Development of a Monitoring Program for a Deep Geological Repository for Used Nuclear Fuel

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ABSTRACT

Title: **Development of a Monitoring Program for a Deep Geological Repository for Used Nuclear Fuel**
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Abstract

This report outlines the Nuclear Waste Management Organization's (NWMO's) approach for developing a repository monitoring program within the framework of implementing Adaptive Phased Management (APM), the approach selected by the Government of Canada for the long-term management of Canada's nuclear fuel waste. The report defines the basis for the monitoring function, examines requirements and possible monitoring methods during specific phases in the life of a geological repository, and outlines a plan for the development of monitoring system designs.

The end-point of APM is placing used nuclear fuel in a deep geological repository constructed in a suitable rock formation. Monitoring used nuclear fuel in a deep geological repository is a key feature of APM. Within this context, there are two primary monitoring functions: i) confirming the long-term safety performance of the repository and, ii) providing information that may be required for future decisions.

Current deep geological repository concepts for nuclear fuel waste are based on passive safety. This derives from the premise that long-term safety can only be assured if further actions to ensure safety are not required after the end of repository operations. However, although it is expected that actions to ensure safety will not be required, it is considered important to provide the means for verifying that repository performance will be as predicted.

NWMO will continue to develop conceptual repository designs that include methods for monitoring repository performance as well as preliminary systems to assess the potential viability and effectiveness of several monitoring functions. There is a need for defining the basis and scope of a repository monitoring program within the APM work plan. This report takes the initial steps to fulfill that need and identifies a set of specific goals for the different stages of implementation of the APM project. The important elements of the monitoring work plan include:

- stating a clearly defined basis for monitoring;
- establishing a process for identifying important monitoring parameters;
- developing monitoring strategies for the potential host rock formations;
- selecting key monitoring parameters based on preliminary repository designs;
- identifying suitable technologies to monitor those parameters;
- developing preliminary monitoring system designs; and
- applying the developed processes and strategies to a site-specific repository design.

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1 INTRODUCTION

NWMO has developed deep geological repository design concepts based on placing long-lived, corrosion resistant used fuel containers, surrounded by engineered barriers, inside tunnels excavated in a suitable rock formation. Preliminary repository designs have been developed for two specific types of geological media: crystalline rock, and sedimentary rock. Although these design concepts are based on passive safety, it is considered important to provide the means for verification of repository safety and also to provide information that may be needed for making future decisions, such as that of closing the repository. These constitute the two primary functions of a repository monitoring program. This report describes a work plan for development of a repository monitoring program as part of implementation of Adaptive Phased Management (APM), the method selected by the Government of Canada for the long-term management of Canada's nuclear fuel waste.

The intent of this report is to describe the basis and identify the essential components of a monitoring program that will produce the design concepts, monitoring strategies and, ultimately, the system designs that will perform the required monitoring functions in a repository designed for the selected repository site. In general terms, the monitoring work program can be divided into two distinct phases: a) before the selection of a repository site the work plan will include the development of monitoring concepts and applicable methods for monitoring a set of key safety parameters during the repository preclosure period, and: b) following the selection of a preferred repository site, work will be focused on the development of site-specific system designs and on the advancement and demonstration of suitable monitoring technologies.

There is a need to define the basis and scope for the repository monitoring program and to outline the monitoring activities for the APM work plan. This report takes the initial steps to fulfill that need. The activities outlined here identify specific goals for the different stages of implementation of the APM project. Its key elements include:

- stating a clearly defined basis for monitoring;
- identifying a process for selection of important monitoring parameters;
- selecting key monitoring parameters based on preliminary repository designs;
- developing monitoring strategies for the two candidate rock types;
- identifying suitable technologies to monitor those parameters;
- developing preliminary monitoring system designs; and
- applying the developed processes and strategies to a site-specific repository design

This report addresses the tasks identified in the first three activities and partially addresses the fourth activity by presenting a preliminary discussion of monitoring strategies for a repository in crystalline rock. The scope of the report is limited to monitoring activities to be conducted during the preclosure period, which includes the repository operational phase and an extended monitoring period, is envisaged to be of the order of 100 years.

2 BASIS FOR MONITORING

Current deep geological repository concepts for nuclear fuel waste are based on passive safety. Although it is expected that after the repository operating phase further actions will not be required to ensure repository safety, it is considered important to have the means for verifying the repository performance and to provide repository-related data that would inform future decisions. This will be accomplished by implementing a monitoring program that will develop, design, and place in service in a timely manner the engineered systems that will perform a number of specified monitoring functions. The definition of those functions and the development of monitoring systems will take place in parallel with the evolution of repository designs and the associated safety cases.

2.1 Repository Evolution and Long-term Safety

The safety case for a repository includes the examination of a set of repository evolution scenarios, each based on a postulated set of conditions or events. Both normal evolution and disruptive-event scenarios are considered. The Normal Evolution Scenario represents the expected evolution of the site and facility; Disruptive Event scenarios examine the effects of possible, although unlikely, events that might lead to abnormal degradation of engineered barriers and loss of containment.

Scenarios of interest are identified through consideration of a set of Features, Events and Processes (FEPs) that could affect the repository system and its evolution. These FEPs are classified into either internal or external, and they are used to generate the repository evolution scenarios analyzed in the safety case for the specific repository design. The safety analyses determine the radiological consequences and make it possible to rank the scenarios according to the associated risk. The need/importance of specific monitoring functions can then be assessed based on the risk associated to each specific scenario. The process of conducting a systematic ranking of monitoring parameters is not done in this report. Only illustrative examples of important monitoring parameters are given and associated monitoring concepts are discussed. It should be emphasized that a thorough review and understanding of the repository safety case is essential to ensure that a comprehensive set of monitoring parameters is identified and used for development of the repository monitoring program.

The reference system used for this study is the generic repository design for crystalline rock developed in 2011 (SNC-Lavalin, 2011). A summary description of the repository design is given in the next section. The External FEPs for an APM repository in crystalline rock were reviewed to identify those that could potentially affect repository performance and should therefore be included in the Normal Evolution scenario. Based on the characteristics of the preliminary design, the repository depth and the site’s geological characteristics, it can be concluded that the repository is largely unaffected by many external FEPs. Repository safety is further discussed in Chapter 4.

3 REPOSITORY CONCEPTUAL DESIGN FOR CRYSTALLINE ROCK

The APM deep geological repository concept consists of encapsulating the used nuclear fuel in durable containers and placing the containers in a repository constructed in a stable geological formation. For the purpose of this report we specifically consider a repository designed for crystalline rock using an in-floor borehole configuration for used fuel containers. This concept has also been extensively studied in Sweden, Finland and Canada as part of the development of deep geological repository concepts in crystalline rock (SKB 2007, Vieno and Nordman 1999, Villagran et al. 2011). An illustration of the APM repository concept is shown in Figure 1.

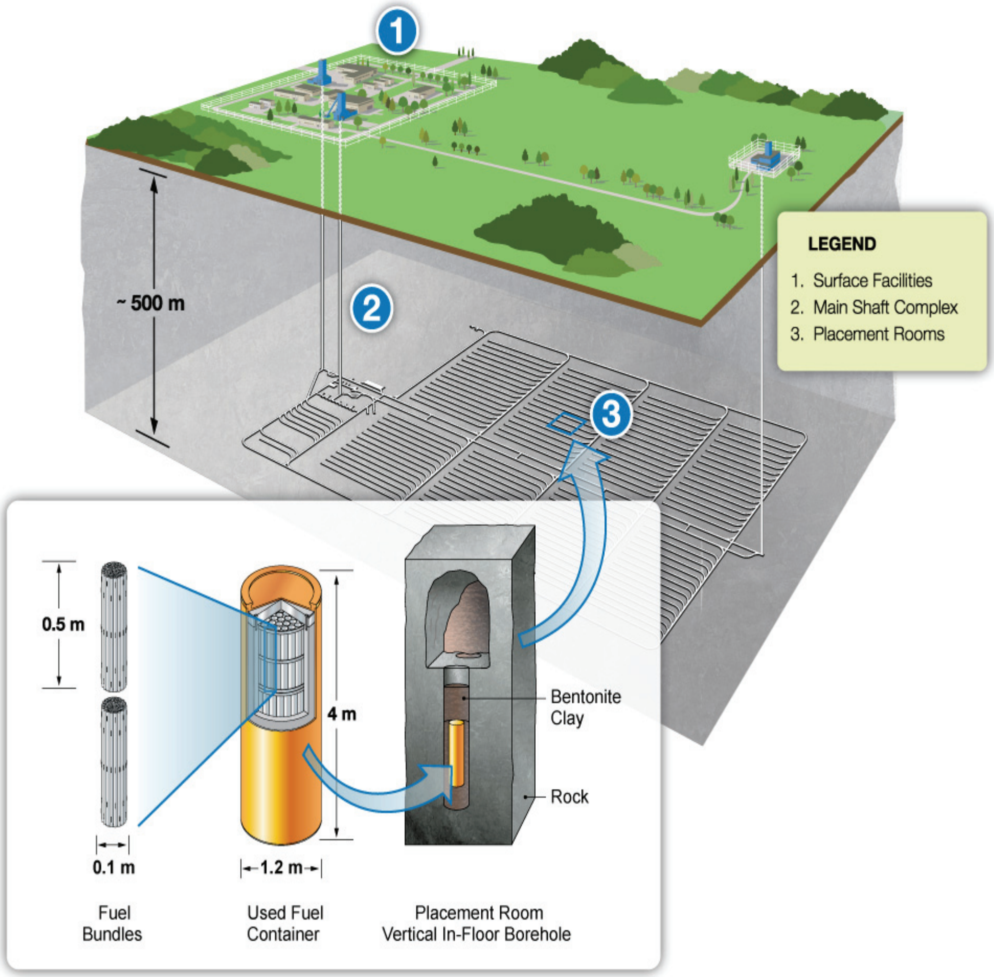


Figure 1: Conceptual Design for a Deep Geological Repository in Crystalline Rock with In-floor Borehole Placement of Used Fuel Containers

3.1 Underground Facilities

For the purpose of preliminary design and safety studies for a hypothetical site in crystalline rock, the used fuel container repository is assumed to be developed on a single level, at a depth of approximately 500 m. An example layout is illustrated in Figure 2.

