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INCORPORATING LONG-TERM MONITORING INTO A MODIFIED NUCLEAR FUEL WASTE REPOSITORY

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ABSTRACT

An approach to long-term monitoring for a Canadian geologic repository for the isolation of used nuclear fuel waste is described. The monitoring approach begins with the siting of the facility and continues with preclosure monitoring through repository operation, extended underground monitoring, decommissioning and closure. At the completion of the closure activities, the repository should be passively safe. A program of postclosure monitoring from surface is proposed that could continue as long as required by stakeholders. The proposed postclosure monitoring program described should not jeopardise the long-term, passive safety of the repository.

I. INTRODUCTION

In 1994, Atomic Energy of Canada Limited (AECL) submitted an Environmental Impact Statement (EIS)[1] on the concept for deep geological disposal of Canada's nuclear fuel waste to a federal Environmental Assessment and Review Panel. The lack of a comprehensive approach to long-term monitoring beyond the decommissioning and closure of the repository was noted as a deficiency by reviewers of the EIS and documented in their submissions to the Nuclear Fuel Waste Management and Disposal Concept Environmental Assessment Panel. In their 1998 report[2], the Panel recommended the development of practicable long-term waste management options, including a modified AECL concept for deep geological disposal, which would include a long-term monitoring program. The Panel noted that it believed, "… better technologies for safe postclosure monitoring and retrieval must be developed and incorporated."

The Nuclear Waste Management Organization (NWMO) was formed in 2002 November to study and assess approaches for long-term management of nuclear fuel wastes in Canada and to recommend an approach to the government of Canada. The nuclear waste management options being considered include:

- a modified AECL concept for deep geological disposal,
- continued storage at reactor sites, and
- centralized storage, either above or below ground.

One of the most significant modifications to the AECL concept for deep geological disposal is the inclusion of provisions for long-term monitoring of the repository. This paper describes the long-term monitoring concepts and technologies being developed by AECL and Ontario Power Generation (OPG) that could be applied to a deep geological repository for nuclear fuel waste.

The various waste emplacement configurations proposed for a geologic repository for the permanent isolation of nuclear fuel waste in Canada share a number of features. They consist of horizontal arrays of waste emplacement rooms at a nominal depth of 500 to 1000 m in plutonic rock of the Canadian Shield. Each waste emplacement room contains used fuel within corrosion-resistant containers spaced in a uniform array, either vertically within boreholes drilled into the floors of the rooms (in-floor borehole emplacement method) or horizontally within the confines of each room (in-room emplacement method), and surrounded by repository sealing systems (e.g., clay-based buffer and backfills). One concept for in-room emplacement is illustrated in Figure 1. The rooms are linked by a network of 12 to 20 km of access tunnels, which are connected by 3 to 5 access shafts and/or inclined ramps to the surface (Figure 2).

Monitoring is the continuous or intermittent observation and recording of conditions, and is an essential and integral activity in the preclosure and postclosure phases of a geologic repository. The repository would be monitored to confirm that the facility was performing as expected. The main objectives of long-term preclosure monitoring[3,4] are to:

- obtain sufficient, accurate and pertinent baseline data so that design requirements for the repository can be met;
- ensure that regulatory compliance requirements are being met, which will entail the early detection of any unacceptable environmental emissions so that corrective actions can be taken;
- detect any performance problems with repository systems and components at an early stage so that corrective actions can be taken in a timely manner; and
- develop sufficient confidence in the performance of the repository facility design to enable stakeholders to decide to decommission and close the repository.

