated dose rates.

FEP Screening

Include FEP in all scenarios.

FEP # 2.3.03 Near surface aquifers

Description

The characteristics of aquifers and water-bearing features within a few metres of the land surface.

FCS Screening Analysis

The reference FCS site does not contain any near-surface aquifers (NWMO 2012, Section 2).

FEP Screening

Screened out.

FEP # 2.3.04 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 [2.3.02.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 into the surface.

Other considerations are provided under:

2.3.04A Wetlands
2.3.04B Lakes and rivers
2.3.04C Springs and discharge zones.

FEP # 2.3.04.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 also 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.

FCS Screening Analysis

Wetlands are present in the surface topographical map for the reference FCS regional area (see Figure 3.12). Specifically, groundwater from the repository discharges to the East, Central and Western Wetlands.

Small lakes near the repository might also fill in and become wetlands over the time scales of interest.

In the FCS biosphere model, wetlands are present whenever the water table is less than 0.5 m from the surface. In this case, the shallow soil model is used to calculate contaminant concentrations in soil. Groundwater discharge from the repository can enter (i.e., flow into) the wetland soil block directly, without need for capillary action to bring water from the water table to the surface. Contaminants can be sorbed onto the wetland soil, and can be leached out of the wetland soil by the water flowing through the soil block (e.g., with runoff water). Wetland soils (e.g., peat) can be used as fuel for heating (see *Other contaminated materials [3.3.03]*).

FEP Screening

Include FEP in all scenarios.

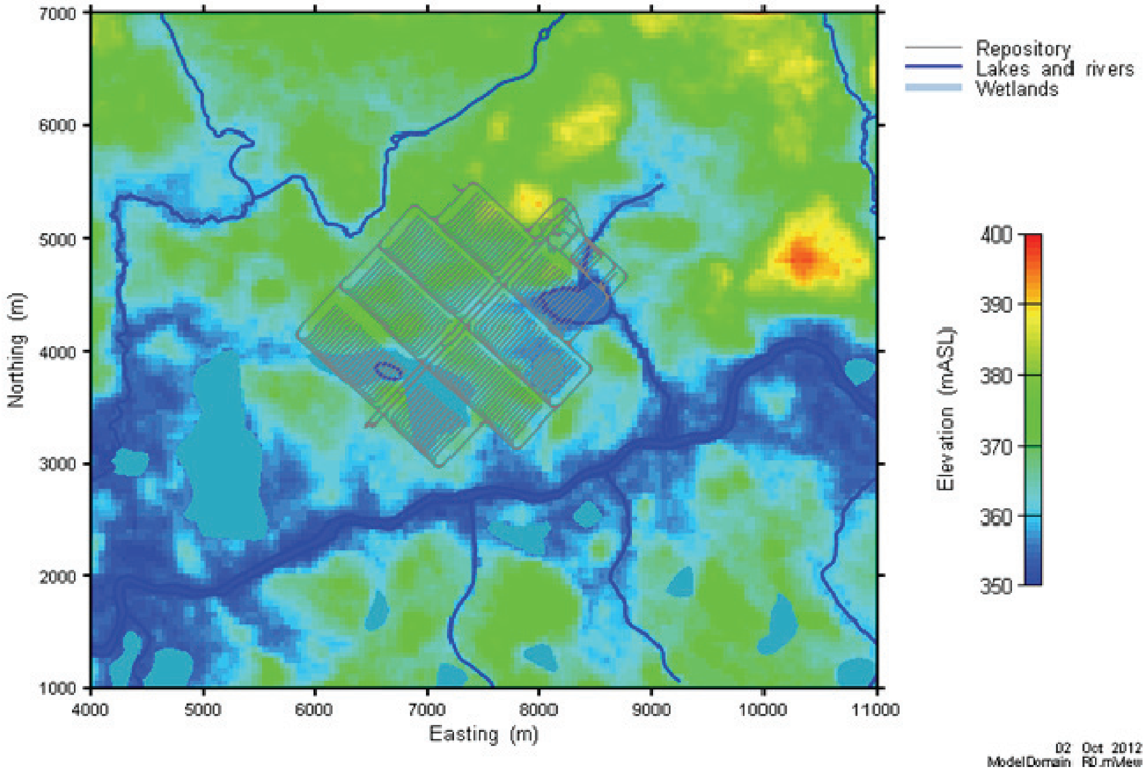


Figure 3.12: Close-up of the area around the repository site, showing the major water bodies (lakes, rivers and streams) and wetlands. The projected location of the repository at surface is also shown.

FEP # 2.3.04.B Lakes and rivers

Description

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

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

- Surface water pH is a major concern in 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.
- 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. Flushing rates are variable and some water bodies on the Shield are stagnant with little or no flushing.
- 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 water extraction. Conversely, discharges to the bottom of a lake may not be well mixed because of density effects where a warm surface layer (epilimnion) floats on a cold bottom layer (hypolimnion), especially for deep lakes and during cold seasons. Mixing processes could also stir up contaminated sediments.
- Rate of sedimentation. Rivers and streams often carry large quantities of particulate material produced by erosion of river banks. These particulates can sediment, or be deposited, in areas where water currents are slow, such as at river deltas and in lake bottoms. See also *Aquatic sediments [2.3.02.C].*

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

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

FCS Screening Analysis

At the FCS repository site, there are two surface water bodies into which contaminated groundwater from the repository discharges - the Lake and the River (see Figure 3.12). The Lake discharges into the River upstream of the groundwater discharge into the River. The River itself drains a much larger watershed area than just the repository area.

For the FCS safety assessment, we identify a reference surface water body that could be used by the critical group as a source of drinking water and irrigation water. Both the Lake and River are of sufficient size for this to be plausible. However, the River has a much larger flow and, hence, dilution. Thus, in the FCS, the Lake is considered to be a potential source of water for the critical group.

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]*.) The Lake is assumed to be well-mixed, and the water flow rate through the Lake and River are related to the precipitation and runoff (see *Meteorology [2.3.10]*).

In the FCS, 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 Lake is neglected. However, a range of Lake parameter values will be used for sensitivity or probabilistic analyses, thereby providing some indication of the influence of temporal changes to Lake properties.

FEP Screening

Include FEP in all scenarios.

FEP # 2.3.04.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 at the margin or bottoms of lakes and wetlands (bogs and marshes). Springs may also be found at various elevations depending on factors such as the lithology and stratigraphy of the geosphere and the location of outcropping geological units.

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

Springs and other discharge zones can be associated with salt licks, which refer to localized areas where the discharge of saline groundwater, followed by evaporation, leads 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 a seasonal occurrence. Climate changes can also bring about evolution of surface water bodies and springs, such as flooding of land to create a lake or a new river bed.

FCS Screening Analysis

Discharge zones are required to explicitly link the geosphere to the biosphere and are, therefore, explicitly modelled in the FCS.

Groundwater discharges 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 FCS model allows for discharges to both aquatic and terrestrial areas.

Given the relatively shallow topography of the FCS repository site, drinking water is most likely to come from a well or a lake, rather than a spring. Thus, in the FCS Reference Case, the critical group uses water from a deep (100 m) well. For conservatism, this well is located such that it intercepts the most contaminated groundwater plume from the repository. Since contaminant concentrations in a surface spring would be lower than in the well water (i.e., as it moves upward, the contaminated groundwater plume is diluted by clean water infiltrating from the surface), surface springs are not considered as possible water sources for the critical group in the FCS.

FEP Screening

Include FEP in all scenarios.

FEP # 2.3.05 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.

FCS Screening Analysis

Coastal features of lakes or seas/oceans are not included in the FCS since the hypothetical repository site is located within a regional groundwater flow system that does not include ocean or the Great Lakes.

Some effects of the ocean that are carried inland by the wind (notably background stable iodine and chlorine concentrations) can be felt some distance away. However, these would not be important for most Canadian Shield locations, and are assumed therefore not relevant to the FCS hypothetical site.

FEP Screening

Screened out.

FEP # 2.3.06 Marine features

Description

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.

FCS Screening Analysis

Marine features are not included in the FCS. The repository in the FCS is assumed to be sited in the Canadian Shield far from seas and oceans. Therefore, there is no need to include marine features in the FCS.

FEP Screening

Screened out.

FEP # 2.3.07 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, ploughing, irrigation and saltation. Saltation refers to the process by which detached soil particles bounce along the soil surface.
- Processes affecting surface waters include degassing, bubble bursting and wind suspension or aerosol formation.
- Processes involving vegetation include fires, which are routinely used to clear land for agricultural use, to reduce peat, to kill weeds and to remove stubble. Natural forest and grass fires are important natural features of the Shield and occur frequently and regularly. Related fires include burning of peat, wood and other fuels for household heating purposes. Forest and other fires can become potent agents for atmospheric contamination if the material is contaminated. Concomitant effects can also occur from the smoke and entrained carcinogens.

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

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

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

The atmosphere also has huge dilution potential. For instance, wind is a major environmental force in the transport of contaminants through the atmosphere, by processes of advection, dispersion and diffusion. Wind could also have indirect effects on the behaviour and transport of contaminants through processes such as evapotranspiration, fires, and deposition onto soil and vegetation. The wind attributes are discussed under *Meteorology [2.3.10].*

FCS Screening Analysis

The atmosphere is included in the FCS.

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 [3.3.02]*).

FEP Screening

Include FEP in all scenarios

FEP # 2.3.08 Vegetation

Description

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 the contaminant, soil, plant 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. And fluctuations in water tables in response to local climate variation. Some changes, such as the formation of mature forests, can take hundreds of years.

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

FCS Screening Analysis

Vegetation is included in the FCS. Vegetation in the FCS is used as food (by humans and animals) and for fuel and building materials (trees).

Contaminant concentrations in terrestrial vegetation are calculated in the FCS. These concentrations are affected by uptake of contaminants from soil, atmospheric deposition, irrigation water deposition, washout of deposited material, and plant yields.

The properties of "generic" garden and forage field plants (representative of agricultural garden and fruit plants, and animal forage and wild Canadian Shield plants, respectively) are used in the FCS; rather than properties of specific plants (e.g., beets, grass, spruce trees, etc.). Plant properties are assumed to be time-independent.

The nature of the plants growing near the site can change with the onset of glaciation. During permafrost periods, for example, farming is not practiced and the critical group diet could consist mainly of caribou meat. Caribou are assumed to eat mainly lichens, which have very different properties from vascular plants. These differences are taken into account in the glaciation study of Garisto et al. (2010), which is the basis of the discussion of glaciation effects in the Reference Case of the FCS Normal Evolution Scenario.

FEP Screening

Include FEP in all scenarios.

FEP # 2.3.09 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.

FCS Screening Analysis

For temperate climates, the critical group for the FCS is a self-sufficient farm household (see *Diet and liquid intake [2.4.02]*). Therefore, domesticated food animals (beef and dairy cows, poultry) and fish are explicitly included in the FCS since these are potential pathways for exposure to contaminants.

In the FCS, a quantitative discussion of the influence of glaciation is included as part of the Reference Case of the Normal Evolution Scenario. This discussion is based on the glaciation study of Garisto et al. (2010). In this study, the animal populations vary with the climate so that domesticated farm animals are present at the repository site during periods of temperate climate whereas caribou are present during periods of permafrost. No animals are present when ice sheets cover the repository site.

All animal characteristics are assumed to be time-independent throughout a single simulation, although their properties are treated as varying within a range in the probabilistic calculations.

The FCS models do not include invertebrates, carnivore food chains or aquatic plants. But, for the selected critical group, these are not important exposure pathways.

Impacts on non-human biota are determined for the Normal Evolution and All Containers Fail Scenarios. Animals can become exposed to contaminants through the following pathways: air inhalation, soil ingestion, plant ingestion, water ingestion and, for radionuclides, external radiation exposure from ground and water contamination. In the FCS, the potential impacts of radionuclides on non-human biota are determined by comparison of radionuclide concentrations in various biosphere media to no-effect concentration limits. Further, 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 2012).

FEP Screening

Include FEP in all scenarios.

FEP # 2.3.10 Meteorology

Description

The characteristics of weather and climate.

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

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 on 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.