The used fuel container placement rooms consist of a series of parallel tunnels arranged in eight panels. The placement rooms have a centre-to-centre spacing of 40 m and a single access from the corresponding repository cross-cut. The rooms entrance have a turning radius of 50 m and the total length of the rooms is approximately 400 m. The used fuel containers are placed in vertical boreholes drilled on the floor along the room axis, with a center-to-center spacing of 4.2 m. Within the boreholes, the containers are surrounded by highly-compacted bentonite disks and rings that form the primary isolation barrier between the container and the rock. This material, (referred to as the Buffer) is designed to inhibit groundwater flow, block or delay the transport of radioactive species and inhibit the development of bacteria. Following the completion of used fuel container placement operations within a particular room, the room will be sealed with dense and light backfill. A container placement room longitudinal cross section is shown in Figure 3.

3.2 Used Fuel Container

The reference used fuel container used for this study is the IV-25 copper container, which has a capacity of 360 bundles. The container has a copper outer shell that provides a long-lived corrosion barrier and a steel inner vessel that provides mechanical strength; their main design parameters are given in Table 1. The steel vessel lid has a bolted closure and the vessel is filled with an inert gas. The copper vessel lid is sealed by a stir-welding process. The total mass of the container is 26,700 kg. The container and fuel basket are illustrated in Figure 4.

The dimensions of the container placement borehole are determined by the used fuel container dimensions and the required buffer thickness. In this case the buffer placed between the container and the rock, consists of cylindrical and ring-shaped blocks of highly compacted bentonite.

Table 1: IV-25 Container Design Parameters

IV-25 Outer Copper Vessel	
Total vessel height	3,842 mm
Copper vessel outside diameter	1,247 mm
Copper vessel wall thickness	25 mm
Mass of copper vessel with lid and bottom	4,170 kg
Vessel Material	Oxygen-free, phosphorous-doped, high purity copper
IV-25 Inner Steel Vessel	
Total vessel height	3,700 mm
Inner vessel outside diameter	1,195 mm
Inner vessel wall thickness	102.5 mm
Mass of inner vessel	12,650 kg
Vessel Material	ASTM A516 Gr 70 steel

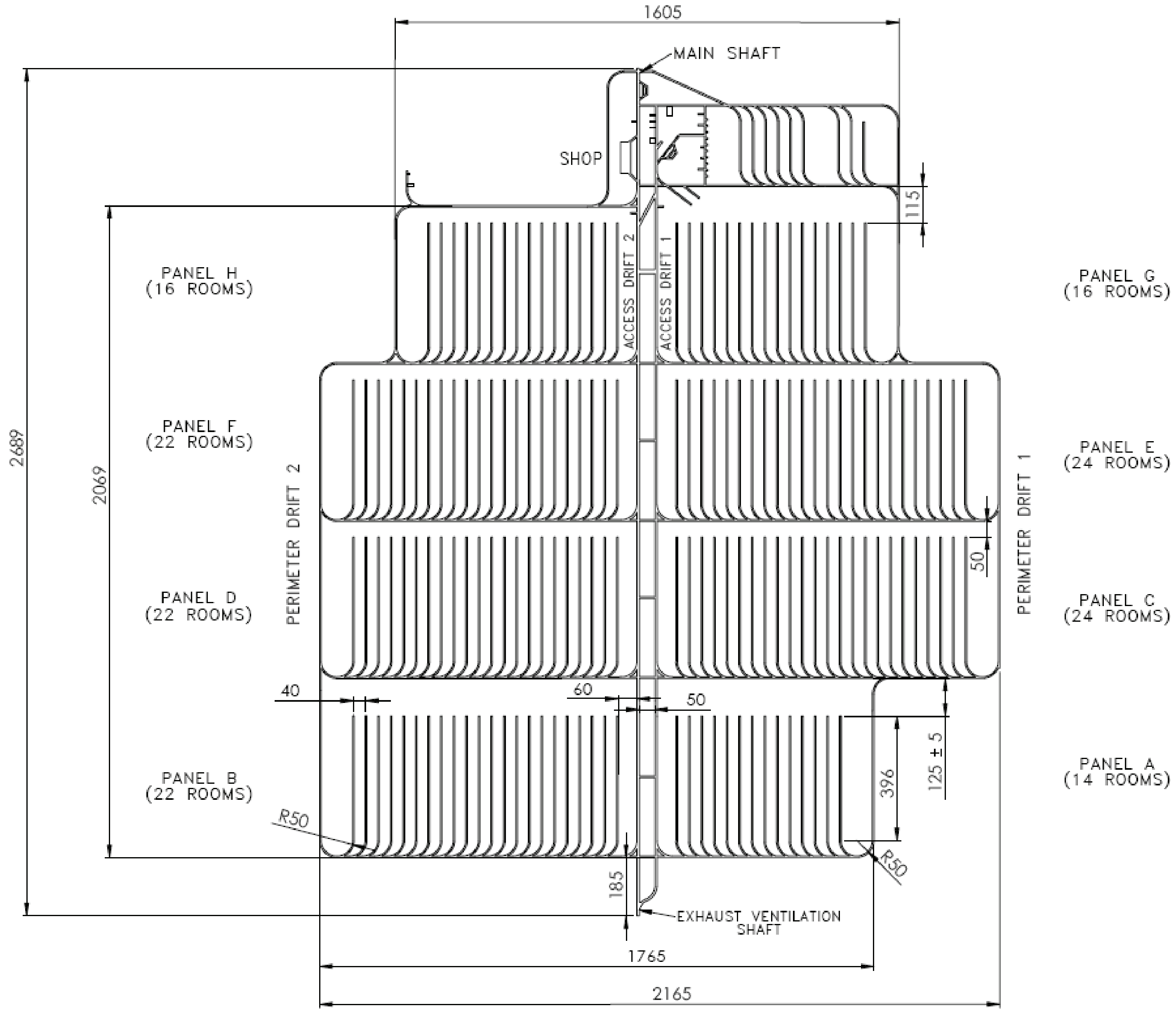


Figure 2: Example Underground Repository Layout for a Deep Geological Repository in Crystalline Rock

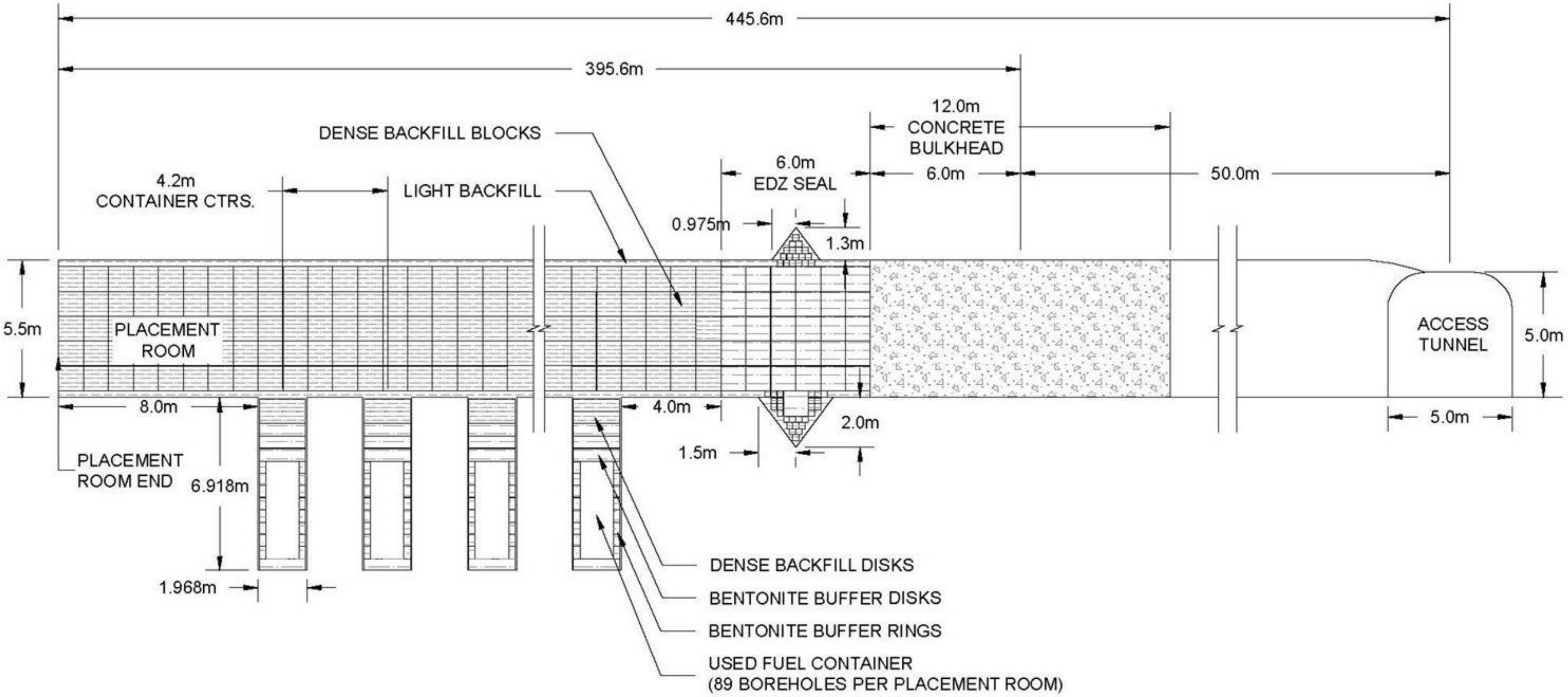


Figure 3: Longitudinal Section of the Container Placement Room - In Floor Borehole Configuration

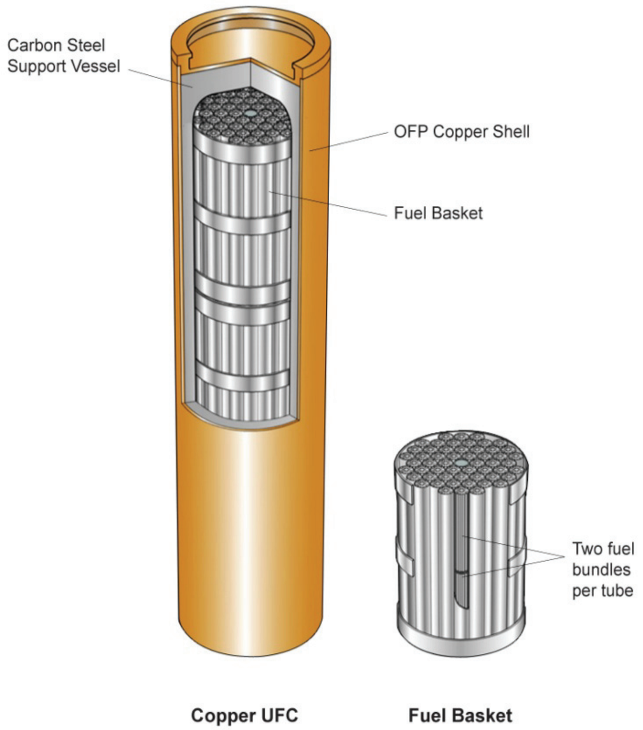


Figure 4: Example Copper Used Fuel Container and Fuel Basket

3.3 Engineered Barriers

The buffer placed between the container and the rock, consists of cylindrical and ring-shaped blocks of highly compacted bentonite. A minimum thickness of 35 cm of buffer material is required, which results in a minimum borehole diameter of approximately 2.0 m.