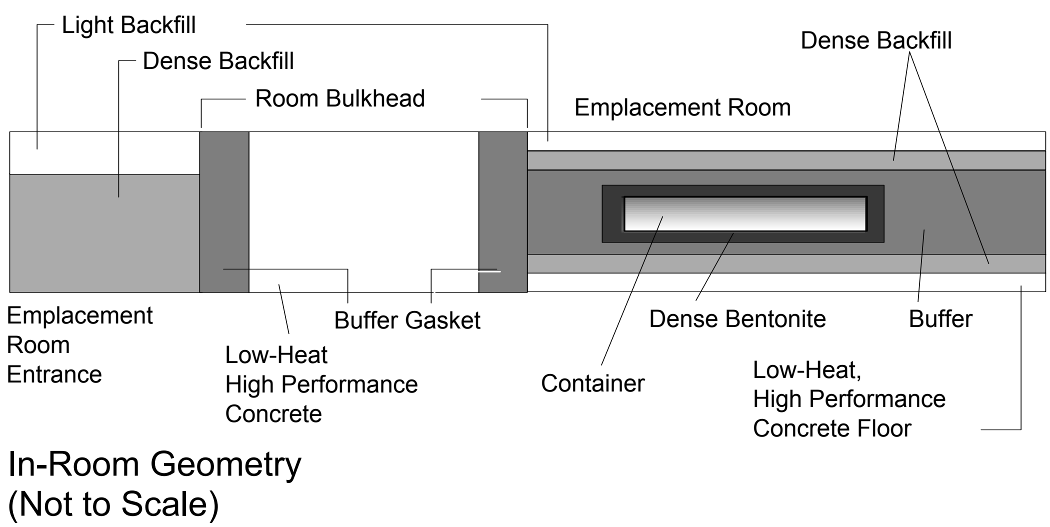

Figure 1: An in-room emplacement arrangement[5].

Following closure of the repository, the main objectives of long-term postclosure monitoring are to:

- demonstrate that the repository continues to meet compliance and performance monitoring requirements (i.e., continued design validation);

– detect any anomalous behaviour so that remedial actions may be taken as necessary to protect public health and the environment; and
– allow stakeholders to develop confidence in the performance and safety of the closed repository.

The long-term monitoring approach described will not compromise the intended passive safety of the closed geologic repository.

II. MEASURABLE REPOSITORY PARAMETERS

In a long-term repository-monitoring program, data would be gathered on parameters that are indicative of, or that can be used to determine conditions indicative of the performance of the repository and surrounding biosphere and geosphere. These include:
– temperature;
– *in situ* stress changes in the rock, rock displacements and acoustic emission/ micro-seismic events;
– groundwater movement and pressure;
– groundwater chemistry; and
– radionuclide concentrations in groundwater.

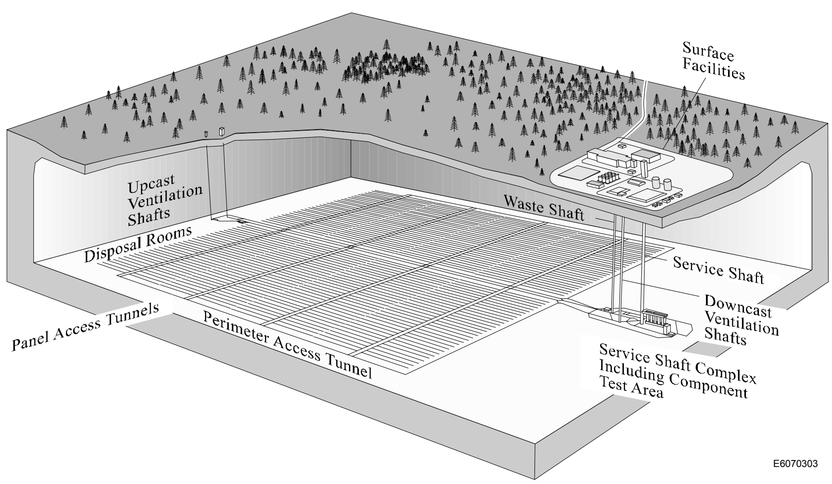

Figure 2: Typical repository layout.

The first four of these are expected to show measurable responses to the operation of the repository. Monitoring of radionuclide concentrations in groundwater will provide data on the release of natural radionuclides from the surrounding rock caused by changes in geosphere chemistry due to repository excavations. The radionuclide concentration in the groundwater from an undetected through-wall defect of a waste container is not expected to be detectable outside the repository emplacement room for a very long time.

The temperature of the repository will change over time as a function of the decay of the radionuclides inside the containers. The temperature of the surface of the hottest container is expected to peak at about 30 years[6]. McMurray et al. (2003)[7] estimate the peak average temperature at the centre of the repository is greater than 70°C from 100 to 3000 years. Other studies provide similar results in which temperature increases may occur sooner. Temperature increases in the panels between emplacement rooms will be measurable over relatively short time periods during repository operation.

