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Monitoring of Geological Disposal
- Current Status and Technical Possibilities -

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FOREWORD

The geological disposal technologies ensure the long-term safety by providing an engineered system with sufficient allowance that takes into full account uncertainty of safety assessments and the limits of reliability of knowledge for the deep geological environment. At the same time, in terms of considering that it will take long time, or an order of hundred years from planning phase through emplacing and closure of geological facilities it is important to strive to improve reliability of geological disposal technologies through such means as: constantly accumulating information and knowledge concerning geological environments; improving the very latest geological disposal technologies; and reflecting these on the development.

In executing geological disposal, the limits of reliability in applicable technologies should be in consideration, and then an operation of monitoring considers confirming the required safety performance and the conditions of the actual geological repositories from the stage of site selection through to a specified time after a closure of geological repositories.

The Radioactive Waste Management Funding and Research Center (RWMC) have conducted research and study regarding monitoring of geological disposal, based on a commission of the Ministry of Economy, Trade and Industry (METI). Also, RWMC has been undertaking research and study activities through the hosting of international workshops, and ongoing deliberations by the Advisory Committee for Geological Disposal Monitoring Systems of RWMC, which is comprised primarily of geological disposal experts.

This report describes a systematic review of studies currently being conducted, including different approaches and technical possibilities of monitoring for understanding various aspects of HLW geological repositories.

Content

1. Introduction

1.1 Background

The safety of a geological repository that contains high level radioactive waste must in principle be assured through passive means, without the premise of any kind of control including monitoring, implemented after closure for the purpose of assuring long-term safety (OECD/NEA, 1982; IAEA, 1995, etc.). However, recently, a general consensus has been reached that, even though passive safety assurance has been an initial concept, it is still desirable to prepare various institutional control methods that confirm that safety has being ensured[1]. One such method, which has gradually gained widespread acceptance in international studies as an important way of enhancing public confidence in underground geological disposal, is the implementation of monitoring that extends from the early stages of the Repository Site selection process until a specified time after the repository has been closed (IAEA, 2001).

The implemental body in Japan, NUMO (the Nuclear Waste Management Organization of Japan), solicited public opinions concerning the selection of "Preliminary Investigation Areas (PIAs)" related to the geological disposal of vitrified-high-level radioactive waste (HLW) in December 2002. This marked Japan's entry into the first preparatory stage of the full-fledged implementation of geological disposal (NUMO, 2002).

Prior to that, in 2000, the Nuclear Safety Commission of Japan (NSC) formulated a basic framework for national safety regulations designed to facilitate the formulation of policies that are required to ensure the safety of geological disposal (NSC, 2000). The Commission's report defined the following measures as "*safety securing principles*": long-term safety securing measures (site selection, engineering measures); and safety assessment measures, which confirm that safety has been ensured. The report also states that safety should be confirmed in each stage of disposal operations, including: site selection (selection of Preliminary Investigation Areas (PIAs), Detailed Investigation Areas (DIAs) and Repository Sites); application for approval to operate; construction; repository operation; and repository closure. It also states that activities including of monitoring and inspection may be implemented at each stage, from initial siting to the termination of operations.

The Radioactive Waste Management Funding and Research Center (RWMC) have conducted research and study regarding monitoring of geological disposal, based on a commission of the Ministry of Economy, Trade and Industry (METI). Also, RWMC has been undertaking research and study activities through the hosting of international workshops, and ongoing deliberations by the Advisory Committee for Geological Disposal Monitoring Systems of RWMC, which is comprised primarily of geological disposal experts.

This report describes a systematic review of studies currently being conducted, including different approaches and technical feasibilities of monitoring for understanding various aspects of HLW geological repositories.

1.2 Objectives and Scope

Implementation policies and plans for monitoring for understanding various aspects of geological repositories may be in practice formulated by interested parties, including the Japanese government and related organizations and agencies. RWMC's research have therefore conducted with the following objectives: to extensively survey and summarize information concerning relevant discussions and technologies of various monitoring addressed in Japan and abroad to date; to formulate an approach to monitoring for understanding or interpreting various aspects of vitrified-HLW geological repositories after repository closure (named "*geological disposal monitoring*") based on those surveys and technologies; to consider technical possibilities for *geological disposal monitoring*; and to summarize the outstanding issues.

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[1] See, Attachment A

According to safety assessments of HLW geological disposal, geological repositories are not expected to ionize significantly detectable radiation near their engineered barriers or the surrounding geological environment for a long period after they will have been backfilled, assuming that the waste has been properly manufactured and the engineered barriers have been properly installed. In this respect, geological disposal facilities differ from nuclear power facilities or chemical industries that expose the environment to radiation or environmentally related substances in certain concentrations.

The long-term safety of geological disposal can be demonstrated by: positing various scenarios related to multi-barrier systems; performing numerical analyses based on many models and parameters related to the scenarios; and performing safety assessments based on the numerical analyses. However, it has been pointed out that the analytical results obtained through this procedure entail uncertainty arising from the scenarios, models and parameters themselves.

In addition, safety assessments show that geological environments that are disturbed by human activities such as disposal site selection surveys, emplacement of waste, and repository closure, eventually return to their original state after a given amount of time.

Therefore, *geological disposal monitoring* is considered to be necessary to be established in terms of reflecting on the measurement for understanding of the evolutions of repositories environment and geological environment, while taking into account the effects of human disturbance, as well as confirming that the environment is restored to its original state.

At the same time, *geological disposal monitoring* must be continuously done using methods that do not compromise the long-term safety of the disposal facility, with technologies that can be used reliably for long periods over several generations. For example, post-closure monitoring may be required by society because of the uncertainties in the safety case.

As the foregoing indicates, *geological disposal monitoring* must be thoroughly studied in terms of what parameters are measured for how long and by which technologies for understanding or interpreting various aspects of vitrified-HLW geological repositories after post-closure. Unlike other technical issues associated with geological disposal, research on monitoring should therefore be approached from the perspective of the "***5W1H***" questions: ***Why (objective); Who; When (from/to); Where; What; and How (methodologies)***. With regard to "How" in particular out of "***5W1H***", technologies must be developed that can maintain a high degree of reliability over a long period of time. Therefore, RWMC's following mid-term aims are specified relations between *objectives* of *geological disposal monitoring, information* for understanding or interpreting various aspects of vitrified-HLW geological repositories after closure and *technologies options* available of measurement, then comprehensively summarized them, and systematized that can contribute to the planning of monitoring programs by various organizations and agencies.

1.3 Background to Post-Closure Monitoring

Monitoring technologies for geological disposal are defined as one type of "institutional control technology" since they require institutional support for implementation. Even if the geological disposal itself is a measure to isolate high level radioactive waste without depending on institutional control, it is desirable to actually monitor and confirm that the geological disposal facility is providing the predicted and required degree of safety. Monitoring in geological disposal is expected to be one of the measures which can meet the societal demands for additional security.

1.4 Approach to Report

This report describes a systematic review of studies currently being conducted, including different approaches and technical feasibilities of monitoring for understanding various aspects of HLW geological repositories.

First, the definition and purposes of monitoring for vitrified-HLW geological disposal are summarized, followed by a review and summary of discussion points concerning various items related to geological disposal and their relationships to geological disposal monitoring. Then, on the basis of these factors, a preliminary view of geological disposal monitoring is presented, and also some speculations are introduced.

In addition, the studies on monitoring technologies included extensive surveys of current technologies, an examination of the possibilities of measuring technologies, and a study of transmission technologies used to transmit measurement data from deep underground to the surface. The results of these studies are summarized and the feasibilities of geological disposal monitoring are discussed and simultaneously outstanding issues are summarized.

1.5 Report Structure

Section 1 of this report provides the background to this study. Section 2 describes the definition and purposes of monitoring for vitrified-HLW geological disposal (named "*geological disposal monitoring*"), followed by a review and summary of discussion points concerning various items related to geological disposal and their relationships to *geological disposal monitoring*. Section 3 provides the studies on monitoring technologies included extensive surveys of current technologies, an examination of the feasibilities of measuring technologies.

2. Approaches to Monitoring of Geological Disposal

As stated in the Introduction, in Japan, “monitoring” is generally used in a sense of such as surveillance, observation and measurement, which means “monitoring” is used in a wide range of situation. More specifically, it can be interpreted as a method of continuously or periodically measuring and observing the status of a system.

This chapter describes the approaches to geological disposal monitoring that have been explored by international authorities and other organizations, and clearly present the results. In carrying out this work, it was referred to a wide variety of perspectives, including: discussions on geological disposal monitoring conducted by the Exploratory Committee for Geological Disposal Monitoring Systems; investigations conducted in Japan and abroad[2]; workshop results[3]; and surveys of academic experts and specialists.

2.1 Definitions of Monitoring of Geological Disposal

The first task was to examine some existing definitions of monitoring of geological disposal.

Here, definitions of monitoring of geological disposal are summarized through surveys of other countries, as well as IAEA-TECDOC-1208 (IAEA, 2001).

2.1.1 Definitions in other countries

In 2004, European Commission published a report “Thematic Network on the Role of Monitoring in a Phased Approach to Geological Disposal of Radioactive Waste” (EC, 2004). In this report, their various considerations of monitoring including definition, law, plans and techniques by different nations are represented. Those definitions are summarized in Table 2-1 below.

2.1.2 International Atomic Energy Agency (IAEA-TECDOC-1208, IAEA(2001))

IAEA defines monitoring of geological disposal as follows in a technical document on the topic:

> ***For the purpose of the present publication the following definition of monitoring has been employed: continuous or periodic observations and measurements of engineering, environmental or radiological parameters, to help evaluate the behaviour of components of the repository system, or the impacts of the repository and its operation on the environment***

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[2] Attachment B

[3] Attachment C

Table 2-1 *The definitions of monitoring of geological disposal and the description (EC, 2004)*

Country	*Definitions*
Belgium	*Monitoring means the continuous or discrete observing and measuring of the parameters that help to form an assessment of the behaviour of different components of the disposal system and/or of the impact of the repository and its operation on the environment. 'Monitoring' in this context therefore does not only mean routine checks on operational safety.*
Finland	*Systematic way of collecting and interpreting information from the facility environment with the objective of detecting possible changes caused by the construction and operation of the facility in relation to the baseline conditions.*
Germany	*Continuous or periodic measurements of properties considered important to safety.*
Spain	*Continuous, periodic or sporadic surveillance for the verification of compliance with requirements and to support the assessment of performance, including data acquisition, interpretation of measures and acceptability contrast*
Sweden	*Continuous or repeated observations or measurements of parameters to increase the scientific understanding of the site and the repository, to show compliance with requirements or for adaptation of plans in light of the monitoring results.*
Switzerland	*a) Definition used regarding waste management in general* *"Periodic or continuous determination of the status of parts (or components) of the disposal system, its environment or of related features (e.g. properties of waste streams, ...) and issues (e.g. alternative waste management options, state-of-the-art in science and technology, societal values, view of "affected groups",...)* *b) Definition used regarding development of a repository project* *"Periodic or continuous determination of the status of specific components of the disposal system by means of appropriate measurements and observations (as opposed to one-time measurements!); the nature of these measurements depend on the geological environment and the details of the repository concept."*
UK	*Measurements of parameters and observations that may have implications for the design and management of the phased disposal system, for its performance assessment, and for the development of confidence in the phased disposal system performance and its assessment.*

2.2 Objectives of Monitoring of Geological Disposal

This section summarizes the objectives of monitoring of geological disposal. First, the status of IAEA studies is described, then it is presented as wide a range of objectives of monitoring of geological disposal as possible, compiled from the results of surveys conducted with authorities and organizations that are involved with the geological disposal of high level radioactive waste both in Japan and abroad. Through this approach, it is clearly shown that there are a great variety of objectives (needs) for monitoring of geological disposal, and so attempt to organize these diverse monitoring objectives into discrete categories between objectives.

2.2.1 Summary of Objectives Identified by IAEA in IAEA-TECDOC-1208 (IAEA, 2001)

I. *To provide information for making management decisions in a stepwise program of repository construction, operation and closure,*

II. *To strengthen understanding of some aspects of system behavior used in developing the safety case for the repository and to allow further testing of models predicting those aspects,*

III. *To provide information to give society at large the confidence to take decisions on the major stages of the repository development program and to strengthen confidence, for as long as society requires, that the repository is having no undesirable impacts on human health and the environment,*

IV. *To accumulate an environmental database on the repository site and its surrounding that may be of use to future decision-makers and*

V. *To address the requirement to maintain nuclear safeguards, should the repository contain fissile material such as spent fuel or plutonium-rich waste.*

2.2.2 Summary of Objectives of Monitoring of Geological Disposal

Based on objectives in IAEA Report (IAEA, 2001) and other objectives of monitoring by domestic and overseas authorities and organizations involved in the geological disposal[4], with considerations of vitrified-HLW geological disposal concepts in Japan, objectives of *geological disposal monitoring* was broadly classified as follows:

Objective 1: Confirming safety performance and the adequacy of the repository's engineered measures**,**

Objective 2: Confirming compliance with statutory requirements,

Objective 3: Providing information for making decisions on policy and operations,

Objective 4: Understanding the baseline characteristics of the geological environment at Preliminary Investigation Areas, etc. and

Objective 5: Providing information for public decision-making

Objective 1: *Confirming safety performance and the adequacy of the repository's engineered measures*

Viewed from a technical perspective, monitoring provides the basis for confirming that the actual environment of the disposal system (which constitutes the conditions that lead to safety assessment results) is in fact similar to the conditions that were predicted through prior analyses, thereby indicating that the system's engineered measures reflecting on the environment are adequate. One way to confirm the performance that is objectively evaluated on the basis of the safety assessment is to survey the conditions of the geological environments and engineered barriers. This includes the hydraulic and hydrogeological characteristics surrounding the underground repository that contains the waste, as well as the heat, hydraulic, stress and hydrogeochemical characteristics surrounding the waste itself.

The period for monitoring changes in these characteristics needs to be studied while taking into account such factors as the uncertainty that was previously described. For example, if monitoring were continued for several decades or a century after the repository is closed (equivalent to the duration that hydraulic recharging of the underground facilities is expected to take), it could still yield valuable information for understanding how safety can be assured in the future.

It is also essential to obtain environmental baseline data (including groundwater levels) before the environment is disturbed by repository construction, etc., so that comparisons can be made with groundwater levels after a closure of repository.

1) Confirming the functionality of disposal system components

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[4] Attachment B

The overpack, buffer materials, rock mass, and other components of the disposal system must be checked to confirm that their functions are working as expected. Also, the following should be confirmed: that the values that are obtained through indoor tests of the physical properties of engineered barriers and other components are the same as those obtained in actual construction environments, and that the predictions that were analytically projected on the basis of those values, were in fact appropriate for such major evaluative parameters as physical properties (including stress-buffering function and rises in temperature) and chemical properties (related to corrosion and water quality).

2) **Confirming values established for design and construction**

The cavity is designed under the assumption that the physical properties of the rock mass and the tectonic stress are either uniform or variable In actual practice however, some rock masses have non-uniform properties that generate great spatial fluctuations. Similarly, such factors as the amount of sump water, geothermal gradient, and the amount of groundwater recharge should be taken into consideration in the design, based on survey results. To demonstrate the reliability of a geological disposal system, it is important to show how much tolerance has been built into the conservative design values that have been set as described above. The design and construction assumptions must be tested and confirmed during the repository's development phase.

3) Verifying safety assessment models

Verification is done to check whether model structures and the physical and chemical quantities used in each model are properly set in terms of: i) rock mass crack network models and creep models, which are formulated as part of system safety assessments based on groundwater scenarios; and ii) redox potential, pH, and other parameters of each model. These also include the boundary conditions of the safety assessment models, including wide-area hydraulic gradient distribution and the characteristics of EDZ(Excavation Disturbed Zone).

4) Making decisions concerning improvements or repairs in the operation and construction of the repository

Feedback data should be obtained for assessing improvements in engineering policies such as the selection of excavation, drainage, and ventilation methods, as well as safety measures in case of earthquakes or accidents. Also, if the quality of supports, overpack, buffer materials, etc., is found out to have deteriorated for any reason, repair work may be necessary. To decide whether or not to perform repairs, it is important to establish various criteria levels or values. Canada has adopted this approach by setting: i) allowable levels or values to be used as criteria for determining whether or not to conduct a detailed investigation; and ii) emergency limit values that indicate repairs must be conducted immediately (Simmons et al., 1994).

Objective 2: *Confirming Compliance with Statutory Requirements*

Many countries use a phased approach in their geological disposal projects. The entire project process is divided into multiple phases, beginning with site investigation from the ground surface through to final closure of the disposal repository. When proceeding from one step to the next, it may be necessary for the disposal implementing entity to obtain safety confirmation or permission from a safety regulator. In such a case, the entity would be expected to draw up or modify application forms in accordance with notifications, technical standards, etc. issued by the regulator as criteria for judging whether or not confirmation/permission should be given, while taking into account monitoring information.

A large amount of monitoring data and quality management records are generated to achieve Objective 1 above (confirming the functionality of disposal system components). From among that information, the most important data and reference values are generally adopted as requirements by the regulator and are reflected in laws and regulations.

During the construction and operation of the repository, it may be necessary to implement monitoring for the following purposes: to measure and observe radiation and other parameters to the same degree as is done at nuclear power plants to ensure the safety of facility workers and local residents; and to ensure compliance with general safety monitoring and regulatory criteria concerning the environment, including water quality.

1) Post-closure statutory requirements

Japan still needs to formulate safety regulations that apply to geological disposal monitoring. In the US, the Environmental Protection Agency (EPA) stipulated general radiation protection standards in its 40 CFR Part 191 (EPA, 1993). To ensure compliance with this document, the EPA subsequently established detailed, long-term monitoring requirements for Waste Isolation Pilot Plant (WIPP) sites in its 40 CFR Part 194 (EPA, 1996). In accordance with this latter document, the US Department of Energy (DOE) has selected pre/post-closure monitoring parameters for WIPP that are called Compliance Monitoring Parameters (COMP). These were derived from sensitivity analyses based on the Evaluation of the Applicability of Biosphere-Related Features, Events, and Processes (FEP) or related scenarios. Thus, monitoring plays a role in post-closure safety regulations that are specific to geological disposal.

2) Statutory requirements applied to construction and operations (safety of workers and local residents)

In many countries, safety regulators require monitoring not only to ensure technical reliability but also to check radiation amounts to ensure the safety of workers and local residents during construction and operation. The purposes of this type of monitoring are classified as follows.

- *Monitoring radiological effects on facility workers and the public during repository operation in compliance with legal regulatory requirements, as is the case with ordinary nuclear facilities,*

- *Monitoring non-radiological effects on the environment surrounding the repository during operation, in compliance with legal regulatory requirements for the environment concerning water flowing into water sources or changes in water quality resulting from excavation or construction work and*

- *Confirming compliance with the safety requirements applied to the underground facilities of general, non-nuclear industries with regard to such factors as dust, gases, and noise.*

3) Statutory requirements related to environmental impact

In many countries, regulators require monitoring for the purpose of assessing environmental impact. Many of the monitoring items in this category overlap with those in the category of monitoring to obtain a baseline.