The bentonite buffer blocks have a specified uniform water content at the time of installation. During the first few years after placement of a used fuel container in a borehole the heat from the container would cause the moisture in the buffer to be redistributed, with the region closest to the container becoming drier than the peripheral region. This moisture migration process will be reversed over time as the containers temperature diminishes and groundwater from the near-field rock is absorbed into the bentonite clay. In the longer term the moisture content of the clay will gradually increase until full saturation of the buffer is achieved.

This is the normal process through which the buffer will attain its maximum swelling pressure, which ensures protection of the container surface and a diffusion-dominated transport regime. After saturation, the water will be practically immobilised in the bentonite pores, which would inhibit advective transport. The amount of time required to achieve this condition depends primarily on the geometry of the container placement room, the properties of the sealing materials and the permeability of the rock. Previous analyses have estimated that for a range in hydraulic conductivity from 10^{-11} m/s to 10^{-14} m/s, the buffer saturation times would range from 20 to 20,000 years (McMurry et al, 2003).

4 REPOSITORY DEVELOPMENT

During site characterization, several sets of data will be collected to further evaluate the geological properties of the site. These data could be enhanced via the construction of an underground demonstration facility adjacent to the proposed repository that would serve to demonstrate repository technology and monitor key features of the repository design at depth. Long-term tests in the underground demonstration facility could be used for example to study the corrosion behaviour of used fuel containers and to confirm predictions of repository evolution. The advantage of such facility would be to enable the study of near-field phenomena such as engineered barriers evolution and container corrosion over a time scale of many decades, including during the preclosure monitoring period.

Although an underground demonstration facility may be constructed, some of the phenomena to be modelled, such as the saturation of the engineered barriers, may not be tested because their evolution might exceed the length of the repository operating phase and preclosure period. In addition, the spatial variation in rock permeability may limit the value of such measurements and it might make the direct measurement of engineered barrier parameters necessary in order to confirm repository performance.

4.1 Construction and Operation

During construction and operation of the repository, in-situ measurements can be conducted as access shafts and tunnels are excavated and long-lived containers are placed in the repository. These data will serve to confirm the function of repository systems over the operations time frame. Much of the geological and engineering data from quality assurance activities during the repository construction and quality assurance activities will become part of the repository monitoring database.

During the operating period, the near-field environment surrounding the used fuel containers will start to evolve from an initial unsaturated aerobic phase towards an unsaturated anaerobic phase (which may last many hundreds of years). In the long-term, as the engineered barriers saturate the near-field environment will evolve into an anaerobic saturated phase that will prevail indefinitely (Kwong and Villagran 2011). Both the container corrosion behaviour and contaminant transport processes during these periods will depend on container and repository temperatures, on buffer saturation and total pressure as well as on geochemical conditions. The permeability of the host rock will be the key factor determining the time required for the engineered barriers to reach saturation and, specifically, for the buffer to reach final swelling pressure.

Seismic activity monitoring will be conducted at both the local and regional scale. Also, the structure and hydrology of the surrounding rock mass will be investigated and subsequently monitored using instrumented boreholes in the periphery of the repository. Several of these instrumented boreholes may remain active after repository closure. They will serve to monitor hydraulic head profiles and confirm that hydraulic pressures and groundwater flows have been restored. These data, along with groundwater flow models, will serve to identify potential changes in transport paths and travel times to the surface environment for any contaminants that could potentially be released from the repository.

4.2 Extended Monitoring Period

At the end of the repository operating phase, the container placement rooms will be backfilled and sealed, but access tunnels and shafts will remain open. During this extended monitoring period, the collection of data from systems located underground will produce valuable information for assessing the repository evolution and confirm the safety of the system. Monitoring data can be used to confirm that the engineered barriers are performing as planned and will be important for making a decision to close the repository.

The repository is expected to remain open for several decades after the used fuel container placement activities are completed. The container placement rooms will be closed by means of a clay seal and a concrete bulkhead but the access tunnels and drifts will remain open. An extended repository monitoring program will be conducted during this period, with the primary objective of verifying that the repository evolution is according to design and its performance is as predicted. This period of time is referred to as the extended monitoring period. A future society will decide the length of the extended monitoring period and will choose the time when the repository will be finally closed.

4.3 Repository Decommissioning and Closure

Once the extended monitoring period has been completed, the facility will formally enter a decommissioning stage, where the underground openings will be prepared for closure and then backfilled in a retreating manner towards the main shaft. The order of tunnel backfilling and sealing operations will be planned to ensure the safe and appropriate sealing of all excavated volumes. This will involve the strategic placement of seals to limit the length of interconnected volumes. These seals will be designed to interrupt potential transport pathways along the excavation damage zone that may exist in the near field rock. This operation will include also the sealing of any fracture zones or high-permeability areas intersecting the repository shafts and the placement of multi-component seals and bulkheads in the shafts.

After the underground facilities have been closed and sealed, the remaining surface facilities will be decommissioned and removed returning the land to a green-field condition.

The APM project will conclude with the decommissioning and closure of the repository facilities. However, there might be a need for monitoring during a post-closure period. For example, the monitoring of hydraulic heads in an area of the site surrounding the repository might be used to verify the restoration of the groundwater flow regimes after the repository tunnels and shafts are backfilled and sealed. Possible monitoring activities after closure of the repository are outside the scope of this report.

5 REPOSITORY SAFETY

Postclosure safety is assessed by examining the repository evolution under a set of future scenarios, each defined by a postulated set of conditions or events. The purpose of the process is to develop a comprehensive range of possible future condition against which the performance of the repository can be assessed. Both Normal Evolution and Disruptive Event scenarios are considered. The Normal Evolution Scenario represents the expected evolution of the site and facility, while Disruptive Event Scenarios examine the effects of unlikely events that might lead to the abnormal degradation of barriers and loss of containment, resulting in the release of radioactive contaminants to the environment.

Scenarios of interest are identified based on the consideration of a comprehensive set of Features, Events and Processes (FEPs) that could affect the repository system evolution. The FEPs are separated into two classes “external” and “internal” FEPs, depending on whether they are outside or inside the spatial and temporal boundaries of the repository system. This classification of FEPs is an arbitrary choice made for the purposes of safety analysis and not relevant for the purpose of identifying of monitoring parameters. The external FEPs include decisions related to repository design, operation and closure; those that can significantly affect either the evolution or safety functions of the repository are used to generate repository evolution scenarios.

5.1 Normal Evolution Scenario

The Normal Evolution Scenario considers a set of internal and external FEPs that have the potential to affect the repository safety performance. Table A1 in Appendix A lists the External FEPs used to generate the Normal Evolution Scenario. The most significant of the scenario generating FEPs are discussed below.

The used fuel containers have a robust design and are subject to a stringent quality assurance process. The lid closure weld is made using a friction-stir welding process chosen for its reliability, and it is subjected to two independent quality assurance tests. However, considering the large number of containers in the repository, there is a finite probability that a small number of containers placed in the repository could have undetected defects. For example, we assume that there is a 1/5,000 probability of placing in the repository a container with an undetected through-wall defect in the container closure weld. Consequently, for a used fuel inventory of 4.6 million fuel bundles packaged in about 12,800 used fuel containers, in the Normal Evolution Scenario it is conservatively assumed that three containers with undetected weld defects are placed in the repository.

Analysis of this scenario indicates that within the time frame of the assessment the only contaminant releases would originate from the three defective containers, but that if the rest of the repository systems (engineered barriers, seals) perform as per design, the contaminants could take many tens of thousands of years to reach the surface environment and the radiation doses to humans would be well below acceptable limits. There are no other FEPs considered in the Normal Evolution Scenario that would result in unacceptable radiation doses. Therefore, Disruptive Event Scenarios that consider combinations of external and internal FEPs need to be considered as well.

5.2 Disruptive Event Scenarios

Tables A2 and A3 in Appendix A provide a list of external and internal FEPs that have the potential to impact repository safety. Those considered in the present discussion on monitoring are highlighted. The FEPs that might impact repository safety include:

- Placement of containers with an undetected defect in the repository (included in the safety assessment as part of the repository Normal Evolution Scenario);
- Failure of the engineered barriers to evolve and perform as designed;
- Enhanced rock permeability in a fracture assumed to intersect the repository following an earthquake or a glaciation period;
- Inadvertent human intrusion; for example, drilling an exploratory borehole through a container placement room.

It is important to recognize that the probability of occurrence of events such as those listed above, or combinations of such events, is very low. For example, if we assume that the probability of having a borehole with a defective buffer (poorly sealed borehole scenario) is 1/5,000, the same value as the probability of having a defective container, the probability of having a defective container placed in a poorly sealed borehole would equal the product of both probabilities: $(1/5{,}000)^2$, which is equal to 0.4×10^{-7}. Although highly unlikely to occur, such scenarios need to be identified and examined in order to evaluate the associated risk, which is an important factor in establishing the need for monitoring related parameters. Failure of the engineered barriers in a borehole with a defective container will be used here as an example.

Under normal conditions, a saturated buffer that has reached its target swelling pressure protects the container surface from corrosion processes and precludes water movement, providing a diffusion controlled environment for transport of solutes. This, added to the sorption properties of the buffer, results in either the delay or immobilization of contaminants that may be released from a defective container. The dose consequences from a contaminant release are therefore mitigated as a result of the increased decay time of the released radioactive nuclides. Consequently, the only evolution scenarios that result in significant doses are those that include the enhanced transport of contaminant that would result from the breach of engineered barriers and/or increases in permeability that would create new or enhanced transport paths to the surface.

Since the potential presence of three defective containers in the repository is assumed to be part of the Normal Evolution Scenario, the possibility of having defective buffer surrounding one of these containers needs to be considered. The cause for buffer failure could be either the use of defective material for making the buffer blocks or having poorly installed buffer blocks, or could also be a design flaw that causes the buffer not to remain properly confined in the borehole as it saturates, failing therefore to attain the required swelling pressure. These events could occur in one or more of the three boreholes holding a defective container. Failure of the buffer to perform as per design (“buffer failure”) in a borehole that contains a defective container will be included in a Disruptive Scenario used for the purposes of this discussion.