The heat from the used fuel will cause thermal expansion of the rock mass, which in turn will generate stresses and deformations and pore-pressure changes. The calculated thermally induced horizontal stress increase at the repository centreline is expected to be about 15 MPa at 80 years after emplacement in moderately fractured rock or 25 MPa at 100 years after emplacement in sparsely fractured rock[8]. Vertical stress changes are anticipated to be lower because the surface above the repository is free to displace upwards.

Thermally induced displacements will occur as the temperature rises in and around the repository. Lateral rock displacements will be less than 100 mm because of the elastic constraint provided by the adjoining rock mass beyond the repository perimeter. Because the surface above the repository will be vertically unconstrained, all heated ground will be free to displace upwards, with maximum predicted uplift of less than 1 m occurring a few thousand years after container emplacement.

In response to stress changes induced by excavation and/or thermal expansion, the stiff granitic rock close to the excavations of a used-fuel repository may deform in an elastic-brittle manner, resulting in the initiation of microcracks and the accompanying creation of low-amplitude seismic signals that are transmitted through the surrounding rock mass[9]. These events may be expected to occur concurrently with excavation and over the period of operation, extended underground monitoring, decommissioning and closure.

Estimates of the time for re-establishing equilibrium conditions in the groundwater regime are dependent on the site conditions and on the repository design. In sparsely fractured rock, it is unlikely that complete saturation and pressurization will take place until the peak thermal transient at and near the container surface has passed (e.g., 10 to 50 years) and the temperature gradient between the container and the surrounding repository components has reduced. The saturation and pressurization of the sealing materials in a repository may take many tens to hundreds of years or more after repository closure[10,11,12] and may be highly spatially and temporally variable within the repository depending on local boundary conditions and temperature gradients.

A potential effect of temperature on groundwater conditions is the thermal expansion of water in the pore spaces within the rock and sealing materials. An increase of pore fluid volume due to thermal expansion in sparsely fractured rock may lead to pore pressure increases exceeding 400 kPa/°C[13]. If the excess pore pressures are high enough relative to the in situ stresses, microcrack propagation by hydraulic fracturing is possible, although since temperature changes in the rock will be gradual, it is expected that pore pressures will gradually dissipate as the water flows away through the rock matrix.

The chemical responses in and around a repository can be categorized as changes that result from evolutionary processes, from anomalous processes, and from anomalous events. Evolutionary processes are the anticipated changes in chemical conditions that result from the natural system reaching steady state or geochemical equilibrium conditions during and after the emplacement of the containers of waste and sealing systems in the repository. Anomalous processes are unanticipated changes in these conditions.

The chemistry of the groundwater above and surrounding the repository can be monitored over the long-term. Unlike the other measurable parameters, groundwater chemistry monitoring provides a direct measurement, hence a means of tracking general evolutionary trends and the long-term repository performance and safety. However, the time necessary to detect changes in repository conditions at a point of measurement away from the container may be quite long because of the time required for contaminants to be transported from the containers to the measurement location.

III. MONITORING METHODS

An approach to long-term monitoring that uses both non-invasive and invasive measurements has been described[3,4]. Non-invasive measurements use remote methods or boreholes less than 10-m-deep. Invasive measurements require the drilling of boreholes from surface or from the excavated access shafts or ramps and tunnels. In both methods it is important to minimize any long-term perturbations caused by the measurement installation to the repository system being measured.

The environment surrounding a geologic repository includes a volume beginning beyond the outer edge of the repository within which an open borehole would compromise the passive safety of the repository. Therefore invasive monitoring boreholes within or penetrating this volume need to be backfilled and sealed prior to repository closure and, if used for surface-based postclosure monitoring, only be periodically unsealed for measurements. The outer surface of this volume will be irregular and could be nearer the repository within a large volume of competent rock and further away within a fracture zone that intersects or comes very close to the repository. In designing a monitoring system, the designers must consider a number of factors including the:

- relevance of a measurable parameter as an indicator of the performance and safety of the repository;
- ability to take a direct measurement of a relevant parameter;
- instrument conformance;
- frequency of measurements required;
- physical characteristics of the selected instrument;
- signal-to-noise ratio;
- errors from a range of potential sources; and
- instrument reliability and longevity.

