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Monitoring of geological repositories for high level radioactive waste

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FOREWORD

Geological repositories for the disposal of high level radioactive waste are designed to provide isolation of the waste from the human environment for many thousands of years. Monitoring the environment of such repositories is not therefore expected to reveal any increase of radioactivity due to the repository; it is planned and intended for other purposes. These include providing reassurance that the repository is fulfilling its intended purpose, but there can be other reasons of a technical nature.

This report discusses the possible purposes for monitoring geological repositories at the different stages of a repository programme, the use that may be made of the information obtained and the techniques that might be applied.

It is intended as one of several IAEA contributions to the continuing discussion on how to provide for the long term safety of radioactive waste repositories.

The report was produced as a result of a number of consultants meetings and an Advisory Group meeting. A list of those who attended the meetings appears at the end of the report. The IAEA officers responsible for the report were M. Raynal and F. Gera.

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1. INTRODUCTION

1.1. BACKGROUND

Monitoring is expected to play an important role in both development and execution of geological disposal programmes. In particular, monitoring will contribute essential information for the satisfactory completion of the various phases of the repository programme and, in doing so, will strengthen confidence in long term safety, which is the key objective of radioactive waste disposal [1].

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.*

The process leading to the commissioning of geological disposal facilities[1] for long lived radioactive waste is quite lengthy and involves a number of decision points. Once authorized to operate the facilities are expected to remain in activity for long periods of time before their eventual decommissioning and closure. Monitoring of various aspects of the disposal system is likely to be an important support to decision-making at all stages of the repository development programme.

After closure, the long term safety of geological disposal facilities, due to the duration of the hazard associated with the waste, cannot rely on institutional controls, including monitoring. However, continuing monitoring is likely to be a societal demand for some time after repository closure. Such monitoring, besides showing that the process of decommissioning surface facilities has been successfully completed, would also strengthen the confidence, at least in some sectors of society, that the evolution of the waste isolation system is in accordance with expectations. The need to safeguard nuclear materials contained in the repository may also cause some form of monitoring or surveillance to continue in the post-closure phase.

1.2. OBJECTIVES

Basic guidance on monitoring has already been outlined in an IAEA publication [2]. The present report updates the monitoring sections of this earlier work and enlarges upon them. It is intended to act principally as a ***discussion document*** to identify key issues which national programmes might wish to consider in developing their own approaches to monitoring. A companion publication, currently under preparation, will deal with monitoring and surveillance of near surface disposal facilities.

1.3. SCOPE

The extent and the nature of monitoring will change throughout the various stages of repository development, and monitoring plans drawn up at an early stage of a programme will need to reflect this. It may also be expected that the plans will be revised periodically in response to technological developments in monitoring equipment, modifications to the repository design and changing societal demands for information. Data obtained from

[1] It should be noted that, for the purposes of this report, such facilities are taken to include either deep, excavated repositories accessed from the surface, or deep boreholes.

monitoring programmes will constitute an important component of the repository records that are expected to be preserved over a long period of time.

A key point of discussion at present is how monitoring data might be used. This report focuses on the different objectives that monitoring might have at various stages of a programme, from the initiation of work on a candidate site, to the period after repository closure. Each objective may require somewhat different types of information, or may use the same information in different ways. Having evaluated monitoring requirements, the report concludes with a brief evaluation of available monitoring techniques.

A number of routine operational monitoring activities common to nuclear facilities and industrial plants will also be required during the lifetime of a repository. These activities, which are designed to ensure operational safety for both personnel and the public, are well documented elsewhere and are not considered in this publication.

Activities required to show compliance of waste shipments with waste acceptance criteria, while important for the safety of a geological repository, are also considered to be outside the scope of this report.

1.4. STRUCTURE

Section 2 of this publication outlines the key objectives of monitoring within a staged repository development and describes the typical stages during which monitoring is likely to be required. Section 3 discusses the appropriate targets for monitoring during each stage according to the objectives first identified, with a discussion on how the information might be used throughout the decision making process. Section 4 provides an outline of available monitoring techniques and methodologies applying to their use.