FCS Screening Analysis

Meteorology is included in the FCS. 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 Canadian Shield specific values for parameters dependent on meteorological conditions (e.g., temperature, rain fall rate, snow fall, etc.), including soil absorption coefficients, plant yields, vegetation type, holdup times for animal forage, etc.

Meteorological parameters are defined by probabilistic distributions, thereby ensuring that the natural variability in meteorology is taken into account. However, meteorological parameters are assumed to be constant throughout a given simulation, so potential effects due to the natural (short-term) temporal variations in meteorology are not included. Sensitivity studies carried out for the Third Case Study did not indicate that calculated human dose rates were sensitive to meteorological parameters (Garisto et al. 2004a, 2005a.)

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 on the Canadian Shield (due to, for example, global warming or glaciation).

In the FCS, a quantitative discussion of the influence of glaciation is included as part of the Reference Case of the Normal Evolution Scenario. This discussion is based on the glaciation study of Garisto et al. (2010), in which 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 # 2.3.11 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 and plants, to water bodies. Moreover, runoff is an important component in the water balance which, together with precipitation and evapotranspiration, determines irrigation water needs.

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

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

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

FCS Screening Analysis

The local surface hydrological regime and water balance is included in the FCS. Specifically, water flows through the local Lake and River are calculated in terms of the runoff and the watershed surface area, and the precipitation rate is used in the calculation of the wet deposition rate to soil and plants, and contaminant leach rates from soils. Also, irrigation rates are inversely correlated to the precipitation rate.

For constant climate conditions, the hydrological regime and water balance are assumed to be constant throughout the simulation period. The natural variability in the hydrological regime is taken into account by using probabilistic density functions to define the associated parameter values. The probability density functions do not include extreme events, nor long-term climate changes (due to, for example, global warming or glaciation).

In the FCS, a quantitative discussion of the influence of glaciation is included as part of the Reference Case of the Normal Evolution Scenario. This discussion is based on glaciation study of Garisto et al. (2010), in which the hydrological regime and water balance vary with the glacial cycle. For example, the water flow rate through the proglacial lake is much larger than through the Lake because of its larger watershed area; and the runoff per unit area is lower during permafrost periods than temperate periods because the rainfall rate is lower during permafrost periods.

In the FCS, it is assumed that all contaminants discharged into the local environment (i.e., via a well or at discharge zones) are also discharged into the local Lake (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 Lake from runoff and other upstream surface water bodies.

FEP Screening

Include FEP in all scenarios.

FEP # 2.3.12 Erosion and deposition

Description

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

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

FCS Screening Analysis

Soil erosion and deposition are not included in the FCS.

Except during glaciation events, erosion and deposition are slow processes on the Canadian Shield (see *Erosion and sedimentation [1.2.07]*). Furthermore, neglect of soil erosion and deposition is conservative for the calculation of dose rates to the most exposed groups, i.e., those living in the vicinity of the repository; because such processes would tend to decrease contaminant concentrations in the environment near the repository. Furthermore, although these processes could transport contaminants "downstream" from the local modelled environment, the downstream concentrations would be lower than those in the local environment.

Rates of erosion and deposition are higher during periods of glacial advance and retreat over the repository site. Nevertheless, soil erosion and deposition are not included in FCS, even when discussing the effect of glaciation since these processes were neglected in Garisto et al. (2010), which is the basis for the discussion of glaciation effects in the Reference Case of the Normal Evolution Scenario. This is expected to be conservative because contaminants in the soil layer remain in place, even after glacial retreat, and are, thus, available to expose humans and non-humans living near the repository site as soon as the site becomes ice free. More importantly, soils are available immediately for farming at the start of temperate periods, i.e., directly after glacial retreat. This is conservative since the farmer critical group receives the highest dose rates (Garisto et al. 2010).

The FCS does include the movement of sediments from "mixed sediments" to deeper "compacted sediments" over longer time periods, where they become effectively isolated from the biosphere.

FEP Screening

Screened out.

FEP # 2.3.13 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;
- biological interim storage, which refers to temporary holdback of nutrients including contaminants;
- 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 which include surface water contaminated by a repository (see also *Future human actions [1.4]* and *Human behaviour [2.4]*). The main issue is whether and how these changes might influence contaminant transport and exposure routes.

Finally, the effects of the repository on ecosystems should be considered with respect to possible changes to local conditions such as moisture levels, groundwater flows, salinity and temperature. For instance, a repository sited in an environmentally sensitive area might have a relatively small change to some biota which has more serious impacts on other biota, some of which might be already endangered.

FCS Screening Analysis

The ecosystems of the surface environment provide the background within which contaminant migration may occur, should such contaminants be released to the biosphere. These include natural (forest, wetland, aquatic) and man-made (agricultural) ecosystems. Contaminants may migrate through these systems, e.g., via root uptake into vegetation (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 quantitatively discussed in the FCS as part of the Reference Case 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 of a glaciation scenario (Garisto et al. 2010), these changes were 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.

2.4 Human Behaviour

FEP # 2.4.00 Scope of sub-category 2.4

Description

The general habits and characteristics of the potentially affected individuals or populations, e.g., critical groups, including how these habits and characteristics might change over long periods of time (but subject to the considerations described under *Future human action assumptions [0.0.07]* and *Future human behaviour (target group) assumptions [0.0.08]*, and to the human activities described under *Future human actions [1.4]*).

There are 11 subcategories that account for the main features and variations in human behaviour:

- 2.4.01 Human characteristics (physiology, metabolism)
- 2.4.02 Age, gender and ethnicity
- 2.4.03 Diet and liquid intake
- 2.4.04 Habits (excluding diet)
- 2.4.05 Community characteristics
- 2.4.06 Food and water processing and preparation
- 2.4.07 Dwellings
- 2.4.08 Wild and natural land and water use
- 2.4.09 Rural and agricultural land and water use
- 2.4.10 Urban and industrial land and water use
- 2.4.11 Leisure and other uses of the environment.

FEP # 2.4.01 Human characteristics (physiology, metabolism)

Description

The characteristics (e.g., physiology, metabolism) of individual humans. Physiology refers to body and organ form and function. Metabolism refers to the chemical and biochemical reactions which occur within an organism in connection with the production and use of energy.

These characteristics can affect the impacts on humans from internal and external exposure to contaminants. For instance, iodine taken into the human body tends to concentrate and metabolize in the thyroid gland which would then be most affected by radioactive iodine-129, whereas carbon and hydrogen are distributed throughout soft tissues which would be most affected by radioactive carbon-14 and tritium. Chemical toxics may also concentrate and metabolize in specific organs; for instance mercury tends to accumulate and disrupt metabolic processes in the brain.

People vary in their physiology, and metabolism. In addition to the variation in individual humans, different groups, such as 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 [2.4.02].*

FCS Screening Analysis

Generally, the FCS 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 FCS 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 FCS uses reference man (ICRP 1991a) as representative of the dose impacts that would be seen for a wide range of human characteristics. See also the discussion under *Dose response assumptions [0.0.09]* and *Future human behaviour (target group) assumptions [0.0.08].*

FEP Screening

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

FEP # 2.4.02 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.

FCS Screening Analysis

In the FCS, 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, since the variation in dose rates are not expected to be large and since 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, these gender-averaged dose coefficients are not yet available.

Ethnicity is not a relevant factor in the Fourth Case Study – the ICRP dose models to not include ethnic variations.

FEP Screening

Screened out.

FEP # 2.4.03 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, yoghurt, cheese and eggs), wild game, fish and fish roe, mushrooms, nuts, tree sap (maple syrup), offal, fungi, aquatic crustaceans, terrestrial invertebrates, honey, normal crop plants, native non-berry plants, medicinal plants and water. Humans may inadvertently ingest soil with food or from their hands, or they may have an unnatural (possibly pathological) craving for soil ingestion due to mineral deficiency. (Soil ingestion can be particularly important for contaminants that have low biomobility.) Human diet may also include a variety of drugs that might be produced where they could become contaminated.

The total amount of food consumed can also vary with factors such as age and 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:

2.4.03A Farming diet
2.4.03B Hunter/gatherer diet
2.4.03C 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 considered covered within the farming and hunter/gatherer diets, or may require a third community-specific diet.

FEP # 2.4.03.A Farming diet

Description

The food and water intake characteristics of persons living a farming lifestyle on the Canadian Shield.

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.

FCS Screening Analysis

The diet and liquid intakes of the human exposure group as well as the source of these foodstuffs are explicitly included in the FCS. Only adult radiological dose rates will be calculated in the FCS (see *Age, gender and ethnicity [2.4.02]*), and, hence, the human diet and fluid intakes are those for adults.

Of the various plausible critical group lifestyles (Zach et al. 1996b), 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 FCS will include 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. In the calculations, these ingestion rates are prorated so that the human total energy intake equals the selected human total energy requirement.

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 to the critical group because of greater dilution. Plants ingested by humans are grown in a garden, whereas animals take food from a forage field.

FEP Screening

Include FEP in all scenarios.

FEP # 2.4.03.B Hunter/gatherer diet

Description

The food and water ingested by persons living a hunter/gatherer lifestyle on the Canadian Shield. 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.

FCS Screening Analysis

In the FCS, the critical group is a self-sufficient farmer during temperate periods. However, a quantitative discussion of the influence of glaciation is included as part of the Reference Case of the Normal Evolution Scenario. This discussion is based on the glaciation study of Garisto et al. (2010). In this study, the critical group is 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 diets for these three critical groups are described in detail in Garisto et al. (2010). The self-sufficient farmer receives the highest dose rate in Garisto et al. (2010) mainly 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 # 2.4.03.C Other diets

Description

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.

FCS Screening Analysis

Zach et al. (1996b) considered several alternative diet/lifestyles in the context of the EIS case study, 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 EIS median case simulation; while, 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 varied only 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 FCS scope of work.

FEP Screening

Screened out.

FEP # 2.4.04 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 ploughing, cultivation and harvesting, which can create dust and lead to inhalation and external exposure;
- dwelling location, such as underground or partially buried, or on bodies of water; and
- use of physical resources such as peat, wood, stone and water.

Other examples are discussed in *Community characteristics [2.4.05]*, and *Leisure and other uses of the environment [2.4.11].*

FCS Screening Analysis

The habits (excluding diet) of the exposure group are explicitly included in the FCS.

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 [2.4.05.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 # 2.4.05 Community characteristics

Description

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:

- 2.4.05A Community type
- 2.4.05B Community location
- 2.4.05C Water source.

FEP # 2.4.05.A Community type

Description

The general nature and size of the community, and in particular their degree of self-sufficiency.

Communities found on the Canadian Shield 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-gather community might best describe a subsistence lifestyle employed by nomadic or semi-nomadic groups who roam relatively large areas of land, hunting wild game and fish, and gathering native fruits, berries, roots and nuts.
- 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.
- A 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 have the potential for unique exposure pathways; for instance ploughing of contaminated agricultural land may be an important inhalation and external exposure pathway.

FCS Screening Analysis

The general nature of the potentially exposed community and their degree of self-sufficiency is included in the FCS (Garisto et al. 2005c).

For the FCS, 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 since large communities draw on larger supply ranges, which would include uncontaminated food and water sources, and, thus, lead to lower calculated 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). This assumption is made in part for reasons noted in *Future human action assumptions [0.0.07].* Also, because the assumed 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 # 2.4.05.B Community location

Description

The location of the community relative to areas which might 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 largest impacts because dilution effects occurring in the biosphere are small. All exposure pathways could be affected.

Alternatively, the largest impacts might be experienced by a community situated at a downstream location, where contaminants from multiple groundwater discharge areas converge and contaminants accumulate. This location also has the potential for largest 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.

FCS Screening Analysis

In the FCS, it is assumed that the exposed community resides near the surface location where groundwater from the repository is discharged and 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 [2.4.05.C]*). Furthermore, the home and fields are conservatively located where radionuclide concentrations and, hence, calculated dose rates would be highest (i.e., at the terrestrial surface discharge points for groundwater from the repository).

Dose rates to groups living "downstream" of the repository site should be lower than for groups living near the discharge locations, because contaminants would be diluted as they travel to "downstream" locations.