Objective 3: *Providing Information for Making Decisions on Policy and Operations*

The implementor may use monitoring to facilitate operations and modify plans at each stage of repository development in ways that are distinct from the technical concerns of Objective 1 and the statutory concerns of Objective 2. Specifically, monitoring data and assessment results might be used for revising written materials that explain site safety, or for obtaining basic data for design changes.

In ordinary tunnel construction, it is common to adopt a flexible approach (often referred to as "reversibility" or "design as you go") to accommodate the uncertainty of information about the geological environment. Design and construction methods are modified freely based on information about the actual geological environment that is obtained as construction proceeds. Likewise, for geological disposal programs involving long-term safety, it is not reasonable to specify every design condition necessary for repository construction or the emplacement of waste before construction and operation begin. In practice, construction and operation programs will be pursued on the basis of design parameters. If monitoring provides in-situ data that differs from design assumptions, design or construction methods can be flexibly modified accordingly.

1) Providing information for public decision-making

In recent years, Japan, Europe and the US have tended to adopt a phased approach to geological disposal projects. Phased policies are being adopted not only because of the extremely long-term nature of the projects, but also because they permit reversibility as a project is implemented, thereby providing one way to enhance public confidence in disposal operations. Stages encompassed by the early phase of a project include the phased selection of the site for final disposal facilities, and changes in design. Further stages are encountered as the project progresses, including repository construction, operation, and closure. In the safety case defined by IAEA (see Attachments D and E), allowance is made for unsolved problems which may emerge in each phase of project development, and decision-making (including policies to solve such problems) can be implemented in a subsequent phase. Geological disposal monitoring will play a critical role in the decisions made by project operators in each phase, including: i) whether or not to proceed from the construction phase to the operation phase; ii) how waste emplacement should be implemented in different phases over the course of several decades; iii) how emplaced waste should be retrieved (described later); and iv) whether or not to proceed to the disposal/access tunnel closure phase after operations have been terminated. SKB is planning to implement preparatory emplacement prior to full-scale emplacement, and monitoring will be used to help decide when to proceed from the former to the latter (see Attachment B).

2) Retrievability of emplaced waste

Retrievability, which means being able to recover emplaced waste, is an important concept that merits study from a broad perspective in implementation policies designed to bring greater flexibility to geological disposal (OECD/NEA, 2001).

France and the US are good examples of countries that have identified the retrievability of emplaced waste either as a national necessity or as a policy of the implementing entity (EPA, 1993; ANDRA, 1991). The French believe that there is a close relationship between retrievability and geological disposal monitoring, in that active monitoring of such factors as the degree of waste constriction resulting from rock mass creep, or the corrosive environment surrounding the waste, can help to guarantee retrievability.

Objective 4: *Understanding the Baseline Characteristics of the Geological Environment at Preliminary Investigation Areas, etc.*

"Understanding the baseline" means measuring the characteristics of the geological environment of the final disposal site before it has been disturbed by such activities as boring surveys conducted from the ground surface (which are done when selecting a repository site) or disposal facility construction. Baseline information can provide useful parameters for confirming repository performance or implementing engineering measures, and much of it overlaps with monitoring carried out for Objective 1.

From the perspective of society, one of the purposes of geological disposal monitoring cited under Objective 5 is "Compiling databases for future generations." Baseline information, which records initial environmental conditions, is an important component that should be recorded in these databases.

Baseline information on the characteristics of the geological environment might also be necessary to ensure statutory compliance as described in Objective 2. Therefore, an understanding of the baseline characteristics of the Preliminary Investigation Areas will be crucial as a source of fundamental information for implementing geological disposal programs.

1) Understanding baseline characteristics of geological environments

An understanding of the baseline characteristics of geological environments (such as underground hydraulic and hydrogeochemical properties) can help to clarify the environmental impact of a repository project. It can also be important as a means of tracing geological environmental information while taking into account the expanse of space extending from the ground surface to deep underground, as well as long periods of time.

According to the results of surveys conducted overseas, nearly all advanced countries have implemented or intend to implement policies designed to obtain an understanding of the baseline characteristics of geological environments. As already noted, geological disposal projects involve the selection of repository sites in phases. An understanding of the baseline is expected to be needed during the initial survey phase, before activities such as boring down from the ground surface unavoidably disturb the geological environment.

Objective 5: *Providing Information for Public Decision-Making*

Geological disposal monitoring that falls under this category can be further divided into two purposes: i) providing technical information concerning geological disposal necessary to public decision-making, which is the present generation's needs ; and ii) compiling databases to help future generations make decisions.

As noted previously, monitoring that is implemented in connection with waste retrievability or the phased implementation of disposal operations plays a role in providing technical information oriented toward public decision-making.

In Switzerland, EKRA (EKRA, 2000) has adopted the following geological disposal concept that depends on long-term monitoring.: Before the repository is closed, information is collected on the performance of its various disposal systems and on the characteristics of the geological environment surrounding it. After public acceptance is obtained concerning the safety of the said geological disposal systems, the repository is closed. In this concept, monitoring is used to collect data and confirm repository performance until closure.

1) Enhancing the confidence of the public, including local residents with regard to geological disposal

Information, based on actual measurements, that testifies to the safety of a geological disposal system can enhance the confidence of the public (particularly local residents) with regard to disposal site operations. In a public dialog that contributes to public decision-making through Public Involvement (PI), specific geological disposal monitoring items might be discussed that are both feasible and helpful in promoting public peace of mind.

2) Compiling databases for future generations

IAEA is currently considering another objective for geological disposal monitoring: compiling environmental data at and around repository sites which might contribute to future decision-makers.

As discussed above, it turned out that monitoring of geological disposal has many functions corresponding to a wide range of objectives. Those objectives are summarized in Table 2-2 below.

Table 2-2 *The objective of monitoring of geological disposal and the description*

Objective	Description
1. Confirming safety performance and the adequacy of the repository's engineered measures	♦ **Confirming whether or not disposal system components function as planned** ♦ **Confirming design/construction assumptions** ♦ **Verifying safety assessment models** ♦ **Judging the need for facility improvements or repairs related to repository operation/construction**
2. Confirming compliance with statutory requirements	♦ **Confirming compliance with regulations after a closure of repository** ♦ **Confirming compliance with safety regulations for workers and local residents during construction and operation** ♦ **Confirming compliance with environmental impact assessment regulations**
3. Providing information for making decisions on policy and operations	♦ **Providing information for decision-making** ♦ **Dealing with the retrievability of emplaced waste packages**
4. Understanding the baseline characteristics of the geological environment at Preliminary Investigation Areas, etc.	♦ **Clarifying the baseline characteristics of the geological environment**
5. Providing information for public decision-making	♦ **Enhancing the confidence that the public (particularly local residents) have in geological disposal** ♦ **Compiling databases for future generations**

The objectives for geological monitoring listed above can be correlated with each other as described below.

Objective 1 *(Confirming safety performance and the adequacy of the repository's engineered measures)* and ***Objective 2*** *(Confirming compliance with statutory requirements)* have comparatively clear-cut measurement targets and assessment methods. The information related to these two objectives will be actively utilized as the project proceeds.

In contrast, ***Objective 3*** *(Providing information for making decisions on policy and operations)* involves information to help project operators and policy-makers make decisions based on such factors as the progress of future geological disposal programs, the different circumstances surrounding geological disposal, the advancement of geological disposal technologies, and public acceptance.

Objective 4 *(Understanding the baseline characteristics of the geological environment at Preliminary Investigation Areas, etc.)* can be thought of as covering the collection of fundamental data to meet diverse requirements, including the objectives and assessments described in Objectives 1, 2, and 3. For geological disposal that involves the postulation of extremely long periods of time, monitoring in this category is also meant to ensure the traceability of geological environmental information, both spatially between the surface and deep underground, and temporally over extended periods.

Objective 5 *(Providing information for public decision-making)* seems to overlap extensively with the other objectives. What distinguishes it, however, is that it enables the determination of monitoring parameters that should be measured on the basis of full discussion and public decision-making when the time comes to select a final disposal site.

2.3 Monitoring and Quality Control of Geological Disposal

Quality control is critical to defining quality-related policies, objectives, and responsibilities that are directly related to the safety of a multi-barrier system, as well as ensuring that the components comprising the disposal system are functioning at their targeted level.

Quality control related to repository construction and operation is likely to be modeled on quality control case examples that have been applied to conventional industries in accordance with Japanese Industrial Standard (JIS) and other regulations[5], with the aim of aggressively securing the prescribed system performance (including safety).

Plans for the quality control system described above will be formulated more specifically as part of a geological disposal project plan.

Although geological disposal monitoring overlaps with quality control to some extent, its main focus is on monitoring the system's status after the repository has been closed, which is a unique characteristic of geological disposal. Unlike quality control, therefore, monitoring is not aimed at actively securing prescribed performance from engineered or natural barriers.

The repository can be viewed as a product, in which sense measurement confirmations can be likened to completion checks that must be carried out through the various stages of construction, operation, and final closure. These measurement confirmations are distinct from geological disposal monitoring, and their details will probably be examined and finalized systematically based upon quality control and related plans.

A repository is completed as a system when it is closed. Prior to closure, long-term system behaviors are analyzed and predicted through safety assessments. The purpose of subsequent geological disposal monitoring is to confirm, through the acquisition of data directly related to various assessment parameters, that the actual behavior of the repository conforms to analytical predictions. Because analytical predictions involve both temporal and spatial uncertainties, the above-mentioned monitoring data provides a means for confirming that the repository's post-closure behavior does not greatly deviate from the scope of the analytical predictions. Should such a deviation occur, the data can be used to compare changes over time with analytical predictions, thereby clarifying the repository's post-closure behavior.

As described above, there is a difference between quality control and monitoring. Quality control involves confirmation testing to ensure prescribed quality and system performance before the repository is closed. Monitoring, on the other hand, is primarily concerned with understanding repository conditions after closure, although it also comes into play in pre-closure stages as a means of obtaining initial baseline values for tracking long-term changes over time. Because of this difference, the approach to which the agencies that plan and execute these two distinct activities are not necessarily the same as those they take to the technology to apply. In view of this, the systems and technologies used for quality control and monitoring must be developed separately.

2.4 Stakeholders' Concern to Monitoring

Table 2-3 summarizes how stakeholders[6] in monitoring of geological disposal, such as the disposal project implementing organization, safety regulatory authority , and society (the general public and the peer reviewers are expected to relate to the objectives of geological disposal monitoring as described in section 2.2.2 above.

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[5] Ex. JIS Z 9904/ISO 9904: *Control of quality means every activity to set out quality policy, quality objectives and responsibilities, and to carry out quality plans, quality control (in the narrow sense), quality assurance and improvements in quality system*

[6] The workshop report (OECD/NEA, 2000) states in its preface that stakeholders include waste generators, waste management agencies, safety regulators, potential host communities, elected representatives, and technical intermediaries between the public and decision-makers.

2.4.1 Disposal project implementing organization

Disposal project *implementing organization*s are likely to implement different kinds of monitoring geared toward all five objectives shown in Table 2-2. Monitoring for Objective 1 of monitoring is particularly important for presenting an enhanced safety case. Objective 2 of monitoring is for the responsibility of project *implementing organization*, who will likely use monitoring information in order to prove that the requirements are met which are set by safety regulatory authority. Objectives 3 of monitoring would prove to be useful for gathering appropriate decision-making data for such purposes as project improvement and rationalization. For Objective 4, monitoring could be used to confirm geological environmental conditions, while for Objective 5 it could provide clear corroborative information related to the phased implementation process of the repository (site selection, construction, operation, closure, etc.), and help to promote dialog with the general public through the preparation of post-closure monitoring and other options.

2.4.2 Safety Regulatory Authority

DOE Waste Isolation Pilot Plant (WIPP) in the US is the only example in the world in which detailed statutory requirements regarding geological disposal monitoring are established; other countries are still studying the issue. Generally speaking, *Safety Regulatory Authority* will not require disposal *implementing organization* to confirm their technical compliance with statutory standards until the statutory requirements concerning geological disposal monitoring have been established.

In WIPP's case, the Department of Energy (DOE), which is the operator, developed a Compliance Monitoring Program (CMP) to support its performance confirmation programs for the purpose of satisfying the monitoring requirements established by the Environmental Protection Agency (EPA). As part of that effort, the DOE selected 10 Compliance Monitoring Parameters (COMP). The DOE is required to submit a compliance confirmation application to the EPA every five years.

Regarding Objective 2, requirements in other objectives might be included in laws and regulations. Objective 2 is mainly related to laws and regulations, while other Objectives are somewhat related to laws and regulations.

2.4.3 Society (General Public and Engineers)

In general, residents living near a candidate site want confirmation that the repository will be safe especially both for themselves and for their children and grandchildren. The policy that implementing organizations adopt in response to this is an important element in the residents' decision-making process. Therefore, public confidence in the way the implementing organization implements the disposal process is a key concern, as is the geological disposal monitoring that includes parameters selected under Objective 3, which includes such options as post-closure monitoring. In addition, the peer reviewers who act as intermediaries between the general public and decision-makers will probably show their concern with all five objectives.

Table 2-3 *Relationships between Monitoring Objectives and Stakeholders*

	Stakeholders	Disposal project Implementing Organizations	Safety Regulatory Authority	Society (public and technical intermediaries)
Monitoring objectives	1. Confirming safety performance and the adequacy of the repository's engineered measures	Enhancing safety case		Review by engineers
	2. Confirming compliance with statutory requirements	Reporting to regulators	Judging the items shown at left column	Review by engineers
	3. Providing information for making decisions on policy and operations	Demonstrating the process of phased implementation and corroboration; dialogue with public		Review by engineers Participation by administrators and policy-makers
	4. Understanding the baseline characteristics of the geological environment at Preliminary Investigation Areas, etc.	Improving and rationalizing project; Dealing with defects, in any defects		Review by engineers
	5. Providing information for public decision-making	Confirming phased implementation		Public decision-making

2.5 Monitoring from Site Selecting Phase to Post-Closure Phase

In recent years, many countries have tended to favor making decisions in each operational phase to ensure technical and public flexibility in geological disposal projects (e.g., OECD, 2001). Table 2-4 correlates the objectives of geological disposal monitoring with each project phase to examine the role which monitoring plays in each phase.

2.5.1 Disposal site selection phase

Monitoring will provide information that:

- *Is important for meeting safety regulations; for making policy decisions concerning repository siting and the initiation of construction; and for facilitating public decision-making concerning siting,*
- *Will be needed by implementing organizations to develop appropriate safety cases for disposal systems, based on an understanding of the baseline characteristics of the site environment and*
- *Will provide information needed in both technical and social contexts, based on data on trends in the long-term conditions of the geological environment extending beyond closure; the impact of the repository before and after installation; and the trends of recovery in the geological environment after closure.*

2.5.2 Construction, operation, and closure phases

Monitoring will provide:

- *Data concerning engineered measures and safety performance that meet safety regulations and*
- *Information that contributes to phased project development and public decision-making.*

2.5.3 Post-closure phase

Because geological disposal systems are not expected to require active safety control, monitoring is expected to:

- *Provide an understanding of recovery and stabilization trends in the geological environment surrounding the repository, after baseline characteristics have been determined and*
- *Contribute to waste retrieval and to the provision of post-closure information needed by society.*

Table 2-4 Roles of Monitoring in Each Project Phase

	Project phase	Selection of disposal site	Construction / operation	Determination of closure/closure	Post-closure
Monitoring objectives	2. Confirming compliance with statutory requirements	Regulatory requirements for approval	Regulatory requirements for construction/operation	Regulatory requirements for closure	Not applicable
	1. Confirming safety performance and the adequacy of the repository's engineered measures	Not applicable	Applicable (Regulatory requirements)	Applicable (Regulatory requirements)	Not applicable
	3. Providing information for making decisions on policy and operations	Applicable (Siting decisions)	Applicable (Phased project development)	Applicable (Determining repository closure)	Not applicable
	4. Understanding the baseline characteristics of the geological environment at Preliminary Investigation Areas, etc.	Applicable (Prior baseline data)	Applicable (Site disturbance caused by project implementation)	Applicable	Applicable (Restoration/stabilization after repository closure)
	5. Providing information for public decision-making	Public decision-making about siting	Confidence in disposal project	Public decision-making about repository closure	Monitoring continues as long as society requires

2.6 Considerations of Monitoring Parameters

In view of the monitoring objectives summarized above, geological disposal monitoring must be directed toward the engineered components composing of engineered barriers and repositories, surrounding environmental conditions, and far-field as the structural components of natural barriers.

It is particularly important to recognize that the act of monitoring itself provides a pathway by which radionuclides migrating from the waste packages can pass through engineered and natural barriers. In view of this, consideration should first be given to the factors presented in Figure 2.1, which are considered to be the standard scenario for evaluating long-term repository behavior.

Concerning near-field performance, major factors include the behavior of the waste packages and buffer materials, as well as the environment of surrounding rock mass that exerts an influence on them. Because these factors also relate to discussions on waste retrievability, they are likely to draw the attention of stakeholders. It must be kept in mind, however, that direct monitoring of these factors would entail much equipment to be installed, which would ultimately have a negative impact on barrier performance.

The assessment of far-field performance can provide corroborating information to demonstrate that the conditions in which the repository has been placed are appropriate. Specifically, this means such things as ascertaining that the groundwater is in a reducing environment and is flowing slowly, and that the deep geological environment is stable. To meet such requirements, it is important to conduct technical reviews with a focus on implementing the necessary long-term monitoring.

Technical approaches to geological disposal monitoring will be discussed in Chapter 3.

2.7 Monitoring and Pilot Facilities

Directly accessing the waste packages for the purpose of monitoring could negatively affect the long-term performance of engineered barriers. One way to solve this problem is to build a pilot facility at another site set apart from the actual disposal site and implement monitoring there (IAEA, 2001).

The pilot facility proposed by EKRA of Switzerland (see Attachment B) is a small-scale facility to be constructed before waste packages are emplaced in the main underground disposal facility. A small amount of waste packages, fitted with monitoring equipment to confirm safety, will be emplaced in the pilot facility, and no monitoring will be implemented in the main facility itself. The pilot facility will remain in use even after the main facility begins operating.