2. MONITORING PURPOSES WITHIN A REPOSITORY DEVELOPMENT PROGRAMME

Geological disposal of long lived radioactive wastes is intended to isolate radionuclides from the accessible environment so that they either decay in situ to insignificant levels, or so that any eventual releases are in concentrations that constitute an insignificant hazard to people and the environment. It is a widely accepted principle of disposal that, once the wastes are isolated in a sealed repository, then the long term safety of the disposal system should require no further actions on the part of future generations. This principle of inter-generational equity requires that present generations, who have had the benefits of nuclear power, should not pass the burden of managing the associated wastes onto future generations, who will not have had those benefits, and who may, in any case, be unable to accept the responsibility [3].

One component of this principle is that the long term safety of the disposal system should not be based on the continual monitoring of its behaviour. This is not to say that people in the future might not want to monitor the repository in some way, but its safety would not depend on them being willing, or able, to do so. The system should be designed to be intrinsically and passively safe. Why, then, is monitoring of interest in developing a disposal programme?

First, monitoring could have several useful technical applications in the potentially extensive period up to the eventual closure of a geological repository, which may occur many decades after the start of the repository development programme. Second, there may be a valid, and extremely strong, social requirement to demonstrate aspects of technical knowledge and safety at all stages, up to and even after repository closure. This too, may require monitoring activities.

During the potentially long period prior to repository closure, both future operators and other sectors of future society will need to make critical decisions about how, when and if to implement various steps in the management of the repository system. The primary objective of monitoring is to provide information to assist in making those decisions. In this context, the key purposes of monitoring of deep disposal systems are seen to be:

(1) to provide information for making management decisions in a stepwise programme of repository construction, operation and closure;

(2) to strengthen understanding of some aspects of system behaviour 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 society at large the confidence to take decisions on the major stages of the repository development programme and to strengthen confidence, for as long as society requires, that the repository is having no undesirable impacts on human health and the environment;

(4) to accumulate an environmental database on the repository site and its surroundings that may be of use to future decision makers;

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

In addition to these key objectives, which are all concerned with establishing confidence in the ability of the repository to isolate the wastes properly after closure, monitoring would also be carried out for purely operational reasons during the emplacement of the wastes. Such activities are common to any nuclear facility or major industrial enterprise:

(1) to determine any radiological impacts of the operational disposal system (as with a nuclear installation, like a power plant) on the personnel and on the general population, in order to comply with statutory and regulatory requirements;

(2) to determine non-radiological impacts on the environment surrounding the repository, to comply with environmental regulatory requirements (e.g. impacts of excavation and surface construction on local water supply rates and water quality);

(3) to ensure compliance with non-nuclear industrial safety requirements for an underground facility (e.g. dust, gas, noise, etc.).

Techniques and requirements for monitoring in these contexts are well established and tested in a wider sense (e.g. as for nuclear installations and mines), and none of these latter objectives is thus discussed further in the present publication.

To achieve the five key objectives outlined above, monitoring may be required at various times throughout a repository development programme and at various locations in and around the repository. In developing a strategy for monitoring, the benefits from gaining data on the behaviour of the system components need to be balanced against any detriments resulting from the process of monitoring. Potential detriments may include:

- radiation doses to personnel carrying out monitoring;
- degradation of materials in the repository resulting from delay in putting engineered barriers in place whilst monitoring programmes are completed (potentially leading to incomplete development of engineered barrier design properties);
- formation of pathways through the barriers by the installation of monitoring equipment, leading to increased potential for radionuclide migration within or around the repository;
- an increased likelihood of human intrusion or adverse impacts by natural or induced processes (e.g. flooding) if repository access is kept open to allow monitoring;
- interference with other repository operations.

All of the objectives and considerations described above need to be taken into account in the various stages of a repository development programme. The typical stages in a development programme are discussed in the next section.