FEP Screening

Include FEP in all scenarios.

FEP # 2.4.05.C Water source

Description

The origin of water used by the critical group for domestic purposes, including drinking, and to meet irrigation demands.

Humans require water for domestic use, including drinking, cooking, washing and bathing. They may also require water to irrigate gardens and large agricultural fields used for crops and forage, to provide drinking water for livestock and to serve other purposes such as supply and maintenance of water for fish hatcheries or process water for industry. Potential water sources on the Canadian Shield 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 derive from a dedicated water-supply well whereas water for irrigation may be taken from a nearby lake or from a different water-supply well. In addition, the volume of water required, and hence the type of water source will be affected by the size, lifestyle and occupation of the community, and additional volumes and sources might be required for a growing community.

These sources could be contaminated to different degrees, with factors such as volume of diluting water, sedimentation and sorption affecting contaminant concentrations in the water. Moreover, the ingestion of contaminated drinking water could involve a relatively direct exposure route, with few delay and dilution processes. Consequently, radiological and chemical toxicity impacts on the critical group could depend strongly on 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 [2.3.03]* and *Surface water bodies [2.3.04]* which are further concerned with water sources; and
- other uses of water (and land) discussed under *Rural and agricultural land and water use [2.4.09]* and *Urban and industrial land and water use [2.4.10].*

FCS Screening Analysis

The water source for the potentially exposed persons ("critical group") is included in the FCS.

In the FCS, 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 100 m) that intersects the contaminant plume 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 the well.

The critical group characteristics vary during a glacial cycle, including the water source. In the glaciation study of Garisto et al. (2010), which is the basis for the discussion in the FCS of the effects of glaciation on calculated impacts for the Reference Case of the Normal Evolution Scenario, the water source is a well for the self-sufficient farmer and a lake for the self-sufficient hunter or fisher (see also *Lakes and rivers [2.3.04.B]*).

The fate of contaminants in waste water from the household is not explicitly modelled in the FCS. Instead, this is implicitly accounted for by the conservatisms used in the biosphere model. For example, the contaminant flux reaching the well is also assumed to simultaneously enter the reference surface water body, i.e., the contaminant flux entering the biosphere from the geosphere is overestimated. In this way, the fact that contaminants in well water will eventually be discharged into the watershed of the Lake and enter the Lake is implicitly accounted for and need not be explicitly modelled.

FEP Screening

Include FEP in all scenarios.

FEP # 2.4.06 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 (i.e., growing of crops without soil) and related practices, followed by cleaning and preservation, might involve the use of more or less contaminated soil and water.

FCS Screening Analysis

The effect of food and water processing and preparation is generally not included in the FCS. Contaminants in water and foods are usually lost as a result of processing and preparation. In the FCS, such losses are neglected in the calculation of exposure dose rates. This makes the calculated FCS dose rates conservative.

The FCS does however account for the effect of radioactive decay between the time food is harvested and the time it is consumed. Since these holdup times are generally small, this only affects radionuclides with short half-lives.

FEP Screening

Screened out.

FEP # 2.4.07 Dwellings

Description

The characteristics of the houses or other structures or shelter in which humans spend time.

Factors that may affect their occupants' exposure modes and levels include:

- the dwelling location which may be particularly important for impacts from radon (see *Radon and radon daughter exposure [3.3.08]*);
- materials used in construction such as wood, stone and ashes, especially for those materials that tend to accumulate contaminants;
- 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, faeces 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 (see *Radon and radon daughter exposure [3.3.08]*);
- creation of household dust and fumes from indoor and outdoor sources and activities, which could affect contaminant concentrations inside the household; and
- the introduction into the dwelling of contaminated furnishings, household plants, etc.

Many of these factors are important because they could affect contaminant concentrations in air, affecting exposures from inhalation. Other external exposure pathways, and ingestion exposure, could also be influenced.

FCS Screening Analysis

In the FCS, the characteristics of the house or shelter used by the critical group are included in all scenarios.

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 # 2.4.08 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 [2.4.03]*, notably *Hunter/gatherer diet [2.4.03.B]*), fishing (see also *Habits (excluding diet) [2.4.04]*), and gathering of peat and wood for household heating (see also *Dwellings [2.4.07]*).

Other examples of wild and natural land and water use are discussed elsewhere, such as under *Community characteristics [2.4.05]*, *Surface environment, human activities [1.4.06]* and *Water management (wells, reservoirs, dams) [1.4.07].*

FCS Screening Analysis

The use of wild (or natural) land and water is included in the FCS. 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 all the food it consumes. However, a natural woodlot is used to obtain wood for fuel or construction material, fish are obtained from a local surface water body, peat may be gathered for heating fuel, rock may be used for construction, and lake sediment may be used for growing food. A variant case, in which the self-sufficient farm household takes water from a lake (i.e., a natural water source), was studied in the Third Case Study and, as expected, doses were much lower than for the critical group using a well because of the greater dilution of contaminants in the lake.

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 FCS, the effects of glaciation are discussed as part of the Reference Case of the Normal Evolution Scenario.

FEP Screening

Include FEP in all scenarios.

FEP # 2.4.09 Rural and agricultural land and water use

Description

The use of land and water for agriculture, fisheries, game ranching and similar practices.

An important set of processes are those related to agricultural practices which can affect the land form, hydrology and natural ecology, and which can also have direct effects on key elements of local food chains. Examples of such agricultural practices include:

- irrigation of gardens and fields, whether from a well or nearby surface water source;
- supply of water and local feed for domestic animals;
- draining of wetlands for farming use;
- growth of a range of crops or intensive monoculture crops; and
- use of intensive farming practices such as greenhouses or hydroponics.

Other agricultural practices, possibly having lesser impact, include:

- the use of crop fertilizers (chemicals, manure, fish meal, minerals, ashes and sewage sludge), soil conditioners (peat moss, leaf litter or lake sediments);
- the use of herbicides, pesticides, fungicides and related products;
- recycling, particularly of organic materials in, for example, soil conditioners; and
- outdoor spraying of water to cool buildings and control dust.

Fish hatcheries and fish farming could expose fish to contaminated water, sediments and feed. Game ranching of indigenous (bison, elk) and imported (ostrich, llama) animals could affect dose impacts because many wild animals have much leaner meat or use different foods than domestic animals; also game animals tend to be older when slaughtered. In addition, there are markets for products such as antlers and gall bladders that could represent new exposure pathways.

In considering rural and agricultural use of land and water, the duration of the use may need to be considered since the land (or water) may not be able to sustain the use indefinitely. For example, long-term irrigation of soils with groundwater tends to lead to the accumulation of salts in the topsoil, and agricultural practices such as tilling and grazing may lead to accelerated erosion rates. In practice, these may be compensated by crop rotation, or otherwise leaving the land fallow for an extended period.

FCS Screening Analysis

The use of land and water for agriculture and fisheries is included in the FCS. 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 this group 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
- using lake sediments as soil.

In the Inadvertent Human Intrusion Scenario, one of the critical groups is a resident near the repository site that grows food on contaminated soil.

FEP Screening

Include FEP in all scenarios.

FEP # 2.4.10 Urban and industrial land and water use

Description

The use of land and water for urban or industrial purposes, and the effect on hydrology and potential contaminant pathways.

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 including preserving, 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 affect 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 [2.4.05], Surface environment, human activities [1.4.06]* and *Water management (wells, reservoirs, dams) [1.4.07].*

FCS Screening Analysis

In the FCS, for conservatism, dose rates are calculated for the critical group that is most exposed to radionuclides released from the repository. This critical group is a self-sufficient farm during temperate periods or a self-sufficient hunter during permafrost periods. They reside near the location of the groundwater discharges from the repository, where exposure to contaminants released from the repository are expected to be highest.

Urban residents and industrial workers would be less exposed to radionuclides discharged from the repository because, for example, the food and water they consume would likely come from uncontaminated sources (i.e., a supermarket and municipal water supply, respectively). Therefore, urban and industrial land and water use is not included in the FCS.

FEP Screening

Screened out.

FEP # 2.4.11 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.

FCS Screening Analysis

In the FCS, for conservatism, dose rates are calculated for the critical group that is most exposed to radionuclides released from the repository. During temperate periods, this critical group is a self-sufficient farm household that resides near the location of the groundwater discharges from the repository whereas a self-sufficient hunter is the critical group during permafrost periods of the glacial cycle.

The leisure activities of the critical group are not explicitly included in the FCS because they are not likely to significantly affect exposure doses. (For a self-sufficient farm household that grows its own food, gardening is assumed not to be 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.

3. CONTAMINANT FACTORS

FEP # 3.0.00 Scope of main category 3.

Description

Factors in the repository and its nearby geosphere and biosphere that are specific to the release and migration of radionuclides and other contaminants, or to the human dose or environmental consequences of these radionuclides or other contaminants.

There are three main categories under radionuclide and contaminant factors:

3.1 Contaminant characteristics
3.2 Contaminant release and migration factors
3.3 Exposure factors.

3.1 Contaminant Characteristics

FEP # 3.1.00 Scope of sub-category 3.1

Description

The characteristics of the radionuclides and other contaminant species that might be considered in a postclosure safety assessment.

There are six sub-categories under contaminant characteristics:

- 3.1.01 Radioactive decay and ingrowth
- 3.1.02 Chemical and organic toxin stability
- 3.1.03 Inorganic solids and solutes
- 3.1.04 Volatiles and potential for volatility
- 3.1.05 Organics and potential for organic forms
- 3.1.06 Noble gases.

FEP # 3.1.01 Radioactive decay and ingrowth

Description

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 mass of such progeny as a result of the decay of the parent nuclide. A decay chain is a set of radioactive nuclides (or radionuclides) that decay sequentially from the first to the last member of the set. It is the particles and energy emitted during radioactive decay that leads to potential dose and damage to living organisms.

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. The half-life is 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].*

FCS Screening Analysis

Radioactive decay and ingrowth will be explicitly accounted for in the FCS throughout the modelled system, including the repository, geosphere and biosphere.

FEP Screening

Include FEP in all scenarios.

FEP # 3.1.02 Chemical and organic toxin stability

Description

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].*

FCS Screening Analysis

In the FCS, the potential impacts on humans and non-human biota of releases of chemically toxic elements from the repository are examined for the Normal Evolution and All Containers Fail Scenarios using the approach of 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 impact assessment it is assumed the element is in a relatively simple but stable form.

FEP Screening

Include FEP in the Normal Evolution and All Containers Fail Scenarios.

FEP # 3.1.03 Inorganic solids and solutes

Description

The characteristics of other contaminant or constituent inorganic solids and solutes that may be of concern.

Most contaminants are 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, uranium-238, is an inorganic element. Also, most minerals in the geosphere and substances introduced into the repository are inorganic compounds. For instance, the weathering and dissolution of feldspars generally involves several intermediates: initial products include leached alkalis (sodium and potassium) and alkaline earths (calcium and magnesium) and the final solid product could be kaolinite or another clay. These ions could affect contaminant mobility; for instance, potassium may reduce the sorption capacity of bentonite. Another example is cement, which can elevate pH and concentrations of calcium ions in groundwater.

The inventories of substances of potential concern are described in *Waste inventories [2.1.01].*

FCS Screening Analysis

The near-field groundwater and clay-based sealing materials will influence the groundwater composition within the repository and container, which, in turn, will control radionuclide solubilities. In the FCS, a reference groundwater composition for granitic rock is selected (Garisto et al. 2012) and used to calculate contaminant solubilities.

In the FCS, both radiological and chemical toxicity impacts are determined (see *Impacts of concern [0.0.03]*). Therefore, transport of both radionuclides (e.g., U-238, I-129) and stable elements (e.g., As and Br) are modelled. Transport of stable Zr also needs to be modelled because this determines the dissolution rate of the Zircaloy cladding (see *Zircaloy cladding dissolution [2.1.02.E]*).

In the FCS repository, the amount of concrete is limited and low-lime cement will be used. Therefore, the contribution of concrete degradation products does not need to be included.