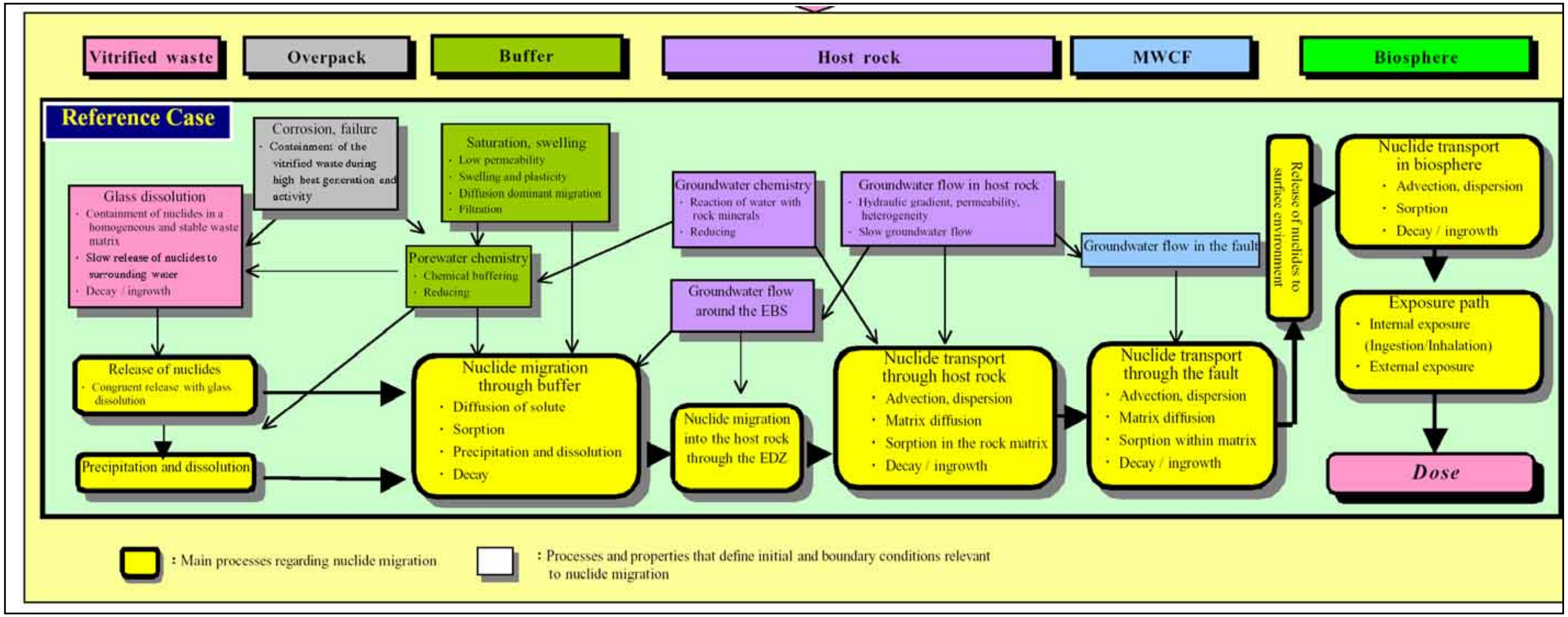


Figure 2.1 *Reference Case for Performance assessment of geological disposal (JNC, 1999)*

2.8 Assessment System of Monitoring Data

RWMC held an international workshop in February 2002 (see Attachment C), where the following questions were raised: What should be done if the data obtained through monitoring deviates from the scope of behavior initially expected? To assess the data obtained through monitoring, it is important to correctly correlate the measured values obtained through monitoring with the assessment tools needed to understand the data. To illustrate this, the concept of trigger values as applied at WIPP of the US is presented below, based on a presentation given at the workshop.

WIPP trigger values

Trigger values mean the upper and/or lower limit of monitoring data of the WIPP. Those values are the voluntary standards set by the implementor (the U.S. Department of Energy) in order to investigate the causes of the appearance of unexpected values in monitoring, if any, and assess whether or not there exists any effect on regulation compliance. In some cases, different measures may, if necessary, be taken depending on assessed results; in other cases, simply modifying the trigger values would be enough. The trigger values are not given to some monitoring parameters, which cannot precisely represent the long-term performance of a repository. Although the EPA does not make it compulsory to apply such a system to pre/post-closure monitoring programs, the DOE considers the trigger value the most important part of the entire monitoring program. The DOE has gone through the following five steps in order to extract trigger values for each monitoring parameter:

First step: *Transparency in data properties of monitoring (e.g., measured values, observed values, notified values, etc.)*

Second step: *Mapping the monitoring-related data to performance assessment factors (performance assessment parameters, FEP deterministic grounds, conceptual models, etc.)*

Third step: *Transparency in the data of the parameters, which were used for proving performance assessment in association with application for compliance confirmation*

Fourth step: *Transparency in the effect, which may be exerted on disposal system performances by variations in performance assessment factors*

Fifth step: *Decision on whether or not to give trigger values (by experts in charge of performance assessment studies). If yes, trigger values are set as the monitoring parameter and monitoring data, or either of the two.*

The DOE has given trigger values to seven out of ten compliance monitoring parameters set in the WIPP.

In view of the example presented above, it appears that the standardization of the following items may be a key task in establishing a monitoring-related measurement/assessment system:

- *Methods of collecting data,*
- *Methods of evaluating data and*
- *Methods and criteria for making decisions (expert judgments)*

3. Technologies for Monitoring of Geological Disposal

The technologies used for monitoring of geological disposal should be developed while taking into consideration the diverse monitoring objectives summarized in Chapter 2. Also, as already noted, the different roles and objectives of implementing organization, safety regulators, local governments, and other interested parties should be taken into account when monitoring is implemented. These many different objectives (needs) should be accommodated when monitoring is implemented in the future.

With this in mind, it was determined to initiate the development of monitoring technologies for the purpose of preparing a "***technology menu***" in additional further studies that breaks down the development of monitoring technologies into categories by asking the so-called "***5W1H***" questions: ***Why (objective); Who; When (from/to); Where; What; and How (methodology)*** in order to develop monitoring plans. This approach increases the flexibility in the monitoring programs of different agencies as monitoring technologies are developed. The investigative methodologies which lead to developing monitoring plans are shown in Figure 3.1.

From the site selection through to the construction and operation phases of a disposal project, measuring equipment can be accessed relatively easily through open boreholes and survey tunnels. This means that most of the existing measuring technologies and methods would be able to be used to implement monitoring of geological disposal. What is more important, however, is forecasting the applicability of technologies slated for use after the repository has been closed, when access to the repository and monitoring equipment will be severely restricted. The technology menu for geological disposal monitoring therefore would be to list technologies that are highly stable and reliable over an extended period of time. They would be prepared for confirming that a repository is operating safely even after repository closure, which can be considered the most important and uniquely characteristic feature of geological disposal.

A goal is to create a specific and appropriate menu based on the technical characteristics of geological monitoring, with obtaining knowledge through an examination of case studies and technical surveys. It is focused on measuring technologies (sensors) and wireless transmission technologies that could be applied to the geological disposal in this study.

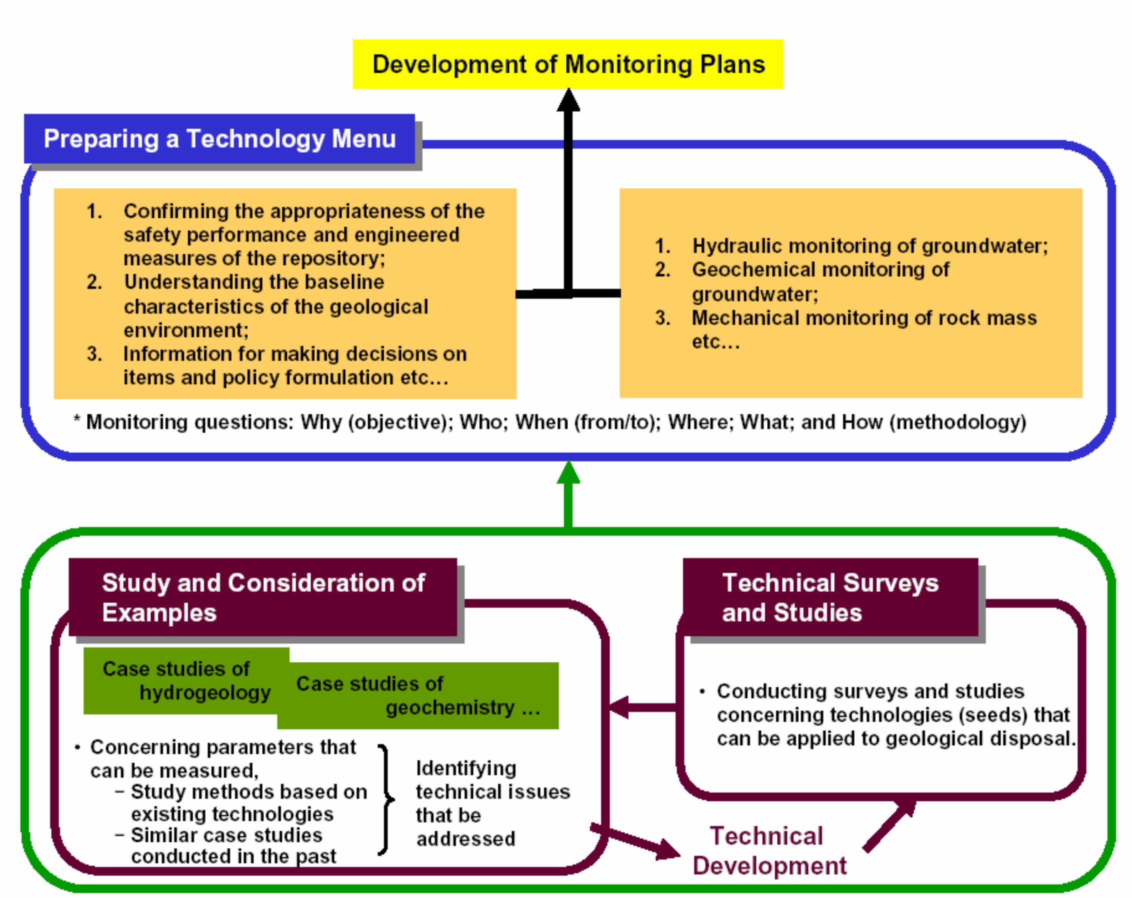


Figure 3.1 *Flowchart related to the Development of Monitoring Plans*

3.1 Approach to Identifying Monitoring Techniques

With the exception of measurements taken near the ground surface, most technologies for geological disposal monitoring must be developed while taking into account the environmental conditions for measurement shown in Table 3-1.

Table 3-1 *Environmental Conditions for Measurement to be Considered for Geological Disposal Monitoring*

Items	**Near fields of the waste package**	**Far fields of the waste package**
Temperature	**100 °C max.**	**45 °C (depth of 1000 m) ***
Pressure	**11 MPa** (depth of 1000 m)**	**10 MPa** (depth of 1000 m)**
Water quality	**Salt water/Fresh water**	**Saline water/Fresh water**
Radiation***	**3X10^{-0} mGy/h (gamma ray)**	—
	3X10^{-2} mGy/h (neutron radiation)	

* JNC (2000)

** It is assumed that swelling pressure (1 MPa) of buffer materials is added to hydrostatic pressure (10 MPa) at a depth of 1000 m .

*** The value on the overpack surface when the thickness of overpack is 190 mm (JNC, 2000)

In attempting to clarify the technical issues involved with geological disposal monitoring, it is necessary to consider factors and methodologies such as the following from among the 5W1H questions which would be indicated in the technology menu: time (when measurement is started, how long it lasts, how often it is conducted, and when it is terminated); place (two-dimensional space on the ground surface, and depth); how the system of the measuring equipment is maintained; and whether or not the equipment can be replaced.

The results of survey conducted up to now indicate that studies should be conducted on existing technologies that can be applied to geological disposal monitoring, and that the following two issues are considered as worth undertaking for possible monitoring parameters :

- *Monitoring hydraulic and hydrogeochemical properties and*

- *Developing wireless underground communication technologies*

The above two issues were selected for the following reasons.

Safety evaluation scenarios for the disposal of high level radioactive waste (as referred to in the reference case included in the H12 Report (JNC, 1999) and shown in Figure 2.1 in Chapter 2 above) indicate that the action of groundwater could dissolve radionuclides contained in the waste packages and transport them through geological strata (natural barriers) to the ground surface where people live. Therefore, it has been placed priority on the development of monitoring that measures hydraulic and hydrogeochemical properties so that technical forecasts can be made. Wireless underground communications technology will be a common component of many monitoring technologies as a means of transmitting to the ground surface measurement data that is obtained deep underground. Because it does not use cables to transmit data from the sensors, wireless technology offers a promising way to implement monitoring without compromising the performance of the repository after closure.

3.2 Measuring Technologies

Surveys were conducted on the content of measurements being taken at deep underground research laboratories (URLs) and other facilities in Japan and abroad in connection with geological disposal (see Attachment F).

The chemical properties of groundwater, particularly its oxidation-reduction potential (Eh) and its hydrogen-ion concentration (pH), are closely related to the physical movement of radionuclides and are therefore important parameters to measure. In studies on monitoring, these measuring technologies are among the first that should be addressed. In URLs in Japan and abroad, it was found no example of continuous measurements except measurements made of sampled groundwater.

Concerning Eh, a survey of currently available equipment, for clarifying oxidation-reduction environments has clarified no equipment for continuous monitoring of oxidation-reduction environments deep underground over long periods of time. A similar situation was found with regard to pH. There are two methods in general use to measure pH: electrical measurement, and measurement through color comparison. It was studied on various measuring devices that utilize these two methods to determine their applicability to disposal environments in terms of such factors as temperature, pressure/shock, oxidation-reduction ambience, degree of contact between sensors and water, radiation, and long-term characteristics. As the devices used to measure both Eh and pH rely in principle on chemical reactions for detection, they are ill-suited to long-term, continuous monitoring, and this gives rise to a technical need to calibrate the equipment to accommodate the environment in which it will be used, to change the materials used, and to develop ways to protect against deterioration. Therefore, the scope of survey has been broadened to investigate technologies that are similar to the systems that have been developed for understanding oxidation-reduction environments deep underground, such as the sensor technology used in the Shinkai 2000 manned research submersible, or in space exploration and development, or in the medical field, where compact, energy-efficient technologies are found.

Also, one of the latest trends in measurement technology is sensors combined with fiber optics, which are increasingly being used to measure factors such as chemistry, temperature, and deformation. Then, surveys of the measurement principles and sensor performance of these latest technologies are being conducted and ways to apply them to geological disposal monitoring are being studied.

The current status of trends in sensor technology is presented in Table 3-2 below for the measured parameters that are expected to be relevant to geological disposal monitoring.

Table 3-2 *Trends in Sensor Technology for Different Measured Parameters*

Measurement category	Measured items	Measurement method	Issues raised in discussions of technologies for monitoring of geological disposal
Heat	**Temperature**	**Thermoelectric measurement**	**Because the measuring device uses electrically conductive metal, it is subject to change and deterioration in the environment.**
Groundwater	**Water level; pore water and moisture content**	**Water-level gauge; moisture meter**	**The long-term reliability of chemical methods and electrical methods (measurement of electrical conductivity) is an issue.**
Stress	**Rock pressure; fractures; displacement and deformation**	**Acoustic emissions (AE); distortion / displacement gauge**	**Supplying power to acoustic emission transmitters and receivers**
Chemistry	**Water-quality chemistry** **Dissolved component**	**Eh / pH measurement**	**Finding ways to prevent changes and deterioration in the sensors, which operate on the principle of chemical reaction**
Other combined measurements	**Composite fiber-optical sensors (reflective type, permeation type, etc.)** - **Stress: changes in the characteristics of light permeation** - **Chemistry: light wavelength** - **Sensible heat: light wavelength, changes in refractive index**		**The chemical and structural durability of the sensor and fiber materials is unknown. Reflecting knowledge of optical fiber cables, etc.**

Regarding Measured items & Measurement method, refer to IAEA (2001), POSIVA (2003), and SKB (2001)
Regarding Composite fiber-optical sensors, refer to Jobmann (2000)

3.3 Transmission Technologies That Use Wireless Underground Communications

In Japan, the geological disposal of high level radioactive waste entails the emplacement of the waste at least 300 meters underground. In order to confirm that a repository, especially the vicinity of near-field at that depth is operating safely, remote monitoring would be listed as useful technique. However the remote monitoring technique tends to decrease as the distance from where it is implemented to the repository increases. As a possible alternative to remote monitoring, repository-based techniques are thought to hold considerable promise in terms of measuring data directly, especially if repository-based monitoring can be combined with wireless transmission technologies. Therefore, it is worth exploring the possibilities of wireless transmission technology which could be applied to the radioactive waste disposal even after repository closure.

Wireless transmission can make use of electromagnetic waves (including light) or sound waves. From the perspective of suitability for geological disposal monitoring, the high-frequency range of electromagnetic waves that is normally used for communications is considered inappropriate because of the significant degradation that occurs when the waves pass through the transmission media of water and rock. In practice, optical communications require the use of cables, whereas communications based on sound waves suffer fundamental problems related to signal deterioration and limitations on how much data can be transmitted.

In contrast to these options, the use of low-frequency electromagnetic waves is considered the most applicable, based on actual results obtained under conditions that resemble geological disposal monitoring, such as the transmission of measurement data on ground subsidence(Reclaimed ground subsidence monitoring for Kansai International Airport,2000～), and applications in civil engineering. Development is therefore being pursued in this area, including efforts to reduce the size of transmitters and receivers (which have been quite large until now) and to reduce energy consumption through function verification tests in actual underground environments. The prototype units used in these tests is shown in Photo 3.1 below.

Tests were first conducted on underground wireless transmission using low-frequency electromagnetic waves undertaken by RWMC in 2002, by the courtesy of SKB, at the Hard Rock Laboratory (HRL) in Sweden, where it was confirmed experimentally that basic communication could be achieved. Through a comparison of the results of these tests with a theoretical analysis of electromagnetic wave transmission, theoretical studies are being conducted on the basic characteristics of underground communications. As shown in Figure 3.1, the communications test results obtained at HRL are reproduced analytically, showing the receiving characteristics with the conductivity of different underground mediums tentatively set. In this way, the validity of the methodology is proved. From test results and the theoretical analysis of two-dimensional transmission implemented so far, it has been found that data can be transmitted approximately 100 meters in both uniform crystalline rock and salty groundwater environments.

Future studies will focus on analytical methods applied to three-dimensional structures, with the aim of applying the methods to various geological environments encountered in actual repositories. These studies will be accompanied by validation tests conducted in different types of underground facilities that have environmental features similar to those of the sites where the technology will be actually used.

Studies are also needed to ascertain such variables as the depth of the repository (for example, up to 1,000 meters in crystalline rock and about 500 meters in sedimentary rock), the special characteristics of the repository in question, as well as to help achieve longer communication distances and determine the ability to withstand pressure, heat, and radiation. Other issues that must be addressed include securing a power supply so that the equipment can function; improving operability and maintainability while keeping in mind long-term reliability and applicability; and reducing equipment size.