2.1. STAGES IN A REPOSITORY DEVELOPMENT PROGRAMME

The development of a geological disposal facility for high level and other long lived radioactive waste involves a series of stages, beginning with the definition of the disposal concept and moving through site selection and characterisation into the phases of construction, operation and closure. These stages of the repository programme are described in different IAEA publications [5, 6, 7]. For the purpose of the present publication and to consider objectives and needs for monitoring, seven stages, considered typical of most development plans for geological repositories, are defined:

- surface exploration;
- access construction and underground exploration;
- construction of the repository;
- emplacement of waste and near field engineered barriers;
- disposal tunnel/vault backfilling;
- backfilling of remaining openings and repository sealing;
- post closure.

These are outlined in more detail below.

2.1.1. Exploration from the surface

Exploration from the surface is used both to distinguish between different potential sites and to characterise in detail a candidate repository site. The objectives of this work are to provide a comprehensive understanding of the nature and properties of the surface and deep environments which can be used to support safety assessment and basic repository system design. Exploration from the surface would continue until confidence in the potential of a candidate site was sufficient to move to the stage of underground exploration.

2.1.2. Access for underground exploration and construction

Underground reconnaissance and investigation work will supplement site characterisation data acquired during the surface exploration. The underground investigations will require the drilling of boreholes and, in most repository development programmes, the excavation of access shafts or adits, which is likely to constitute the first stage of repository construction. At this stage, the preliminary layout of the access galleries will be decided and information will be collected to allow the optimisation of the repository design. Significant perturbation of the natural system would be expected to occur as underground excavation commences. For a repository involving deep borehole emplacement of waste from the surface, this stage would not be relevant.

2.1.3. Construction of the repository

This is the main pre-operational stage, in which drilling of boreholes would continue and excavation of shafts, waste emplacement galleries or disposal vaults would be undertaken. These activities may be carried out as part of a single construction campaign or progressively with waste being emplaced before additional regions of the repository are constructed. In some programmes, it is envisaged that construction of the main repository might be preceded by a pilot stage, in which demonstrations of technology can be made to enhance confidence in the concept. As discussed later, this approach might be linked to the construction and commissioning of parts of a repository specifically designed for intense, long term monitoring, throughout the pre-closure stages.

2.1.4. Emplacement of waste and near field engineered barriers

This stage begins with the commissioning of the repository and continues through a lengthy period of operation. The main activity is the emplacement of the waste packages within their immediate engineered barriers. There are different options for the time at which these various barriers may be put in place, depending on waste and rock characteristics. Any national approaches to requirements for waste package retrievability may have a significant influence on the options chosen. However, it is important that these latter considerations do not prejudice the design basis of the near-field engineered barrier system. For example, delay in emplacing barriers immediately adjacent to waste packages might, in some concepts, lead to less than optimum performance in the post-closure period.

2.1.5. Disposal tunnel/vault backfilling

Backfilling of sections of a repository where disposal has been concluded will depend again on national decisions on retrievability and on constraints dictated by the properties of the host rock. It could occur concurrently with continued construction or disposal activities in other sections of the repository. This may allow sections of the repository, where waste emplacement has been completed, to be backfilled promptly to isolate individual emplacement tunnels or vaults.

2.1.6. Repository backfilling and sealing

Repository backfilling and sealing constitutes the final stage in closing a repository. All access ways including shafts will be backfilled and sealed to isolate the disposal zone. The decision to close the repository will depend on a number of factors including technical considerations, societal choices and the implications on safety of keeping the repository open. The decision of how and when to proceed with repository closure will be a matter of national policy.

2.1.7. Post-closure (institutional/non-institutional)

The post-closure phase will begin when the repository access ways have been backfilled and sealed. Some programmes may choose to begin the post-closure phase with a period of institutional control. With or without such a period, monitoring and surveillance could be maintained for as long as society considers it beneficial, although (as noted above) it is a principle of geological disposal that assurance of safety does not require post-closure monitoring. It should be noted also that any post-closure monitoring decided by future generations should be designed in such way that no negative impacts on the performance of the containment barriers and therefore on the long term safety of the repository would occur.