A rigorous discussion of probability of occurrence and consequences of scenarios generated by the above events is the subject of the repository safety analysis, and is beyond the scope of this report. For the present purpose, the buffer failure scenario will be assumed to justify monitoring the evolution of the buffer.

6 MONITORING PROGRAM DESIGN

The proposed approach for identification and selection of monitoring parameters is based on first considering and ranking repository evolution scenarios on the basis of risk and then examining the FEPs associated with those scenarios. This process and can be used to construct a list of parameters that can be prioritized on the basis of risk. This process is shown in Figure 6.1. A partial list of potential monitoring parameters is given in Table 2.

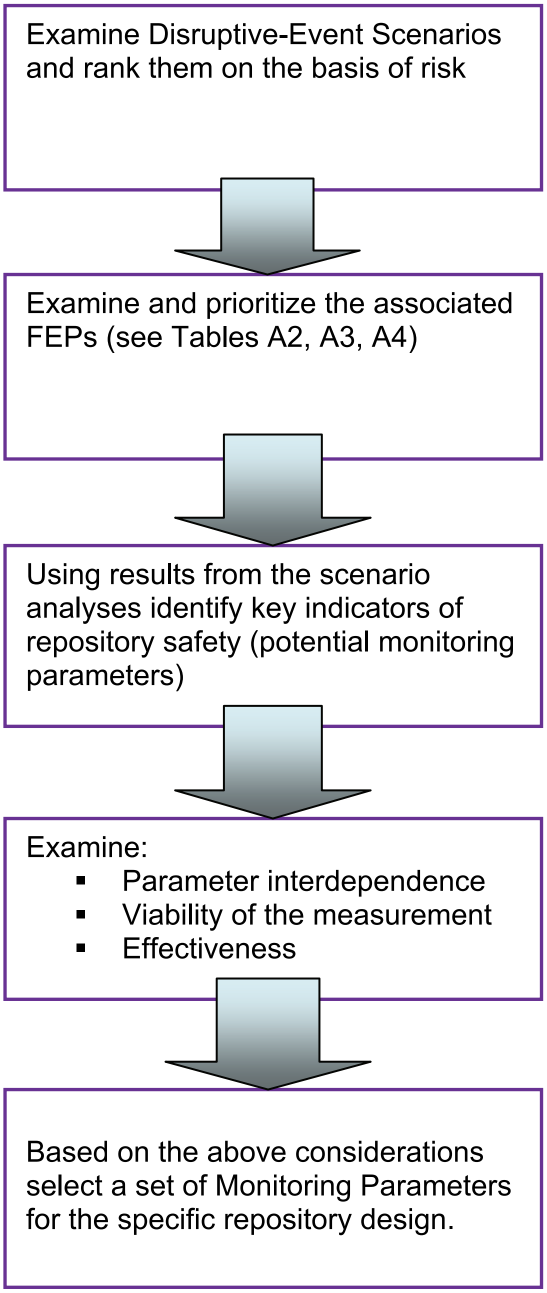


Figure 5: Process for Selection of Monitoring Parameters

Table 2: Potential Monitoring Parameters

Parameter	Media / Location	Measurement Methods / Comments
temperature	container surface	remote sensing methods and modelling, although more practical to monitor in a demonstration facility container surface temperature affects corrosion processes and may impact engineered barriers performance
temperature	engineered barriers	remote sensing methods, but more practical to monitor in a demonstration facility temperature close to the container surface is critical to long-term buffer performance
saturation	engineered barriers	measured using conventional probes and combined conventional and wireless readout technologies the level of saturation determines both total pressure and the container corrosion regime
total pressure	engineered barriers	total pressure cells with wireless output readout total pressure upon saturation determines engineered barriers performance
saturation	placement room seals	can be measured as previously indicated for the buffer; in this case power supply and signal transmission cables may be used important parameter for the preclosure extended monitoring period
total pressure	placement room seals	the proximity to the placement room entrance allows the use of conventional methods
temperature	near-field rock	remote sensing methods rock temperatures throughout the repository are important to assess its evolution and to confirm model predictions
stress distribution	near-field rock	stress cells in instrumented boreholes stress changes is an important factor in tunnel stability and repository performance

Table 2 (continued): Potential Monitoring Parameters

Parameter	Media / Location	Method / Comments
bulkhead displacement	placement room concrete bulkhead	can be monitored using either extensometers or a laser scanning system important during preclosure
hydraulic pressure	along specific profiles through repository and adjacent rock volume	piezometer network both within the repository and in a network of peripheral test boreholes monitors change in groundwater flow regime
temperature	in adjacent rock volume and in the far-field	thermistors or thermocouples rock temperatures are important to assess geosphere evolution and also for temperature correction of other measured parameters
mechanical stress	throughout repository and adjacent rock volume	sensor network both within the repository and in peripheral test boreholes
micro-seismic activity	throughout repository and adjacent rock volume	geophone network several applications in monitoring the geosphere and engineered barriers evolution
seismic activity	local and regional seismograph stations	dedicated seismographs near repository and national seismograph network. important to assess near-field rock mass response to seismic events
saturation	placement room bentonite clay seals	measured directly using different types of probes, wireless readout may be required full saturation, confirming that seal will perform as predicted, would be achieved over varying time scales depending on rock permeability
total pressure	placement room clay seals	piezometers and associated data loggers the final total pressure in confined clay seals determines the seal’s effectiveness
displacement	placement room bulkheads	position sensors useful to confirm the integrity of seals
hydraulic pressure	in rock volume adjacent to the repository	sensor network in long-term monitoring boreholes drilled in rock volume surrounding repository hydraulic pressure profiles serve to confirm configuration of the groundwater flow regime

The process outlined in Figure 6.1 requires knowledge of relevant geological data, monitoring technologies and safety analyses. The parameter selection process needs to consider also the interdependence between parameters and between monitoring functions in the context of the considered evolution scenarios. This task is an iterative process that will evolve along with the repository design and safety case. In order to illustrate the tasks involved in the development of a monitoring system, it will be argued that for a vertical borehole configuration, monitoring the buffer evolution carries a high priority.

Regardless of the specific set of assumptions used for the safety analysis, the transport time of released contaminants to the surface is an important parameter. If the buffer has evolved according to design, the transport of any released contaminants will be extremely slow. The delay in reaching the biosphere will limit radiological doses resulting from any potential release. Failure of the buffer could significantly reduce contaminant transport times. Therefore, buffer performance is a key contributor to repository safety, and parameters that can confirm its proper evolution are important indicators of repository safety. In this case, a key measurable parameter is the attained total pressure in the buffer. It can be measured with a good level of accuracy in the periphery of the buffer, and it could be measured using wireless technology, which would help preserve the integrity of the engineered barriers.

6.1 Monitoring System Concept for Engineered Barriers

For example, the proposed system for monitoring repository safety performance parameters includes two independent subsystems designed to confirm the evolution of the buffer. The buffer design and evolution are described in Section 3.3.

If the buffer evolves as per design, it would provide both mechanical and corrosion protection for the container, as well as barrier to contaminant transport. Verifying its performance provides assurance of safety over a broad range of evolution scenarios, therefore, its integrity is considered a key parameter and two separate subsystems are proposed to provide independent measurement of the buffer evolution. These two systems are designed to confirm that the swelling pressure of the buffer evolves according to model predictions, providing assurance of its effectiveness. These two systems, designated as “EB System A” and “EB System “B”, are independent from each other; they look at two different samples of the borehole population and monitor the buffer evolution in their respective target sample using two different measurement methods.

EB System A is intended to measure total pressure in the buffer in a large sample of the in-floor boreholes in the repository. The current repository design has 12,800 boreholes, to accommodate an inventory of 4.6 million used fuel bundles. The intent for this monitoring system is to measure total pressure in the buffer at three points in each borehole, in a large sample of the borehole population. The design concept for these sensors is described in Section 6.2. Placing a large number of sensors in the repository is possible by using a very simple, self-powered sensor that would provide only a single output signal when the chosen parameter, in this case total pressure, reaches its target value.

EB System B is intended to measure the rise in pressure in the buffer as a function of time in a much smaller sample. The sampled boreholes would be strategically selected based on factors that include knowledge of the near-field hydrology and outputs signal transmission capabilities. The intent in this case is to look at a significantly smaller sample and provide a measurement of the rate of buffer saturation as a function of time at selected locations in the repository.

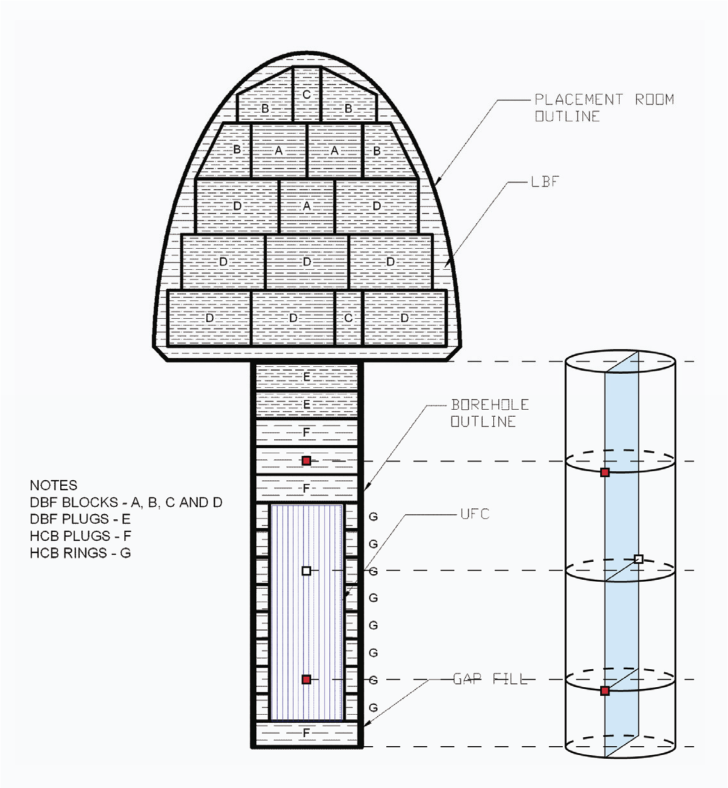
The information provided by these two systems, together with long-term container corrosion tests conducted at an underground demonstration facility, will provide evidence that the used fuel will remain encapsulated for the design life of the copper containers and that, consequently, radioactive releases will not occur over that period. Potential releases assumed to originate from containers with an undetected defect are expected to have dose consequences well below the acceptable limit. Any possible radioactive releases that would occur beyond the design life of the containers are also expected be well below acceptable limits, since the residual activity in the nuclear fuel waste would be at that point comparable to that of natural uranium deposits. A preliminary design concept for each of these two systems is described below. A key requirement for both is that the presence and operation of the sensors in the repository must not have a negative impact on the function of the engineered barriers.