The design, fabrication, calibration, installation and operation of monitoring systems must be done within an approved quality assurance/quality control system that defines the procedures to be applied and the records to be maintained. Similarly, an approved quality assurance/quality control system must be applied to the collection and storage of data to ensure its integrity and security, and the effective dissemination of collected data for use by stakeholders.

Monitoring Thermal Changes

Postclosure temperature measurements would be made primarily to confirm that the temperature in the rock mass surrounding the repository was changing as predicted. Current predictions indicate that the highest and earliest temperature changes will occur within a 200-m zone around the repository over the first 100 years. Therefore, most temperature measurements (at least early on in the measurement program) should be performed within this zone. Potential locations for measurement are in boreholes drilled from surface, both above the repository and surrounding it. The thermal front is expected to extend 200 m laterally from the edge of the repository after about 100 years, so a line of monitoring boreholes can be located at various distances from the edge of the repository in one or two directions.

All boreholes required for temperature monitoring are expected to be invasive. Since the temperature monitoring will be general in nature, rather than discrete, the temperature measurement borehole locations can generally be selected to minimize any compromise to safety.

Two methods for measuring temperature are commonly used; a portable temperature probe that is inserted into any open borehole to determine temperature profiles along its length, and individual temperature transducers that are fixed at locations along the borehole. If temperature-monitoring boreholes are categorized as being in an insensitive invasive monitoring zone, then they may be left open indefinitely, possibly with a long-life but temporary casing, so that periodic temperature measurements can be conducted with a temperature probe. Otherwise, individual temperature transducers might be installed within sealed sections of the boreholes.

For intermediate-term installations, packer systems may be used. For long-term installations, full-length seals of clay and cement-based materials may be used. Temperature transducers can be efficiently integrated with other measuring systems. This approach should be used wherever practicable to minimize the number of monitoring boreholes.

There are a variety of potential configurations for dedicated temperature transducers within sealed monitoring boreholes. Where an electrical connection to a surface-based data logger is established through a continuous wire, the sealing effectiveness of long-term installations of both the intermittent and full-length seals are considered only temporary because the wire might eventually degrade to a point where it could provide an enhanced hydraulic connection. If a battery-operated in-hole datalogger is coupled with a temperature transducer, then the installation can be completely sealed with a borehole sealing system as described later.

Thermistors, thermocouples or resistance temperature detectors could be used depending on the application. Generally probe-type transducers will provide more accuracy than dedicated "in-place" transducers since they can be regularly calibrated. As part of the monitoring strategy, it would be prudent to conduct temperature measurements with a probe-type transducer along any measurement borehole that has been opened up on a periodic basis for sampling or instrument refurbishment. This type of measurement might be done at a frequency of typically five to twenty years, depending on the location of the borehole and when access was available.

Monitoring Mechanical Response

During the operating and extended preclosure underground monitoring phases, rock displacements at the repository level could be monitored from accessible areas using the BOF-EX extensometer system[14]. Alternatively, the PAC-EX coupled packer/extensometer system[15] could be used, particularly to monitor displacements across fractures or fracture zones. However, it is not considered feasible to use the BOF-EX for monitoring of the thermally induced, localized displacements surrounding the waste emplacement rooms from surface, because such measurements would impact long-term passive safety[16].

The thermally induced surface uplift of tens of millimetres in the first 100 years and hundreds of millimetres within 5000 years is measurable by non-invasive methods such as conventional optical surveys and potentially measurable by satellite-based radar interferometric surveys. Uplift monitoring can be conducted using permanent survey points affixed to bedrock outcrops or to concrete piles extending down through overburden to the basement rock. A reasonable grid pattern of survey points can be used well past the repository footprint (e.g., 1000 m past the edge of the waste emplacement area of the repository level), perhaps every 100 to 200 m. The elevation of the survey points can be measured every 10 to 20 years to determine any trends in surface heave with time. The survey points distant from the repository can be used as datum points. The absolute elevation of datum points should be measured independently to determine if any general elevation changes, such as those caused by glacial isostatic rebound, are occurring.

