Monitoring the Long-Term Safety Performance of a Repository for Used Nuclear Fuel - 12294

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ABSTRACT

The nuclear waste management programs of several nations include plans for the design, construction and operation of deep geological repositories. Some of these programs have initiated the licensing process for their repository designs. Monitoring strategies and systems are at different levels of development in each program and there is common ground with respect to the ultimate goal of the monitoring function. In this context, the primary functions of a monitoring system are considered to be the verification of safety performance and making available information that may be required for implementation of future decisions such as the timing of repository decommissioning and closure or the possible retrieval of waste containers. This study examines some of the relevant issues and outlines a conceptual monitoring system for further study and development during implementation of Adaptive Phased Management, the method selected by the Government of Canada for long-term management of used nuclear fuel.

INTRODUCTION

Current deep geological repository concepts for used nuclear fuel and high-level radioactive waste are based on designs that ensure passive safety over the long term. This derives from the premise that long-term safety can only be assured if further actions to ensure the safe performance of the repository will not be required following closure of the facility. The primary function of a repository monitoring system is to provide information to support verification of repository safety performance.

In order to define a set of monitoring parameters and the basic components of a preclosure and postclosure monitoring system, a hypothetical site in the Canadian Shield was assumed for a reference deep geological repository for used fuel (Gierszewski el al. 2004). The safety analyses for this hypothetical site and repository design were used to identify important monitoring parameters and to develop specific monitoring systems for further study and investigation over the next several years as part of the repository technology program (Villagran et al. 2011).

REPOSITORY AND CONTAINER DESIGN

The Nuclear Waste Management Organization (NWMO) is implementing Adaptive Phased Management, Canada’s plan for long-term management of used nuclear fuel. Adaptive Phased Management includes sealing used nuclear fuel within durable long-lived containers and placing the containers in a deep geological repository. This paper specifically considers a repository designed for a hypothetical low permeability crystalline rock site in the Canadian Shield using an in-floor borehole configuration for used fuel containers. The vertical in-floor borehole container placement method has been selected for development of repository designs by several nuclear waste management organizations, including those of Sweden, Finland and Canada.

The reference Adaptive Phased Management deep geological repository concept in crystalline rock is illustrated in Figure 1.

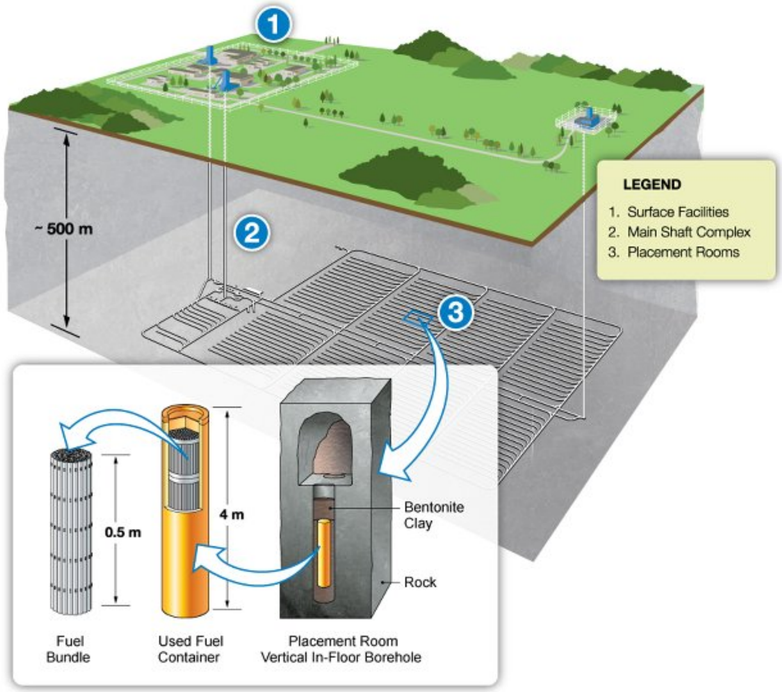

Figure 1: Conceptual design for a deep geological repository in crystalline rock with in-floor borehole placement of used fuel containers.