The monitoring system concepts described below specifically address buffer evolution in a container placement borehole for the repository design described in Chapter 3. They do not intend to represent the only required monitoring systems for engineered barriers for either this or other repository configurations.

6.2 Design Concept for EB System A

The sensors for this sub-system consist of three total pressure cells installed in each sampled borehole. The sensor location should be on the periphery of the buffer, essentially between the buffer and the rock. These pressure cells would not require an external power supply and would be actuated when the buffer total pressure reaches a specified threshold, likely its target value at saturation. The design concept is that of a self-driven pressure sensor capable of generating a signal detectable by a dedicated network of receptors (e.g. geophones) located in the near-field rock. This network could be installed in a set of sub-horizontal, small-diameter boreholes drilled from the cross-cut tunnels into the rock pillars, at a specified distance from container placement tunnels. The system could be active during both, the repository operational phase and the preclosure monitoring phase. The geophone network would be expected to receive three signals from each container placement borehole indicating that the target value of the buffer total pressure has been attained in each of the instrumented boreholes. The time required for the buffer to reach saturation will depend on the permeability of the geosphere, which determines the rate of water supply to the buffer. Therefore, for low permeability the time required for the buffer to attain the final swelling pressure could be very long.

The time and spatial distribution of the pressure sensor signals will provide a global view of the repository evolution. The sensors would be installed along the axial plane of the placement room, as shown in Figures 6.2 and 6.3. Since they are required to indicate only that a target value has been attained a specific location, their power demand would not be large. A long-life power cell could be used as power supply for these sensors, or they could be designed to use the stored energy in the buffer to generate an output signal. The sensors could potentially be designed to produce an output signal at a discrete number of pressure values instead of just a single reading. However, their ultimate purpose is to indicate that the target total pressure for the buffer has been attained in a specific borehole.



NOTES
DBF BLOCKS - A, B, C AND D
DBF PLUGS - E
HCB PLUGS - F
HCB RINGS - G

Figure 6: Cross-section of a container placement room showing the proposed location of the total pressure sensors for EB System A

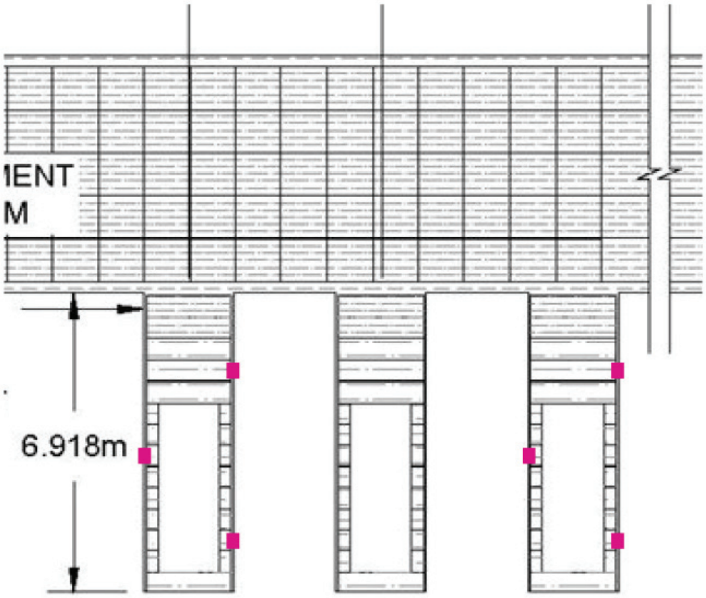


Figure 7: Longitudinal section of a container placement room showing the proposed location of total pressure sensors for EB System A

6.3 Design Concept for EB System B

Sub-system B would potentially look at a smaller sample of the borehole population that would be chosen to represent local hydrogeological conditions in each repository panel. The instruments installed at each sample point would monitor the development of total pressure in the buffer, and would include a controller unit, with a power supply and signal processing capabilities, installed above the borehole. The controller unit would also be capable of wireless transmission of the received signals to a readout unit in the open access tunnel. The sensors for this system would be installed at strategic points in the buffer, in a configuration that would have minimal impact on barrier performance. Transmission of the output signals to the controller unit would be routed along the interface between the buffer and the rock. Therefore, they would not impact the buffer function.

Although it would be useful to track saturation, a meaningful measurement of saturation time would require the measurement of pore pressures in locations close to the container, and this would not be possible without creating a potential water and contaminant transport path along the route of the wires, penetrating the barrier provided by the buffer. Also, this path would potentially alter the saturation process it is trying to characterize. Therefore using pressure sensors in the periphery of the buffer is considered the best approach to monitor the buffer evolution. The sensors in EB System B would provide a periodic signal monitoring the increase in total pressure in the buffer as it saturates. The selection of monitor locations would be dictated by several strategic considerations that would depend on the configuration of the repository as well as on geosphere features. It is recognized that the required longevity of the system would be one of the more challenging design requirements.

The pressure sensors could be hard wired to a control/signal processing unit located inside the container placement room, capable of supplying power to a number of sensors and of providing wireless relay of the output signals to a data-logger situated in the cross-cut tunnel, outside the respective emplacement room. Such configuration would minimize the required distance for transmission of wireless signals. If the emplacement room configuration allows placement of the power supply/controller units close to the entrance of each emplacement tunnel, the required distance for wireless data transmission would be reduced to a value approximately equal to the thickness of the placement tunnel seal (~ 6 m of compacted bentonite clay).

Total pressure in the buffer is considered the key indicator of buffer performance. It could be argued that direct measurement of pore pressures along a buffer profile should be measured to obtain readings directly related to buffer saturation, but a similar argument as that made against the measurement of saturation in the case of EB System A also applies in this case. Essentially any measurement of the saturation profile could compromise the integrity of the buffer barrier.

Information on the buffer saturation and evolution of total pressure could also be provided by a repository system model installed at a demonstration facility co-located with the geological repository. Such arrangement would allow monitoring the evolution of pore pressures along different buffer profiles. A full-scale model of the engineered barriers could be instrumented for this purpose as well as to measure other system parameters in an environment simulating the conditions in the repository. The demonstration repository model would serve for example to confirm predictions on other system variables, such as the containers corrosion rate.

7 DISCUSSION AND CONCLUSIONS

7.1 Discussion

A process for identification and selection of monitoring parameters that would form the basis for development of a repository monitoring program has been outlined. This process is based on elements of the repository safety case and considers the repository Normal Evolution Scenario as well as Disruptive Scenarios and the associated FEPs. associated with these scenarios. are used to identify potential monitoring parameters, and the results of the safety analyses are used to assess their importance.

The identification and ranking of monitoring parameters will be a process based on the thorough examination of the repository evolution scenarios. The set of FEPs associated with these scenarios will serve to identify key monitoring parameters for the system. Then, the viability, reliability and effectiveness of the applicable monitoring methods will need to be assessed. It is expected that, in general, there will not be a unique approach for each monitoring function, and alternative methods and technologies may play an important role as they may offer different options to confirm the repository safe performance.

It is desirable to have, if possible, two independent methods of measurement for each parameter. Redundancy in the determination of each parameter value is common practice in safety applications and it is considered essential in this case, where significant future decisions may depend on the reliability of the measurement results. Therefore, verification of results via independent measurements is considered an important requirement for the monitoring function.

An example monitoring system has been outlined to monitor the evolution of the bentonite buffer, an important safety feature of the engineered barrier system of the deep geological repository concept.

The discussion and preliminary development of approaches to monitoring a repository designed for crystalline rock presented in this report have benefited from international work conducted in recent years under OECD and EU programs, more specifically, from the work published by the MoDeRn Project, conducted under the EU 7th framewotk (EC, 2011), and by the NEA/RWMC Integration Group for the Safety Case.

7.2 Conclusions

One of the benefits from the early development of design concepts addressing specific monitoring functions is that they provide a basis for identifying the areas where technology development is needed. This would help identify requirements, potential obstacles and alternative solutions to different monitoring tasks.

Repository monitoring concepts have been developed for the purpose of this report, based on a preliminary repository design and the associated safety case. A path forward has been outlined identifying the essential components of a work program for development of repository monitoring systems within the APM framework.

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APPENDIX A:
FEPS AND POTENTIAL FAILURE MECHANISMS USED FOR DEVELOPMENT OF REPOSITORY EVOLUTION SCENARIOS

(Source: NWMO-TR-2016, in preparation)

Table A1: External FEPs for the Normal Evolution Scenario……………………………………………………………….22

Table A2: External FEPs Potentially Compromising Long-term Safety……………………………………………………....28

Table A3: Internal FEPs Potentially Compromising Long-term Safety………………………………………………………35

Table A4: Potential Failure Mechanisms and Associated Disruptive Scenarios……………………………………………… 39

Table A1: External FEPs for the Normal Evolution Scenario

External FEP			**Status***	**Remark**
1.1	***Repository Factors***			
	1.1.01	Site Investigation	**Included**	The site is hypothetical. The topography and hydrological properties are based on a Regional Groundwater Flow Model relevant to Canadian Shield conditions. The fracture network[1] is based on a statistical representation of Canadian Shield fracture patterns. It is assumed that there are no identified commercially viable mineral resources at the site.
	1.1.02	Excavation and Construction	**Included**	The repository is built consistent with the design basis as described in Chapter 3. Controlled drill and blast excavation is used, which minimizes but does not prevent the formation of an excavation damaged zone.
	1.1.03	Emplacement of Used Fuel Containers and Backfill	**Included**	The in-floor container placement method is used. Rooms are backfilled as containers are placed as described in Chapter 3. It is assumed that a 1/5,000 fraction of the large population of emplaced containers have an undetected, through-wall welding defect in the copper shell.
	1.1.04	Closure and Repository Sealing	**Included**	The repository is closed and sealed as described in Chapter 3. This includes sealing of a fracture intersecting the repository footprint and the shafts.
	1.1.05	Repository Records and Markers	**Included**	Repository records and markers (and passive societal memory) are assumed sufficient to ensure that inadvertent intrusion would not occur for at least a few hundred years.
	1.1.06	Waste Allocation	**Included**	The repository holds 4.6 million CANDU fuel bundles. There is no co-disposal of other radioactive or chemically hazardous material at the site.
	1.1.07	Repository Design	**Included**	The repository design concept is described in Chapter 3.

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[1] For the purpose of the safety analyses fractures are significant permeable features of the geosphere explicitly included in groundwater modelling simulations as a network of interconnected fracture zones. These fracture zones are represented in modelling simulations as equivalent porous media with a thickness of 1m. The effects of smaller scale permeable features are included within the hydrogeological properties of the rock mass.