It is recommended that in situ stress conditions in the rock mass be determined periodically during both the preclosure and postclosure periods to monitor any stress changes taking place with time. A combination of overcoring and hydraulic fracture methods should be employed[17].

During the preclosure underground monitoring period, Acoustic Emission/Microseismic (AE/MS) monitoring can be conducted from an array of sensors located strategically around the volume of rock to be monitored. Sensors typically need to be positioned within 10 to 20 m of the target rock volume, so it is impractical to monitor the entire repository. However, representative parts of the repository where activity is expected can be monitored. For postclosure monitoring, a less sensitive, but more inclusive AE/MS system can be installed to monitor the entire repository on a grosser scale (i.e., less accuracy in determining the source of the recorded event) and at higher energies (i.e., events of greater magnitude) using relatively short boreholes (e.g., 100 to 200 m). Such a system has been proposed for nuclear safeguards purposes[18].

Monitoring Groundwater Flow And Pressure

From the beginning of site characterization, the hydraulic conditions within the rock mass surrounding the repository site will be monitored using a number of boreholes drilled from surface. These boreholes, which will range from shallow holes to those extending below the repository, will be completed with casing systems that allow measurement of hydraulic heads and collection of groundwater samples in specific zones in the rock mass[19]. Precise location of hydraulic monitoring boreholes would be determined from the geotechnical information obtained during the various stages of repository site evaluation, site confirmation and repository construction, operation and monitoring.

For postclosure monitoring, borehole locations should be selected that are outside the rock mass volume within which an open borehole could affect passive repository safety, or intermittent monitoring systems should be installed as described in the Section titled *postclosure surface-based monitoring*. In general, the borehole network for post-closure monitoring is likely to consist of key boreholes from the previous characterization activities, modified to meet postclosure monitoring requirements and of new boreholes drilled specifically for postclosure monitoring. These modifications may include sealing portions of the key boreholes that pass through the repository area or pass through the volume of the rock mass in which an unsealed borehole could affect passive repository safety, enlarging of the borehole diameters or reconfiguration/replacement of the borehole packer systems. The boreholes drilled specifically for postclosure hydraulic head monitoring should be in place for several years prior to closure to develop sufficient background data to interpret the significance of the postclosure hydraulic head perturbations. The hydraulic head monitoring boreholes also provide the means to collect groundwater samples from the rock mass for chemical analyses. Borehole sites should include locations sufficiently dispersed to monitor the evolution of the groundwater flow field from its initial undisturbed state, through its changes caused by repository excavation, operation, extended underground monitoring, closure and postclosure stages.

Monitoring Geochemical Conditions

The only viable method for postclosure monitoring of groundwater chemistry changes due to the repository involves the chemical and isotopic analyses of water samples. These may be direct in situ measurements or laboratory analyses of groundwater samples obtained from shallow standpipes or from packed-off sections of intrusive boreholes. Alternatively, these may be indirect analyses of any chemical species that are selectively sorbed in perforated canisters of chemical “getters” or scavengers, installed within boreholes for a specified period of time. Chemical getters or scavengers are chemical materials that are used to concentrate one or more chemical species in the environment. A classical example is a charcoal trap used to collect 222Rn from the air in buildings and underground excavations. After a period of time, the charcoal getter is removed and the captured amount of 222Rn or its daughters determined radiometrically. Chemical scavengers occur in nature; one example is monazite, (Ce, La) PO4 that has the property of scavenging rare earths and actinides from groundwaters and is a principal ore of Th and rare earths. To our knowledge, no chemical getting or scavenging technologies are currently established for in situ monitoring of geological systems, although fission-track sampling and analysis of α-particles in the geosphere is marginally related as a geochemical prospecting method. Potential chemical getters or scavengers include finely divided hematite or goethite and insoluble phosphates such as apatite. To improve their scavenging capability, microspheres coated with hematite, goethite or apatite can be used. Chemical getters may be loaded in perforated canisters to be installed within sealed boreholes for predetermined periods of time.

Groundwater samples should then be analyzed in a laboratory for dissolved gases, major and minor cationic, anionic and neutral species, total organic carbon (TOC) and total inorganic carbon (TIC). The pH should be determined and dissolved oxygen measured. The analysis of dissolved gases may give an indication of failed containers if a specific gas, one that can be uniquely discriminated from others in the environment (e.g., helium), is used to fill the void space within the inner vessel of these containers.