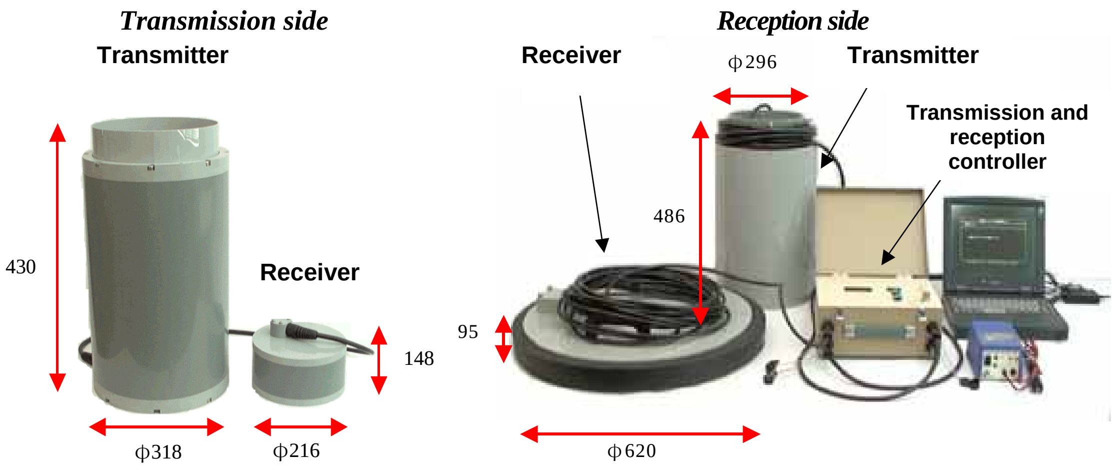
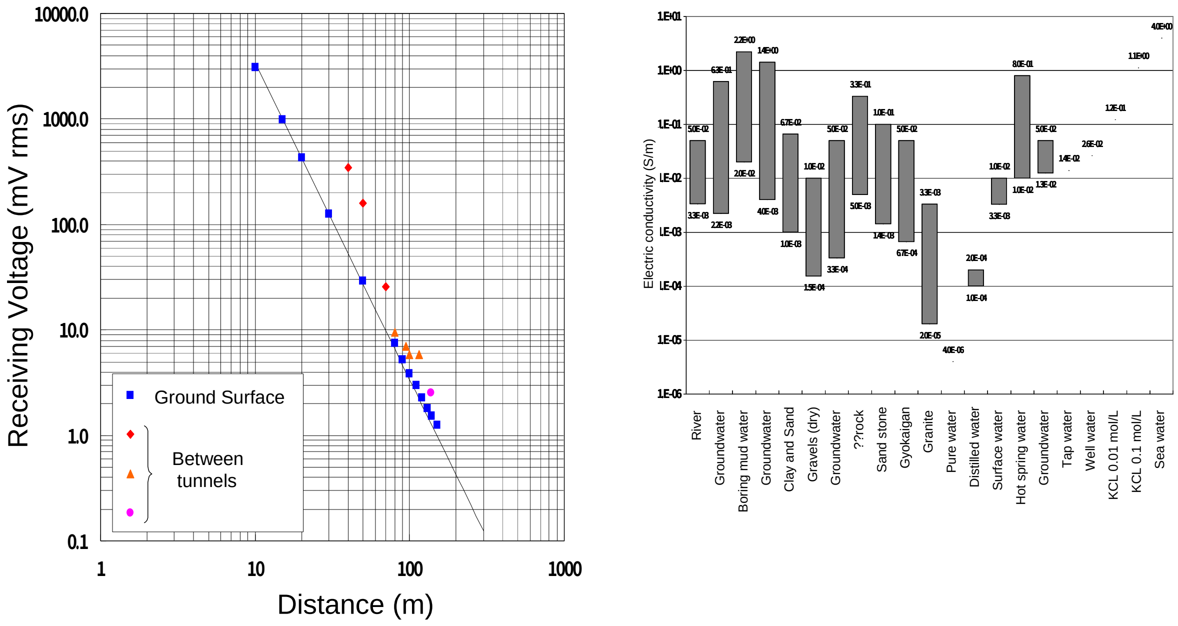


Figure 3.1 Underground Wireless Radios (Prototype Units) (Dimension: mm)



Result of communication test between tunnels (Sweden: Äspö)

Electric Conductivity of various underground mediums

Figure 3.2 Results of Wireless Underground Communications and Data of Electric Conductivity of Underground Mediums

Future Work Programs

The debate on what type of monitoring system to use for geological disposal will no doubt continue as advances are made in the phased development of geological repositories. To facilitate to make a decision on such a debate, it is important to clearly indicate the technical feasibilities. To fulfill the purpose, a technology menu for geological disposal monitoring is being worked and formulated.

This report has outlined the current status and purposes of geological disposal. Using this as a foundation, it will be considered to creating a technology menu that will contribute to the development of monitoring programs from the perspective of the 5W1H questions.

With regard to the applicability of technologies, surveys and research must still be conducted to clarify the technical feasibilities of elemental geological disposal monitoring technologies, including measurement and data transmission technologies. Also, it is necessary to prepare and organize technical information with regard to data in terms of taking advantage of and obtained in the field of deep geological environments.

As has been pointed out, the environmental conditions that must be dealt with in geological disposal monitoring require sensors and other technologies that can provide long-term monitoring. Since there has been no market for such technologies until now, new development is required. Therefore, technical surveys ("seeds" surveys) must be continued in a wide range of advanced scientific and technical fields, such as space and ocean development. Also, verification tests on sensor and underground transmission technologies conducted in the field at deep underground research facilities must be continued both in Japan and other countries, with the aim of building more reliable monitoring systems.

The promising geological disposal monitoring technology requires to be established in order to technically develop more reliable monitoring system. Furthermore, the development of such technology needs to be conducted performing test confirmation in the fields such as deep geological laboratories domestically and abroad.

Acknowledgements

This report is described on the latest information and knowledge concerning geological disposal monitoring based on the research results obtained in the "Survey on Improving Monitoring Device Technologies" implemented by RWMC entrusted by METI.

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Attachment A The Current State of International Discussions Concerning Institutional Control

Institutional control[7] has been a topic of discussion in various countries since the 1970s. One document that mentions this subject, OECD/NEA (1982), recognizes the effectiveness of institutional control, but advocates that, essentially, steps should be taken to formulate passive disposal methods that do not depend upon institutional control. In OECD/NEA (1995a), an evaluation was conducted on the actions of careless workers, and more active institutional control was mentioned. Furthermore, in OECD (1995b) the ethical problems associated with the disposal of radioactive waste were discussed, including the need for fairness both between generations and within a single generation. Additionally in OECD/NEA (2001), the issues of retrievability and reversibility were discussed, and further consideration was given to the 1995 inter-generational ethics issue cited above, focusing on the rights of future generations to make their own decisions.

In OECD/NEA (1999), the word "confidence" was defined as follows: *"To have confidence is to have reached a positive judgment that a given set of conclusions are well-supported."* On the basis of this definition, the report stated that perfect knowledge of a system should not be a requirement when making decisions concerning the development of disposal sites. Therefore, a crucial issue for people involved in the management of radioactive waste is building confidence in the long-term safety of geological disposal, as well as finding communication methods that inspire such confidence. To this end, the report underlined the importance of developing disposal sites in a phased and flexible manner. Further discussions on retrievability and ethical aspects were carried out in workshops (IAEA, 2000) and a forum (OECD/NEA, 2000) focused on the confidence of stakeholders. Debate from the perspective of public confidence continues to this day.

Within this context of international discussions concerning public confidence, IAEA published IAEA-TECDOC-1208, which summarizes the studies that have been conducted on the purposes of monitoring, the use of information, and methodology.

Taking all of the above into consideration, outline of international trends regarding institutional control can be summarized as follows.

- *Principle: The assurance of the safety of geological disposal does not depend on institutional control,*

- *From the 1980s, the effectiveness of institutional control as a means of obtaining the necessary public confidence was clearly recognized by international institutions and*

- *In recent years, the need for a flexible, phased approach to the development of repositories has been debated, and institutional control has been given a greater role. Today, the use of monitoring (which is one method of institutional control) is being considered, with a view toward encouraging social confidence and acceptance.*

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[7] ***Institutional Control:*** *Control of a waste site (for example, disposal site) by an authority or institution designed under the laws of a country or state. This control may be active (monitoring, surveillance, remedial work) or passive (land use control) and may be a factor in the design of a nuclear facility (for example, near-surface disposal facility). (IAEA, 1995)*

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Attachment B Survey and Analysis of the status of Monitoring Studies in Japan and Abroad

B-1 Status of Monitoring Studies in Various Countries

To assist monitoring studies in Japan, surveys on the status of monitoring studies on geological disposal programs in various other countries were conducted from 2001 into 2002. The countries surveyed were: Sweden, Finland, France, Switzerland, Belgium, Spain, the UK, Germany, the USA (YMP and WIPP) and Canada. In addition to perusing the literature and collecting information through the Internet and other means, the survey team commissioned reports on relevant topics from the institutions concerned in each country and, when necessary, visited these institutions and conducted interviews.

The results of these surveys are summarized in Table B-1 below, which covers the following.

- ***Approach to the management of geological disposal***
  - *Basic approach*
  - *Underground testing facilities for verification tests and other purposes*
  - *Retrievability*
- ***Monitoring requirements imposed by regulatory bodies***
- ***Status of monitoring efforts by the implemental bodies, etc.***
  - *Necessary conditions*
  - *Plans*
  - *Conditions for the selection of monitored items*

B-2 Management of Geological Repositories

1) *Phased implementation*

The approach to geological disposal adopted in foreign countries is based on "The Principles of Radioactive Waste Management," SS 111-F (IAEA, 1995), which states in principle that, with respect to radioactive waste management, necessary safety functions should depend on long-term, institutional control as little as possible. Some countries have clearly defined basic disposal policies, while other countries are still in the study phase. All of the countries that have established a basic policy have clearly committed themselves to phased repository development, with clearly indicated or implied implementation of related monitoring.

2) *Underground Testing Facilities*

Concerning underground testing facilities for such purposes as conducting verification tests on disposal technologies, the following countries have either indicated or implemented the policies described.

- ***Sweden:*** *In the SKB program, 10% of the waste material will be emplaced in advance in the first* *phase of the project, and geological monitoring will be conducted for a prescribed period. The knowledge gained from this process will then be evaluated and, if agreement is reached, a disposal area will be constructed to house the remainder of the waste material package.*

- ***The US (WIPP):*** *Part of the repository is being used as an underground laboratory for such tasks as monitoring bedrock behavior and conducting retrievability verification tests.*

Also, in Switzerland, the Expert Group on Disposal Concepts for Radioactive Waste (EKRA) has developed a concept of long-term monitored geological disposal, which calls for the construction of test facilities and pilot facilities in addition to the actual waste emplacement facility (main facility) in order to carry out monitoring and management activities (EKRA, 2000). Recently in the US as well, a panel of experts affiliated with the National Academy of Sciences (NAS) has stated that the Yucca Mountain repository program be pursued in stages and with a high degree of flexibility, and has recommended to the Department of Energy (DOE) that a test phase should be planned in order to test at least the key concepts of the project (National Research Council, 2003).

3) Retrievability

Finland, France, and the US (YMP, WIPP) explicitly mention waste retrievability or reversibility (a component of retrievability) in their disposal plans or laws. It was also discovered that, spurred by recent international study conditions, relevant institutions in other countries have initiated internal studies on retrievability, as well.

The results of the above survey show that the recent international trend is toward phased implementation of repository development, and that issues such as retrievability are being studied. Even countries that have not previously clearly indicated such a stance or considered the issue of retrievability, are now indicating that internal studies have begun. Meanwhile, international agencies are taking the lead in creating documents and hosting workshops as a means of dealing with public decision-making (OECD/NEA, 1999 and 2000; IAEA, 2000; etc.). Hence, it turned out all countries now recognize the importance of these issues. In view of this, further research and development must be pursued with a concomitant commitment to exchange information and monitor the direction of future debate among different countries and international agencies.

B-3 Monitoring Purposes

In accordance with general safety requirements, repositories are in principle designed so that long-term safety does not depend on the monitoring activities of future generations. However, various countries are studying the possibility of implementing monitoring activities because of the conditions and requirements cited above in relation to phased implementation and other regulatory concerns. The US and Canada have adopted regulations that specify minimum monitoring requirements.

Table B-1 provides an overview of all studies in each country related to monitoring. Except for WIPP in the US, which has already been in the operational phase, plans concerning monitoring are still in the study stage in all countries surveyed.
Note that the content cited below was valid at the time that the surveys for this research project were conducted, but includes items that do not reflect the official views of the countries or institutions in question.

a) ***Supplementing safety assessments and promoting the verification and understanding of models or hypotheses:*** *Sweden, France, Switzerland, Belgium, Spain, UK, US, and Canada,*

b) ***Supplementing or verifying repository design/construction data:*** *Switzerland, Spain, and Canada,*

c) ***Obtaining a baseline:*** *Sweden, Spain, UK, Germany, US and Canada,*

- d) ***Enhancing understanding, obtaining feedback, making repair decisions, etc. in order to:*** *Canada,*
- e) ***Providing information and promoting understanding to facilitate public decision-making:*** *Switzerland, Spain, and Canada,*
- f) ***Monitoring related to retrievability or reversibility:*** *France and Spain,*
- g) ***Building public confidence:*** *Canada,*
- h) ***Sustaining a sense of confidence among future generations:*** *Switzerland,*
- i) ***Reassuring to the public after site management has ended:*** *UK,*
- j) ***Verifying that regulatory requirements are observed and obeyed:*** *Switzerland, Germany, US, and Canada,*
- k) ***Evaluating general environmental impact:*** *Finland,*
- l) ***Evaluating the non-radiological and radiological effects of the repository on the environment, the general public, and repository workers:*** *Sweden, Switzerland, Spain, UK, and Germany and*
- m) ***Complying with requirements for security measures associated with nuclear non-proliferation:*** *Sweden, Switzerland, and Spain.*

Items *a)* through *j)* in the above list can be further categorized as follows:

- ***Verifying the engineering measures and safety functions of the repository:*** *a), b)*
- ***Obtaining an environmental baseline:*** *c)*
- ***Providing information for managerial decisions:*** *d)*
- ***Social aspects:*** *e), f), g), h), and i)*
- ***Confirming compliance with legal and regulatory requirements:*** *j)*

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OECD/NEA: STAKEHOLDER CONFIDENCE AND RADIOACTIVE WASTE DISPOSAL, Inauguration, First Workshop and Meeting of the NEA Forum on Stakeholder Confidence in the Area of Radioactive Waste Management, Paris, France 28-31 August (2000).

Table B-1 *Results of Monitoring Surveys in Foreign Countries (1 of 3)*

Survey Item		Sweden	Finland	France	Switzerland
Approach to managing geological disposal	Basic approach	The basic conditions for managing repositories in Sweden are as follows: 1. The long-term safety of the repository should not depend on the monitoring or maintenance activities of future generations. However, this does not necessarily mean that no monitoring will be performed after waste disposal or site closure; 2. The design of the repository must not obstruct any future decisions concerning repository modification or waste retrieval and 3. Knowledge concerning the waste material, the disposal system, and the disposal site must be preserved in a logical and ongoing manner.	STUK has adopted the following approach to repository management: "*To ensure long-term safety, disposal shall be undertaken in such a way as to not require repository monitoring. In addition, planning must accommodate the possibility of waste canister retrieval in the event that technical development generates favorable options.*"	In the law regarding the management of radioactive waste, the principle of reversibility is incorporated in the following article: "*(Authorization for disposal) will be implemented in each stage. Therefore, reversibility is a necessary condition for each stage. All built structures, etc. must be removed when the relevant authorization period ends.*" Also, a law promulgated in 1992 emphasizes the need for retrievability by stating: "*In any type of research concerning the effects of waste facilities, reference must be made both to site restoration conditions and to waste retrieval technologies that should be used in the event that other technologies cannot be introduced.*" In France, the concept of "*reversibility*" is broader than the concept of "*retrievability*," and includes the discontinuation of operations.	Switzerland's approach to repository management is as follows: "*In Switzerland, long-term repository safety must be achievable without dependence upon post-closure monitoring or (institutional) control.*" In addition, a report issued by EKRA states that the goal of long-term repository management should be "*the protection of human beings and the environment; the assurance of fairness, both for future generations and between generations; and to facilitate the societal decision-making process.*"
	Underground testing facilities	SKB will dispose of waste in phases as the repository is developed. The geological repository is being constructed in two phases. In the first phase, 10% of the total waste will be emplaced and an assessment will be conducted. If the predicted results are obtained in the first phase, the second phase will be initiated.	No concept of a demonstration area was found in Finland (at least not in the published information that was surveyed for this study).	No concept of a demonstration area was found in France (at least not in the information that was surveyed for this study).	In the EKRA report titled, "*Concept of Geological Disposal with Long-Term Monitoring,*" it is recommended that testing and pilot facilities be built in addition to the main repository. In response to this recommendation, Nagra plans to conduct a study of disposal concepts.
	Retrievability	SKB studies reversibility in each phase. SKI is now formulating regulations that include current requirements for retrievability.	Posiva has just begun to formulate plans to ensure retrievability. These are expected to include policies (not yet officially announced) regarding monitoring and retrievability both before and after site closure. Until now, Posiva's view has been that "*the current disposal concept fully satisfies requirements for retrievability*."	As cited above, France has established laws concerning retrievability and, to make it possible to implement reversibility in geological repositories, considers it important for ANDRA to understand in specific terms how the repository is actualized and operated at each stage, as well as all chemical, hydraulic, and mechanical disposal activities. The following is also explicitly stated: "*If the concept of reversibility is included in the design, there is nothing to prevent the repository from being completely or partially backfilled. Therefore, at the start of the project, methods for retrieving waste containers (for example, special handling technologies to protect workers from waste-container radioactivity, etc.) must be given the same priority as the concept of disposal.*"	Swiss policy regarding the perspective of society and the issue of retrievability is recorded as follows: "*Measurements of any kind implemented for the purpose of waste retrieval or repository monitoring/management shall not be allowed to compromise the essential function of the repository as a safety barrier.*" In response to this policy, the EKRA report states that "*societal demands continue to tend toward the concept of retrievability. Therefore, EKRA developed its 'Concept of Geological Disposal with Long-Term Monitoring,' which deals simultaneously with the two issues of disposal and retrievability."*