External FEP			Status*	Remark
	1.1.08	Quality Control	**Included**	Construction, operation, monitoring and closure of the repository are all undertaken under a project quality plan that ensures that the design and safety basis are met.
	1.1.09	Schedule and Planning	**Included**	The assumed schedule is 38 years operation, 70 years monitoring and 25 years for closure.
	1.1.10	Repository Administrative Control	**Included**	Administrative controls ensure proper operation and closure of the repository. Institutional controls (e.g., land use restrictions) will be implemented on closure to prevent inadvertent human intrusion.
	1.1.11	Monitoring	Excluded	Any postclosure monitoring activities would not compromise the safety of the repository.
	1.1.12	Accidents and Unplanned events	Excluded	Preclosure abnormal or unplanned events that could impact the long-term safety of the repository will be mitigated before the repository is closed.
	1.1.13	Retrieval of Wastes	Excluded	The repository schedule includes an extended monitoring period after emplacement rooms have been filled, before the tunnels and shafts are backfilled sealed, which would facilitate container retrieval if required. However, retrieval after closure is not expected and is not included in this safety assessment.
1.2	***Geological Processes and Effects***			
	1.2.01	Tectonic Movement and Orogeny	Excluded	The hypothetical site is in a tectonically stable region away from plate margins, with no tectonic activity over the time scale of interest (i.e., 1,000,000 years).
	1.2.02	Deformation (Elastic, Plastic or Brittle)	**Included**	The Canadian Shield is one of the most tectonically stable regions on the planet. Over the next million years, the only significant deformation forces will be due to ice sheet advance/retreat over the site. This could cause crustal depression of 500 m, but would occur on a continental scale. Ice sheet weight could cause local movement along existing fractures but would not lead to creation of new fractures.

External FEP			**Status***	**Remark**
	1.2.03	Seismicity (Earthquakes)	**Included**	Earthquakes will occur over the time scale of interest; however, since the Shield is not a seismically active region, the likely magnitude, frequency and distance of earthquakes would limit their impact at the repository location. Larger earthquakes are more likely during retreat of ice sheets. These could reactivate existing faults. The main associated concern would be shearing along a fracture plane intercepting the repository, providing either a groundwater pathway or damaging containers.
	1.2.04	Volcanic and Magmatic Activity	Excluded	No volcanic or magmatic activity over the time scale of interest due to the site location.
	1.2.05	Metamorphism	Excluded	No processes occur over the time scale of interest that will cause metamorphism.
	1.2.06	Hydrothermal Activity	Excluded	The hypothetical repository is located on the Shield, which is geologically stable with a low geothermal flux. Hydrothermal processes therefore act too slowly to be of concern over the time scale of interest.
	1.2.07	Erosion and Sedimentation	Excluded	Topographically, the area is relatively flat and the surface is primarily granite bedrock, so there is limited potential for large-scale denudation. The ice sheet erosion that has occurred over the past 1,000,000 years has removed easily erodible material.
	1.2.08	Diagenesis	Excluded	The site is granitic rock, not sedimentary rock.
	1.2.09	Salt Diapirism and Dissolution	Excluded	No significant salt deposits are in the vicinity of the site because it is in the granitic rock of the Canadian Shield.
	1.2.10	Hydrological Response to Geological Changes	**Included**	A severe seismic event could potentially change fracture permeabilities or activate a fault and therefore change local hydrology. For this and other reasons, fractures at the repository site are modelled using conservative permeability values.
1.3	***Climate Processes and Effects***			
	1.3.01	Global Climate Change	**Included**	After a period of global warming, it is assumed that glacial / interglacial cycling will eventually resume since the solar insolation variation driving this cycling will continue.

External FEP			Status*	Remark
	1.3.02	Local and Regional Climate Change	**Included**	In the near term, global warming is likely to cause temperature and precipitation changes, although the local / regional climate is likely to remain generally temperate due to its northerly latitude location. In the long-term, it will respond to global climate change, and in particular will cool or warm with glacial cycles.
	1.3.03	Sea-level Change	Excluded	Changes in sea level do not affect the site due to its assumed mid-continental location.
	1.3.04	Periglacial Effects	**Included**	These will occur during colder climate states experienced during the glacial cycles that are likely to occur at the site over a one million year timeframe. In particular, this would include permafrost development.
	1.3.05	Local Glacial Effects	**Included**	Ice sheets will cause a range of local effects. These include change in rock stress (FEP 1.2.02), earthquake initiation (FEP 1.2.03), change in surface and near-surface hydrology (FEP 1.3.07), penetration of glacial waters to depth, changes in ecosystems (FEP 1.3.08) and human behaviour (FEP 1.3.09).
	1.3.06	Warm Climate Effects (Tropical and Desert)	Excluded	Climate change is unlikely to result in development of tropical or hot desert conditions at the site due to its northerly latitude. An initial period of human-induced global warming is not expected to result in an extreme temperature rise in this region.
	1.3.07	Hydrological Response to Climate Change	Excluded	Surface and near-surface groundwater systems could be altered by large climactic change to wetter or drier conditions. Specifically, the water table on the Canadian Shield is generally within a few meters of the surface and is maintained by a small influx of the total annual precipitation. The deep groundwater system at the site would not be significantly altered by climatic change to wetter or drier conditions due to its low-permeability and depth. Changes in hydrology due to glaciation are discussed under Periglacial Effects (1.3.04) and Local Glacial Effects (1.3.05).
	1.3.08	Ecological Response to Climate Changes	**Included**	Flora and fauna at the site change in response to glacial / interglacial cycling.

External FEP			**Status***	**Remark**
	1.3.09	Human Behavioural Response to Climate Change	**Included**	Human behaviour changes in response to glacial / interglacial cycling.
1.4	***Future Human Actions***			
	1.4.01	Human Influences on Climate	**Included**	Human actions are a possible cause of global climate change, which is included in expected evolution (see FEP 1.3.01, Global Climate Change).
	1.4.02	Deliberate Human Intrusion	Excluded	Deliberate human intrusion into the repository is not considered. It is assumed that any future society wishing to recover materials would have the technology to understand and manage the hazards.
	1.4.03	Non-Intrusive Site Investigation	Excluded	Non-intrusive site investigations would not have any effect because of the repository depth.
	1.4.04	Drilling Activities (Human Intrusion)	Excluded	The drilling of deep exploration boreholes that penetrate to the repository is excluded from the normal evolution scenario due to the repository depth (~ 500 m) and the assumed absence of commercially viable natural resources at the site. The drilling of shallow wells is considered under FEP 1.4.07.
	1.4.05	Mining (Human Intrusion)	Excluded	It is assumed that no commercially viable mineral resources are present at the repository site.
	1.4.06	Surface Environment, Human Activities	Excluded	Unlikely to have any direct impact on repository due to the repository depth.
	1.4.07	Water Management (Wells, Reservoirs Dams)	**Included**	The drilling of shallow water wells in the area is considered once institutional controls are no longer effective (see FEP 1.1.10). Wells in the deeper groundwater zones are excluded since the groundwater in these zones is not potable. The construction of dams and reservoirs is assumed not to have significant effects on the deep groundwater system.
	1.4.08	Social and Institutional Developments	**Included**	Institutional controls ensure appropriate use and control of the site in the near term. Eventually, the site is assumed to return to land use typical of the region and the site is occupied, including drilling of wells (see FEP 1.4.07).

External FEP			Status*	Remark
	1.4.09	Technological Developments	Excluded	It is assumed that the capabilities of future humans will largely resemble present-day capabilities. No credit is taken for advances that might further reduce or mitigate potential risks from the repository.
	1.4.10	Remedial Actions	Excluded	Remedial actions following closure of the repository are not considered in the safety analyses.
	1.4.11	Explosions and Crashes	Excluded	Most surface explosions and crashes would have no direct impact on the repository due to its depth.
1.5	***Other External Factors***			
	1.5.01	Meteorite Impact	Excluded	Excluded due to low probability (due to relatively small panel footprint) and /or low consequence (due to depth of repository).
	1.5.02	Species Evolution	Excluded	No evolution of humans assumed, consistent with the ICRP recommendation to apply the concept of present-day Reference Man to the disposal of long-lived solid radioactive waste (ICRP 2000). Similarly, no evolution of non-human biota is assumed.
	1.5.03	Miscellaneous FEPs	Excluded	Unusual FEPs such as earth tides, reversal of earth's magnetic poles, etc. are excluded because of their low probability or because they have no significant effect on the repository.

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

Table A2: External FEPs Potentially Compromising Long-term Safety

Safety Feature	Potentially Compromised by	Consider as Failure Mechanism
1. The depth of the host rock isolates the repository from surface disturbances and changes caused by human activities and natural events.	Near-surface design adopted (FEP 1.1.02).	**No**, only a deep design is being considered for the repository
	Meteorite impact (FEP 1.5.01).	**No**, due to low probability of meteor impact capable of compromising safety due to relatively small panel footprint (~4 km^2) and depth of repository (~500 m). See Garisto and Gierszewski (2012) for further discussion of probabilities.
	Exploration borehole penetrates into repository providing enhanced permeability pathway to surface environment and potential for direct exposure to waste (FEP 1.4.04).	**Yes**, although the absence of economically exploitable resources, and the depth (~500 m) and relatively small panel footprint (~4 km^2) mean that the probability of such a borehole intruding into the repository would be very low during the period of greatest potential hazard.
	Mining and other underground activities resulting in excavation in the vicinity of the repository (FEP 1.4.05).	**No**, due to assumption of the absence of commercially viable mineral resources at or below repository level. Shallow quarrying or tunnelling activities are unlikely to affect the repository because of repository depth (~500m). Also, most underground activities would likely be preceded by exploration boreholes, as addressed above.
	Deliberate human intrusion into repository (FEP 1.4.02).	**No**, exclude deliberate human intrusion since it is expected that the intruders would take appropriate precautions.
	Could discover resources that were not identified during site investigations (FEP 1.1.01) or exploit existing rocks that have become a commercially viable resource. These new resources are exploited by drilling or mining at or below repository level (FEP 1.4.04 and 1.4.05).	**No**, The lack of resources at the site is assumed to be consistent with regional information. Even if the existing rocks became commercially viable, the repository site is unlikely to become a mine site because similar rocks exist near the surface over a large lateral extent of the Canadian Shield. Also, deep mining activities would likely be preceded by an exploration borehole, which is considered under FEP 1.4.04.
	Repository, intersecting fractures and shafts not properly sealed at time of closure providing an enhanced permeability pathway to the surface environment (FEP 1.1.04).	**Yes**, although NWMO quality control and regulatory oversight will ensure that poor sealing is very unlikely.