The conceptual design for repository was developed on a single level at a depth of 500 m with capacity for 3.6 million used CANDU fuel bundles. Access and ventilation are provided via vertical shafts. The underground development includes perimeter drifts, cross-cuts, and used fuel container placement rooms. The placement rooms consist of a series of parallel tunnels arranged in several panels. The placement rooms have a centre-to-centre spacing of 40 m and a single access from the corresponding repository cross-cut. The length of the rooms is about 400 m and the in-floor boreholes where the used fuel containers are placed have a center to center spacing of 4.2 m and are 1.97 m in diameter. After the container placement operations are completed in each room, the room will be backfilled and sealed by means of a 6 m long clay seal and a concrete bulkhead (SNC-Lavalin 2011).

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 and the transport of radioactive species as well as inhibit the viability of bacteria. When the buffer reaches saturation, the pore water will be practically immobilised in the bentonite pores, which results in diffusion becoming the dominant form of transport in the buffer.

A similar process occurs in the other engineered barriers, which results in the diffusion-dominated transport of contaminants through the repository. The time for the buffer to reach saturation will depend on the permeability of the rock and the fracture network at the repository site, and may be as long as thousands of years (McMurry et al. 2003).

Used Fuel Container

The current reference design for the used fuel container (IV-25) consists of an outer copper shell, an inner carbon steel vessel and three carbon steel baskets used to load the fuel. Each basket holds two layers of 60 used CANDU fuel bundles, yielding a total container capacity of 360 fuel bundles. Therefore, a used fuel inventory of 3.6 million fuel bundles would require a total of 10,000 used fuel containers.

The reference copper container design (IV-25) is illustrated in Figure 2. It has a 25 mm thick copper corrosion shell and a 102 mm thick inner steel vessel for mechanical support. The container is designed to withstand a maximum isotropic pressure of 45 MPa which may occur during glaciation cycles. The service life of the copper containers in a deep geological repository is expected to be over one million years (Kwong and Villagran, 2011).

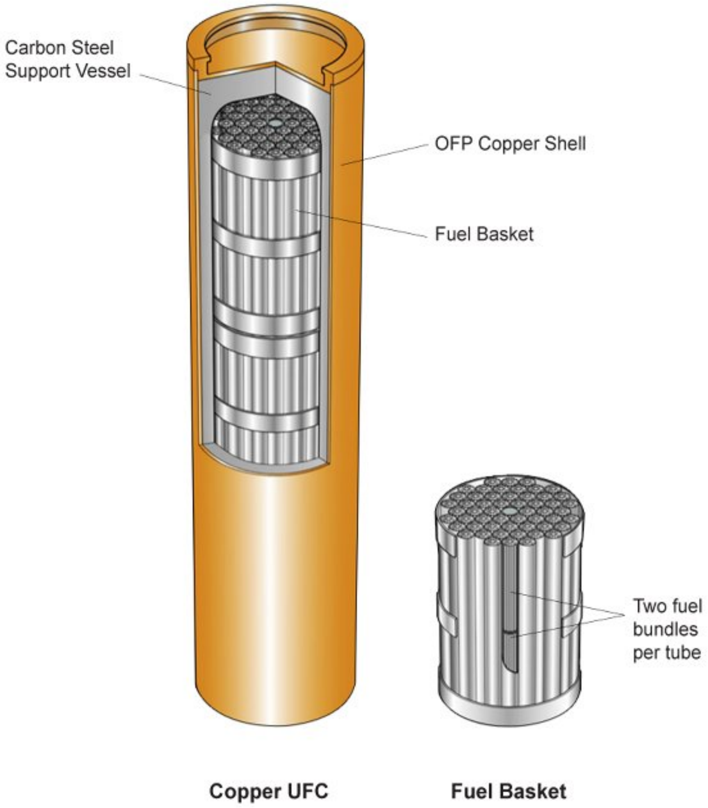

Figure 2: Copper used-fuel container and fuel basket

BASIS FOR MONITORING

Deep geological repository programs are envisaged as projects to be implemented in an incremental manner, with decisions being made in consultation with multiple stakeholders that include regulatory bodies and members of the public. As each project advances through its

different stages, more detailed safety assessments will be prepared, enhancing the level of confidence in the safety of the repository.
The Nuclear Energy Agency (NEA) has outlined a number of considerations regarding the monitoring of deep geological repositories (NEA 2005). These considerations include the following:

1. Monitoring programs should have a clearly defined strategy that establishes: when, why, what, and how to monitor; and
2. Monitoring programs should ensure the soundness of the program through a clear identification of purpose, methodology and limitations.

These NEA considerations will be helpful in developing monitoring systems.

REPOSITORY MONITORING PERIODS

Conceptually, the lifetime of a deep geological repository can be divided into a number of periods or phases of implementation. Typically, the preclosure period includes siting, environmental assessment and licensing, construction, operation, extended monitoring and decommissioning. The postclosure period follows closure of the facility. The nature and duration of any postclosure activities, including monitoring, would be the subject of decisions by a future generation.

During siting, several sets of scientific data will be collected in order to characterize and evaluate the geological properties of the repository site. These data could be enhanced via the construction of an underground facility adjacent to the repository to further characterize the site, demonstrate repository technology and monitor key features and geosphere properties at repository depth. For example, long-term tests in an underground demonstration facility could be used to monitor the corrosion of the used fuel containers and to confirm predictions of repository evolution and container lifetime.

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 time. Much of the geological and engineering data originating the repository construction and operation quality assurance process will become part of the repository monitoring database.

During the operating period, the near-field environment surrounding the used fuel containers will evolve from an initial unsaturated aerobic phase to an unsaturated anaerobic phase (which may last many hundreds of years), and finally evolve into an anaerobic saturated phase that will prevail indefinitely (Kwong and Villagran 2011). Corrosion and radionuclide transport processes during this period are dependent on container and repository temperature, buffer saturation and total pressure, host rock permeability and geochemical conditions.

Some components of the monitoring system will be located some distance from the repository. For example, 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 transport paths and travel times to the surface environment for any contaminants released from the repository.

At the end of the repository operating phase, the used fuel 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 evolution of the repository and to 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 decommission and close the repository. After repository closure, a postclosure monitoring system could be installed to provide information needed to verify the long-term safety of the repository.

MONITORING PARAMETERS

The results from site characterization activities and safety analyses can be used to identify important parameters for monitoring. In the absence of specific site information, generic case studies which assess the long-term safety of deep geological repository designs for used nuclear fuel can be used. For example, Gierszewski et al. (2004) conducted a generic safety assessment for a used fuel repository at a hypothetical site in low-permeability crystalline rock in the Canadian Shield. The results from this safety analysis and other similar studies indicate that the long-lived and relatively mobile isotopes of iodine and chlorine, I-129 and Cl-36, are the only radionuclides that reach the biosphere in measurable quantities Figure 3.

The potential parameters for monitoring during the preclosure and postclosure periods are listed in Tables 1 and 2, respectively. However, it is expected that the features and characteristics of the repository site, as well as the final design of the repository and the safety analyses will determine the important parameters to monitor.