Survey Item		Sweden	Finland	France	Switzerland
Regulators' monitoring requirements		SKI's basic requirements: Regarding the underground disposal of high level radioactive waste, the repository's long-term safety must not depend on the monitoring and maintenance activities of future generations. In addition, the safety of the repository must not be threatened by the implementation of monitoring programs.	According to Finland's Atomic Energy Law, the state has the authority to demand that measures be taken to monitor radioactive waste and ensure repository safety. General safety requirements, however, prohibit long-term safety from depending in any way upon repository monitoring. Therefore, if some kind of monitoring is sought after repository closure, that monitoring cannot be for the purpose of making decisions concerning safety or the removal of canisters.	No requirements on monitoring were found to be imposed by regulators in France (at least not in the information surveyed for this study).	Swiss policy concerning monitoring further states that "*no measurement activity of any kind should be applied for the purpose of guaranteeing safety. Repositories must be designed so that they can be sealed within several years.*" This statement is also included in the EKRA report.
Monitoring arrangements (implemental bodies, etc.)	Monitoring conditions	Purposes of monitoring on SKB: 1. Understanding the baseline, including seasonal changes, in order to determine and evaluate the effects of repository development and operation, as well as effects after closure. 2. Promoting an understanding of system behavior that helps to supplement safety assessments of the repository and to verify models and hypotheses. 3. Evaluating the repository's non-radiological and radiological effects on the environment. 4. Confirming that, during the period of construction and operation, non-radiological and radiological safety requirements are met for workers. 5. Complying with safeguard requirements related to nuclear nonproliferation.	The following requirements can be found in Posiva's EIA report: 1. Understanding the baseline before the repository is closed 2. Evaluating the repository's radiological effects on the environment 3. Evaluating general environmental effects 4. Complying with safeguard requirements related to nuclear nonproliferation	ANDRA sets the following monitoring requirements: "*Monitoring of the underground environment must be specified in accordance with all periods of reversibility and all phases of implementation. In particular, it is necessary to develop instruments to monitor changes in the underground environment, the facilities, and the waste containers.*" To this can be added the "*monitoring for reversibility*" cited above.	Nagra defines the monitoring purposes in each phase as follows: 1. Supplementing the repository's design, construction, and safety assessment data 2. Collecting data to verify compliance with regulatory requirements and to understand the radiological and non-radiological effects of the repository on workers, the general public, and the natural environment 3. Providing information to facilitate the public decision-making process regarding the repository's phased developmental process 4. Verifying compliance with security requirements 5. Sustaining the confidence of future generations
	Plans	Regulators have no specific strategy. Similarly, SKB has no specific plans after the site characteristics have been surveyed.	A proposal for environmental follow-up monitoring has been prepared, which will be implemented in two phases: one before the repository is closed, and one after. For the post-closure follow-up, Posiva proposes the following procedures: measurement of radioactivity both on the ground surface and in boreholes; measurement of such aspects as groundwater level, flow, and chemistry in boreholes; and measurement of micro-earthquakes on the ground surface.	To achieve the monitoring purposes related to reversibility, ANDRA assumes the following measurements: 1. Observations and measurements of changes in the constituents of the deposition hole and tunnel 2. Measurements of the environment surrounding the deposited waste containers 3. Measurements of the repository environment to verify conformity with predicted repository performance	Nagra has set monitoring purposes for repositories, but because regulators do not require long-term monitoring, it could be found no official positions based on a discussion of details such as: what parameters should be monitored during each phase of repository development; what measuring technologies should be used; what performance standards and acceptance criteria should be used; and how monitoring results should be used in decision-making with regard to final closure, intervention, and retrieval.
	Conditions for selecting items	SKB imposes the following conditions on item selection: 1. Can the measuring equipment be calibrated and monitored? 2. Can the predicted values be set within the scope of uncertainty? 3. Are any actions anticipated in the event that results fall outside the predicted scope?		ANDRA has adopted the following policy: "*Monitoring of the underground environment must be specified in accordance with all periods of reversibility and all phases of implementation. In particular, it is necessary to develop instruments to monitor changes in the underground environment, the facilities, and the waste containers.*"	

Table B-1 *Results of Monitoring Surveys in Foreign Countries (2 of 3)*

Survey Item		Belgium	Spain	U.K.
Approach to managing geological disposal	Basic approach	NIRAS/ONDRAF is developing their geological disposal concept as follows: "*In principle, a system that does not require or depend upon monitoring.*" However, even if it is judged that retrievability is necessary, the current disposal concept poses no technical problems. In such a case, however, repository monitoring will become an indispensable element.	Currently, Spain's concept of deep geological disposal is based on the idea of the final disposal of radioactive waste, without considering retrieval. Regulators were found to have no official stance concerning retrievability.	The guidelines formulated by the UK's Environment Agency (1997) establish the following four principles as conditions that must be fulfilled before approval can be given for the disposal of radioactive waste: ***Principle 1:*** *Safety that does not depend on management* ***Principle 2:*** *Future impact* ***Principle 3:*** *Optimization* ***Principle 4:*** *Radiation protection standards* The administrative interpretation of Principle 1 dictates that the closure provided by the disposal system after the repository is closed, and the continuous safety of future generations in particular, must not depend upon such activities as monitoring, overseeing, preventive action, or restorative action. If this requirement is not met, the regulators shall not authorize disposal.
	Underground testing facilities	No concept of a demonstration area was found in Belgium (at least not in the information that was surveyed for this study.)	No concept of a demonstration area was found in Spain (at least not in the information that was surveyed for this study.)	The UK has not established whether or not a demonstration area is required, nor has it defined which phases of repository development would be affected.
	Retrievability	Currently, Belgium has no laws/regulations or authorization requirements concerning the retrieval of HLW or spent fuel. A Cabinet order has been officially issued regarding LLW, however, and it is possible that the same conditions will be applied to the disposal of HLW or spent fuel in the future. NIRAS/ONDRAF defines the purposes of retrievability as follows. 1. To protect the rights of future generations with regard to environmental protection, including the wish to intervene concerning the level of contamination sources and the eruption of unexpected civil unrest. 2. To ensure an access method in case the decision is made to use spent fuel as a resource.	Although regulators are not considering retrievability as stated above, regulatory conditions for retrievability have been established for ENRESA's ILW/LLW disposal sites, and it is possible that retrievability will become required for HLW deep geological disposal, as well. ENRESA has decided to conduct research on the significance of retrievability vis-à-vis repository design and safety, with a view to encouraging public acceptance of the phased development of deep geological repositories. ENRESA also gives the following three reasons for retrieval: 1. The development of new technologies such as partitioning and transmutation (PT) 2. Reuse of energy sources (U, Pu) 3. In cases where it is clear that repository safety conditions are not adequate	Nirex believes that it may become necessary to remove backfill and reach the containers after the arch-shaped underground vault has been backfilled to seal the repository. To demonstrate that such a retrieval operation is possible, it conducted an actual validation test, in which life-size waste containers were removed from a backfilled repository through the use of water jets and robotic arms.
Regulators' monitoring requirements		Because Belgium has no laws or ordinances concerning long-term monitoring, no decisions have been made (at least in the information surveyed for this study) concerning how monitoring results are to be reflected in areas such as: monitored items in each phase of repository development; measuring technologies; performance standards and acceptance criteria; and decision-making concerning final closure, intervention, and retrieval.	(At least not in the information surveyed for this study)	In addition to the basic principles, the guidelines include 11 supplemental requirements, one of which concerns monitoring. It states: "*To maintain safe conditions, the developer must implement a program to monitor any changes that are caused by facility construction and waste emplacement.*"

Survey Item		Belgium	Spain	U.K.
Monitoring arrangements (implemental bodies, etc.)	Monitoring conditions	NIRAS/ONDRAF is developing their geological disposal concept as follows: "In principle, a system that does not require or depend upon monitoring." However, if disposal is developed with the idea that retrievability is necessary in order to gain public acceptance, long-term monitoring becomes an objective. In such a case, measurement would be carried out with the following goals in mind: 1. Confirming model data by comparing measured values with predicted values 2. If a good match is found between measured and predicted values, using those results to build confidence in performance assessments	Monitoring is thought to be needed in Spain for the following reasons: 1. Providing knowledge (including a baseline) for use in repository design and construction and in the assessment of repository long-term safety 2. Providing knowledge for evaluating the impact on workers, the public, and the environment 3. Safeguard requirements for nuclear non-proliferation 4. Providing data on retrievability and verifying that the system is performing as expected, thereby supporting the public decision-making process	The guidelines formulated by the UK's Environment Agency (1997) include the following policies concerning monitoring: 1. To maintain safe conditions, changes caused by the emplacement of waste and the construction of facilities must be monitored. 2. Rational methods and implementation plans must be established for monitoring the site and facilities. Monitoring procedures must not compromise the facility's long-term safety. 3. To obtain a baseline, monitoring must be initiated in the survey and pre-construction phases. It is also necessary to measure geological, physical and chemical parameters regarding behavioral changes and safety issues arising from construction and waste emplacement. 4. Radiological monitoring must be implemented, radiation limits must be observed, and public proof of radiological protection assurance must be shown. 5. On the basis of Principle 1, the guarantee of facility safety after management has ended must not depend on monitoring or supervision. Monitoring is to be implemented primarily for the sake of reassuring the public.
	Plans	The monitoring posited by NIRAS/ONDRAF is as follows: 1. Near-field monitoring during the operational period or before closure of the transport galleries 2. Far-field monitoring after the repository is closed	No specific studies concerning monitoring are being carried out at present. However, the formulation of a future monitoring strategy is a main component of the iterative process that is currently underway in Spain, and it is expected that monitoring will be implemented when the deep geological disposal of radioactive waste is carried out.	The UK currently has no plans concerning monitoring.
	Conditions for selecting items	Because Belgium has no laws or ordinances concerning long-term monitoring, no decisions have been made (at least in the information surveyed for this study) concerning monitored items and measuring technologies.		

Table B-1　Results of Monitoring Surveys in Foreign Countries (3 of 3)

Survey Item		Germany	U.S.A.（YMP）	U.S.A.（WIPP）	Canada
Approach to managing geological disposal	Basic approach	DBE's approach to monitoring is based on the IAEA principle that the safety of geological disposal must not depend on monitoring. The German government has not designated specific monitoring items, but does demand compliance with regulations. With regard to monitoring, therefore, DBE indicates conformity with regulations, and interprets this as one method of receiving authorization. After authorization is received, DBE also indicates that the status of the repository conforms to predictions, and uses monitoring as a way of enhancing confidence in system safety.	YMP authorizes and operates disposal on the basis of calculated overall system performance results that predict the long-term behavior of the repository during and after the regulatory period. To provide data for performance assessment, it implements performance confirmation programs in every operational phase. Also, in accordance with the Nuclear Waste Policy Act and other laws, retrievability must be sustained for 50 years from the time that operations are initiated. In 2003, the board of the National Academy of Sciences recommended to DOE that the repository program should be pursued in a highly flexible, phased approach.	DOE (the WIPP operator) is required to submit to the EPA (the regulator) a compliance recertification application every five years. This procedure is intended to verify that disposal is being appropriately implemented and that the disposal system is safe. Also, 40CFR Part 191 establishes that the disposal system must not limit the possibility of retrieval.	In Canada, general participation and monitoring are implemented continuously throughout the operational period, and public consensus obtained through this process forms the basis for progress through each developmental phase. An extended monitoring period around the time that the site is closed is believed to make a particularly important contribution to public agreement concerning final site closure.
	Underground testing facilities	No concept of a demonstration area was found in Germany (at least not in the information that was surveyed for this study).	No clear concept of a demonstration area was found in the USA (YMP) (at least not in the information that was surveyed for this study). However, performance confirmation programs are planned for all phases of YMP, including repository site selection, approval, construction, operation, and monitoring, and validation concerning disposal will be implemented inside the facility.	Part of the WIPP repository is used as an underground laboratory. This part serves as a demonstration area in that it was used to conduct geological surveys during the site selection phase, and is now being used for monitoring bedrock behavior and verifying retrievability.	Canada has not publicly announced any concept concerning an official demonstration area. However, AECL is considering placing one or more waste containers for validation use in a demonstration area and installing mediation material (to act as a surrounding barrier), backfill material, and an appropriate monitoring system in the bedrock for continuous monitoring until the closure phase. It is also considering retrieving the waste containers.
	Retrievability	Until now, Germany has defined the final disposal of radioactive waste as the maintenance-free, safe, and final removal of waste. Therefore, there were absolutely no retrieval plans. In accordance with this definition of radioactive waste disposal, Germany has no standards regarding the retrievability of radioactive waste from repositories. However, in light of the status of new international studies, the German Federal Government is currently conducting a review regarding the retrievability of radioactive waste that has been disposed of deep underground.	No information concerning proof of retrievability was found in the public information that was surveyed for this study. However, among the planned performance confirmation programs, there is one that calls for the verification of material depletion of the waste emplaced in the tunnel, and it is conjectured that this program would serve as a means of proving waste retrievability.	In 1992, retrieval was verified at WIPP. All retrieval operations were performed using remote-controlled equipment.	No studies have been conducted on specific methods of demonstrating retrievability. In theory, however, AECL has indicated that retrieval is achievable using current technologies.
Regulators' monitoring requirements		There are no laws that specify monitoring items.	The minimum number of monitoring items from a regulatory perspective is presented in 10CFR Part 60 (code of federal regulations concerning repositories for high-level radioactive waste) and 10CFR Part 63 (code of federal regulations regarding the Yucca Mountain site).	The minimum number of monitoring items from a regulatory perspective is presented in 40CFR Part 191 (code of federal regulations concerning high-level TRU) and 40CFR Part 194 (code of federal regulations regarding WIPP).	Regulatory requirements are indicated through R-104 (including purposes, required items, and policies regarding the disposal of radioactive waste).

Survey Item		Germany	U.S.A.（YMP）	U.S.A.（WIPP）	Canada
Monitoring arrangements (implemental bodies, etc.)	Monitoring conditions	According to DBE, monitoring consists, on the one hand, of the recording of states of affairs and, on the other hand of the comparison of the recorded results with assessment standards. The recording is carried out mainly by different types of measurement and graphical surveys. The assessment standards are defined as limits or operational conditions, or derived from representative model calculations. The objective of monitoring procedures is the compliance with the assessment standards. This is closely related to safety analysis and so largely depends on the final repository situation.	Monitoring at YMP will be implemented (as of February 2001) as part of 24 performance confirmation programs, for the purposes of validating and verifying engineering technologies associated with the performance, construction, and operation of the repository.	The objectives of monitoring at WIPP are as follows: 1) Verifying conformity with all state regulations, official ordinances, federal regulations, and health and safety requirements 2) Providing characteristic values used in site selection 3) Providing data that indicates a baseline 4) Providing data that verifies performance assessments (PA) and predictions, and minimizes uncertainty	Canada indicates the following purposes of monitoring: • Understanding the baseline • Determining conformity with legal and regulatory requirements • Checking the performance of the disposal system and its elements • Verifying functional assessment and design assumptions • Enhancing understanding of and confidence in elements (natural barriers, engineered barriers, facilities, waste, etc.) and processes (construction and operation methods, etc.) • Verifying predictions of performance assessment models • Providing understanding and feedback for improved operations • Deciding on the need for repairs and predicting repair results • Providing information and understanding for decision-making • Building public confidence
	Plans	DBE is giving consideration to monitoring items that would satisfy the requirements set forth by Germany's mining laws and by safety regulations formulated by relevant regulatory bodies.	Twenty-four performance confirmation programs are planned for the YMP repository. In the current site selection phase, two or three programs have been initiated. Future programs will be initiated after detailed studies have been completed.	Monitoring is implemented according to the compliance application, which establishes 10 monitoring parameters that apply before repository closure and five items after closure.	The following are considered monitoring programs that should be implemented in the future: 1. Baseline monitoring: measuring the baseline conditions of a designated site before disruptions are caused by project activity 2. Conformity monitoring: verifying that disposal project operations satisfy regulatory requirements and performance criteria 3. Performance confirmation monitoring: approving design assumptions, promoting understanding of the disposal process, and verifying performance assessment models
	Conditions for selecting items		DOE is currently working on a detailed study called the "Assessment Plan for Testing and Analysis," which concerns material testing and monitoring. According to a preliminary draft of the plan, consideration is being given to selecting monitoring items on the basis of legal and regulatory requirements as well as the need to verify repository performance, while taking into account such elements as measurability and uncertainty.	At WIPP, monitoring items were selected for the compliance application. The items were selected on the basis of FEP and legal/regulatory requirements, with consideration given to such aspects as sensitivity analysis, fluctuations over time, uncertainty, and measurability.	The method for selecting specific monitoring items has not been studied.

Attachment C Record of Workshop on Monitoring

This attachment summarizes the main points covered at the "Workshop on Monitoring of Geological Repositories for HLW (The Present Status, Framework and Issues of Monitoring Projects"), which was sponsored by Radioactive Waste Management Funding and Research Center (RWMC) on February 18, 2002.

C-1 Workshop Overview

Date: February 18, 2002
Place: Toranomon Pastoral (4-1-1 Toranomon, Minato-ku, Tokyo)
Purpose: Review of and information exchange on monitoring-related research conducted by the RWMC
Participants:

Satoru Tanaka, Prof. (***Chairman***)	University of Tokyo
Ferruccio Gera	Member to drafting and review of IAEA-TECDOC-1208
Daniel B. Bullen	Iowa State University, Member of NWTRB
Michael J. Apted	Monitor Scientific LLC
Richard L. Beauheim	Sandia National Laboratories (SNL)
Eric Webb	Sandia National Laboratories (SNL)
Cecelia Williams	Sandia National Laboratories (SNL)
Tomoki Sibutani	Ministry of Economy, Trade and Industry (METI)
Hiroo Numata	Ministry of Economy, Trade and Industry (METI)
Kazuhiko Tamate	Ministry of Economy, Trade and Industry (METI)
Hidenari Akasaka	Nuclear Waste Management Organization of Japan (NUMO)
Mitsuo Takeuchi	Nuclear Waste Management Organization of Japan (NUMO)
Katsuhiko Ishiguro	Japan Nuclear Cycle Development Institute (JNC)
Kaname Miyahara	Japan Nuclear Cycle Development Institute (JNC)
Tai Sasaki	Japan Nuclear Fuel Limited (JNFL)
Susumu Takada	Central Research Institute of Electric Power Industry (CRIEPI)
Yasuhiro Mitani	Kyushu University
Takao Tsuboya	Radioactive Waste Management Funding and Research Center (RWMC)
Jin Ohuchi	Radioactive Waste Management Funding and Research Center (RWMC)
Ai Fujiwara	Radioactive Waste Management Funding and Research Center (RWMC)
Hajime Takao	Radioactive Waste Management Funding and Research Center (RWMC)
Kazunori Sugiyama	Radioactive Waste Management Funding and Research Center (RWMC)
Osamu Kato	Radioactive Waste Management Funding and Research Center (RWMC)

Takao Ikeda; Atsushi Mukunoki; Junichi Ishiguro; Takeshi Sugiyama (JGC Corporation)
Shigeyuki Saito; Ryoichi Sasaki; Kouhei Yamaguchi (Mitsubishi Materials Corporation)
Mitsuaki Furuichi; Kazuo Okutsu; Kazuhiko Masumoto; Hisashi Takamura (Kajima Corporation)
Kiyoshi Amemiya (Hazama Corporation)
Takamichi Kito; Yoshihiko Takubo (Mitsubishi Research Institute, INC.)
Norio Nakayama (National Institute of Advanced Industrial Science and Technology)
Shigenobu Hirusawa; Masahide Nakamura (The Institute of Applied Energy)
Makoto Yoshizoe; Kenichiro Sugita (Mitsubishi Corporation)

The following presentations and discussions regarding the monitoring of geological disposal were conducted at this workshop:

1) ***Explanation of research conducted by the RWMC***

2) ***The status given to monitoring in the IAEA technical document, IAEA-TECDOC-1208***

3) ***Monitoring at the Yucca Mountain Project (YMP)***

4) ***Monitoring at the Waste Isolation Pilot Plant (WIPP)***

5) ***Discussion and conclusion***

The main points concerning *2)* and *5)* above are summarized below.