2.2. MONITORING TO ESTABLISH BASELINE INFORMATION

Certain monitoring activities should begin at the earliest possible time within a repository development programme, before the perturbations caused by repository construction and operation begin to accumulate. This early information is important because it allows an understanding to be developed of the nature and properties of the natural, 'undisturbed' environment of the disposal system. So-called 'baseline' information is used to underpin each of the first four of the five objectives identified earlier in this section. For example, it will be used to evaluate changes that occur in the rock and groundwater system during the construction and operational stages and, in the post-closure period, to evaluate any impacts that the presence of the repository may have on natural processes and the environment. In practice, the monitoring programme will begin during the site investigation stage.

The characteristics of primary interest in the context of establishing baseline information are:

- the groundwater flow field in the host rock and in the surrounding geological environment (groundwater pressure distributions, hydraulic gradients, regions of recharge and discharge, etc.);
- geochemical characteristics of groundwater (redox, salinity, major and trace element concentrations, natural radionuclide content, etc.);
- background levels of natural radioactivity in groundwater, surface waters, air, soils and sediments, animal and plant life;
- meteorological and climatic conditions;
- hydrology of surface water systems, including drainage patterns and infiltration rates;
- ecology of natural habitats and ecosystems.

Baseline data should be established as part of the site characterisation activity, e.g. measurements from local and regional boreholes and surface investigations. Where important parameter values are found to follow an increasing or decreasing trend, baseline monitoring will need to be continued until that trend is established with confidence and the reasons for the trend are sufficiently well understood. The establishment of baseline values for surface environmental indicators is relatively straightforward, because the process of measurement will, in general, not affect the parameters being measured (e.g. measurements relating to climatic factors and surface hydrology). However, it is to be appreciated that invasive investigations will themselves perturb the natural groundwater system to a degree based on site specific conditions. In order to establish baseline conditions with which to judge later impacts, e.g. changes to groundwater pressures and hydrochemical conditions in response to repository construction, sufficient information needs to be collected in the surface exploration phase to have confidence that the undisturbed conditions have been adequately characterised both spatially and temporally.

Given the pervasive requirement for baseline information, the subsequent discussion (Section3) of strategies to meet the five monitoring objectives defined earlier, does not reiterate the discussion above.

3. USING MONITORING INFORMATION

This section discusses how information generated by monitoring activities might be used to meet the five objectives defined in the previous section.

The construction of a repository will disturb the pre-existing natural system. The subsequent phase of repository operations will cause further changes. Some of these changes may take many years to manifest themselves. Therefore, an important aspect of the monitoring programme will be concerned with changes to the repository environment resulting from effects, such as:

- mechanical disturbance, as a result of the excavation activities;
- hydraulic and hydrochemical disturbances, resulting from excavation and drainage;
- thermo-mechanical effects, caused by the emplacement of heat-producing waste;
- geochemical disturbance due to chemical reactions caused by the repository construction and operation (primarily the introduction of air but also of backfill and seal materials and of the waste itself).

These changes will have particular relevance in regard to the objectives 1, 2 and 3. The use of monitoring to meet all five objectives is discussed below.

3.1. SUPPORTING MANAGEMENT DECISIONS IN A STAGED PROGRAMME OF REPOSITORY DEVELOPMENT

The first objective of monitoring defined in Section 2 is:

'to provide information for making management decisions in a stepwise programme of repository construction, operation and closure'.