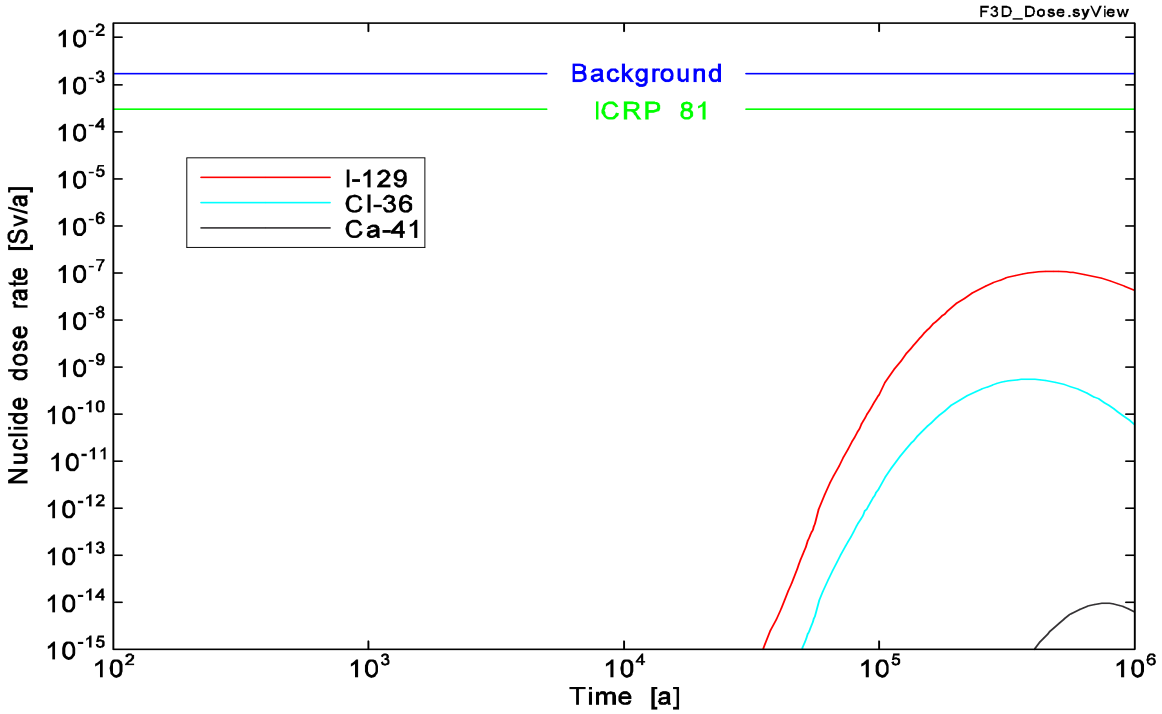

Figure 3: Calculated dose rates to a self-sufficient farmer (Gierszewski et al. 2004).

Table I: Potential Repository Monitoring Parameters - Preclosure

Parameter	Media / Location	Method / Comments
temperature	container surface	remote sensing methods and modelling, although more practical to monitor in a demonstration facility container surface temperature influences corrosion processes
temperature	buffer	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	buffer	measured using conventional probes and combined conventional and wireless readout technologies level of saturation determines both total pressure and the container corrosion regime
total pressure	buffer	total pressure cells with wireless output readout total pressure upon saturation determines buffer performance
saturation	backfill	can be measured as previously indicated for the buffer not a critical parameter
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 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

Parameter	Media / Location	Method / Comments
rock displacement	placement rooms, tunnels and shaft walls	can be monitored using both extensometers and/or a laser scanning system important during preclosure
bulkhead displacement	placement room concrete bulkhead	monitored using either multi-point extensometers or a laser scanning system important during preclosure
water seepage	throughout repository	water seepage collection, sampling and analysis is required, particularly from EDZ around emplacement room bulkheads
geochemistry and radioactive species	throughout repository and adjacent rock volume	analysis of water samples collected from repository openings and borehole network important to establish chemical signature of groundwaters and to monitor for radionuclides
hydraulic pressure	along specific profiles through repository and adjacent rock volume	piezometer network both within the repository and test boreholes in the surrounding rock volume
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
excavation damage zone development	around placement rooms, access tunnels and shafts	instrumented boreholes monitored during construction and preclosure period important for assessing contaminant transport