C-2 The Status Given to Monitoring in IAEA-TECDOC-1208

The main points covered by the editor of IAEA-TECDOC-1208, Mr. Ferruccio Gera, in his presentation and question-and-answer session are summarized below.
First, Mr. Gera explained that IAEA technical documents are premised on a phased approach to geological repository development. According to that premise, decisions must be made before a project can move from one phase to the next, at which time it is essential to rationally understand the issues involved. If decisions are made by a regulatory authority, that authority must verify safety, and the safety case that is made must be based on a database. Monitoring has many purposes, but one of the most important long-term purposes is to advocate a safety case. For that, Mr. Gera explained, a robust debate is needed so that safety advocacy that overcomes uncertainty can be made to enable safety advocacy that overcomes uncertainty.

The IAEA technical document cites the following five purposes of monitoring.

Purposes of Monitoring (IAEA-TECDOC-1208):

(1) *To provide information for making management decisions in a stepwise program of repository construction, operation and closure,*

(2) *To strengthen understanding of some aspects of system behavior used in developing the safety case for the repository and to allow further testing of models predicting those aspects,*

(3) *To provide information to give the public the confidence to take decisions on the major stages of the repository development program and to maintain confidence, for as long as society requires, that the repository site is having no undesirable impacts on human health and the environment,*

(4) *To accumulate an environmental database on the repository site and its surroundings to assist future decision makers and*

(5) *To address the requirement to maintain nuclear safeguards, should the repository contain fissile material such as spent fuel or plutonium-rich waste*

Based on the results of detailed studies of the above purposes and related phenomena, potential monitoring parameters were divided broadly into the following six categories:

- ♦ *Degradation of repository structures,*
- ♦ *Behavior of the waste package and its associated buffer material,*
- ♦ *Near-field chemical interactions between introduced materials, groundwater and host rock,*
- ♦ *Chemical and physical changes to the surrounding geosphere,*
- ♦ *Provision of an environmental database and*
- ♦ *Nuclear safeguards*

(IAEA-TECDOC-1208)

Also, concerning monitoring in general, the following considerations were emphasized:

- *To make rational decisions, cost effectiveness must be analyzed. In other words, it is necessary to understand the advantages and disadvantages of implementing a monitoring program. In particular, the disadvantages of inserting measuring devices must be fully understood, including their impact on long-term safety.*

- *Some people believe that once a safety case has been accepted, no additional monitoring is needed.*

- *Near-field monitoring threatens degrading repository performance. One solution can be come up with using a test facility. is to use a test facility. In such a scenario, three levels of measurement might be implemented: sufficient actual measurements to instill onsite confidence; sufficient measurements to enable the parties concerned to make decisions with confidence; and sufficient measurements to clarify the behavior under typical repository conditions.*

Finally, Mr. Gera brought up the following subjects concerning the ethical aspects of monitoring.

- *Some make the argument that, if the burden of monitoring is to be placed on future generations, then efforts should be made to properly prepare the resources that future generations will need to perform the monitoring. Thought must therefore be given to developing a mechanism that will ensure this,*

- *However, it is impossible at present to predict what decisions will be made by future generations. Therefore, we have only an uncertain basis for thinking about the mechanism mentioned above,*

- *This matter must be discussed at the international level, but ultimately decisions will probably be made at the national level. It is important for all concerned parties to participate, and for progress to be made with the understanding that this is a "learning process " and*

- *It is also necessary to recognize that, even if certain decisions are made today, they might not be applied without modification by future generations.*

Mr. Gera also prepared written responses to questions about the IAEA technical document in advance of the workshop. They include the following content concerning post-closure monitoring, which is a topic that was not adequately explained on the day of the workshop.

Concerning retrievability: Content on retrievability can be broadly divided into two options. One involves delaying the placement of the **E**ngineered **B**arriers (EB) to enable the waste material to be accessed easily over an extended period of time. The other is to place the barriers in such a way that they can be returned to their original positions as needed.

Concerning post-closure monitoring: There is widespread agreement that, in view of the continuous, long-term danger posed by most radioactive waste that is disposed of in geological repositories, there must be rational guarantees that the disposal system will passively realize the required safety level. This means that, once the repository is closed, its safety should not depend upon any kind of institutional control, including monitoring. Knowledge acquired regarding this point indicates that adequate safety can be achieved by doing two things: 1) selecting a site and host rock with appropriate characteristics; and 2) ensuring that the multi-barrier system used is solid and reliable enough to ensure waste isolation at the required level. Despite this, waste management programs in many countries are having difficulty obtaining the authorization necessary to construct geological repositories for long-lived radioactive waste. This difficulty can be traced to some public doubt regarding the soundness of the proposed disposal method (that is, abandoning the repository once it has been closed and relying solely on the effectiveness of its multi-barrier isolation system). In addition, there is a specific reason continued management and monitoring of the repositories which store substances that cannot be placed outside of the safeguard system may be justifiable. These considerations gave rise to proposals for a more flexible approach, which can be summarized as follows.

- *The long-term safety of geological repositories that store long-lived radioactive waste must be assured with safety cases that do not depend (either scientifically or technically) on institutional control (including monitoring) after repository closure. However, if continued monitoring after repository closure would make decision-making easier and help to alleviate public fears, there is no reason to disallow certain designated countries from continuing post-closure monitoring.*

- *Because post-closure monitoring activities are not carried out for the sake of safety requirements, it is impossible to establish a priori during a set period for these activities. It is therefore important to indicate that this point depends upon the reevaluation and decision-making carried out by future generations.*

- *However, it is essential that any and all activities carried out after closure be planned and executed without compromising the safety of the geological disposal system.*

C-3 Discussion and Wrap-Up

Discussions were pursued at the initiative of Dr. Michael J. Apted. The main discussion points are summarized below.

First, opinions were exchanged concerning the definition of "monitoring." Monitoring is defined in IAEA-TECDOC-1208 as follows: "Continuous or periodic observations and measurements of engineering, environmental or radiological parameters, to help evaluate the behavior of components of the repository system, or the impacts of the repository and its operation on the environment." In response to this definition, Dr. Beauheim mentioned that the definition should also include the monitoring of human activity.

Next, it was proposed that the following distinctions be made between the two following pairs of terms, which are easily confused: "variability/uncertainty," and "reversibility/retrievability."

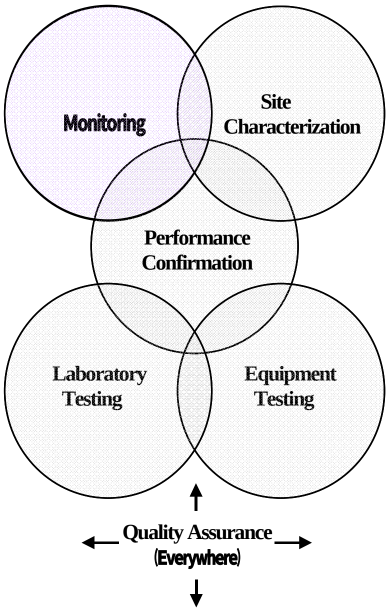
Variability: *Natural variation or properties and conditions of a repository system (a property of the system). For example, it refers to baseline behavior such as the year change of an underground water level, a long-term tectonic movement.*

Uncertainty: *Limitations in our knowledge or ability to measure properties of repository systems. There are different kinds of uncertainty, including measurement uncertainty, conceptual model uncertainty, and scenario uncertainty.*

Reversibility: *An approach in which each step of repository implementation is fully reversible, including retrieval of waste during closure.*

Retrievability: *A sub-set of reversibility in which waste can be retrieved to the surface (up until the time of permanent closure).*

Dr. Apted said that, historically, the concept of retrievability was introduced in the US in the late 1970s. Recently, the concept of reversibility has been discussed in an effort to grasp a broader meaning. Concerning this, Mr. Gera introduced the following information about historical developments at IAEA. Reversibility was originally proposed by the French delegation and was adopted as a general term after discussion, as most people believed that there were serious problems associated with seeking retrievability, which meant leaving the repository open by not backfilling it. Reversibility was proposed as a possible solution, at which point the Swedish delegation stated that, if the waste packages were robust enough to remain sound for thousands of years after backfilling, the disposal concept of reversibility could still be adequately addressed by pursuing the original repository plans.



FigureC-1 *Relationships of terms and "Monitoring"*

Next, in discussions concerning monitoring, Dr. Apted presented Figure C-1, which clarifies the relationships between relevant terms, and provided the following explanation. Figure C-1 tabulates some of the activities at Yucca Mountain, with reference to "performance confirmation." Performance confirmation encompasses the major issue of monitoring, as well as site characterization, laboratory testing, the need to conduct actual onsite studies (such as measuring bedrock pressure), and equipment testing and retrieval technologies. Figure C-1 shows some of these activities. In this way, performance confirmation involves collecting information beyond these boundaries. In addition, performance confirmation takes on unique characteristics depending on the specific site, the concept and the host rock. In any case, quality assurance applies to all parts. For example, the entire program must be written down so that decision content can be tracked.

Dr. Apted compiled the comments received from workshop participants and used them as discussion points for continued explanation. First, ***why*** should monitoring be done? This question needs a specific answer. Monitoring might reflect many different kinds of objectives. It might be used to implement changes over the service life of the repository. More generally, it might be used to provide back-up for decisions made in a phased process. In the case of the US, monitoring is a regulatory requirement. Planners at Yucca Mountain must present evaluative conditions not only to regulators but also to a public, independent peer review group showing that their activities are safe. In addition, monitoring is necessary to guarantee safety to the public and to gain public acceptance. Other objectives for monitoring, though not directly relevant here, include ensuring worker safety and performing proper environmental stewardship. ***What*** should be monitored? It must of course be measurable parameters. ***When*** should monitoring be implemented? A baseline should be initiated at an early stage in the process. ***How good*** should the monitoring be? This question relates to such issues as determining what trigger level indicates that conditions are not normal; what values will trigger action; and what actions will be taken if predictions and measured values do not match. ***How*** will monitoring be implemented? A system is needed that can withstand a harsh environment over a long period of time. Dr. Apted said that strategies that have been adopted in the aerospace field might prove useful.

Dr. Apted presented a table showing how different monitoring purposes come into play in different phases of geological disposal operations, and continued discussions (Table C-2).

Table C-2 *Disposal Stage and Monitoring Objective*

Monitoring objective	**Siting**	**Operations**	**Closure**	**Post-closure**
Decision support	**Applies**	**Applies**	**Applies**	**No apply** (After the closure procedure has been approved , no monitoring or institutional control is needed.)
Confirm site	**Applies** （Baseline）	**Applies** （Large volume）	**Applies** （Long-term）	**No apply** ?
Confirm engineered barriers	**No apply**	**Applies** （WP—WP） （WP—Host rock）	**Applies** （Long-term）	**No apply** ?
Safeguard	**No apply**	**Applies**	**Applies**	**Applies** （Remote surveillance）
Public acceptance	**Applies** (Are the local residents of the candidate--site safe even after site characterization has been approved?)	**Applies** (Can local residents withdraw if they find the site or concept unsatisfactory?)	**Applies** (Can monitoring be used to confirm the appropriateness of the premised conditions regarding safety and the model used?)	**Applies** (Maintaining long-term surface monitoring measures for as long as society deems them desirable: Stewardship)
Regulator/tech peer review	**Applies**	**Applies**	**Applies** （scenarios, robustness）	**No apply** **?**
Optimization	**Applies** （Site characterization）	**Applies** （Repository design） （Engineered barrier design）	**No apply**	**No apply**

The following opinions were exchanged among participants during the discussion:

- *While it is important to maintain flexibility, in the US example such a policy also has disadvantages.*
- *There are limits to pursuing confidence only through safety and performance assessments, and it may be worth using natural analogues and monitoring to raise confidence and reduce uncertainty.*
- *Concerning confidence, attention should be directed to the monitoring objective second up from the bottom of the table: namely, having reviews performed not only by regulators but also by a technical peer group. The peer group is likely to ask some very tough questions, and monitoring would prove useful in such a case.*
- *Perhaps a distinction should be made between monitoring carried out before approval application and that carried out after operations have begun. In the pre-approval period, monitoring can provide extensive information useful for such tasks as gathering information, understanding the baseline, understanding the system, and building a safety case. After operations have begun, the main focus is on maintaining a relationship of trust with the general public, which depends on how much information can be made public. Even if that information differs from predictions, the question is how it can be publicly released. Another related issue is determining how to deal with information that has been collected.*
- *In verifying an engineered barrier system, monitoring has the advantage of helping us to understand processes that cannot be detected in the laboratory, such as the interaction between waste packages and the bedrock. Long-term monitoring also has the advantage of increasing our understanding of baseline behavior.*
- *Monitoring is effective in promoting public acceptance. Explanations can be given concerning the types of monitoring being implemented, such as impact on drinking water, local safety, or post-closure management. Monitoring allows operators to answer people's questions.*
- *Monitoring provides a technical basis for providing information when studying such scenarios as earthquakes, changes in sea level, or changes in climate.*
- *Monitoring can also be considered to have the added value of contributing to the optimization of the disposal system, low-cost design, and modifications in disposal methods.*
- *There are limits to the reliability of monitoring results. If measured values are obtained that do not match predicted values, and it is also known that this result does not have a major impact on the safety case, that particular item can be designated as a supplemental measurement. When specific measurement items are selected, their validity and basis must be designated.*
- *The relationship between measured values and the interpretive tools used for understanding this data must not be forgotten.*
- *The system has a service life, which defines the monitoring period. However, it is impossible to say at present how long the system will continue to function.*
- *When repository closure has been approved, there is no need from the scientific perspective to continue institutional control and monitoring. However, there is a social demand for continuation. Also, there are requirements for safeguard security measures.*

After the above discussion, Dr. Apted wrapped up the workshop with comments about the social and technical aspects of monitoring, including some suggestions pertaining to research conducted at the Radioactive Waste Management Funding and Research Center (RWMC).

Social Aspects

At candidate sites, it is important to talk to the general public about monitoring as a means of ensuring safety now and for future generations, especially children and grandchildren. Also, focus groups are an effective way of finding out what ordinary people are worried about, what motivates them, and what can be done to instill confidence in them. In order to learn from past examples of these kinds of social aspects, RWMC is conducting surveys in various foreign countries.

Technical Aspects

Planning and policy-making related to monitoring will probably depend on the repository concept (site, design). For example, the following items will have an effect: type of host rock; design of engineered barriers; important processes related to safety; and site-specific elements (whether or not an active fault is present, relationship with the ocean, etc.).

Also, as many of the participants stated, it is important to have a baseline. By measuring a baseline, it becomes possible to: confirm that the selected site is appropriate; understand disturbances caused by underground development; compare the values predicted by the model with actual measured values; and confirm the degree of impact on surroundings. Also, although it was not particularly discussed at the workshop, the fact that Japan is seismically very active would suggest that monitoring is indispensable from the perspective of geological engineering. Because temperature gradient problems, which will cause deformation of rock, are generated by the existence of high-radiation, high-temperature locations, consideration must be given to what exactly is monitored. In this respect, conditions in Japan can be considered more difficult than those encountered at WIPP. In addition, for the monitoring, there is an important link between modeling of performance assessment and related research. The following issues must be considered: What parameters fail to match performance assessment predictions? What is the degree of discrepancy, and do changes occur over time? What parameters are important for the purpose of securing safety? And, can a realistic model be developed for system optimization?

Participants had the following question concerning the last item of the above explanation: Does the link between performance assessment and monitoring have significance within overall performance assessments? In response, Dr. Bullen provided the following explanation based on his experience at Yucca Mountain. Because initial surveys did not provide an adequate understanding of site characteristics, it was impossible to design appropriate waste packages, and this had an impact on cost evaluations. This was a lesson learned in the US, but if it is possible to understand the site by linking monitoring with performance assessment, it is important to incorporate that concept into the design immediately. This will enable a realistic response to conduct cost estimates.

Attachment D The Status of Safety Cases and Associated Monitoring

The concept of "safety cases" has been discussed in recent years, especially with regard to the safety of high-level radioactive waste disposal. A safety case is a larger framework designed to increase the understanding of non-specialists (including policymakers) and the general public regarding difficult disposal technologies that are not easily accommodated by previous safety assessment frameworks. To that end, a safety case is intended to convey a sense of safety and secure confidence (for example, "Confidence in the Long-term Safety of Deep Geological Repositories–Its Development and Communication–" (OECD/NEA 1999)). In Japan, this issue has also begun to be discussed (for example, in "Waste Disposal Reference No. 6-3" (Sixth meeting, February 6, 2002) (Special Advisory Board on High-level Radioactive Waste Disposal Safety of the Nuclear Safety Commission of Japan)). Discussion concerning the status of monitoring within the safety case framework provides an important basis for various other discussions on monitoring. The definition of "safety case" and the role of monitoring within it are discussed below.

D-1 Definition of "Safety Case"

Three examples of definition and content of “safety case” are as follows:

(1) Dr. Michael *Apted* presented this definition of "*safety case*" at a monitoring workshop sponsored by RWMC on February 18, 2002.