The chemistry within the container/repository will be considered time-independent, although changes could occur over a million year simulation due to ionic exchange in the buffer/backfill and dissolution of minerals such as gypsum and calcite in the buffer/backfill (Arcos et al. 2006). However, these changes have been considered in the selection of the reference groundwater composition.

FEP Screening

Include FEP in all scenarios.

FEP # 3.1.04 Volatiles and potential for volatility

Description

The characteristics of radionuclides and chemical contaminants that are volatile or have the potential for volatility in the repository or the surface environment.

Some radionuclides may be isotopes of noble gases (see *Noble gases [3.1.06]*) or may form volatile compounds, such as C-14 incorporated into carbon dioxide or methane, I-129 forming iodine gas, and tritium (H-3) incorporated into hydrogen gas or water vapour. Similar comments apply to the stable isotopes of these and other elements.

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) [2.1.12]* and *Gas sources and effects (geosphere) [2.2.11].*

FCS 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 amount of volatile or semi-volatile radionuclides released from the fuel in a defected container should be sufficiently low that they would be dissolved in the water phase, i.e., the vapour pressure of the dissolved element does not exceed the hydraulic pressure. Therefore, it is not necessary to consider gas transport of volatile nuclides in the FCS.

Formation of a gas phase in the repository or geosphere, due to for example production of H_2 by steel corrosion, will not be modelled in the FCS, as discussed under *Gas sources and effects (repository) [2.1.12]* and *Gas sources and effects (geosphere) [2.2.11].*

FEP Screening

Include FEP in all scenarios.

FEP # 3.1.05 Organics and potential for organic forms

Description

The characteristics of radionuclides or chemical contaminants that can be incorporated into organic species under repository or surface environment conditions. This 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) [2.1.10], Biological processes and conditions (geosphere) [2.2.09],* and *Ecological systems [2.3.13].*

FCS Screening Analysis

The chemical form of contaminants, including formation of organic forms, is not explicitly modelled in the FCS. 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., sorption coefficients, which are often derived from field values and reflect typical speciation. See also the discussion under *Complexation by organics (repository materials) [2.1.10.B].*

FEP Screening

Screened out.

FEP # 3.1.06 Noble gases

Description

The characteristics of the noble gases: helium, neon, argon, krypton, xenon and radon (He, Ne, Ar, Kr, Xe and Rn).

Since these elements are chemically inert, they are largely unaffected by sorption, will not precipitate, and will thus move with little delay through various transport media. One isotope of special concern is Rn-222 (radon-222), the decay product of Ra-226 (radium-226). This isotope of radon has a half-life of about 4 days and decays through a series of very short-lived radionuclides (with half lives of 27 minutes or less) to a lead isotope (Pb-210) whose half life is 21 years. The behaviours of Rn-222 and its daughters are unique and can lead to different modes of exposure to humans, described under *Radon and radon daughter exposure [3.3.08].*

FCS Screening Analysis

The characteristics of the radionuclides of the noble gases Kr, Ar and Rn are explicitly accounted for in the FCS. The radionuclides of the other noble gases are relatively short lived (with no long-lived parents or daughters) and are, therefore, neglected since they do not contribute to the calculated postclosure dose rates.

FEP Screening

Include FEP in all scenarios.

3.2 Contaminant Release and Migration Factors

FEP # 3.2.00 Scope of sub-category 3.2

Description

The processes that directly affect the release or migration of contaminants in and around the repository, including consideration of how these processes might evolve over long periods of time.

There are 13 subcategories under contaminant release and migration factors:

3.2.01 Dissolution, precipitation and crystallisation (contaminant)
3.2.02 Speciation and solubility (contaminant)
3.2.03 Sorption and desorption (contaminant)
3.2.04 Colloid interactions and transport (contaminant)
3.2.05 Complexing agent effects (contaminant)
3.2.06 Biologically mediated processes, excluding transport (contaminant)
3.2.07 Water-mediated transport of contaminants
3.2.08 Solid-mediated transport of contaminants
3.2.09 Gas-mediated transport of contaminants
3.2.10 Atmospheric transport of contaminants
3.2.11 Biological-mediated transport of contaminants
3.2.12 Human action mediated transport of contaminants
3.2.13 Food chains and uptake of contaminants.

FEP # 3.2.01 Dissolution, precipitation and crystallisation

Description

The dissolution, precipitation and crystallization of radionuclides and chemical contaminants under repository or environmental conditions. Dissolution is the process by which molecules of a solid dissolve into solution. Precipitation and crystallization are processes by which solids are formed from molecules in solutions.

Water is an excellent solvent; its dipolar nature allows it to dissolve most metals and metalloids which tend to form ionic compounds, and its ability to hydrogen bond means it can dissolve many organic compounds. The maximum or saturated concentration for each solute is primarily determined by the properties of the solute and solvent, and influenced by other factors such as temperature, presence of other solutes including (for ionic species) common ions, pressure and ionic strength. This maximum concentration is also known as the solubility limit (see *Speciation and solubility (contaminant) [3.2.02]*).

Formation of some precipitates can be kinetically hindered. In some cases, the solutions may become temporarily oversaturated, and it is generally not possible to predict when precipitation might start. Moreover, an intermediate solid phase might form. For instance, the first precipitated solid phase may have an amorphous structure which later transforms into the more stable crystalline structure at a rate that depends on the temperature and other factors. An example is iron in oxidizing solutions, which may initially precipitate as an amorphous ferric hydroxide, $Fe(OH)_3$, and later transform to crystalline goethite (FeOOH).

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

The various domains of a repository system will have different local conditions of temperature and groundwater composition so that precipitation and dissolution of the same species may occur simultaneously, but at different locations.

Dissolution, precipitation and crystallization can be important processes because they change the proportion of dissolved and solid species. Dissolved species are more mobile than solid species (but see also *Colloid interactions and transport (contaminants) [3.2.04]*). Dissolution may open pores and transport pathways; conversely, the formation of precipitates can act to plug pores and constrict water movement and contaminant transport.

Further discussion of these processes is included under:
  3.2.01A Dissolution and precipitation (repository)
  3.2.01B Dissolution and precipitation (geosphere)
  3.2.01C Dissolution and precipitation (biosphere).

FEP # 3.2.01.A Dissolution and precipitation (repository)

Description

Dissolution and precipitation processes occurring in the engineered barrier system.

Most contaminants are released from the waste form when they dissolve into the groundwater that has entered the container. The largest concentration of most contaminants is likely to occur inside the container, and many could form precipitates. The mass of these precipitates could increase until dissolution of the waste form ceases, after which the mass would decrease as the precipitate itself dissolves. Precipitation could also occur in the buffer and backfill or elsewhere in the repository if there is an abrupt change in the chemical environment (including groundwater composition and temperature) or if ingrowth from radioactive decay produces a local increase in concentration.

The engineered barrier system or repository will also experience the largest variations in temperature and radiolysis effects, and the infiltrating groundwater will likely undergo compositional changes from reactions with buffer and backfill, and with other material in the repository. These changes to the chemical environment of the repository could lead to evolution of the dissolution and precipitation of contaminants. For instance, the migration of dissolved contaminants may be enhanced near the hotter container, with precipitation occurring at a cooler location in the backfill, or at a redox front whose position moves as oxidants are consumed. Note, however, that some solids whose solubility decreases with an increase in temperature, such as gypsum, might move in the reverse direction; that is, they might migrate to the hotter container.

FCS Screening Analysis

The dissolution of the used fuel matrix, the dissolution of contaminants (including radionuclides) from the used fuel and the precipitation of contaminants in a failed container is explicitly modelled in FCS.

Precipitation of contaminants in the buffer/backfill are not modelled since contaminant concentrations outside the container should be less than contaminant solubilities (given that contaminant precipitation in the container is modelled and the dilution of contaminants as they diffuse outwards from the container defect), assuming chemical conditions are similar throughout the repository.

Contaminant solubilities are conservatively selected or conservatively calculated based on the reference groundwater composition. Contaminants solubilities are assumed to be time independent for a given simulation (see discussion under *Inorganic solids and solutes [3.1.03]* and *Water chemistry and evolution (repository) [2.1.09.A]*).

FEP Screening

Include FEP in all scenarios.

FEP # 3.2.01.B Dissolution and precipitation (geosphere)

Description

Dissolution and precipitation processes of contaminants occurring in the geosphere.

Contaminants moving through the geosphere could be subjected to precipitation and dissolution at different points along their flow paths, caused by changes in temperature, groundwater chemistry, mineralogy (primary minerals and rock alteration products), or microbes. Changing flow rates may also have an influence, especially in the case of kinetically hindered reactions. These causes may change with time (see also *Chemical processes and conditions (geosphere) [2.2.08]*).

Precipitation of contaminants is usually conservative in that it holds up transport. However, for decay chains it is not certain that precipitation is conservative; for instance, if a parent precipitates in the near-surface geosphere while a more hazardous daughter does not, possibly leading to a higher daughter flux to the biosphere.

FCS Screening Analysis

The highest concentrations of contaminants occur in a failed container, where precipitation of contaminants is modelled in the FCS. Concentrations in the geosphere should be considerably lower because of dilution, as contaminants are transported away from the used fuel. Therefore, contaminant concentrations in the geosphere should not exceed contaminant solubility limits. Hence, precipitation (and redissolution) of contaminants in the geosphere is not modelled in the FCS.

Also, it is usually conservative to neglect precipitation because contaminant concentrations and, hence, calculated impacts decrease if precipitation occurs.

FEP Screening

Screened out.

FEP # 3.2.01.C 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 thereby 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) [3.2.02.C]* and *Sorption/desorption (biosphere) [3.2.03.C].*

These processes can change in response to processes such as daily and seasonal changes in meteoric precipitation, climate change, and land change use.

FCS Screening Analysis

Precipitation (and redissolution) of contaminants in the biosphere will not be explicitly modelled in the FCS.

Many of the biosphere contaminant parameter values used in the FCS (e.g., plant concentration factors, soil K_d values, etc.) are based on field or laboratory experiments. These biosphere parameter values could, in theory, be affected by dissolution and precipitation processes. Thus, such processes, if important, would be implicitly included in the FCS, although it would not be possible to ascertain the importance of such processes on the calculated impacts.

FEP Screening

Screened out.

FEP # 3.2.02 Speciation and solubility (contaminant)

Description

The chemical forms or species of an element dissolved in groundwater, and its solubility. The solubility of an element is the maximum (or saturated) concentration that can exist in the groundwater and is dependent on the species, temperature, pressure, presence of other solutes, and the ionic strength. An element may also be present in groundwater as particulates; see *Colloid interactions and transport (contaminants) [3.2.04].*

Several dissolved species may co-exist. The nature of the dominant species may be important. For instance, clay and most rock minerals sorb cations more strongly than anions.

An important parameter that could influence the chemical speciation and solubility of some elements is the electrochemical potential or Eh of the water. For instance, technetium is generally quite insoluble for reducing (low Eh) conditions, but very soluble under oxidizing (high Eh) conditions. Other redox-sensitive elements are U, Pu and Se. Although homogeneous redox reactions can exhibit slow chemical kinetics (e.g., reduction of aqueous U(VI) in reducing water), the presence of Fe(II) solids can accelerate such reactions.

Dissolution may produce a number of species which would also reach their solubility limits. For instance, dissolution of the solid $UO_2CO_3(s)$ to its solubility limit in pure water would produce aqueous species that include UO_2^{2+}, $UO_2(CO3)_2^{2-}$ and $UO_2CO_3(aq)$ which would attain maximal concentrations for the specified conditions.

Solubility of a chemical species may be affected by other dissolved components. One complicating factor is called the ‘common ion effect’. For instance, the solubility of solid $UO_2CO_3(s)$ in water would be decreased if the water contained $CaCO_3$ because of the common ion, CO_3^{2-}. Another complicating effect is the possible formation of other solids. For example, if the stable uranium solid is calcium uraninate, then a solubility limit for $UO_2CO_3(s)$ cannot be defined. (It is always possible, however, to define the solubility of a chemical element - it is determined by the stable solid phase(s) containing that element.)