Analysis of the groundwater samples should be conducted to detect isotopic signatures that differ from naturally occurring material. Detection of any isotopes present in used fuel and absent from the natural environment would indicate a container failure.

IV. SUGGESTED MONITORING STRATEGY

Demonstration testing and long-term preclosure monitoring

Monitoring activities will commence during site characterization, and will continue through construction and operation of the repository[20]. A network of invasive and non-invasive monitoring boreholes drilled from surface will be established during site characterization and will be used for preclosure monitoring.

It is not advisable to install monitoring systems within the waste emplacement rooms, as these would jeopardize the long-term performance and safety of the repository. Such monitoring systems would have to be very invasive to gather data from the container, the sealing systems and the adjacent rock. Instead, a program of component and demonstration testing that would begin during underground evaluation of the site and continue until repository closure is proposed[6]. Data on the performance of the container and emplacement room sealing system would be obtained from controlled tests in locations where the containers could later be removed and, if necessary due to the instrumentation installed, the used fuel could be repackaged in non-instrumented containers and emplaced in a final isolation environment. These component tests would be separate from the emplacement rooms, either in a single component test area (see Figure 2), in strategically located and spatially distributed specially excavated test rooms within the repository, or some combination of the two.

It is also proposed that a series of physical material properties tests, technology demonstration tests and performance assessment tests be conducted in the component test area(s) to provide information on the short-term in situ performance of the repository systems at the specific site. It is recommended that demonstration tests be installed at an early stage in the component test area(s). These demonstration tests would be heavily monitored to evaluate the effectiveness of the various barriers. Each installation could be decommissioned over the time that access to the component test area is available. The last of these installations would be decommissioned at the time of a decision on final closure of the repository.

A phased approach to decommissioning of the repository is recommended. This approach would allow access to the emplacement room panels for an extended monitoring period followed by an additional monitoring period after the access tunnels, perimeter tunnels, the emplacement room panel tunnels and some access shafts/ramps are decommissioned. In the initial phase of extended preclosure monitoring, all the emplacement rooms within the emplacement panels would be sealed, but the access and panel tunnels would be left open. Monitoring boreholes would be drilled to various points of interest in the rock mass between emplacement rooms from these tunnels to measure parameters, such as rock temperatures, stress changes, acoustic emissions (potential rock failure), rock pore water pressures, etc. This initial phase of extended monitoring could be continued as long as required, perhaps between 50 and 100 years.

After a decision had been made to move to decommissioning, the first phase would involve removal of all instruments installed in the monitoring boreholes drilled from the access and perimeter tunnels. These boreholes would then be permanently sealed. The upcast ventilation shafts, the access tunnels and the perimeter tunnels would then be sealed and closed. The component test area and at least two shafts at the service shaft complex would be left open to continue extended preclosure monitoring of key tests in the component test area and monitoring systems installed in boreholes drilled from the remaining open areas underground. This period of extended underground monitoring could continue until a decision is made to complete decommissioning and close the repository.

When a decision is made to complete decommissioning and close the repository, any operational tests in the component test area would be decommissioned and examined and all remaining monitoring boreholes collared underground would be decommissioned and sealed. Then the balance of the repository facility, including most remaining structures on surface, would be de-commissioned and closed.

A time frame for the period of underground extended monitoring (also referred to as post-operational monitoring) of about 70 years followed by 15 years of decommissioning has been suggested[21]. However, this period of extended monitoring could be lengthened, if so desired, prior to final closure of the repository. The functional life of the structures, systems and equipment required for post-operational monitoring and decommissioning of the repository must be capable of surviving with appropriate maintenance and refurbishing over this extended time frame.

The concept of a phased approach to operating and decommissioning a deep geologic repository has been identified previously by others[22].