Table II: Repository Monitoring Parameters - Postclosure

Parameter	**Media & Location**	**Method / Comments**
corrosion	container	not measured directly, but long-term corrosion tests could be conducted in a demonstration facility
saturation	shaft 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	shaft clay seals	piezometers and associated data loggers the final total pressure in confined clay seals determines the seal's effectiveness
displacement	shaft bulkheads and seal components	position sensors useful to confirm the integrity and performance of accessible shaft seals
temperature	rock volume adjacent to the repository	temperature sensors such as thermocouples or thermistors useful parameter to track repository and geosphere evolution
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
seismic activity	using local and regional seismograph stations	measurement of seismic events allows the assessment of possible impact on near-field rock mass or on relevant fractures
radioactivity and contaminants in groundwater	in strategically located boreholes around the repository site	measurement of I-129 and Cl-36 in water samples from monitoring boreholes and from discharge zones is the key monitoring function to confirm repository safety essential to confirm the absence of radioactive contaminants in the groundwater

PRECLOSURE MONITORING

Many of the activities conducted to provide assurance of repository safety during the operational phase will be part of the construction and operation quality assurance program. Both, quality assurance and specific monitoring activities will complement each other and contribute to the repository monitoring database. At the end of the operations phase, there will be an extended preclosure monitoring period during which some of the monitoring activities conducted during operations will continue until the repository is finally closed.

During the preclosure period, access tunnels will remain open and the collection of data from sensors that have data loggers located in the access tunnels (cross-cuts) can also be continued. This capability is important because it will enable monitoring of the engineered barriers (EB) evolution for many decades. Ultimately, the selection of a preclosure monitoring system will be an evolutionary process. Although more comprehensive data sets are likely to provide more evidence of repository safety, it will be a decision by a future society to establish how much information is required to provide the required level of confidence.

An important challenge for monitoring during the preclosure period is how to monitor important parameters without compromising the integrity of the engineered barriers and the safety of the repository. The particular preclosure monitoring system outlined below is an initial conceptual design to assess the performance of the buffer following placement of used fuel containers in the borehole, backfilling and sealing of the placement rooms.

Monitoring System Concept for the Buffer

The proposed system for monitoring parameters related to the repository safety performance includes two independent subsystems designed to confirm the evolution of a key engineered barrier (EB), the bentonite buffer that surrounds the used fuel container. The two monitoring system components are intended to confirm that the water uptake and swelling pressure of the buffer evolve according to model predictions. These two monitoring subsystems are designated as EB System “A” and EB System “B” and are independent from each other. The intent is to provide two independent measurements on different sets of samples of the borehole population in the repository.

EB System A will measure total pressure in the buffer in a selected sample of the in-floor boreholes in the repository. The current design has 10,000 boreholes, to accommodate a total inventory of 3.6 million used fuel bundles. The intent for this system is to look at a large sample size and measure total pressure in the buffer at three points in each sample borehole.

EB System B will measure both the water uptake and the rise in pressure in the buffer as a function of time. The optimum sample size will also be determined at a later time, however, the intent is for this system to look at a significantly smaller sample size.

The information provided by these monitoring systems, together with long-term container corrosion tests conducted at the underground demonstration facility, will provide evidence that the used fuel will remain encapsulated for the design life of the copper containers and that any possible radioactive releases would be well below acceptable levels. The high-level conceptual design for each of these systems is described below. One key requirement for both systems is that the presence and operation of the sensors must not have a negative impact on the function of the buffer.

EB System “A”

The sensors for this sub-system consist of three total pressure cells installed in each sample borehole with a used fuel container, on the periphery of the buffer, essentially between the buffer and the rock. These pressure cells will not require an external power supply and will be actuated when the buffer total pressure reaches a specified threshold or target value. The type of instrument is not yet specified in detail; the design concept is that of a self-driven pressure sensor capable of generating a signal detectable by a dedicated network of geophones. The network would consist of installed in sub-horizontal boreholes drilled from the cross-cut tunnels into the rock pillars, between placement rooms. The system will be active during both repository operational and preclosure monitoring phases, and is expected to receive three signals from each borehole indicating that the target value of the buffer total pressure has been attained at each of the instrumented boreholes. The permeability of the geosphere will determine the rate of water supply to the buffer and therefore the length of the time period over which saturation of the buffer will occur.