The operators of a repository must make numerous decisions during its construction and operational life. Some of these will be made early, in response to site characterisation information, others will be made much later, after all construction has ceased and the repository has been operational for decades. Monitoring information is likely to play a key role in the latter. Setting aside the major 'political' decisions associated with repository closure (which are discussed in Section 3.4), the operators may typically need to consider matters such as:

- adjusting the later stages of repository layout or design in response to long term monitoring of rock stresses and groundwater flow;
- modifying waste handling and emplacement procedures, or engineered barrier design or material properties in response to long term monitoring of the behaviour of initial waste emplacements;

- postponing the final design of seals and selection of backfill materials for the various stages of repository closure, basing them on long periods of observation of rock stress response, the movement and chemistry of water in excavation damaged zones around openings or the creep behaviour of plastic formations;
- deciding when to emplace certain types of buffer material, such as cement or crushed rock material around ILW packages or concrete vaults, based on monitoring package degradation behaviour, gas production and variations of surface physical and chemical properties of tunnel and vault walls, such as the growth of new mineral phases or biofilms, or oxidation or spalling of the rock which may affect seal bonding;
- the optimum time to backfill and seal disposal regions, in the context of long term stability of openings;
- whether to carry out repairs or remedial engineering work to excavation support systems, based on monitoring of rock movements, rock stresses and the degradation of rock bolts and other support materials;
- adjustments to the repository de-watering scheme to account for variable resaturation of different completed regions and consequent long term changes in the groundwater flow pattern or in groundwater chemistry.

Although the initial plans for a repository will make assumptions about all of these matters as part of the design basis, it is probable that decades of operational experience will allow early decisions to be adjusted and modified to take advantage of what is learned from concurrent monitoring information.

In general, the approach will be to accumulate information from the construction and operation stages to allow the design of the repository to be checked, refined and, where necessary, modified. The aim will be progressively to enhance confidence in the design concept, to allow the successive steps to take place. In some cases, monitoring may be used to provide information about the retrievability of the waste, if such an option is included in the disposal strategy of the country.

This type of monitoring will begin in the early stages of repository construction (e.g. shaft sinking) and continue throughout the construction and operational phases until the repository access ways have been sealed. At each stage the measurements taken as part of the monitoring programme would be used to provide the necessary confidence to take the next step. As appropriate, the monitoring information may also be used to support the necessary submissions to the authorities to seek required regulatory approvals.

3.1.1. Monitoring conditions of emplaced waste packages

Waste package conditions are relevant to waste retrievability and monitoring of parameters that indicate the integrity or the status of waste packages would be particularly important as long as some form of facilitated access to the waste is to be maintained.

However as engineered barriers are emplaced during the evolution of the repository, the capability to monitor package integrity will become progressively lower. The addition of the buffer[2], expected to take place immediately after waste package emplacement in many disposal concepts, will drastically limit the access to the waste package. As disposal openings

[2] Buffer is taken to mean the material, usually clay or cement, placed immediately adjacent to waste packages, whereas backfill refers to a potentially wide variety of materials used to fill tunnels, vaults and other excavations.

are backfilled, the possibility of performing measurements on the waste packages is reduced even more. In practice this creates an insuperable difficulty as direct access to the waste packages for the purpose of monitoring their evolution would imply some form of penetration through the engineered barriers with potentially negative impacts on their long term performance.

A solution occasionally proposed is a dedicated demonstration facility in a small part of the repository (or parts, to reflect variable rock conditions) or nearby in the same host rock, with sufficiently dense instrumentation to assure that all relevant factors are being closely monitored. This is expected to assist in achieving the needed confidence in the understanding of the behaviour of the waste packages in representative disposal conditions.

Logically this demonstration should take place before the authorization of repository operations; however in some geological disposal programmes the continuation of demonstration, and thus the associated monitoring, concurrently with disposal operations in the repository has been suggested. The anticipated advantage of such strategy would be to provide additional confirmation of the reliability of assumptions about waste package performance.

In some repository designs, particularly for low and intermediate level waste, the analysis of waste-derived gases, as close as possible to the waste packages, may provide useful indications about their integrity and/or about the performance of already emplaced engineered barriers.

3.1.2. Monitoring repository structures

The monitoring programme should include conventional observations of underground openings. As a matter of routine in the construction of such openings, rock stresses, deformations and loads on rock supports need to be monitored, in order to gain an understanding of the structural behaviour of the excavations. It will generally also be necessary to take routine temperature measurements around openings and to measure structural deformations in walls and linings.