An element will precipitate when its concentration (given by the mass of all species of that element in a unit volume of water) exceeds the elemental solubility limit. Chemical kinetics might affect the nature of the solid phase that forms. From a practical viewpoint, if a solid phase is slow to form and the time frame short, then the effective solubility of an element might be relatively large, perhaps equal to the solubility limit of an amorphous solid.

Further discussion is provided under:
- 3.2.02A Speciation and solubility (repository)
- 3.2.02B Speciation and solubility (geosphere)
- 3.2.02C Speciation and solubility (biosphere).

FEP # 3.2.02.A Speciation and solubility (repository)

Description

Speciation and solubility processes occurring in the engineered barrier system.

Chemical speciation could have important effects in the engineered barrier system, where contaminant concentrations are likely largest. Small concentrations of complexing agents could form stable dissolved species, enhancing the dissolution of contaminants from the waste form and increasing their solubility. Conversely, solubility limits will be smaller when complexing agents have low concentrations or where the chemical environment decreases the stability of dissolved species or enhances the stability of a solid phase.

Solubility limits, and thus formation or dissolution of precipitants, could be different at different positions in the repository because of differences in temperature, groundwater composition (complexing agents) and other factors. The evolution of the chemical environment will affect the solubility of different species, and hence will also affect where precipitants form or dissolve (see also *Chemical processes and conditions (repository) [2.1.09]* and *Radiation effects (repository) [2.1.13]*). Solubility limits, especially of dissolved gases, can also be affected by increased pressures from buffer swelling. Chemical kinetics could also have large effects on effective solubility limits.

See also *Dissolution, precipitation and crystallisation [3.2.01].*

FCS Screening Analysis

The solubility of a contaminant in a failed container will be taken into account in the FCS. If the concentration of the contaminant in the container exceeds its solubility limit, then the contaminant precipitates. The solubility for the contaminant in the container is based on the expected water chemistry in the repository. See also *Dissolution, precipitation and crystallisation (repository) [3.2.01.A].*

Solubility limits are only calculated inside the container, since the concentration of the contaminants will be highest there. Neglecting precipitation elsewhere in the repository is conservative for estimating transport out of the repository.

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 (see *Inorganic solids and solutes [3.1.03]*). Conservative values are selected for the solubilities of other elements. The solubility values calculated by PHREEQC are used in the FCS but the chemical speciation information available from PHREEQC is not explicitly used in the FCS.

Complexing agents are discussed in *Complexing agent effects (contaminant) [3.2.05].*

FEP Screening

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

FEP # 3.2.02.B Speciation and solubility (geosphere)

Description

Speciation and solubility processes occurring in the geosphere.

The speciation of contaminants in groundwaters containing different inorganic and organic components will affect their solubility. Groundwater composition will vary at different locations in the geosphere. For instance, in the Canadian Shield, shallow groundwaters typically have a composition similar to fresh meteoric water, but deep groundwaters can be more saline than sea water. Groundwater composition could also be affected by the presence of trace concentrations of minerals nearby, or by the presence of ores at some distance; for instance, minerals containing iron or sulphur can have a strong influence on the electrochemical potential.

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

See also the discussion under *Dissolution, precipitation and crystallisation [3.2.01].*

FCS Screening Analysis

In the FCS, the speciation and solubility of contaminants in the geosphere is not modelled. Neglect of solubility limits in the geosphere should be reasonable because of the lower contaminant concentrations in the geosphere due to dispersion and dilution, and since ignoring precipitation is usually conservative, i.e., precipitation would reduce contaminant concentrations and fluxes (see *Dissolution and Precipitation (geosphere) [3.2.01.B*]).

Chemical speciation in the geosphere is implicitly accounted for in the selection of the associated parameter values and their uncertainty ranges (e.g., geosphere sorption coefficients). That is, these parameter values are derived from experimental data based on tests that include groundwater, minerals and relevant pH/T/Eh conditions, and which are therefore influenced by chemical speciation.

FEP Screening

Screened out.

FEP # 3.2.02.C Speciation and solubility (biosphere)

Description

Speciation and solubility processes occurring in the accessible environment.

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 (including pesticides and herbicides),
- the high concentrations of humates and fulvates normally found in soils (see *Complexing agent effects (contaminant) [3.2.05]*), and
- organic compounds and detritus produced by microbial processes.

There could be a rapid change in composition in depth caused, for instance, when the relatively fresh surface water containing aggressive carbonic acid undergoes chemical reactions as the water moves down through the soil profile.

The composition of waters in the biosphere, including their dependence on location (and depth) and their evolution with time, will affect the formation of contaminant species and hence the solubility of contaminants. For instance, the presence of high concentrations of carbonate could decrease the solubility of calcium but enhance the solubility of uranium, or C-14 could exchange with C-12 in the carbonates and become mineralized. Likewise the presence of oxygen and organic complexes could decrease or increase solubility limits of different elements. Large solubility limits increase the mobility of contaminants, but low solubility limits may lead to larger exposures over time if precipitation occurs in an undesirable location, such as in the surface soil of a vegetable garden or a terrestrial discharge area (see *Sorption and desorption (contaminant) [3.2.03]*).

See also the discussion under *Dissolution, precipitation and crystallisation (contaminant) [3.2.01].*

FCS Screening Analysis

Contaminant speciation and solubility in the biosphere will not be explicitly modelled in the FCS.

Neglect of solubility limits in the biosphere should be reasonable because of the likely lower contaminant concentrations in the biosphere due to dispersion and dilution; see also *Dissolution and precipitation (biosphere) [3.2.01].*

Since biosphere contaminant parameter values (e.g., soil K_d, plant/soil concentration ratios, volatility) are based on field or laboratory experiments, chemical speciation and solubility effects would have influenced the measured experimental data. Thus, such effects are likely implicitly included in the FCS.

FEP Screening

Screened out.

FEP # 3.2.03 Sorption and desorption (contaminant)

Description

The sorption and desorption of radionuclides and chemical contaminants in the repository system. Sorption describes the physicochemical interactions of a dissolved species with a solid phase to remove the species from solution. Desorption is the opposite process.

Most cases of interest will involve solutions containing trace concentrations of contaminants. These solutions are usually discussed in terms of two sorption-desorption mechanisms.
- Ion-exchange processes involve an electrostatic or ionic attraction between charged dissolved species and oppositely charged surfaces.
- Chemisorption involves the formation of a chemical bond. Neutral species and (usually) anions are generally not strongly sorbed.

Sorption and desorption are often described by a simple partition coefficient (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. A related parameter, called the capacity factor is also used to describe sorption in the buffer and backfill. The capacity factor (CF) is given by the equation $CF = \varepsilon + \rho K_d$, where ε and ρ are the porosity and density of the solid sorbing medium.

Factors that affect sorption include the solid and liquid composition, the form of the species in solution (see *Speciation and solubility (contaminant) [3.2.02]*), accessible porosity in the solid, and the presence of colloids (see *Colloid interactions and transport (contaminant) [3.2.04]*) and *Complexing agent effects (contaminant) [3.2.05],* as well as *Biologically mediated processes (contaminant) [3.2.06]*.

Sorption models employing distribution coefficients or storage capacities are linear models which assume the processes are reversible, rapid and have no limits. However, non-linear effects can be significant, such as chemical kinetic effects which favour desorption over sorption, a limited availability of sorption sites or exposed surface area which become saturated, concentration-dependent interactions which may decrease sorption at higher contaminant concentrations, and removal of sorption sites because of competition by other ions in groundwater (particularly saline groundwater). These effects could reduce the extent of sorption.

Sorption processes are important because they can slow down the migration of contaminants, and contribute to the spread of their releases as a function of time (and in space if dispersive effects are important). Thus sorption will attenuate peak concentrations, and the delay times would allow for additional decay or decomposition.

The specific issues are discussed further under
3.2.03A Sorption/desorption (repository)
3.2.03B Sorption/desorption (geosphere)
3.2.03C Sorption/desorption (biosphere).

FEP # 3.2.03.A Sorption/desorption (repository)

Description

Sorption and desorption processes occurring in the engineered barrier system.

Contaminant sorption and desorption can occur throughout the engineered barrier system, including inside the container and container defects. The most important sorption locations, however, are likely to be in the buffer and in the backfill. Sorption may occur on the inter-layer surfaces of the clays or on trace minerals. For instance, cesium isotopes are strongly sorbed on clay surfaces and technetium is thought to be strongly sorbed on ferrous iron minerals that exist naturally in bentonite clay. Special additives designed to sorb key elements may be deliberately placed in the repository.

The sorption properties of bentonite and other clays generally show a strong dependence on the charge of ionic species, coupled with the possibility of differential diffusion in water bound to the clay surface and in porewater between clay layers. Strong sorption generally occurs by ion exchange with cationic species and by chemisorption with elements such as Pu and Np, but anions (such as I^-, CO_3^{2-} and TcO_4^-) and neutral species (such as $UO_2CO_3(aq)$) are generally weakly sorbed. An effect called buffer anion exclusion refers to the combined processes of sorption and diffusion in surface water of dense clays.

Sorption and desorption processes in the engineered barrier system will change with time, due to changes in the groundwater composition or the properties of the engineered barriers (see, for example, *Chemical processes and conditions (repository) [2.1.09]* and *Buffer and backfill materials and characteristics [2.1.04]*). One potentially important change could be a reduction in sorption properties if calcium-rich waters replace sodium in bentonite clay or if incoming groundwaters are highly saline.

FCS Screening Analysis

In the FCS, sorption and desorption of contaminants in the buffer, backfill and excavation damage zone are modelled explicitly assuming a linear sorption isotherm.

No sorption-specific additives are present in the FCS repository sealing materials.

Irreversible sorption is not modelled. Sorption on the iron oxides that would likely form in the interior of the failed container is also not included. These are conservative assumptions.

Sorption properties are considered as constant in time, although a range of values will be considered that can partially indicate the variation with time. After the repository has saturated and returned to reducing conditions, the sorption characteristics of the materials in the repository are not expected to change significantly over a million year time frame because the buffer and backfill materials are not expected to change significantly over this time frame (see *Buffer and backfill materials and characteristics [2.1.04]*).

FEP Screening

Include FEP in all scenarios.

FEP # 3.2.03.B Sorption/desorption (geosphere)

Description

Sorption and desorption processes occurring in the geosphere.

Sorption of contaminants in the geosphere will depend on factors such as the nature of the contaminant and minerals involved (particularly the characteristics of the mineral surface), pH, electrochemical potential, salinity and available complexing agents. Sorption and desorption in the geosphere may be very important in delaying contaminant transport, especially for long flow paths in which groundwater velocities are small. If groundwater flow is limited to flow along fractures, sorption may occur primarily on fracture infilling minerals, which include high-temperature fillings such as pegmatite and chlorite, and low-temperature fillings such as quartz, calcite, gypsum, goethite, hematite and clays. Sorption may also occur on minerals found in the rock matrix or in fractures and pores containing stagnant water (see *Diffusion [2.2.05.B]* and *Matrix diffusion [2.2.05.C]*).

Sorption and desorption processes in the engineered barrier system will change with time, caused by processes that could affect the evolution of the groundwater composition or the properties of the geosphere (see for example *Chemical processes and conditions (geosphere) [2.2.08]*).

FCS Screening Analysis

In the FCS, sorption and desorption of contaminants in geosphere are modelled assuming a linear sorption isotherm characterized by the linear sorption coefficient or K_d value.

Irreversible sorption is not modelled. This is expected to be a conservative assumption.

Sorption properties are considered as constant in time, although a range of values will be considered that can partially indicate the variation with time. After the geosphere has saturated and reducing conditions attained in the deep zones, the sorption characteristics of the deep rock layers are not expected to change significantly over a million year time frame because the rock and groundwater chemistry are expected to only change slowly (see *Chemical processes and conditions (geosphere) [2.2.08]*). Conditions in fractures, especially near 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 # 3.2.03.C Sorption/desorption (biosphere)

Description

Sorption and desorption processes occurring in the accessible environment including weathered overburden and subsoil, and sediments under surface water bodies.

Sorption and desorption are important processes in soil and sediments. Plant/soil concentration ratios are often negatively correlated with soil sorption. Factors affecting soil sorption include primarily soil texture and mineralogy, pH, and Eh.