The time and spatial distribution of the pressure sensor signals will provide a global view of the repository evolution. Their locations would be along the axial plane of the placement room, likely be mounted on two buffer rings (at container height) and one buffer disk (above the container). Since they are required to indicate only that the target value of buffer total pressure has been attained in the borehole, their power demands would not be large. A long-life power cell could be used as power supply for these sensors. If viable, the sensors could be designed to produce an output signal at a discrete number of points 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.

EB System “B”

Sub-system B would potentially look at a smaller sample of selected boreholes that could be chosen to represent the local hydrogeological conditions in each repository panel. The instrumentation installed in each borehole will monitor the saturation process and the development of total pressure in the buffer, and will include a controller and signal processor unit installed above the borehole. The sensors will be installed in the buffer blocks surrounding the container, in a configuration that would have zero or minimal impact on the engineered barrier. They will provide either a continuous or a periodic signal monitoring the evolution of saturation and total pressure in the buffer. The preferred boreholes for this sample will be those closest to the placement room bulkhead.

The system will be configured using total pressure sensors and pore pressure sensors located in the buffer and in the interstitial space between the buffer and the rock. These sensors can be hard wired to a control/signal processing unit installed above the borehole. This unit will supply power to the sensors and provide wireless relay of the sensor signals to data-loggers situated in the cross-cuts, outside the respective placement room. Suitable wireless technology (such as ZigBee) is being developed and currently being tested at the Grimsel Test Site in Switzerland (European Commission, 2011). The minimum required distance for wireless signal transmission in this case is equal to the thickness of the placement room clay seal (6 m) if the receivers are placed in the cross-cuts or, alternatively, several metres through the rock to receivers placed in boreholes drilled into the pillars between placement rooms.

A back-up indication of buffer saturation times and total pressure evolution would be provided by a model container-borehole system installed in a demonstration facility. For this purpose, a full-scale borehole model would be instrumented to measure not only buffer saturation and total pressure but also other system parameters. This demonstration model could also provide material samples to confirm predictions on other system variables such as container corrosion behaviour.

Monitoring Systems in the Open Tunnels

Convergence measurements are in general measured by multi-point extensometers, however, after the repository operational phase, an automated laser system may be the most convenient option to monitor rock displacement. A set of targets for this purpose can be mounted along the tunnels, including on the placement room bulkheads. The position of specific targets groups could be scanned and recorded periodically (e.g., annually) during the preclosure monitoring period. The convergence measurements, along with the records of micro-seismic activity would provide information relevant to the timing of a decision to close the repository.

Another important measurement to be conducted during preclosure is the monitoring of placement room seals. As long as the repository tunnels remain open there will a substantial hydraulic pressure gradient near the openings since the tunnel spaces will be at atmospheric pressure. This will facilitate monitoring of the room closure seal. Conventional seal monitoring methods can be used for the purpose, and they will not be described here. Several other parameters, for example temperature, could be monitored to verify that the repository and the geosphere behaviour are evolving as predicted.

POSTCLOSURE MONITORING

The decision to close the repository will be made after a period of extended monitoring following container placement during repository operations. Repository closure is expected to take place after quality assurance procedures have verified that the used fuel containers and sealing systems were placed in the repository according to design and met all quality requirements, and preclosure monitoring systems have confirmed the expected evolution of the engineered barriers and the near-field geosphere to support the safety case.

As in the preclosure period, postclosure monitoring of important parameters needs to be developed without compromising the integrity of the engineered and natural barriers, and the overall safety of the repository (Thompson et al. 2003).

One approach to consider would be to an array of instrumented boreholes at the periphery of the repository that would monitor seismic activity, hydraulic heads, rock temperature and sample groundwater for key radionuclides. During implementation of Adaptive Phased Management, postclosure monitoring systems will be further studied and developed. Ultimately, the nature and duration of postclosure monitoring activities will be decided by a future society.

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