Measurements relating to the condition of the repository structures and openings will be especially important if the excavations are to remain open for an extended period. If it is intended that waste emplacement operations should be reversible, it may be thought necessary to continue monitoring after backfilling of an excavated opening. Clearly, the scope for such monitoring is very much reduced once an opening has been backfilled. In such cases, remote techniques, such as detection of acoustic emissions caused by rock or engineered barrier strain or other geophysical approaches, might be useful.

3.1.3. Monitoring backfill and seals

The function of the backfill is to fill voids in the repository, thereby increasing its structural stability, and to restrict the movement of water within the previously excavated zones [7]. In many cases the backfill may consist of excavated rock fragments, possibly mixed with sand or clay. Backfill may be used in conjunction with high integrity seals that fill the full diameter of a tunnel or shaft together with the associated excavation disturbed zone [5]. For repositories that lie in the saturated zone, some temporary sealing may be required during the repository operational period. This is aimed at limiting the flow of groundwater into the excavations, for reasons of operational safety, and also to restrict access of groundwater to the waste packages.

Where there is an intention to maintain access by keeping open certain parts of a repository, temporary sealing is again likely to be needed.

The placing of backfills and seals will modify the repository conditions. Understanding the evolution of backfills and seals and the effects that the changes might have on the repository as a whole will be particularly important if the repository is to remain in operation for an extended period. The monitoring programme may therefore include:

- evaluation of stress field as a result of backfill and seals emplacement and changing thermal loads;
- subsequent deformation of underground openings;
- evaluation of changes in flow rates and water chemistry;
- measurement of changes to rock fractures;
- measurement of changes to temperature distribution;
- measurement of changed conditions in the backfilled and sealed zones.

3.2. STRENGTHENING UNDERSTANDING OF SYSTEM BEHAVIOUR

The second objective of monitoring defined in Section 2 is:

'to strengthen understanding of some aspects of system behaviour used in developing the safety case for the repository and to allow further testing of models predicting those aspects'.

Early in a repository development programme, decisions to select a site, to go ahead with construction and to emplace waste in the repository will have been based in part on the results of performance and safety assessments that will have evaluated the long term, post closure behaviour of the disposal system. Much of the information to underpin these assessments will have been derived from site characterisation work and supporting R&D, often carried out over many years. In order to proceed with these early steps, sufficient confidence will need to have been accrued in the ability of the conceptual models, used in the assessment studies, to represent future system behaviour adequately.

Although endorsement of the early programme steps must be based on having sufficient confidence in post-closure safety, it is clear that the opportunity will exist to test and strengthen understanding of some aspects of system behaviour further during the long period, possibly several decades, prior to repository closure. It is possible that society may require this extra time to develop the confidence that its early decisions to place waste under the ground were justified, and that the final step, that of repository closure, can go ahead. It is not possible to predict the length of time that this might take: a time during which, in some programmes, it might be intended to retain the option of waste retrievability.

The aspects of a safety case that can be tested further on the basis of protracted monitoring during the pre-closure period include understanding of:

- the groundwater flow field, which should respond in a broadly predictable fashion, over many years, to excavation and repository operations, in which some regions of the rock may at times be drained and later partially isolated and left to resaturate;
- groundwater chemistry, which may change in composition as different regions of the rock respond to underground operations, thus allowing further tests of hydrogeological models of the host environment;

- the hydraulic and mechanical behaviour of important structures in the rock;
- the thermal field around repository structures (natural variations in geothermal gradients, emplaced heat emitting wastes, heat emissions from the setting reactions of large masses of concrete);
- the response of underground structures and the groundwater system to seismic events (more important in some countries than others);
- the resaturation behaviour of regions of a repository that have been partially completed and isolated from operational areas, particularly the uptake of water by buffer materials whose properties are an important aspect of long term performance in some concepts;
- chemical interactions between engineered barriers and the rock/groundwater system.