In surface waters, contaminants may adhere to particulates suspended in the water column and settle to the bottom. Contaminants can enter sediments from the water column or from below with discharging groundwater from the geosphere. Factors affecting sediment sorption include sediment properties (such as organic matter content), surface water pH, temperature and water flushing rates.

Evolution of sorption and desorption processes could be important in the biosphere which is subject to a wide range of natural and human-induced changes. For instance, contaminant retention or mobility could change in response to seasonal variations in precipitation, or more slowly in response to climate variations and modification of land use.

FCS Screening Analysis

In the FCS, 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.

Irreversible sorption is not modelled. This could, in theory, be a non-conservative approximation since such sorption would prevent leaching of contaminants out of the soil layer, thereby increasing calculated soil concentrations (although such contaminants may then not be available for transfer to plants).

FEP Screening

Include FEP in all scenarios.

FEP # 3.2.04 Colloid interactions and transport (contaminant)

Description

The formation and transport of colloids, and their interaction with radionuclides and chemical contaminants in repository or environmental conditions. Colloids consist of small organic or inorganic particles in the nanometre to micrometre size range, small enough to form long-lasting suspensions in a liquid phase.

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

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

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

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.

FCS Screening Analysis

In order for colloid-facilitated transport to be important, there are three criteria that must be satisfied: (1) sufficient colloids to compete with the immobile surface area for contaminants; (2) contaminants must associate essentially irreversibly with the colloid; and (3) the colloid must be able to move through the media to uncontaminated areas.

A) Colloids within the buffer/backfill:

Colloids in the buffer/backfill could be formed from clay particles. However, these would interact with the buffer material, and therefore not move quickly within the buffer.

If the buffer/backfill colloids were organic-based, they could be negatively charged, and therefore have less interaction with the clay materials. Measurements within Canadian clay-based buffer porewater have indicated ~10 mg/L organics (Stroes-Gascoyne et al. 2000), an amount considered as borderline for having an influence on transport (Andersson 1999, p.49).

Also, due to the small size of the pores in dense buffer, the transport of colloids is expected to be inhibited (e.g., Cigar Lake analog data, Cramer and Smellie 1994, p.240; Pusch 2001, p.142).

Therefore, colloidal transport within the buffer/backfill is not considered important.

B) Colloids within the geosphere:

Migration of Pu by colloids has been proposed as a significant transport process at the Nevada Test Site (e.g., Kersting et al. 1999). Although there is some doubt regarding whether this movement was via colloids in the groundwater or via surface flow and then infiltration at the measurement location, it is clear that Pu in particular can sorb strongly onto inorganic colloids.

The natural colloid concentration in deep groundwaters in the Canadian Shield is expected to be low. See, for example, data from Whiteshell and Atikokan on total colloids (Davison et al. 1994, p.337; Vilks and Bachinski 1997, Vilks et al. 1998) and data on organic colloids in Fennoscandian Shield groundwaters (Andersson 1999, p.49). Consistent with these observations, the assumed reference natural colloid in deep groundwaters at the Fourth Case Study site is 0.4 mg/L, with a range of 0.04-4 mg/L.

However, colloid levels might be increased due to the presence of the repository. In particular, clay colloids might be formed and released at the buffer/geosphere interface. However, if such colloids were formed, they would likely interact with common (clay-like) fracture minerals and therefore not travel quickly (Pusch 2001, p.128). Furthermore, natural analog evidence from Cigar Lake indicates little mobilization of the clay into the rock (Cramer and Smellie 1994), and evidence from Maqarin indicates that the amount of colloidal material generated by cements in the repository will probably be low (Smellie 1998).

Finally, experiments in Canadian Shield moderately fractured rock at the Whiteshell URL in which colloids were deliberately introduced into fractures showed no breakthrough at the observation points, even though the other tracers reached the observation point on the expected time scales, indicating that colloid transport through moderately fractured rock acted more as a filter than as a conduit for colloids (Vandergraaf et al. 2001).

Therefore, colloid-based transport is not expected to be important in the Fourth Case Study geosphere. Nevertheless, colloid transport in the geosphere is included in the system model, assuming contaminants sorb reversibly to the colloid particles in the geosphere, as they do on the host rock, and are transported with the colloids.

Irreversible sorption of contaminants is not presently modelled.

C) Colloids in the biosphere

It is useful to distinguish between the surface soils and sediments, and the near-surface overburden. For example, Vilks et al. (1998) found low colloid levels for the sandy aquifer at Chalk River, Ontario. In the Fourth Case Study, the colloid concentration in the overburden is assumed to be low.

However, in the biosphere, colloids (or suspended particles) may be an important contributor to radionuclide movement, 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:

1. The I-129 and Cl-36 radionuclides that tend to dominate the dose in Canadian postclosure safety assessment studies are not strongly affected by these processes.
2. The transport/holdup through the sediments/soil layer is typically short compared to the transport/holdup through the repository and geosphere, so uncertainties in the soil model have less effect on the contaminant release to the surface.
3. The data for parameters such as the K_d and transfer factors are usually derived from experiments under conditions in which radionuclides are present in colloidal and/or dissolved form. Therefore, the effect of colloids is implicitly included in the biosphere data.

Therefore, no additional specific inclusion of colloidal effects in the biosphere is required.

FEP Screening

Include colloid interactions and transport in the geosphere in all scenarios.

Colloid interactions and transport in the repository and biosphere are not included in the FCS.

FEP # 3.2.05 Complexing agent effects (contaminant)

Description

The modification of speciation or transport of radionuclide and chemical contaminants in the repository system because of the effects of chemical complexing agents.

Chemical complexing agents include simple inorganic ions such as the chloride, fluoride and nitrate anions, small organic species such as the methyl radical, and larger organic-based species such as humic and fulvic acids which occur naturally in soils and in the geosphere. Humic acids and humates are weathering-resistant organic polymers with a gram molecular weight of about 150 000 and are relatively insoluble in water. Fulvic acids and fulvates are weathering-resistant organic polymers with a gram molecular weight of about 1000 and are somewhat soluble in water. These and other complexing agents might be introduced into the repository, for example as natural occurring contaminants found in bentonite clay and surface water.

The chief concern is that these complexing agents can chemically bond with a radionuclide or other contaminant to form another stable species. These reactions might even involve relatively unreactive species like iodide, including I-129. Some chelating agents (particularly organic species) might actually form several chemical bonds with metallic elements to yield very stable species. The formation of new species can have several effects:

- increase (or decrease) the solubility of the complexed element if the species is soluble (insoluble), and
- modify transport properties, for instance, by forming a neutral or anionic complex that is less likely to sorb, or a cationic complex with multiple charge sites.

FCS Screening Analysis

The solubilities of various elements (e.g., Np, Pu, Se, U and Zr) used in the FCS are calculated using PHREEQC (Duro et al. 2010), using the thermodynamic data for these elements and the reference groundwater composition. These calculations include the effects of inorganic complexing agents on solubility. See also *Speciation and solubility (repository) [3.2.04.A].*

The concentrations of organic material in the repository such as fluvates and humates may be sufficient to enhance the solubility of some radionuclides such as Th and Tc (Vilks et al. 1996, 1997). However, contaminant transport out of the repository would not be much affected by complexation with organics because such complexed nuclides would be large, given the size of fluvate and humate molecules, and would diffuse very slowly through the buffer material (Eriksen and Jacobsson 1982). Therefore the effects of organic complexing agents on solubility and transport within the repository are not expected to be important and are not included in the FCS (*Complexation by Organics (Repository) [2.1.10.B]*).

Solubility limits are not considered in the geosphere and biosphere, so the contribution of complexing agents to solubility is not germane in this case. See also *Speciation and Solubility [3.2.02].*

Complexing agents could make some contaminants more mobile by reducing element sorption coefficients. This effect is not expected to be significant, given that larger molecules tend to have lower diffusivities, but is bounded by the analysis of the low sorption variant cases to the Reference Case of the Normal Evolution Scenario.

FEP Screening

Include FEP in all scenarios.

FEP # 3.2.06 Biologically mediated processes, excluding transport (contaminant)

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 [3.2.11].*

Biological-mediated processes occurring in the repository and geosphere are likely to be limited by the availability of nutrients and energy. Possible processes that could affect contaminant properties include the following:

- Biofilms could form on container surfaces and on the repository walls, and in fractures biofilms could cover existing mineral surfaces. The effect might be to increase or decrease contaminant sorption.
- The action of anaerobic bacteria could modify groundwater composition, affecting the pH and Eh and subsequently increasing or decreasing contaminant sorption and solubility. Changes to Eh would be most important for redox-sensitive elements such as technetium and plutonium.
- Micro-organisms might 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 *Complexing agent effects (contaminant) [3.2.05]*).

These last two processes could also occur in the accessible environment, where the potential for biological activity is likely to be less restricted. Other processes occurring in the accessible environment include the following examples.

- Bacteria and microbes may chemically transform contaminants and thereby change their sorption and solubility properties. Properties that lead to increased mobility would promote transport while the reverse effect could cause zones of accumulation and could increase or decrease plant uptake depending on the species and complexes formed and the timeframe.
- Microbes or plants could actively accumulate contaminants and incorporate them into their structure, where they would be held until the organism died and decomposed or was sloughed off. See also *Food chains and uptake of contaminants [3.2.13].*

FCS Screening Analysis

Biologically mediated processes (excluding transport) are not explicitly modelled in the FCS. 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.

FEP # 3.2.07 Water-mediated transport of contaminants

Description

Transport of radionuclides and chemical contaminants in groundwater and surface water.

Contaminants may travel in water dissolved as simple or complexed species and gases (see *Speciation and solubility (contaminant) [3.2.02]*), associated with colloids (see *Colloid interactions and transport (contaminant) [3.2.04]*) or, if flow conditions permit, as larger particulates. Transport may also be attenuated by precipitation effects (see *Dissolution, precipitation and crystallisation [3.2.01]*) and retarded by sorption (see *Sorption and desorption (contaminant) [3.2.03]*).

Water-mediated transport processes include:

- advection or movement with the bulk movement of the fluid;
- percolation or convection, where the movement of the fluid is driven by heat and gravity;
- dispersion, or the spread in the spatial distribution of contaminants with time because of differential rates of advective or convective transport;
- molecular diffusion, or the random movement of individual atoms or molecules within the fluid;
- matrix diffusion or diffusion into stagnant pores; and
- multiphase transport processes including unsaturated flow.

The types of groundwater flow regimes active in the different regions are described elsewhere; see, for example, *Hydrological processes and conditions (repository) [2.1.08], Hydrological processes and conditions (geosphere) [2.2.07], Contaminant transport path characteristics (geosphere) [2.2.05],* and *Near surface aquifers [2.3.03].*

More specific considerations are provided under:

3.2.07A Water-mediated effects (repository)
3.2.07B Water-mediated effects (geosphere)
3.2.07C Water-mediated effects (biosphere)
3.2.07D Coupled solute transport processes.

FEP # 3.2.07.A Water-mediated effects (repository)

Description

Transport of radionuclides and chemical contaminants in groundwater within the engineered barrier system.

One function of the buffer (repository) is to provide a diffusion barrier for contaminant transport. Diffusion is also likely to be important for contaminants escaping from the interior of a container, and for transport though seals and bulkheads, provided permeabilities are sufficiently small and do not increase substantially with time. In the backfill and near-field, advection, convection and dispersion may be important.

Other considerations include the evolution of these barriers (discussed under *Wastes and Engineered Features [2.1]*) to produce alternative transport mechanisms and pathways.

FCS Screening Analysis

Transport of contaminants via water in the repository is modelled in the FCS.

Because of the low hydraulic conductivity of the buffer material used in the FCS, contaminant transport through the buffer will be by diffusion only. In the backfill, contaminant transport will occur by advection and diffusion, with the dominant mechanism depending on the water velocity in the backfill which, in turn, depends on the water velocity in the near-field geosphere. Convection is not expected to be important due to the relatively low temperature gradients and the low permeability of the repository seal materials.

FEP Screening

Include FEP in all scenarios.