> ***Safety Case:*** *The set of arguments and different lines of reasoning (e.g., natural analogues) that indicate the safety of a repository system is adequate to meet safety standards and is reasonably assured.*

(2) Quoted content and original expressions used in "Waste Disposal Reference No. 6-3" (Sixth meeting, February 6, 2002) published by the Special Advisory Board on High-level Radioactive Waste Disposal Safety of the Nuclear Safety Commission of Japan

> *"Within the context of developing and communicating confidence in the long-term safety of geological disposal, a Safety Case is a collection of arguments at a given stage of repository development, in support of the long-term safety of the repository. A Safety Case comprises the findings of a safety assessment and a statement of confidence in these findings. It should acknowledge the existence of any unresolved issues and provide guidance for work to resolve these issues in future development stages."*

Waste Disposal *Reference* No. 6-3 also cites the following as examples of safety assessment approaches used in "multiple lines of reasoning" (OECD/NEA, 1999):

- *Demonstrating safety through a simple and direct approach*
- *Applying various evaluation methods*
- *Natural analogues*
- *Paleohydrogeology*
- *Decisions by specialists*
- *International consensus*

(3) Content on what a safety case should include that was summarized from a discussion concerning standards for geological disposal held at an IAEA/WASSAC meeting (Issues related to the preparation of safety standards on the geological disposal of radioactive waste presented at IAEA WASSAC *Proceedings of a Specialist Meeting* held from 18 to 22 June, 2001)

Safety case: *the following items which should be covered are:*

a) The implementer should be required to clearly document his/her arguments and supporting information,

b) The safety case should be appropriately constructed bearing in mind the need to convince different audiences,

c) A well-structured approach should be used which allows for the iterative development and improvement of the safety case as new information becomes available,

d) It should be built on the safety assessment and describe the results of the safety assessment,

e) It should describe the overall safety strategy and the safety functions of the various barriers,

f) It can be both quantitative and qualitative,

g) Uncertainty should be treated explicitly and the implications for repository performance should be made clear,

h) It should make use of multiple lines of evidence or reasoning,

i) It should demonstrate safe repository performance and compliance with regulatory requirements,

j) It should address safety indicators and how they are used,

k) It should provide sufficient confidence in safety such that consent can be obtained to move to the next step in the approval process,

l) It should describe planned work for the future,

m) It should address the issues of human intrusion, retrievability and multiple barriers (i.e., if and how the safety case relies on more than one barrier) and

n) It should address the use of deterministic and probabilistic assessment approaches.

Decision-making process:

Finally, the safety case and the safety assessment should relate to the decision-making process. It should be made clear that the context for both the safety case and the safety assessment is a stepwise decision-making process. The nature of the safety case and safety assessment should reflect the particular decision at hand and the decision maker. They should provide a clear indication of the level of confidence which can be attached to the repository performance and the implementing organization. Context for the results of the assessments should be given in terms of the levels of safety provided and the time-scales being discussed.

D-2 The Status of Monitoring in a Safety Case

A safety case must fully recognize and respect the different levels of knowledge and decision-making capability of the various entities who must make judgments and receive information concerning the safety of geological disposal sites. Generally speaking, the receivers of information could fall into the following four groups:

- *Site operators and promoters,*

- *Regulators and others on the regulatory side,*
- *Opinion leaders and*
- *The general public*

The problem is how to appropriately convey proper information to people other than those on the operating side so as to ensure understanding.

Because people in different positions have different levels of understanding, and because the levels of the content to be understood are already different, various methods of conveying information must be used, along with different kinds of evidence and grounds for argument. The issues pertaining to these different groups and their respective levels of understanding can be summarized as follows.

- *Because different groups have different levels (including the absence) of knowledge and interest in both the overall picture of geological disposal technologies and their constituent elements, an understanding of the effectiveness of those technologies is an important, fundamental piece of information. Knowledge about the soundness of containers, the closure characteristics of other physical barriers, the stability of the bedrock, and similar aspects are important criteria for some people when making safety judgments,*
- *Mathematical measures such as modeling of future scenarios may not be enough to satisfy the safety concerns of some–or indeed most–people. Such people might demand actual demonstrations of safety rather than logical grounds for argument,*
- *With regard to guaranteeing safety and sustaining peace of mind, it might be possible to increase confidence among certain groups of people by introducing contingency measures that would come into play in the unlikely event of a serious problem. This approach would lead to enhancing the significance of monitoring and retrievability,*
- *To ensure immediate understanding among all interested parties, grounds for argument concerning safety must be expressed without using technical jargon,*
- *It might be necessary to place a high priority on proving the short-term safety of the site (for example, 100 years), which some people show a direct interest in, and*
- *Part of the safety case must deal with the many credible problems and phenomena that attract public attention.*

Approaching the issues from this perspective, monitoring can be given the following status within a safety case.

- *Even if specialists judge that leaks of radionuclide are unthinkable within a thousand years, to satisfy people who worry about leakage planners may feel compelled to develop scenarios in which the unthinkable occurs. If monitoring is implemented, it can clarify leakage conditions and lead to appropriate countermeasures, thus providing safety guarantee.*
- *Even if it is not directly connected to leakage, monitoring can provide a warning and a grasp of related phenomena, making it possible to deduce safety levels. When necessary, it can also be tied in with judgments and countermeasures, or, through linkage with a system that implements countermeasures, it can provide a safety guarantee.*
- *The appropriate construction and maintenance of a monitoring system can itself give people peace of mind.*
- *Through the proper handling and understanding of the technical aspects of monitoring, confidence both in*

monitoring itself and the disposal system being monitored is increased.

- *Monitoring is one way to "demonstrate safety simply and directly," given as an example of approaches and methods for safety assessment by OECD/NEA (1999).*

Therefore, it is desirable that the content of monitoring should be considered so that it can satisfy the status-related conditions cited above.

References

OECD/NEA: Confidence in the Long-term Safety of Deep Geological Repositories – Its Development and Communication (1999)

Special Advisory Board on High-level Radioactive Waste Disposal Safety of the Nuclear Safety Commission of Japan, About the way of thinking of Safety Cases (OECD/NEA), (Waste Disposal Reference No. 6-3 (Sixth meeting, February 6, 2002)

Attachment E How Safety Cases Are Handled by International Agencies

The approaches that have been adopted by international agencies toward safety cases are summarized in Table E-1 below.

In "*Confidence in the Long-term Safety of Deep Geological Repositories–Its Development and Communication–"* (OECD/NEA 1999), which is one of the first reports to advocate safety cases for geological disposal, a "***safety case***" is considered a superordinate concept that includes safety assessment. It is defined as follows: "A collection of arguments, at a given stage of repository development, in support of the long-term safety of the repository. A safety case comprises the findings of a safety assessment and a statement of confidence in these findings."

Similarly, the following definition of "***safety case***" is found in "*Scientific and Technical Basis for the Geological Disposal of Radioactive Wastes*" (IAEA Technical Reports Series No. 413, 2003): "*A collection of arguments and evidence to provide reasonable assurance of the safety of a facility or activity. This will usually include a safety assessment, but would also typically include information (including supporting evidence and reasoning) on the robustness and reliability of the safety assessment and the assumptions made therein*."

As these definitions indicate, a safety case is a collection of information "***data package***" that indicates the safety of disposal in the form of a written safety assessment. As such, it is supplemented and revised as progress is made through each disposal step.

References

OECD/NEA：Confidence in the Long-term Safety of Deep Geological Repositories – Its Development and Communication (1999).

IAEA：Scientific and Technical Basis for the Geological Disposal of Radioactive Waste, Technical Reports Series No.413 (2003).

IAEA：Geological Disposal of Radioactive Waste, Draft Safety Requirements, DS154 (2002).

Table Ⅲ-1 *The Safety Cases of International Agencies (1 of 2)*

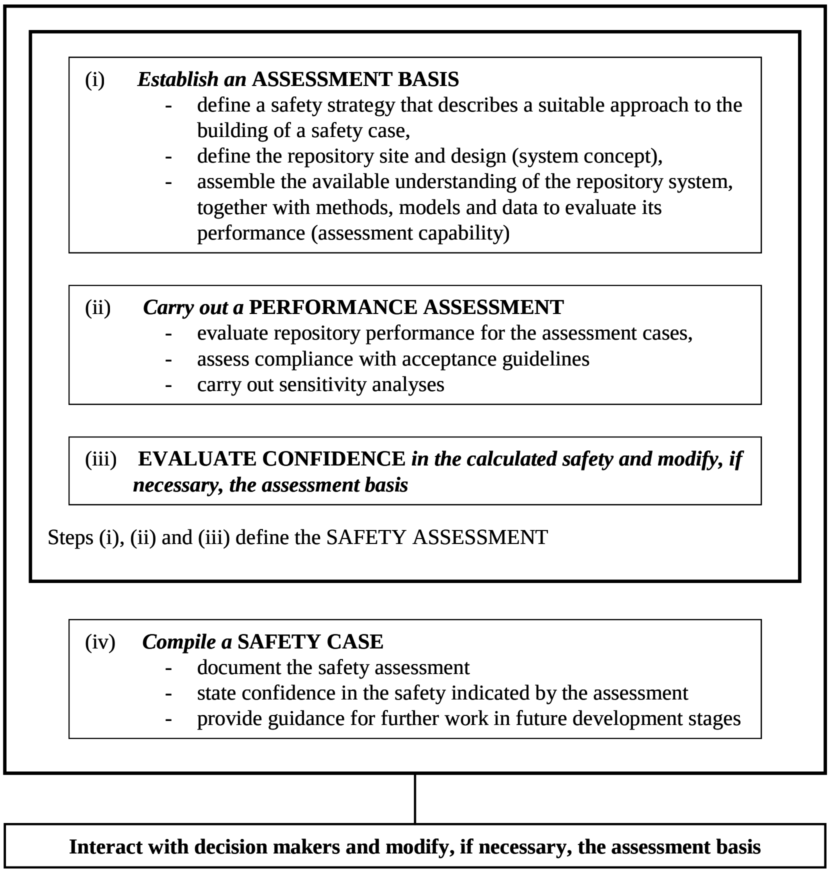
Agencies	References	Content and Approach of Safety case
OECD/NEA	*Confidence in the Long-term Safety of Deep Geological Repositories–Its Development and Communication–* (OECD/NEA, 1999)	***Comparison of safety assessment and safety case*** • ***Safety assessment*** Safety assessment is an evaluation of reliability concerning safety indicated through long-term performance, conformity with acceptance guidelines, and assessment results. • ***Safety case*** "*A collection of arguments, at a given stage of repository development, in support of the long-term safety of the repository. A safety case comprises the findings of a safety assessment and a statement of confidence in these findings. It should acknowledge the existence of any unresolved issues and provide guidance for work to resolve these issues in future development stages.*" ***Process for Development of safety case***  (i) ***Establish an*** **ASSESSMENT BASIS** - define a safety strategy that describes a suitable approach to the building of a safety case, - define the repository site and design (system concept), - assemble the available understanding of the repository system, together with methods, models and data to evaluate its performance (assessment capability) (ii) ***Carry out a*** **PERFORMANCE ASSESSMENT** - evaluate repository performance for the assessment cases, - assess compliance with acceptance guidelines - carry out sensitivity analyses (iii) **EVALUATE CONFIDENCE** ***in the calculated safety and modify, if necessary, the assessment basis*** Steps (i), (ii) and (iii) define the SAFETY ASSESSMENT (iv) ***Compile a*** **SAFETY CASE** - document the safety assessment - state confidence in the safety indicated by the assessment - provide guidance for further work in future development stages **Interact with decision makers and modify, if necessary, the assessment basis**

Table E-1 *The Safety Cases of International Agencies (2 of 2)*

Agencies	References	Content and Approach of Safety case
IAEA	*Scientific and Technical Basis for the Geological Disposal of Radioactive Wastes* (IAEA Technical Reports Series No. 413, 2003)	***Definition of Safety Case (modified definition from the glossary of safety terms of IAEA)*** A collection of arguments and evidence to provide reasonable assurance of the safety of a facility or activity. This will usually include a safety assessment, but would also typically include information (including supporting evidence and reasoning) on the robustness and reliability of the safety assessment and the assumptions made therein.
	Geological Disposal of Radioactive Waste–Draft Safety Requirements (DS154) (October 14, 2002)	***Definition of Safety Case*** *§5.5. The safety case is a collection of arguments and evidence that describe, quantify and substantiate the safety, and the level of confidence in the safety, of the radioactive waste disposal facility. The safety case is an essential input to all the important decisions about the facility. It will include the output of safety assessments (see below) and additional information, including supporting evidence and reasoning, on the robustness and reliability of the facility, its design, the design logic and the quality of safety assessments and its underlying assumptions. The safety case may also include more general arguments related to the need for radioactive waste disposal, and information to put the results of the safety assessments into perspective. The safety case should acknowledge the existence of any unresolved issues at any particular step in the development of the facility and provide guidance for work to resolve these issues.* ***Definition of Safety Assessment*** *§5.6. Safety assessment is the process of making systematic analyses of the radiological hazards associated with the disposal facility, and of the ability of the design to provide the safety functions and meet technical requirements. It will include quantification of the overall level of performance, analysis of the associated uncertainties and comparison with the relevant design requirements and safety standards. Safety assessments should also identify any significant deficiencies in scientific understanding: data or analysis such as might affect the results presented. Depending on the stage of development, safety assessments may aid in focusing research, and their results can be used to determine compliance with internal or external safety goals and standards.* ***Requirements for the Safety Cases and Safety Assessments*** ***Requirement 11 -*** *Preparation of the Safety Case and Safety Assessments* *A safety case and supporting safety assessments shall be prepared and updated, as necessary, at each step during the development of the disposal facility. These shall be sufficiently detailed and comprehensive to provide the necessary technical input to inform the decisions needed at each step.* ***Requirement 12 -*** *Scope of the Safety Case and Safety Assessments* *The safety case for a geological disposal facility shall describe all the safety relevant aspects of the site, the facility design and the managerial and regulatory controls. The safety case and its supporting assessments shall illustrate the level of protection provided and shall give assurance that safety standards will be met.* ***Requirement 13 – Documentation of the Safety case and Safety Assessments*** *The safety case and its supporting safety assessments shall be documented at a sufficient level of detail and quality to support the decision at each step and to allow independent review.*

Attachment F Surveys and Analyses Concerning Underground Research Laboratories (URL) in Japan and Abroad

A survey was conducted on the kinds of measurements being made in connection with geological disposal at Underground Research Laboratories (URL) in Japan and abroad. The results are shown in Table F-1.

Each URL is measuring different things for different purposes. For reference, several examples are given below that might have a bearing on monitoring.

The (TSX) tunnel sealing experiment carried out at Whiteshell in Canada involved the insertion of sand between the plugs of a tunnel at a depth of 420 meters and the evaluation of plug performance by increasing water pressure. More than 900 sensors were used in the test to measure such factors as temperature, pore water pressure, pressure, stress, deformation, distortion, and AE (Acoustic Emission). After three years, 90% of the sensors were still working (94% if the installed inside the concrete plug to measure water content are excluded). In the test, 245 measuring cables with 9.5 mm in diameter were passed through the plug. Because it was known from previous experience that the cables become water channels, countermeasures were taken such as encasing the cable bolts with cement grout or using plugs.

In the Prototype Repository Projects (PRP) being conducted in Äspö in Sweden, also, countermeasures have been taken to prevent cables used for sensing from becoming water channels.

At the Grimsel Test Site (GTS) a Spanish project called FEBEX is being conducted that involves *in situ* testing of full-scale engineered barriers. A total of 632 sensors of different kinds are used to monitor the thermo-hydro-mechanical processes through the measurement of such variables as temperature, total pressure, pore water pressure, water content, and displacement. Sensors installed in bentonite must be capable of withstanding temperatures in excess of 100°C, pressures up to 5 MPa, and highly corrosive environments, with a required service life of three years. Because it was difficult to find sensors on the market that met these requirements, it was necessary to develop sensors that were specially designed and protected (Enresa, 2000). The instruments have performed beyond expectation, with just 5.7% of them suffering failure due to reasons other than water submergence or physical damage. The report states that it is necessary to further extend the service life of all instruments.

As the above URL experiences indicate, certain sensors can be expected to function for several years in geological disposal environments, but the extension of their service life is a topic of future concern. Also, countermeasures are needed to prevent the cables used for sensing that transmit sensor data from acting as water channels.

References

ENRESA：FEBEX project. Full-scale engineered barriers experiment for a deep geological repository for high level radioactive waste in crystalline host rock. Final report, PT-01/00 (2000).

***Table F-1** Overview of objects, major testing and methodologies of URL in various countries (1 of 4)*

	Sweden	Finland	France	Switzerland
URL	Äspö Hard Rock Laboratory（Äspö）	Olkiluoto (candidate site)	Bure (Under construction)	Grimsel Test Site (Granite)
Objects, Remarks	To provide the scientific and technical basis for the work of siting, design, construction and operation of a future geological underground repository facility; construction began in 1990; operating since 1995.	Tunnel adjacent to the Olkiluoto repository for LLW; Characterization and detailed planning of the selected site are scheduled for completion by the end of 2010 and work on building the facility will begin after that.	Under construction; shaft sinking phase; surface exploration 1999; access construction and underground exploration 2000; shaft sinking from 2000 to 2002; examinations in gallery from 2003 to 2006.	Demonstration and assessment of a repository concept; operating since 1983; GTS Phase IV (1994 –1996); GTS Phase V (1997-2002)
Main experiments and parameters related to monitoring in URL	***Prototype repository projects (PRP)*** ・ Temperature evolution of canister, buffer, backfill and rock ・ Hydrogeology of near field rock ・ Deformation and stress in near field rock ・ Coupling of temperature, hydrogy and mechanic ・ Resaturation in buffer and backfill ・ Porewater pressure evolution in buffer, backfill and rock ・ Swelling pressure evolution in buffer, backfill and rock ・ Deformation of canister ・ Gas composition in buffer and backfill ・ Chemical composition in Porewater in buffer and backfill and water in near field rock ***Borehole monitoring*** ・ Groundwater level ・ Hydraulic pressure ・ Electrical conductivity ・ Groundwater chemistry ・ Atmospheric pressure ・ Sea level ・ Rainfall and air temperature on Oskarshamn	***Geological survey*** ・ Rock characteristics (magnetic susceptibility; natural gamma-ray; rock density; neutron back scattering; fracture characteristics) ・ Groundwater flow in borehole ・ High permeable fracture frequency ・ Rock characteristics surrounding borehole ***Monitoring in research tunnels*** ・ Detailed geological mapping of the tunnel surface ・ Surveying of tunnel surface, location of fractures, and half barrels of blast holes ・ Mapping of excavation damage on half barrels of blast holes ・ Determination of mechanical properties of the rock ・ Ground penetrating radar on the floor of the tunnel ・ Inflow mapping ・ Structural modelling	***Deep borehole monitoring*** ・ Various borehole data (total natural gamma radiation; deep resistivity; density of the formation and the photoelectric factor; porosity; diameter of the borehole with the caliper; hydraulic-head recovery; temperature; tests depending on permeability with measurement and acquisition of flow rate, level and temperature parameters) ***Hydrogeology*** ・ Porewater pressure ・ Suction, ・ Water content ・ Water Head ***Rock Mechanics*** ・ Initial state of rock stress ・ Rock deformation ***Groundwater Geochemistry*** ・ Geochemical parameters (content of major ions; dissolved oxygen; pH; Eh; PCO2; electric conductivity etc) ・ Temperature	***GTS Phase IV (1994 –1996):*** 1. Seismic Tomography (TOM), aimed at clarifying the potential of this method for remote identification of structures in the rock. 2. Borehole Sealing (BOS), with the emphasis on testing sealing technologies for long, subhorizontal boreholes. 3. Radionuclide Retardation Project (RRP), focusing on validation of sorption and matrix diffusion models. 4. Full Scale Engineered Barriers Experiment (FEBEX), aimed at demonstrating waste emplacement technologies for high-level waste. 5. Tunnel Near-Field Programme, the study for a crystalline rock environment the relevance of the tunnel near-field as a key issue for performance assessment. ・EDZ (Excavation Disturbed Zone) ・ZPK (Two-Phase Flow in Fracture Networks) ・ZPM (Two-Phase flow in Rock Matrix) ・TPF (Two Phase Flow in Shear Zones)
Methodologies, equipments	・ Temperature: Fiber optics; thermocouple ・ Total pressure, pore pressure: Vibrating string; fiber optics ・ Displacement of canisters: Strain gauges mounted on extensometer-type sensors; strain gauges ・ Hydraulic conductivity: Piezometer ・ Water content: Capacity (RH); psychrometer ・ Groundwater level, groundwater pressure: hydraulic multiplexer; pressure transducer ・ Groundwater electrical conductivity: ECsensor; electric conductivity meter ・ Barometric pressure: stand alone data logger (BORRE) ・ Sea level: Writing recorder is connected to a float in a gauge well	・ Hydraulic properties: single-hole technique ・ Rock properties: hydrophysical logging; Seismic tomography ・ Inflow measurement in the investigation boreholes ・ Monitoring surrounding boreholes: radar techniques; VSP; HSP ・ Surface roughness profiling of borehole: Lazar profilometer ・ EDZ in deposition holes: He-gas techniques; C-14-PMMA	・ Borehole data: Various logging ・ Porewater pressure: Piezometer ・ Suction: Capacitive hydrometer ・ Water-content: Neutron logging ・ Groundwater level: Limnimeter; MADO; THALIMEDES ・ Initial state of rock stress: Hydraulic fracturing test ・ Rock deformation: Vibrating-wire sensor ・ Groundwater chemistry: with specific electrodes ・ Temperature: Metal thermocouple platinum probes; electromagnetic-pressure gauge (EPG)	・ Hydraulic properties: Surface packer; Short interval packer / combined packer system; MMPS system Slim Hole Piezometer Systems; Mini-Sonic Probe ・ Water content profiles in matrix: TDR ・ Geomechanical properties: Mini-Sonic Probe