Safety Feature	**Potentially Compromised by**	**Consider as Failure Mechanism**
	Site investigation / monitoring borehole not properly sealed at time of closure providing an enhanced permeability pathway to the surface environment (FEP 1.1.01 and 1.1.11).	**Yes**, although NWMO quality control and regulatory oversight will ensure that poor sealing is very unlikely.
	Poor construction techniques impact on the performance of the repository and shaft excavation disturbed zones providing an enhanced permeability pathway to the surface environment (FEP 1.1.02).	**Yes**, although NWMO quality control and regulatory oversight will ensure that poor sealing is very unlikely.
	Site investigations do not identify an existing permeable fracture that provides a connection between the repository horizon and shallow groundwater system (FEP 1.1.01).	**Yes**, a nearby fracture could be missed due to the limits of current technologies to identify all fractures in crystalline rock. Note that all known fractures are assumed open (transmissive) in the Normal Evolution Scenario.
	High magnitude seismic event results in reactivation of currently closed fractures and / or failure of shaft or fracture seals which provides an enhanced permeability pathway to higher horizons (FEP 1.2.03).	**Yes**, the assessment time scales are such that a significant event may occur even though the annual probability is low. Even then, the probability that the earthquake could actually reactivate a nearby fracture or fail the shaft or fracture seals is very small.
	Ice sheet erosion removes a significant thickness of rock above repository (FEP 1.2.07, 1.3.01, 1.3.02, 1.3.05).	**No**, Extrapolating the past rate of erosion implies that on the order of 30 m of granitic bedrock may be eroded over 1,000,000 years. This would not significantly reduce the geosphere barrier at the site given the depth of the repository (~500 m).
	Advance / retreat of ice sheets generate large hydraulic gradients which affect groundwater flow velocities in the deep groundwater zone (FEP 1.3.05).	**Yes**, The changing hydraulic head due to ice sheet advance and retreat over the repository site could affect groundwater flow at the repository level, although flow is likely to remain low in the deep rock due to its low permeability.
	Other external geological processes disrupt the repository system, i.e., Tectonic Movement (FEP 1.2.01), Volcanic and Magmatic Activity (FEP 1.2.04), Metamorphism (FEP 1.2.05), Hydrothermal Activity (FEP 1.2.06), Diagenesis (FEP 1.2.08) and Salt Diapirism and Dissolution (FEP 1.2.09).	**No**, since precluded by site's location and assessment time scales.

Safety Feature	Potentially Compromised by	Consider as Failure Mechanism
2. The volume of available competent rock at the repository site is sufficient to host the repository and provide sufficient distance from active geological features such as zones of deformation or faults and unfavourable heterogeneities	Site investigations do not identify an existing permeable fracture that provides a connection between the repository horizon and shallow groundwater system (FEP 1.1.01).	**Yes**, a nearby fracture could be missed due to the limits of current technologies to identify all fractures in crystalline rock.
	High magnitude seismic event results in reactivation of currently closed fractures and/or failure of shaft or fracture seals, which provides an enhanced permeability pathway to higher horizons (FEP 1.2.03).	**Yes**, the assessment time scales are such that a significant event may occur even though the annual probability is low. Even then, the probability that the earthquake could actually reactivate a nearby fracture or fail the shaft seals is very small.
	Other external geological processes disrupt the repository system, i.e., Tectonic Movement (FEP 1.2.01), Volcanic and Magmatic Activity (FEP 1.2.04), Metamorphism (FEP 1.2.05), Hydrothermal Activity (FEP 1.2.06), Diagenesis (FEP 1.2.08) and Salt Diapirism and Dissolution (FEP 1.2.09).	**No**, since precluded by site's location and assessment time scales.
3. The host rock would be considered as moderately fractured to sparsely fractured.	High magnitude seismic event results in reactivation of undetected or unknown existing structural discontinuity and / or failure of shaft or fracture seals which provides an enhanced permeability pathway to higher horizons (FEP 1.2.03).	**Yes**, the assessment time scales are such that a significant event may occur even though the annual probability is low. Even then, the probability that the earthquake could actually reactivate a nearby fracture or fail the shaft seals is very small.
	Other external geological processes disrupt the repository system, i.e., Tectonic Movement (FEP 1.2.01), Volcanic and Magmatic Activity (FEP 1.2.04), Metamorphism (FEP 1.2.05), Hydrothermal Activity (FEP 1.2.06), Diagenesis (FEP 1.2.08) and Salt Diapirism and Dissolution (FEP 1.2.09).	**No**, since precluded by site's location and assessment time scales.

Safety Feature	Potentially Compromised by	Consider as Failure Mechanism
4. The mineralogy of the rock and the geochemical composition of the groundwater and rock porewater do not adversely impact the clay seals or the container. 5. The mineralogy of the host rock, and the geochemical composition of the groundwater and rock porewater are favourable to retarding radionuclide movement.	Infiltration of oxygenated glacial melt-water into the repository leads to oxidizing conditions in the repository, causing relatively rapid corrosion of copper containers and enhanced mobility of redox sensitive nuclides of U, and Tc.	**No**, it is assumed that at this site there is good evidence that oxygenated waters only penetrate a short distance into the geosphere. Repository and boreholes would be located to avoid or seal off permeable fractures.
	Infiltration of glacial meltwater (without oxygen) into the repository modifies the hydrogeochemical conditions in the repository, affecting, for example, the stability of the buffer and backfill materials (i.e., leads to erosion of these materials due to colloid formation) (FEP 1.3.05).	**No**, it is assumed that at this site there is good evidence that in previous glaciations meltwaters have not penetrated to repository depth. Repository and boreholes would be located to avoid or seal off permeable fractures.
	Other external geological processes disrupt the repository system, i.e., Tectonic Movement (FEP 1.2.01), Volcanic and Magmatic Activity (FEP 1.2.04), Metamorphism (FEP 1.2.05), Hydrothermal Activity (FEP 1.2.06), Diagenesis (FEP 1.2.08) and Salt Diapirism and Dissolution (FEP 1.2.09).	**No**, since precluded by site's location and assessment time scales.
6. The host rock is capable of withstanding mechanical and thermal stresses induced by the repository without significant structural deformation or fracturing.	Presence of repository weakens rock near repository, potentially making it susceptible to fracturing during earthquakes which could be caused by ice sheet loading/unloading (FEP 1.2.02).	**Yes,** although all known fractures are assumed open (transmissive) in the Normal Evolution Scenario, an unknown fault or fracture could be reactivated by seismic activity particularly if it has been weakened by presence of repository.
7. Current and future seismic activity at the repository site do not adversely impact the integrity of the repository during operation and in the very long term.	High magnitude seismic event results in reactivation of currently closed fractures and / or failure of shaft or fracture seals which provides an enhanced permeability pathway to higher horizons (FEP 1.2.03).	**Yes**, the assessment time scales are such that a significant event may occur even though the annual probability is low. Even then, the probability that the earthquake could actually reactivate a nearby fracture or fail the shaft seals is very small.

Safety Feature	Potentially Compromised by	Consider as Failure Mechanism
	Large seismic event results in shearing along an existing local fracture that passes through a borehole. The shearing load causes failure of the used fuel container in the borehole.	**Yes**, the assessment time scales are such that a significant seismic event may occur even though the annual probability is low. However, the probability that an earthquake would cause a container failure due to a shear load is likely small (SKB 2011).
8. The expected rates of land uplift, subsidence and erosion at the repository site do not adversely impact the containment and isolation of the repository.	Ice sheet erosion resulting from climate change removes a significant thickness of rock above the repository (FEP 1.2.07, 1.3.01, 1.3.02, 1.3.05).	**No**, see discussion of ice sheet erosion under Argument 1.
	Land uplift decreases depth of repository.	**No**, land uplift occurs on a continental scale so relative depth of repository does not change. Land uplift and large-scale erosion are also not significant factors in affecting repository depth on assessment time scale.
9. The repository is not located within rock formations containing economically exploitable natural resources such as gas/oil, coal, minerals and other valuable commodities as known today. 10. The repository is not located within geological formations containing groundwater resources at repository depth that could be used for drinking, agriculture or industrial uses.	Mining and other underground activities resulting in excavation in the vicinity of the repository (FEP 1.4.05).	**No**, due to assumption of the absence of commercially viable mineral resources at or below repository level. Other underground activities are unlikely to affect the repository (e.g., rock quarry) because of repository depth (~500m). Also, such activities would likely be preceded by exploration boreholes, as addressed above.
	Deliberate human intrusion into repository (FEP 1.4.02).	**No**, exclude deliberate human intrusion since it is expected that the intruders would take appropriate precaution.
	Could discover resources that were not identified during site investigations (FEP 1.1.01) or exploit existing rocks that have become a commercially viable resource. These new resources are exploited by drilling or mining at or below repository level (FEP 1.4.04 and 1.4.05).	**No**, The lack of resources at the site is assumed to be consistent with regional information. Even if the existing rocks became commercially viable, the repository site is unlikely to be the mine site because similar rocks exist near the surface over a large lateral extent of the Canadian Shield. Also, the impact of drilling is already considered under exploration borehole (FEP 1.4.04).

Safety Feature	Potentially Compromised by	Consider as Failure Mechanism
11. Most of the initial radioactivity is held within the UO_2, where it can only be released as the used fuel dissolves. 12. The used fuel is a durable oxide that will take millions of years to dissolve under chemical conditions within the container.	Infiltration of oxygenated glacial meltwater into the repository leads to oxidizing conditions in the repository, causing relatively rapid corrosion of the copper containers and, after container failure, relatively rapid fuel oxidation and contaminant releases from fuel. (FEP 1.3.05)	**No**, it is assumed that at this site there is good evidence that oxygenated waters only penetrate a short distance into the geosphere.
13. The used fuel container has a design life of at least 100,000 years under the likely geomechanical and chemical conditions within the host rock at the repository horizon.	Poor manufacturing techniques or unanticipated material problems / interactions impact on the durability of the used fuel containers (FEP 1.1.03, 1.1.07) significantly reducing the expected lifetime of some containers.	**Yes**, although application of NWMO's quality control will ensure that poorly manufactured containers would be discovered and not used.
	Used fuel containers fail due to increase in the isostatic load caused by a thick ice sheet passing over the repository site.	**Yes**, although the containers are designed to withstand the isostatic load from buffer swelling, hydrostatic load and a 3 km thick ice sheet over the repository site, the possibility that the design load of the container could be exceeded due to the passage of a thicker ice sheet needs to be considered.
	Infiltration of oxygenated glacial meltwater into the repository leads to oxidizing conditions in the repository, leading to relatively rapid corrosion of the copper containers (FEP 1.3.05).	**No**, it is assumed that at this site there is good evidence that oxygenated waters only penetrate a short distance into the geosphere (<50m).
14. The container is surrounded by a layer of dense bentonite based clay that inhibits groundwater movement, has self-sealing capability, inhibits microbial activity near the container, and retards contaminant transport.		
	Bentonite buffer layer not properly installed and, therefore, the density of the buffer around the container is lower than design requirement.	**Yes**, although application of NWMO's quality control will ensure that poor sealing is very unlikely.
	Infiltration of glacial meltwater (without oxygen) into the repository modifies the hydrogeochemical conditions in the repository, affecting, for example, the stability of the buffer and backfill materials (i.e., leads to erosion of these materials due to colloid formation) (FEP 1.3.05).	**No**, it is assumed that at this site there is good evidence that in previous glaciations meltwaters have not penetrated to repository depth.