FEP # 3.2.07.B Water-mediated effects (geosphere)

Description

Transport of radionuclides and chemical contaminants in groundwater within the geosphere.

The characteristics of the geosphere could vary from low-permeable fracture free rock to highly porous and permeable unconsolidated mineral material. Consequently, all transport processes could be important in different parts of the geosphere. The discussion under *Contaminant transport path characteristics (geosphere) [2.2.05]* describes the potential importance of advection, convection, dispersion and diffusion.

Other factors to consider, including evolution of the geosphere, are discussed under *Geological Environment [2.2].*

FCS Screening Analysis

Transport of contaminants through the groundwater system in the geosphere is explicitly modelled in the FCS.

Contaminant transport through the geosphere will be by diffusion or advection-dispersion, depending on the properties of the geosphere zone and groundwater hydraulic gradients. For example, in intact rock with a low hydraulic conductivity, contaminant transport is likely diffusion dominated whereas fracture zone transport is dominated by advection-dispersion.

FEP Screening

Include FEP in all scenarios.

FEP # 3.2.07.C Water-mediated effects (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, and 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 [2.3.04]* and *Near surface aquifers [2.3.03]*). Contaminant removal by flushing, degassing, 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 porewater. 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 [2.3.02]*). Contaminants may also move up and down the soil profile through capillary rise and leaching. 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 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 [2.3].*

FCS Screening Analysis

Transport of contaminants in surface waters and near-surface groundwater flow system is modelled in the FCS. Water-mediated transport processes include advection, diffusion and dispersion, flushing, sedimentation, capillary rise and leaching. Water mediated transport of contaminants to humans (via drinking water) and non-human biota (fish) are included in the FCS.

FEP Screening

Include FEP in all scenarios.

FEP # 3.2.07.D Coupled solute transport processes

Description

In principle, dissolved contaminants (solute) flow can be driven by temperature, hydraulic, chemical and/or electrical gradients. Solute transport in a chemical gradient is classical diffusion, and along with transport by advection with the moving fluid, are covered in the other FEPs in [3.2.07].

Solute flow 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.

Since these processes depend on different gradients than diffusion, they might contribute significantly to solute flow, particularly at low diffusion rates.

FCS 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 - a safety assessment of a deep geologic repository sited in Opalinus Clay (Soler 2001).

The range of values considered for the various coupling coefficients in the Opalinus Clay study are approximately applicable to the clay-based engineered sealing materials in the Canadian repository concept, and so the results of the Opalinus Clay study are indicative of the effects within the engineered barrier system of the FCS.

This Swiss study 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 by then.

For the FCS, this first thermal period occurs when the repository is resaturating, and contaminants would not be available for transport via water due to partial resaturation of the repository, and time scale for container failure and filling with water.

Therefore, coupled solute transport processes are considered to have a small effect and are not included in the Fourth Case Study.

FEP Screening

Screened out.

FEP # 3.2.08 Solid-mediated transport of contaminants

Description

The transport of radionuclides and chemical contaminants in large-scale solid phase movement.

The processes of most interest are large scale erosion processes which are described throughout *External factors [1.]*, such as *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 small particles suspended in water and air are discussed under *Water-mediated and Gas-mediated transport of contaminants [3.2.07 and 3.2.09]*. Transport of solids by human activities is included in *Human action mediated transport of contaminants [3.2.12].*

FCS Screening Analysis

The FCS 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). Erosion and deposition are not modelled even during glaciation (see *Erosion and deposition [2.3.12]*).

In the FCS, dose rates to the most exposed individuals, who reside near the site of the repository, are calculated. By neglecting losses due to, for example, erosion, calculated dose rates would be conservative because, in this way, radionuclides remain within the local environment near the repository.

FEP Screening

Screened out.

FEP # 3.2.09 Gas-mediated transport of contaminants

Description

The transport of radionuclides and chemical contaminants in gas or vapour phase, or as fine particulate or aerosols suspended in gas or vapour, but excludes *Atmospheric transport of contaminants [3.2.10].*

Radioactive and chemically toxic gases may be generated from the wastes, e.g., C-14 as carbon dioxide or methane, and transported in the gas phase through the repository and geosphere. Radioactive and chemically toxic gases, aerosols or particulates may also be transported along with other non-toxic gases. Alternatively, gas pressures could be sufficiently high to form an unsaturated phase where two-phase flow is important, or to expel contaminants dissolved in groundwater from parts of the repository and geosphere.

Issues such as dwelling location, which could affect seepage of gases such as radon into basements, and heating source, which could involve biogas production, are discussed under *Dwellings [2.4.07].* See also *Gas Sources and Effects (Repository and Geosphere) [2.1.12* and *2.2.11], Volatiles and Potential for Volatility [3.1.04]* and *Noble Gases [3.1.06].*

FCS Screening Analysis

After saturation of the repository, low but non-zero gas production in the repository is expected for the Normal Evolution Scenario. The copper used fuel containers are corrosion resistant, but gas could be generated from corrosion of steel in failed containers, from corrosion of residual iron in the repository (i.e., rock bolts), and from trace organics in the seal materials. Some of this gas can be microbially consumed or diffuse away. But the latter process in particular is slow unless there are fractures directly intercepting the repository.

For the All Containers Fail Scenario, the rate of H_2 production would be much higher. Therefore the effects of gas generation need to be considered, including the analysis of the dose consequences of gas-mediated transport of radionuclides from the repository to the biosphere.

FEP Screening

Include FEP in the All Containers Fail Scenario

FEP # 3.2.10 Atmospheric transport of contaminants

Description

The transport of radionuclides and chemical contaminants in the atmosphere as gas, vapour, or suspended fine particulate or aerosol.

Contaminants may enter the atmosphere as a result of processes such as evaporation of volatile species or degassing from soils or water (particularly during irrigation or outdoor spraying of water), transpiration from plants, suspension of dusts due to wind erosion, ploughing or fires (forest, agricultural and from house heating), and extrusion in a volcanic ash. 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 impacts. 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 [2.3.07].*

This subcategory also provides for specific human and animal exposure pathways different from groundwater, notably inhalation and immersion in contaminated air.

FCS Screening Analysis

Atmospheric transport (advection and dispersion) of contaminants is explicitly modelled in the FCS. This includes the volatilization of contaminants from soil and surface water bodies, formation and transport of water aerosols, formation and transport of dust particles, formation and transport of smoke from fires, infiltration of Rn-222 into buildings, release of contaminants into indoor air from water used for domestic purposes (e.g., showers) and atmospheric deposition of contaminants onto soil and plants. 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 # 3.2.11 Biological-mediated transport of contaminants

Description

The transport of radionuclides and chemical contaminants as a result of animal, plant and microbial activity. Other biological effects on contaminant properties are discussed under *Biologically-mediated processes (excluding transport) [3.2.06].*

Animals can have a direct or indirect influence on contaminant transport. For instance, wild animals can ingest contaminated water and food from remote areas, and move to the location of the critical group. Another process is bioturbation of soil and sediment, whereby burrowing animals (such as worms) and trees can physically displace large amounts of soil, promoting the redistribution and uniform mixing of contaminants in soil and sediment. Subsequent transport in soils and soil porewater can then result in a variety of exposure pathways, notably where plants take up contaminants in soil via their roots. Plants can also take up contaminants deposited on their leaves. The extent of root and leaf uptake depends on soil and plant types, the chemical nature of the contaminant, and seasonal effects such as in early spring and summer when plants are actively growing.

Microbes affect contaminant transport indirectly by changing transport-related properties (see the discussion under *Biologically mediated processes (excluding transport) [3.2.11]*). More direct effects include:

- formation of biofilms that restrict or plug groundwater flow and contaminant transport, and
- decomposition reactions of bacteria and microbes to leach or otherwise release contaminants that have been taken up by soils, plants and animals.

This 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 radioactive or chemically toxic contaminants) through the biosphere, geosphere, hydrosphere, atmosphere and anthrosphere.

Some transport related effects of plants and animals are discussed under *Surface environment [2.3]*, and the effects of microbes under *Wastes and engineered systems [2.1], Geological environment [2.2] and Surface environment [2.3]*. See also factors such as bioconcentration, bioaccumulation and biomagnification, under *Ecological systems [2.3.13].*

FCS Screening Analysis

Some biologically-mediated contaminant transport processes are explicitly modelled in the FCS, 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, e.g., by not modelling the spread of contaminants by animals, contaminants remain in the local environment, thereby increasing the contaminant concentrations to which the critical group is exposed.

FEP Screening

Include FEP in all scenarios.

FEP # 3.2.12 Human action mediated transport of contaminants

Description

The transport of radionuclides and chemical contaminants as a direct result of human actions.

Human action mediated transport of contaminants includes processes such as drilling into or excavation of contaminated areas such as the repository 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 ploughing 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 (active) [1.4]* and *Human behaviour [2.4].*

FCS Screening Analysis

Transport of contaminants by human action will be modelled in the FCS.

In the Normal Evolution Scenario, transport of contaminants to the surface biosphere due to well operation is modelled. Well water is used for drinking and irrigation. These are important exposure pathways (Garisto et al. 2004a, 2005a). Other explicitly modelled processes are the transfer of sediments from a lake shore to a garden plot, and 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 will only be 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 the humans recycle their waste to the soil (i.e., use compost piles).

However, contaminant transport by large-scale human activities (e.g., dam construction) is not modelled because of the large inherent uncertainties involved and the likelihood that such projects would spread contaminants over large areas, reducing the contaminant concentrations to which the critical group is exposed.

FEP Screening

Include FEP in all scenarios.

FEP # 3.2.13 Food chains and uptake of contaminants

Description

The incorporation of radionuclides and chemical contaminants into plant or animal species that are part of the human food chain.

Important general processes, also discussed under *Ecological systems [2.3.13],* 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 contaminated water by their roots, and indirectly contaminated through exposure to soil and soil conditioners that are contaminated.
- Animals may become contaminated as a result of inhalation of contaminated air, from external deposition of contaminants onto their bodies, and from ingestion of contaminated food and water.

Microorganisms also form part of the human food chain, directly with foods such as yoghurt and indirectly through processes such as fermentation.

The complexity of possible routes is 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 medication; and for terrestrial animals, may include soil ingestion, either routinely and inadvertently with contaminated plants or sometimes purposefully to meet nutritional needs, and, for aquatic biota, may include ingestion of sediment.

FCS Screening Analysis

The human food chain will be modelled in the FCS. 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 FCS biosphere model. These transfer factors are based on empirical data and, hence, implicitly include the effects of biological processes such as bioconcentration and bioaccumulation.

FEP Screening

Include FEP in all scenarios.

3.3 Exposure Factors

FEP # 3.3.00 Scope of sub-category 3.3

Description

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 sub-categories under Exposure factors:
3.3.01 Contaminated drinking water, foodstuffs and drugs
3.3.02 Contaminated environmental media
3.3.03 Other contaminated materials
3.3.04 Exposure modes
3.3.05 Dosimetry
3.3.06 Radiological toxicity effects
3.3.07 Chemical toxicity effects
3.3.08 Radon and radon daughter exposure

FEP # 3.3.01 Contaminated drinking water, foodstuffs and drugs

Description

The presence of radionuclides and chemical contaminants in drinking water, foodstuffs or drugs that may be consumed by humans.

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 *Food chains and uptake of contaminants [3.2.13]* and throughout *Human behaviour [2.4],* particularly under *Diet and liquid intake [2.4.03]* and *Water source of the critical group [2.4.05.C].*

FCS Screening Analysis

Exposure to contaminated drinking water and foodstuffs will be explicitly included in the FCS. Foodstuffs include fish, plants, meat products 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, 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.

The critical group lives on the site and directly consumes contaminated local water, air and foodstuffs. Exposure to contaminated drugs is not considered.

FEP Screening

Include FEP in all scenarios.

FEP # 3.3.02 Contaminated environmental media

Description

The presence of radionuclides and chemical contaminants in environmental media including soil, water, and air.