Table F-1 *Overview of objects, major testing and methodologies of URL in various countries (2 of 4)*

	Switzerland	**Belgium**	**Spain**	**UK**
URL	Mont Terri Tunnel（Opalinus Clay）	HADES research facility (Mol)	FEBEX (Grimsel Test Site)	Rock Characterisation Facility (Sellafield)
Objects, Remarks	To investigate the geological, hydrogeological, geochemical and rock mechanical properties of the Opalinus Clay formation and to provide input for assessing the feasibility and safety of a repository for radioactive (or chemotoxic) waste in this type of host rock; gallery from a highway tunnel, initiated 1995.	To *in situ* measurements and large-scale integrated experiments; shaft sinking began 1980, operating since 1984 and extended 1998-9	Full-scale Engineered Barriers EXperiment; To study the behavior of the near-field components for a high-level waste (HLW) repository in crystalline rock; The project initially scheduled for 7 years (1994-2001) has been extended to 2003.	A site investigation began at Sellafield in 1989; Nirex planning application for an RCF (Rock Characterisation Facility) at Sellafield was rejected following a Public Inquiry, held between September 1995 and February 1996; All site works and monitoring equipment have been removed, and all site investigation boreholes have been permanently abandoned.
Main experiments and parameters related to monitoring in URL	**Mont Terri Research Programme:** ・ Flow mechanism (fluid logging) ・ Flow mechanism (tracer) ・ Groundwater sampling (*in situ*) ・ Borehole fluid effects ・ EDZ Hydraulic and pneumatic tests ・ EDZ geophysical characterization ・ EDZ self-healing ・ Osmotic pressure ・ High-pH Cement porewater ・ Diffusion in rock ・ Migration in main fault zone ・ Heater experiment ・ Porewater pressure ・ Horizontal raise boring ・ Small diameter disposal drift ・ Deep borehole simulation	**Specific Experiments in HADES:** ***PRACLAY (Preliminary demonstration test for Clay disposal of high radioactive waste)*** ・ Demonstration of the feasibility of construction and operation using techniques that would have to be dealt with for the repository; ・ Erection and support a large connection chamber; ・ Monitoring of the thermal, hydraulic and mechanical behaviour of the clay layer, gallery concrete lining, filling material and metal shroud surrounding the dummy waste. ***CERBERUS (Control Experiment with Radiation of the Belgian Repository for Underground Storage)*** ・ Direct demonstration of combined effects of radiation, heat and drilling (local HLW near-field) ***RESEAL (The Large-scale in situ sealing demonstration test)*** ・ Demonstration of the installation techniques of sealing material and optimization the installation techniques by the use of pre-compacted pellets ***CORALUS (Corrosion of Active Glass in Underground Storage Conditions)*** ・ Performance study of active HLW glass specimens in a geological disposal site in the Boom Clay formation ***CLIPEX (Clay Instrumentation Programme for the Extension of an underground research laboratory)*** ・ Modelling and monitoring of the hydro-mechanical response of the clay during excavation of the connecting gallery	***The project consists of:*** ・ An *'in situ'* test performed under natural conditions and at full scale; ・ A 'mock-up' test, at almost full scale, and ・ A series of laboratory tests to complement the information from the two large-scale tests ***Variables measured are:*** ・ Temperature ・ Humidity ・ Stress ・ Total pressure ・ Displacement ・ Water pressure ・ Generation and transport of gas	The monitoring items measured in Sellafield; ・ Groundwater pressures ・ Groundwater temperature ・ Atmospheric pressure ・ Stream flow data
Methodologies, equipments	・ Hydrogeology: Injection of fluorescene-tracered resin into the rock, overcoring and detection of flow paths filled with resin; Packer-test ・ Hydrochemistry: Groundwater sampling and analysis; squeezing and leaching of rock samples ・ Evaluation of the influence of various fluids on borehole stability: Monitoring of fluid	・ Radiation level (CERBERUS): Ionization chamber and LiF dosimeters ・ Evolution of temperature of rock: Thermo-probes ・ Porewater chemistry (pH, Eh): pH sensor; sampling analysis ・ Total pressure on the host clay / lining outer face: pressure transducers; pressure cells ・ Water pressure (or suction) in the plug / host clay: Piezometers	・ Temperature: Thermocouple ・ Total pressure in borehole in rock (3-D): Vibrating wire ・ Total pressure on heater: Vibrating wire ・ Hydraulic pressure in borehole in rock: Piezoresistive ・ Packer pressure in borehole: Piezoresistive ・ Pore pressure in bentonite: Vibrating wire ・ Water content: Capacitive; Psychrometer; TDR	・ Groundwater pressures: Pressure transmitters, ・ Groundwater temperature: Temperature measurement devices ・ Stream flow data: River and stream gauges,

	Switzerland	Belgium	Spain	UK
	salinity and caliper in boreholes filled with different fluids ・ Hydraulic parameters of the EDZ: Hydraulic tests with various equipment ・ Geophysical parameters of the EDZ: Measurements of the seismic velocity profile in the EDZ with various tools and techniques ・ In situ stress: Stress measurements with the overcoring and undercoring technique / Stress measurements with the borehole slotter technique	・ Radial displacement in the plug / host clay: Displacement sensors; Inclinometers; Extensometers ・ Hydration profile in the plug: Thermal conductivity evolution ・ Stresses in the lining: Load cells (if concrete lining); strain gauges (if cast iron lining) ・ Convergence: Tape extensometers	・ Extensometer in rock: Vibrating wire ・ Heater displacement: Vibrating wire ・ Expansion of bentonite block: Vibrating wire ・ Displacement within the bentonite barrier: Potentiometer; Clinometer LVDT; Crackmeter LVDT ・ Gas pressure in the bentonite barrier: Magnetic ・ Atmospheric pressure: Piezoresistive ・ Resistor intensity / Resistor voltage electric converter	

Table F-1 *Overview of objects, major testing and methodologies of URL in various countries (3 of 4)*

	Germany	USA (YMP)	USA (WIPP)	Canada
URL	Gorleben, Konrad, Morsleben	Yucca Mountain Site	Waste Isolation Pilot Plant (WIPP)	Whiteshell Underground Research Laboratory (URL)
Objects, Remarks	**Gorleben:** Exploratory work for potential repository site suspended for 3-10 years by governmental moratorium on 1st October 2000; shafts constructed 1985-1990 **Konrad:** Galleries in former iron mine; operating since 1980, in licensing stage for a LLW/ILW repository. Morsleben: Former salt and potash mine; repository for LLW and ILW since 1981	*in situ* testing began in 1996; construction of an exploratory side tunnel completed in 1998; under consideration of monitoring for repository	Operating since 1982; licensed transuranic (TRU) waste repository since 1999	To provides inputs for general design of repository system and safety assessment and demonstrate *in situ* techniques related to disposal; monitoring during site investigation stage began in 1980 (1980-1984: monitoring system installed; 1981-2011: measurements); schedules of URL construction are: surface facilities (1982-1987); access to underground (1983-1990); investigation and research (1989-2011); closure and decommissioning (2011-2014)
Main experiments and parameters related to monitoring in URL	**Parameters monitored:** ・ Leveling on surface ・ Convergence measurements ・ Extensometer measurements ・ Inclinometer and incremental extensometer measurements ・ Settlement measurements ・ Stress measurement ・ Temperature measurements ・ Permeability measurements ・ Micro acoustic emission monitoring ・ Humidity and moisture measurements ・ Propagation of moisture in highly compacted bentonite sealing ・ Location of brine reservoirs ・ Groundwater level ・ Strain sensing ・ pH measurements	***Monitoring plan****:* ・ Seepage monitoring; ・ *In situ* package monitoring; ・ long-term materials testing; ・ ventilation monitoring; ・ rock mass monitoring; ・ In-drift monitoring; ・ Introduced materials monitoring; ・ Groundwater level and temperature monitoring; ・ Surface uplift monitoring; ・ Subsurface seismic monitoring; ・ Groundwater quality monitoring ***Performance confirmation testing****:* ・ Recovered material coupon testing; ・ Dummy waste package testing; ・ Recovered waste package testing; ・ Post closure simulation testing; ・ Subsurface sampling and index testing; ・ UZ testing; near-field environment testing; ・ Waste form testing; ・ Waste package testing; ・ Borehole seal testing; ramp and shaft seal testing	No information.	・ Buffer/Container Experiment and Isothermal Buffer/Rock/Concrete Plug Interaction Test ・ Quarried Block Radionuclide Migration Test ・ Grouting Experiment ・ Tunnel Sealing Experiment ・ Solute Transport in Highly Fractured Rock (HFR) Experiment ・ Solute Transport in Moderately Fractured Rock (MFR) Experiment ・ Mine-by Experiment ・ Excavation Stability Study ・ Solute Transport Excavation Damage Zone ・ Characterization Program ・ *In Situ* Stress Program ・ Multicomponent Experiment ・ *In Situ* Diffusion Experiment
Methodologies, equipments	・ Leveling on surface: Digital leveler ・ Convergence: electric potentiometers; fiber optic ・ Extension of rock around tunnel: Extensometers ・ Inclination and increment of rock: inclinometers; incremental extensometer ・ Settlement: settlement measuring instruments with a measuring range of up to 600 mm ・ Stress: Overcoring stress release measurements with biaxial probes; extensometers; borehole inclusion method ・ Temperature: Pt100 sensors / thermistors; fiber	Under consideration of parameters or instruments for monitoring in YMP	***Geomechanical Instrumentation System:*** ・ Cumulative deformation: Sonic probe borehole extensometer; convergence points; wire convergence points; sonic probe convergence meters; joint meters; vibrating wire borehole extensometer; linear potentiometric borehole ・ Cumulative strain: Embedded strain gauges; spot-welded strain gauges ・ Load: Rock-bolt load cells ・ Pressure: Earth pressure cells ・ Fluid pressure: Piezometers	・ Swelling pressure within the clay bulkhead and at the interface between the clay and the rock;: Oil pressure indicator; loop dynamometer ・ Displacements of the clay bulkhead (clay plug): linear potentiometers; sonic probe ・ Deformations of the clay bulkhead, rock and concrete bulkhead: linear voltage differential transformers (LVDT's) ・ Moisture content measurement in bulkhead: thermocouple psychrometer; hygrometers; time-domain reflectometry probes (TDR's) ・ Pore pressure in the rock and concrete bulkhead: Vibrating wire piezometers

	Germany	USA (YMP)	USA (WIPP)	Canada
	optics ・ Permeability: 4-fold packer probe ・ Micro acoustic emission monitoring: Spatially distributed geophones ・ Humidity and moisture: Theta-probes; fiber optics ・ Propagation of moisture in highly compacted bentonite sealing: Theta-probes ・ Location of brine reservoirs: Ground penetrating radar (GPR) ・ Groundwater level: Limnimeter ・ Strain sensing: Fiber optics sensor ・ pH measurements: Fiber optics sensor			・ Pore pressure in the rock: Packer string equipment ・ Temperature: thermocouples; thermistors ・ Displacements within the rock: Borehole extensometers, with LVDT's ・ Cracking in the rock and concrete bulkhead: Microseismic (MS) system; Acoustic emission (AE) system ・ Strains in the concrete: Vibrating wire strain gauges; laser strain gauges; fibre optic strain gauges ・ Water potential or suction within the concrete: Psychrometer ・ Displacement of the concrete-rock: Electromagnetic displacement transducers

Table F-1 *Overview of objects, major testing and methodologies of URL in various countries (4 of 4)*

	Japan	**Japan**	**Japan**
URL	Kamaishi	Tono	Mizunami URL (MIU)
Objects, Remarks	To understand geological properties and acquire data in deep underground geological environment; Galleries in former iron-copper mine; completed in 1998.	To understand deep underground geological environment (geoscientific research); galleries in former uranium mine; operating since 1986	To carry out a wide range of geoscientific researches in order to build a firm scientific and technological basis for the research and development of geological disposal, Two 1,000m deep shafts are on-going and several drifts will be excavated for geoscientific researches and applicability of engineering techniques will be estimated; This project extends over 20 years.
Main experiments and parameters related to monitoring in URL	1. Characterization of the deep underground geological environment: Fracture distribution; age determination; paleomagnetism measurement 2. Geomechanics (excavation disturbance): : *in-situ* mechanical testing; initial stress measurements (in-situ); initial stress measurements (in room); geophysical exploration; AE measurement; seismic wave measurement; displacement / deformation measurement 3. Groundwater flow: Permeability testing (PNC's JFT; within loosened zone; single-hole); Injection testing within tunnel-floor; stress interference testing; groundwater flow analysis 4. Geochemistry: Sampling analysis from surface borehole; sampling research techniques from borehole in tunnel 5. Solute transport: *in-situ* regine injection testing; *in-situ* cold-tracer testing 6. Earthquakes: Seismic observation; geohydrogical observation 7. Grout: Grouting testing 8. Buffer filling: Excavation of borehole; buffer emplacement experiments 9. Mock-up testing of engineered barrier: Coupled Thermo-hydro-mechanical experiments	***Hydrogeology*** ・ Subsurface hydrogical Investigation ・ Borehole Investigation (-1000m level) ***Geochemistry*** ・ Shallow borehole Investigation (from -100 to -200m level) ・ Deep borehole Investigation (from -200m to -1000m level) ***Geomechanics*** ・ Excavation disturbance testing in Hokunobe NATM tunnel ・ Shaft sinking disturbance testing ***Earthquake Frontiers studies*** ・ Seismo-electromagnetic phenomena ・ Earthquake-related water-level changes	**Schedule for the MIU Construction Site:** ***Phase I (Surface-based Investigation Phase):*** ・ Conceptualization of geological features such as: upper highly fractured domain; sparsely fractured domain, and fracture zone along the faults, identified in the granite of the site; ・ Investigation technology such as QA/QC methodologies of data acquisition in the fields of geology, hydrogeology and hydrochemistry; ・ Drilling technique; ・ Technique for Water-conducting feature (WCF) identification, and ・ Field management system. ***Phase II (Construction Phase / Research along with excavation):*** ・ Geological mapping of the main shaft and drift wall; ・ Measurement of inflow rate during the shaft sinking; ・ Cross hole hydraulic test on the WCFs; ・ Groundwater sampling from the shaft and boreholes around the shaft, and chemical analysis of the water sampled; ・ Acoustic Emission (AE) measurement and borehole expansion test for excavation disturbed zone (EDZ) investigation, and ・ Hydraulic pressure and hydrochemical monitoring in the boreholes drilled from the surface around the shaft. ***Phase III (Operations Phase / In-situ investigations and experiments at the depth):*** ・ Geological mapping of the middle and main drifts; ・ Hydraulic interference test focused on a single fracture and a fracture network; ・ Redox experiment in the boreholes drilled from the drift; ・ Geophysical investigations, AE measurements, etc. in the drift for evaluating the EDZ; ・ Tracer experiments focused on the single fracture and fracture zones, and ・ Hydraulic pressure and hydrochemical monitoring in the boreholes drilled from the surface around the shaft.
Methodology, equipment	1. Geomechanics (excavation disturbance): Borehole loading test; release of in-situ stress method; hydraulic fracturing method; AE / DRA / DSCA methods; PS logging / radar reflectivity method / elastic wave refraction method / ultrasonic wave pulse measurement; AE measurement; joint-type displacement gauge 2. Groundwater flow: Measurements of porewater pressure and permeability coefficient etc... 3. Geochemistry: MP (multi packer) system / MOSDAX; sampling by HPG-10 system; redox experiments 4. Solute transport: ・retardation; Overcoring 5. Earthquakes: Distortion gauge 6. Grout: Permeability test; tomographical experiment 7. Mock-up testing of engineered barrier (T-H-M): Thermocouple; water pressure gauge / fracture deformation gauge / Pai-gauge; thermal flow meter / extensometer; earth pressure cell; psychrometer / hydrometer	***Geochemical sampling investigation by deep borehole*** ・ pH ・ Eh ・ Electrical conductivity ・ Sulfide ion content ・ Water temperature ・ Porewater pressure ・ Packer pressure ・ Pressure in sampling cell ・ Sampling volume	In ***Phase I (Surface-based Investigation Phase***), the following investigations are ongoing or planned at the MIU construction site or the surrounding area for surface-based investigations. Some of them are on-going. ・ Geological mapping; ・ Ground geophysics such as seismic reflection/refraction; ・ Shallow borehole investigations; ・ Deep borehole investigations at the site; ・ Cross hole tomography and hydraulic tests using the boreholes at and around the site, and ・ Groundwater monitoring such as hydraulic pressure and hydrochemistry.

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