"Geologic disposal aimed at a final repository configuration offering maximum passive safety can also be implemented in a staged or flexible manner that postpones steps that are difficult to reverse. In Sweden, for example, it is proposed to dispose of only 10% of the used-fuel wastes, initially, and then pause for a number of years in order to evaluate the experience gained and monitor the emplaced waste. In other countries, the possibility of emplacing waste, but delaying the final backfilling or closure of the underground tunnels has been considered (e.g., in Switzerland, the UK and the USA). This creates an underground store from which wastes can be relatively easily retrieved, if necessary, but could also be easily closed if that decision is reached."

Postclosure surface-based monitoring

If a decision were made to continue monitoring the repository after closure, long-term postclosure monitoring would use a surface-based network comprising a combination of:

- non-invasive monitoring systems,
- invasive continuous monitoring systems installed outside the rock-mass volume that could affect passive repository safety, and
- invasive intermittent monitoring systems installed within the rock-mass volume that could affect passive repository safety (an approach to designing these systems is discussed later in this section).

Most postclosure monitoring systems would be invasive and installed in boreholes drilled from the surface, however there are some non-invasive methods of monitoring that can be done from surface or in boreholes less than 10-m long drilled from surface. Examples of these are surface geodetic measurements to measure elevation changes resulting from thermal expansion, or near-surface temperature measurements. These measurements could be continued as long as required. These postclosure monitoring systems could be installed either during repository siting and operation or during the period of extended underground monitoring.

Two layouts of invasive monitoring boreholes are proposed for the monitoring network.

1. A general layout that would provide broad spatial coverage. Broad coverage using invasive monitoring boreholes is required to observe the changing conditions in and around a repository that cannot be measured directly or in a timely manner at surface. The coverage must be sufficient to account for the known variance in site conditions and to provide a sample size sufficient for statistical analysis methods to be used in interpreting the meaning of the monitoring measurements. This layout provides flexibility in locating instruments, in terms of both the measurement itself and the degree of invasiveness. For example, only broad general coverage is needed for measuring the overall temperature and mechanical responses. Instrument locations need not be specifically targeted, although the locations of the instruments must be precisely known, which gives the designer flexibility in selecting locations to minimize difficulties in installing instruments.
2. A discrete layout that would focus on measuring specific types of responses. In contrast to the broad spatial coverage described above, specifically targeted locations are needed for the hydrogeological and chemical monitoring instruments and groundwater sampling ports.

These would generally be located at the intersections of the boreholes and identified fractures/fracture zones. Hydrogeological instrumentation for monitoring the regional and local transient groundwater head responses are likely to be more widely distributed than the instrumentation for monitoring the locations of potential chemical/radiological contaminant plumes.

Key criteria to be used in the design of a practicable monitoring network include:

- instrument locations to monitor specific parameters;
- instrumentation and monitoring system durability/longevity;
- effectiveness of borehole seals for the instrumentation;
- instrumentation and system installation, maintenance, decommissioning and closure;
- integration of multiple measurements within a borehole system;
- re-use of boreholes after permanent seals have been installed; and
- early detection of significant parameter responses.

The process of designing a practicable postclosure monitoring network for a used-fuel repository will follow a similar approach to that used for any other geotechnical application. However, the much longer time frame involved and system safety requirements put unusual constraints on the systems chosen.

Predefined actions must be established that would take place in the event of monitoring observations that exceed preset "threshold" levels. The geosphere close to, but not affected by, the repository should also be monitored to identify any long-term trends (i.e., changing background conditions) not caused by the repository that must be understood to correctly interpret the effects caused by the repository.

Installation of monitoring systems to provide continuous real-time data within the volume of rock that could affect passive repository safety is not recommended. Instead, invasive intermittent installations incorporating full-length borehole seals capable of providing permanent containment should be used. These systems would include long-duration remote down-hole dataloggers integral with appropriate sensors installed at the desired location in a borehole and the balance of the borehole would be sealed with a permanent borehole sealing system. Then, the boreholes could be reopened at intervals, by drilling, to retrieve the dataloggers and download the collected data. A new or refurbished datalogger/sensor combination could then be reinstalled and resealed for the next monitoring period. This approach to invasive postclosure monitoring would maintain the borehole in a passively safe state except for the short periods necessary for data retrieval and instrument reinstallation. This type of installation is shown schematically in Figure 3.