Safety Feature	Potentially Compromised by	Consider as Failure Mechanism
15. Institutional Controls will limit the potential for human encounter with the repository in the near term after closure	Institutional controls on the development of the site are ineffective (FEP 1.4.08). This allows development of the site (1.4.06) and human intrusion into the repository to occur by drilling (FEP 1.4.04) and / or mining (FEP 1.4.05)	**No**, Measures are assumed to be taken in the near term to ensure that information regarding the purpose, location, design and contents of the repository is preserved so that future generations are made aware of the consequences of any actions they may choose to take. With these institutional measures as well as general societal memory, and with the absence of commercially viable natural resources at depth, inadvertent intrusion in the near term after closure is not considered. However, Human Intrusion is considered in the long term, when institutional controls may no longer be effective.

Table A3: Internal FEPs Potentially Compromising Long-term Safety

Safety Feature	Potentially Compromised By	Consider as Failure Mechanism
1. The depth of the host rock isolates the repository from surface disturbances and changes caused by human activities and natural events.	No Internal FEP could result in a significant change in the depth of the repository. Note that FEP 2.3.12 relates to the erosion of surface deposits and not bedrock.	**No.**
2. The volume of available competent rock at the repository site is sufficient to host the repository and provide sufficient distance from active geological features such as zones of deformation or faults and unfavourable heterogeneities	An undetected feature (e.g., a fracture) in the geosphere provides a relatively high permeability connection between the repository horizon and higher horizons (FEPs 2.2.04 and 2.2.12)	**Yes**, a nearby fracture could be missed due to the limits of current technologies to identify all fractures in crystalline rock.
3. The host rock would be considered as moderately fractured to sparsely fractured.	An undetected feature (e.g. a fracture) in the geosphere provides a relatively high permeability connection between the repository horizon and higher horizons (FEPs 2.2.04 and 2.2.12).	**Yes**, a nearby fracture could be missed due to the limits of current technologies to identify all fractures in crystalline rock.
4. The mineralogy of the rock and the geochemical composition of the groundwater and rock porewater do not adversely impact the seals or the container.	Various repository FEPs (e.g., FEPs 2.1.04, 2.1.07 to 2.1.11), e.g., temperature rise in the repository, have the potential to modify the hydrological, mechanical and chemical conditions at repository depth, affecting seal properties and / or radionuclide movement.	**No**, the effects are likely to be localized to the immediate vicinity of the repository and these FEPs can be evaluated through considering different calculation cases for the Normal Evolution Scenario (e.g., no sorption and no solubility sensitivity cases) rather than through the development of alternative Disruptive Scenarios. For conservatism, concrete seals are assumed degraded from the time of repository closure.

Safety Feature	Potentially Compromised By	Consider as Failure Mechanism
5. The mineralogy of the host rock and the geochemical composition of the groundwater and rock porewater are favourable to retarding radionuclide movement.	Various repository FEPs (e.g., FEP 2.1.03, 2.1.04, 2.1.07, 2.1.09, 2.1.10) can influence the durability of the used fuel containers, potentially leading to container failures.	**Yes,** poor local conditions might cause a limited number of container failures. Note that the Normal Evolution Scenario already includes a number of containers with pre-existing defects (e.g., welding defects) which lead to early container failures.
	Various repository FEPs (e.g., FEPs 2.1.07 to 2.1.11) and geosphere FEPs (e.g., FEPs 2.2.05 to 2.2.10) can affect the rate at which contaminants are released from the repository and migrate through the shafts and geosphere.	**No**, the effects of these FEPs can be evaluated through considering different calculation cases for the Normal Evolution Scenario rather than through the development of alternative Disruptive Scenarios (e.g., no sorption and no solubility sensitivity cases). The possibility of repository and shaft excavation damage zones is considered in the Normal Evolution Scenario. Also, concrete seals are assumed degraded from the time of repository closure.
	Changes in porewater chemistry in repository due to, for example, presence of concrete adversely affects clay seals (FEP 2.105, 2.1.06).	**No**, use of low-temperature, low pH concrete in the repository minimizes interactions with clay seals. Also, the amount of concrete in the repository is small compared to the amount of clay sealing materials. Note that the Normal Evolution Scenario already includes a number of containers with pre-existing defects (e.g., welding defects) which lead to early container failures.
6. The host rock is capable of withstanding mechanical and thermal stresses induced by the repository without significant structural deformation or fracturing.	Mechanical and thermal stresses induced by presence of repository are underestimated and cause greater than expected fracturing within the repository and shaft excavation damage zones, providing an enhanced permeability pathway to the surface environment (e.g., FEPs 2.1.07, and 2.1.11).	**Yes**, although application of NWMO's quality control will ensure that stresses are not underestimated and engineering calculations include safety factors.

Safety Feature	Potentially Compromised By	Consider as Failure Mechanism
7. Most of the initial radioactivity is held within the UO_2, where it can only be released as the used fuel dissolves. 8. The used fuel is a durable oxide that will take millions of years to dissolve under chemical conditions within the container.	Various repository FEPs (e.g., FEPs 2.1.08 to 2.1.11 and 2.1.13) can affect the rate at which contaminants are released from the used fuel.	**No**, geological, hydrogeological, and geochemical evidence indicates that the geosphere at a Canadian Shield site will be robust to uncertainties in repository or geosphere FEPs. Furthermore, these FEPs can be evaluated through considering different calculation cases for the Normal Evolution Scenario rather than through the development of alternative Disruptive Scenarios.
	Release due to criticality accident.	**No**, the fuel is natural uranium. The fissile content of the used fuel is too low.
9. The used fuel container has a design life of at least 100,000 years under the likely geomechanical and chemical conditions within the host rock at the repository horizon.	Containers are not fabricated to specifications and so are placed in the repository with defects (FEP 2.1.03).	**Yes**, although the fabrication method is designed to be robust, and there would be multiple methods of inspection, there is statistically some probability of initial defects not being detected such that a few containers are placed with initial defects. Defects in the steel vessel, for example, could lead to container collapse. The Normal Evolution Scenario assumes some containers with undetected defects are present in the repository at the time of closure, leading to early container failures.
	Various repository FEPs (e.g., FEPs 2.1.04, 2.1.07 to 2.1.11) can influence the durability of the used fuel containers, potentially leading to container failures.	**Yes,** although evidence suggests that the copper container would be thermodynamically stable under the reducing conditions expected in the repository, poor local conditions might cause a limited number of container failures. The Normal Evolution Scenario assumes some containers with undetected defects are present in the repository at the time of closure, leading to early container failures.

Safety Feature	Potentially Compromised By	Consider as Failure Mechanism
10. The container is surrounded by a layer of dense bentonite-based clay that inhibits groundwater movement, has self-sealing capability, inhibits microbial activity near the container, and retards contaminant transport.	Various repository FEPs (e.g., FEPs 2.1.04, 2.1.07 to 2.1.11) can influence the durability of the used fuel containers, potentially leading to container failures.	**Yes,** although evidence suggests that the copper container would be thermodynamically stable under the reducing conditions expected in the repository, poor local conditions might cause a limited number of container failures. Note that the Normal Evolution Scenario already includes a number of containers with pre-existing defects (e.g., welding defects) which lead to early container failures.
	Various repository FEPs (e.g., FEPs 2.1.05 to 2.1.11) have the potential to modify the hydrological, mechanical and chemical conditions at the repository depth, affecting properties of clay-based materials.	**No**, the effects are likely to be localized to the immediate vicinity of the repository and these FEPs can be evaluated through considering different calculation cases for the Normal Evolution Scenario (i.e., no sorption and no solubility sensitivity cases) rather than through the development of alternative Disruptive Scenarios.

*: the Internal FEPS are shown in Garisto and Gierszewski (2012)

Table A4: Potential Failure Mechanisms Generating Disruptive Scenarios

Failure Mechanism	Associated Disruptive Scenario
Exploration borehole penetrates into the repository providing an enhanced permeability pathway to the surface environment and potential for direct exposure to waste	Human Intrusion
Poor construction techniques lead to a large excavation damage zone around shaft or fracture seals, which provides an enhanced permeability pathway to the surface environment	Shaft Seal Failure and Fracture Seal Failure
Repository and shafts are not properly sealed at the time of closure, providing an enhanced permeability pathway to the surface environment	Shaft Seal Failure and Fracture Seal Failure
Long-term performance of shaft or fracture seals and excavation damage zone deviates from that expected, due to some unexpected internal processes, resulting in an enhanced permeability pathway to the surface environment	Shaft Seal Failure and Fracture Seal Failure
Site investigation / monitoring borehole is poorly sealed at time of closure providing an enhanced permeability pathway to the surface environment	Poorly Sealed Borehole
Long-term performance of site investigation / monitoring borehole seal deviates from that expected, due to some unexpected internal processes, resulting in an enhanced permeability pathway to the surface environment	Poorly Sealed Borehole
Site investigations do not identify a relatively high permeability fracture that provides a connection between the repository horizon and higher horizons	Undetected Fault
Seismic event results in reactivation of an existing fracture and / or failure of shaft or fracture seals that provides an enhanced permeability pathway to higher horizons	Undetected Fault, Shaft Seal Failure and Fracture Seal Failure
Seismic event results in shearing along an existing local fracture passing through a borehole, resulting in failure of some container(s) due to the shear load.	Container Failure
Manufacturing defect in steel vessel or unexpected high local loads lead to mechanical failure of some containers.	Container Failure
Unexpected corrosion of copper container due to, for example, initial defects in copper, higher microbial corrosion caused by incorrect placement of a low density buffer around container, or unanticipated interaction of copper container with groundwater in the repository.	Container Failure