Each of these topics is likely to have been considered, and predictions made about their impacts on performance, when presenting a safety case for waste emplacement. An additional twenty, forty or more years of observations can only serve to improve understanding. Some aspects of system behaviour will most likely differ from those envisaged at the outset. To maintain and improve confidence towards the final step of closure it will be necessary to show convincingly that these differences do not affect long term performance, and that the safety case is robust. If this cannot be shown, then it may be necessary to seek a different disposal solution. This perception lies behind the demand for maintenance of retrievability in some programmes.

An additional factor in monitoring to build understanding is that some of the experience gained in one repository and one national programme will be transferable to subsequent repository projects elsewhere or, possibly, even on the same site.

3.3. SOCIETAL DECISION MAKING

The third objective of monitoring defined in Section 2 is:

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

There are several critical points in a repository development programme that are likely to demand input from a broader range of societal groups than the repository operators and regulators alone. These will vary from one national programme to another, as will the nature and level of involvement of interested parties. It is conceivable, for example, that society, having endorsed the solution of geological disposal at a political level, would want to be involved in making decisions on at least the location of a repository, and on approving its eventual backfilling, sealing and closure.

A decision on repository siting will mostly be based on technical information, site characterisation data, safety assessments and a range of other technical and non-technical factors. The main use of monitoring programmes here will be to establish baseline information for the sites under consideration, as discussed in Section 2.2.

A decision to backfill and seal a repository is likely to demand a close evaluation of monitoring information collected over what could, by this stage, be many decades of repository operation. Several technical factors derived from monitoring programmes will have to be taken into account:

- the structural stability of repository openings and roof support systems, including the evolving thermal and stress field and the effects of any remedial or maintenance work that has been carried out since construction;
- the developing properties of engineered barriers, such as the resaturation of buffer materials or the integrity of concrete liners (relevant for repositories in weak rocks);
- interactions between engineered barriers and the rock-groundwater system, such as the migration of alkaline leachates into the rock;
- the degradation state of waste packages, particularly if not surrounded by engineered barriers, including evidence of corrosion, rates of gas production and possible leakage.

One approach to supporting major decision making with extended monitoring data might be to use the results obtained in the demonstration facility (see Section 3.1.1.), if such structure has been incorporated in the disposal programme.

Society will also have to decide on the level of post-closure control that it wishes to see exercised over the repository. Some countries may decide to have no institutional control period on the land overlying and surrounding the repository location once it has been sealed and the site decommissioned. Others may wish to see that access and activities on the site are limited to varying extents. In either case, there is a high probability that there will be a demand to have the environment of the repository monitored. The period over which this monitoring might continue is impossible to predict, as it will depend entirely on decisions taken by future generations. It can only be assumed that monitoring would continue until society is sufficiently confident to suspend or wind-down monitoring programmes or until the occurrence of an event that would make continuation of monitoring unfeasible.

A key issue in post-closure monitoring is the need for caution, such that any programme of measurements and instrumentation maintenance is not intrusive into the isolation barriers, with possible detrimental impacts on long term performance. Monitoring that makes use of remote sensing or periodic surface sampling is to be preferred. Such a programme may focus on detecting ground movement and heat flow (perturbations to any regional patterns which might be caused by the repository), as well as local water quality.

3.4. ACCUMULATING AN ENVIRONMENTAL DATABASE

The fourth objective of monitoring defined in Section 2 is:

'to accumulate an environmental database on the repository site and its surroundings which may be of use to future decision makers'.

Much information will accrue during the lifetime of a monitoring programme for an operational repository. A large amount of this information will have been gathered and been used specifically to meet the previous three objectives, and will then have limited direct use after repository closure, although it should be maintained as part of the record of the disposal activities.

We are not in a position today to be able to judge what types of information future generations may find useful after the repository has been closed. They may want to be in a position to take decisions about future land use, the context of which cannot presently be envisaged. The previous section noted that post-closure monitoring of some key environmental indicators could be required by society for some indefinite period of time. In order to put these post-closure measurements into context, it would be valuable to be able to pass a comprehensive database of long term environmental observations along to future decision makers.