Because long-term monitoring of a repository would be driven, in part, by the public's desire to assess the safety of deep geologic isolation of nuclear fuel waste, the concept of transparency has been identified as being critical to any planned monitoring of nuclear sites, including those dealing with the long-term management of used fuel. Transparency, as it applies to the reporting of data, refers to the availability of real-time, or very recent, pertinent data to any interested party. In this context, much of the data on rock displacements, water pressures, hydrogeology, etc. would not be of particular interest to the general public, who would likely be more interested in data concerning radiation levels in the air and groundwater at a repository site. Such reporting is already underway at many Japanese nuclear facilities and can be accessed in real time by any interested party through the Internet.

V. CONCLUSIONS

This paper has described a strategy to conduct long-term monitoring that will not compromise the intended passive safety of a deep geologic repository after it is closed. Capabilities presently exist to monitor relevant parameters over the long term using current technologies and reasonable extensions of current technologies.

Long-term preclosure monitoring will begin with the siting of the facility and continue through repository operation, extended underground monitoring, decommissioning and closure.

Postclosure extended monitoring from surface could continue as long as required by stakeholders using both monitoring system installations and borehole locations that maintain the passive safety of the repository.

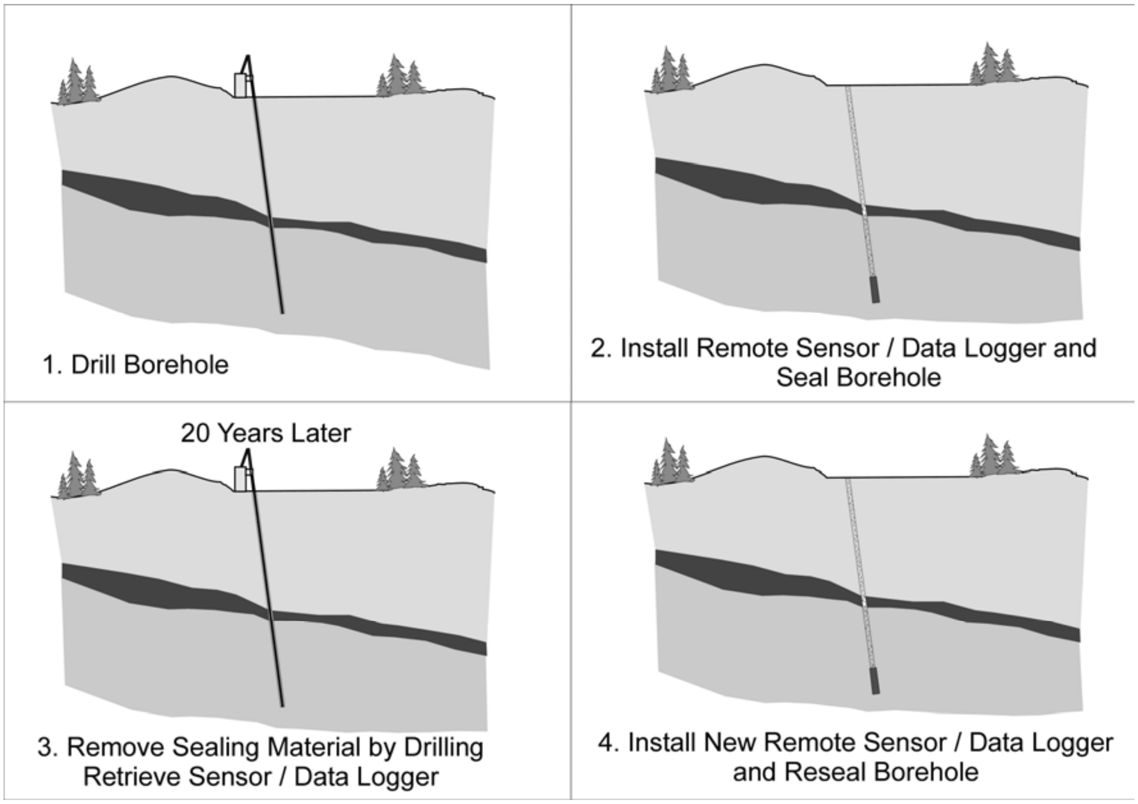

Figure 3: Example application of a remote datalogger/sensor assembly to long-term postclosure repository monitoring.

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