These concentrations will be important in assessing the impact on biota, and also on assessing the external exposure routes for humans. Concentrations in environmental media are also usually required to determine the contaminant concentrations in food. The comparison of calculated contaminant concentrations in environmental media with naturally occurring concentrations of similar species may provide additional information for safety assessment that is less dependent on assumptions 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 [2.3]* describe features and processes that could contribute to contamination of environmental media and the discussions under *Contaminant release and migration factors [3.2]* provide more specific detail on how contaminants from the 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 [2.4]* and *Exposure modes for humans and other biota [3.3.04].*

Some media might attain higher concentrations than their surroundings because of natural processes such as bioaccumulation or evaporation of water. The presence of colloids might correspond to high local concentrations of contaminants (see *Colloid interactions and transport (contaminant) [3.2.04]*). Moreover, human practices such as excessive watering of gardens might lead to higher concentrations or accumulation of contaminants (see *Human action mediated transport of contaminants [3.2.12]*).

FCS Screening Analysis

In the FCS, contaminant concentrations in environmental media will be calculated as part of the models used to calculate dose impact. The environmental media included in the FCS are: indoor and outdoor air, well water, surface water body (lake or river), soil, sediments, plants and non-human biota.

FEP Screening

Include FEP in all scenarios.

FEP # 3.3.03 Other contaminated materials

Description

The presence of radionuclides and chemical contaminants in human manufactured materials or in environmental materials that have special uses.

Common examples of other materials that could be contaminated include:
- wood and rock used as building material and household furnishings;
- natural fibres and animal skins used in clothing;
- peat, charcoal and biogas (from plant materials, faeces 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.

FCS Screening Analysis

In the FCS, exposure to the following "other contaminated materials" is explicitly modelled:
- building materials made from wood or overburden material;
- heating fuels such peat and wood; and
- water used in showers.

FEP Screening

Include FEP in all scenarios.

FEP # 3.3.04 Exposure modes

Description

The exposure of humans and biota to radionuclides and chemical contaminants.

Exposure modes can be broadly categorized as internal and external with respect to the human body or other affected biota. Internal exposure means the contaminant enters and may temporarily or permanently reside in the affected organism. External exposure means the contaminant is outside the organism at all times, although radiation and energy might be transferred into the organism.

Radiotoxic and chemotoxic species differ in their ability to affect organisms.

- Radiotoxic materials can lead to impacts through internal or external exposure.
- Chemotoxic species are only of concern from internal exposure, although there may be apparent exceptions. For instance, chemicals may be sorbed through skin, but subsequent impacts are actually from internal exposure.

This exposure is considered under:
3.3.04A Exposure of humans
3.3.04B Exposure of biota other than humans.

FEP # 3.3.04.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, dust and drugs (including injection of drugs);
- absorption (internal) exposure by uptake through the skin, for example from the use of contaminated health and beauty products such as toothpaste, shaving cream, soap and 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.

FCS Screening Analysis

Human exposures to internal and external radiation doses are explicitly modelled in the FCS. 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 FCS include: air immersion, ground exposure, water immersion and building material exposure.

Human exposures to chemically toxic elements are evaluated for the Normal Evolution and All Containers Fail Scenarios. For chemical toxic elements, a food chain model is not used to determine the impact on humans of 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 # 3.3.04.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 repository site on the Canadian Shield, since 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 pathway would be similar to those for humans - inhalation, ingestion, external contamination or irradiation. However the relative importance of these pathways would likely be quite different from humans and also between species. For example,
- Absorption through skin may be an important pathway;
- Burrowing animals are more directly exposed externally and internally to contaminated soils and sediments;
- Aquatic plants make 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.

FCS Screening Analysis

In the FCS, radiological impacts on non-human biota of radionuclide releases from the repository are assessed for the Normal Evolution and All Containers Fail Scenarios. However, non-human radiological dose rates will not be calculated. Rather the radiological impacts on non-human biota will be assessed by comparing calculated radionuclide concentrations in various biosphere compartments to so-called no-effect concentrations (Garisto et al. 2008).

In the FCS, 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 FCS are protective of both humans and non-human biota (NWMO 2012).

FEP Screening

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

FEP # 3.3.05 Dosimetry

Description

Dosimetry describes the dependence between radiation or chemical toxicity effect and the amount of radiation or chemical agent in the organs, tissues or the whole body. 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 exposure and the lifetime commitment to the exposure.

One special consideration that pertains to radioactive material is the decay of a parent radionuclide (or precursor) to its daughter radionuclide (or progeny), because:
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 [3.3.08].*

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). Additional discussion is provided under *Dose response assumptions [0.09].*

Similar comments apply to chemotoxic effects, except that chemical and biochemical disruption of cell functions, not radioactive emissions, affects the tissues of the body. Chemical toxics can have a wide variation of effects on biota, and 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 and how the toxic component interacts with cells and tissues. A very large number of chemical compounds exist and suitable quantitative dosimetry data may be sparse.

FCS Screening Analysis

In the FCS, 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 Container Fail Scenarios.

Radiation dosimetry is included in the FCS 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 the Garisto et al. (2012).

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., Garisto 2002).

Non-human radiological doses will not be directly calculated in the FCS. Rather the radiological impacts on non-human biota, due to radionuclides released from the repository, are determined by comparing calculated radionuclide concentrations in various biosphere compartments to no-effect concentrations (NECs) (Garisto et al. 2008). However, the derivation of the NECs requires calculation of dose rates to non-human biota from both internal and external exposure to radiation (Garisto et al. 2008). Thus, internal and external dose coefficients for non-human biota are needed, as are the corresponding food chain parameters and transfer factors, for the derivation of NECs.

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 2012).

FEP Screening

Include FEP in all scenarios.

FEP # 3.3.06 Radiological toxicity effects

Description

The effects of radiation on man and other organisms.

Radiation effects can be classified in several different ways:

- somatic or genetic, occurring in the exposed individual or in the offspring of the exposed individual, respectively; and
- stochastic or nonstochastic, where the probability of the effect is a function of dose received) or the severity of the effect is a function of dose received and no effect may be observed below some threshold, respectively.

At high exposure levels, radiation can kill cells outright and this can lead to acute radiation sickness and death. Such exposure levels are considered unlikely in the prudent management of radioactive nuclear waste. At low exposure levels, cancer induction (carcinogenesis) and genetic effects are of main concern, possibly because of mutations that may lead to cancer or, if the reproductive cells are affected, hereditary effects that may be detrimental and transmitted to future generations. Radionuclides could also be teratogenic, that is, cause developmental disturbances in humans and other organisms. High exposures can cause serious malformations, but the situation is less clear at lower doses, especially those at or below background radiation levels where the most likely effect in humans might relate to brain development and mental capacity.

If the effects are widespread throughout a population of some biota, there could also be consequential effects, such as disruption of food webs or ecosystems.

Another possible concern, synergistic impacts, is discussed under *Chemical toxicity effects [3.3.07].*

FCS Screening Analysis

In the FCS, radiological impacts, on humans and non-humans, due to radionuclide releases from the repository are calculated.

For humans, radiological toxicity effects are determined by calculating dose rates to various potential exposed groups of humans and comparing them to the criterion for radiological protection of persons (ICRP 2007). For dose rates below these levels, it is expected that the risk of radiological toxicity from both stochastic and deterministic effects are negligible.

Non-human radiological doses are not directly calculated in the FCS. Rather, radiological impacts on non-human biota are determined by comparing radionuclide concentrations in various biosphere compartments to no-effect concentrations (NECs) (Garisto et al. 2008). The NECs are conservatively derived so that all non-human biota living near the repository would be protected if the NECs are not exceeded. Radiological impacts on non-humans are evaluated for the Normal Evolution and All Containers Fail Scenarios.

FEP Screening

Include FEP in all scenarios.

FEP # 3.3.07 Chemical toxicity effects

Description

The effects of chemically toxic species on man and other organisms.

Some elements in nuclear fuel waste can be chemically toxic to humans and other organisms, including plants. This concern includes elements of radionuclides; 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, with subsequent disruption of food chains that may affect other biota. Detrimental impacts can be found for most elements, but health and environmental impacts from arsenic, cadmium, chromium, lead, mercury and selenium are among those that have received the greatest attention. See also *Impacts of concern [0.01], Dose response assumptions [0.07]* and *Radiological toxicity effects [3.3.06].*

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 man and other organisms. Two or more toxic substances may interact with each other, or interact jointly with an organism, to produce biological effects that can be different in extent and kind than 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, may be beneficial.

FCS Screening Analysis

In the FCS, 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 potential impacts are assessed by comparing concentrations of chemical toxic elements in biosphere compartments to the selected criteria for chemical toxicity effects (NWMO 2012), as described in Garisto et al. (2005b).

FEP Screening

Include FEP in the Normal Evolution and All Containers Fail Scenarios.

FEP # 3.3.08 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 [3.1.06]*) 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.

FCS Screening Analysis

The dose rate from exposure to Rn-222 calculated in the FCS will include doses from radon daughters. This is achieved by using a Rn-222 air inhalation dose coefficient based on dosimetric information for radon and radon progeny nuclides (Zach et al. 1996a).

FEP Screening

Include FEP in all scenarios.

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APPENDIX A: HISTORY OF FEPs REPORT

The Fourth Case Study FEPs report builds extensively on the FEPs assessment prepared for the Third Case Study (Garisto et al. 2004b).

The Third Case Study FEPs database follows the organization of the international FEPs database developed by the OECD Nuclear Energy Agency (NEA 2000). The Third Case Study FEPs assessment was carried out in the years 2003 to 2004. Contributors to the FEPs database include both the assessors who prepared the screening analyses, and the reviewers who critically examined these analyses. The main contributors to the Third Case Study FEPs assessment were Dr. F. Garisto, Dr. P. Gierszewski, Dr. B. Goodwin and Mr. P. Maak.

The Fourth Case Study FEPs screening analyses and report were primarily completed by Dr. F. Garisto. The Third Case Study FEPs screening analyses were reviewed and modified as needed for the Fourth Case Study. For most FEPs, the Third Case Study screening analysis remains valid for the Fourth Case Study. However, some differences do arise due to the different scope of work in the two studies. More importantly, the FEPs screening analyses were updated, as needed, to include more recent work and current thinking.

A brief description of the qualifications of the contributors to the Third Case Study and Fourth Case Study FEPs assessments are presented below.

Dr. F. Garisto is currently a senior technical specialist in the Repository Safety department of the Nuclear Waste Management Organization, where he contributes to the development and use of safety assessment tools and models for geologic disposal of used nuclear fuel. He carried out similar duties with Ontario Power Generation and Atomic Energy of Canada Limited. He has over 30 years experience in (1) environmental safety/risk assessments of, for example, geologic disposal of used fuel, uranium mine tailings and other nuclear facilities; (2) contaminant fate and transport modelling; and (3) geochemical modelling.

Dr. P. Gierszewski is Director of the Repository Safety department at the Nuclear Waste Management Organization, where he is responsible for the safety assessment studies for geological repositories for used nuclear fuel, and for low and intermediate level wastes. He has been working on nuclear waste safety assessments since 1998. He has been responsible for the development of safety assessment capabilities, including methodology, modelling software, and data. He has managed R&D programs including used fuel dissolution studies and in-situ (underground) material tests.

Dr. B. Goodwin has extensive national and international experience in waste management of used nuclear fuel. Up to 1998, he worked with Atomic Energy of Canada Limited, where he was technical lead of a multidisciplinary team charged with preparation of two long-term environmental assessments of the concept for disposal of Canada's nuclear fuel waste. Subsequently, he continued to work in this area as a private consultant. His was a member of the Nuclear Energy Agency's Working Group on the Identification and Selection of Scenarios for Performance Assessment and the Working Group to Develop an International Database of FEPs.

Mr. P. Maak is currently a senior technical specialist in the Used Fuel Container Development department within the Nuclear Waste Management Organization. He has over 30 years of working experience in the Canadian nuclear waste management program. From 1981 to 1997, he worked as a metallurgical engineer at Ontario Hydro Research Division and was responsible for the development of welding and inspection technologies for copper/titanium used-fuel containers and used-fuel dry storage/transportation containers. Since joining the Nuclear Waste Management Division of Ontario Power Generation in 1999, he has been managing a wide range of projects in the development of the used-fuel container design, including corrosion studies, creep studies and structural analyses.