Such a database might be expected to contain long term time series observations (collected over, possibly, 20 to 100 years).

It will be the choice of future generations as to if, and how, eventually to use this information, but the value of long time series records is widely acknowledged in both scientific and non-scientific disciplines.

3.5. NUCLEAR SAFEGUARDS

The fifth objective of monitoring defined in Section 2 is:

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

If the repository accepts waste that is rich in fissile radionuclides, such as spent fuel or plutonium-rich waste, nuclear safeguards are likely to be an important issue. Even after repository closure it may not be possible to declare the waste 'practically irrecoverable' and to meet the requirements for termination of safeguards [8].

For the pre-closure phases of the repository, as with surface waste management facilities, safeguards obligations would be met by suitably designed surveillance measures aimed at ensuring fail-safe accounting of nuclear materials. In this phase, safeguards are not expected to introduce any additional monitoring requirements.

After repository closure, in the present safeguards framework, some kind of control of the site might be required. Any safeguard-related monitoring would be aimed at providing assurance that no unlawful retrieval of material from the repository takes place. A discussion of safeguards for nuclear material in a closed repository can be found in another IAEA publication [9]; here it may be sufficient to highlight some essential requirements of a safeguard related monitoring programme:

- the monitoring programme cannot reduce the safety of the disposal system; therefore intrusive methods relying on the emplacement of instrumentation in the isolation barriers would not be acceptable;
- since the requirement for safeguard-related monitoring can be expected to last for an undefinable but probably long time, the efficiency and cost-effectiveness of the system should be maximized; in other words it should be possible to obtain the required assurance with a very limited effort.

In practice it may be possible to ensure that no drilling or mining activity, which would be a prerequisite for the retrieval of any nuclear material, is taking place at or near the repository site, by relying on periodic site observations by means of site visits, aerial photography or satellite imagery.

If tighter surveillance of the site were required, this might be achievable through a network of microseismic stations designed to reveal the emission of energy associated with drilling and mining.

This is an area that will clearly require further consideration as repository programmes develop.

3.6. MAKING DECISIONS BASED ON MONITORING INFORMATION

Monitoring data are expected to contribute regularly and routinely to decision making throughout repository operations, and for some time thereafter. An aspect that must clearly be considered is the probability of monitoring and recording changes that are unexpected. This implies that the range of expected results for each monitoring activity needs to be evaluated and presented in the earliest stages of a monitoring programme.

For critical parameters, the possible causes and consequences of unexpected readings (out-of-range data or outliers) need to be discussed, and any actions that might then be required should be studied and planned for. Again, this should all be carried out at the beginning of a monitoring programme. This may require that the significance of such results and procedures for dealing with them should be agreed in advance with regulatory agencies. This approach will be particularly important for aspects of repository structural stability during a long pre-closure period.

The key issue here is to be able to demonstrate an understanding of the implications of all types of monitoring results and an appropriate level of response, which may vary from no action at all, through design or procedural changes, all the way to significant remedial action or even retrieval of wastes.

4. METHODOLOGY FOR MONITORING

4.1. KEY ISSUES AND RELEVANT PARAMETERS

Section 2 lists five principal objectives of monitoring and Section 3 goes on to describe the uses that might be made of monitoring data. So, for example, monitoring of the response of the natural groundwater system to the drawdown introduced by the repository construction (and, later, its subsequent resaturation) would provide useful data for testing groundwater models in line with objective 2. Examination of the five objectives shows that the last two (environmental database, safeguards) are quite distinct whereas the first three contain many common issues. The phenomenon of buffer resaturation, for instance, is considered to be important for design and planning (objective 1), model testing (objective 2) and societal decision making (objective 3).

Closer examination of the many phenomena discussed in Section 3 shows that they can be broadly separated into six categories.

(1) Degradation of repository structures.

(2) Behaviour of the waste package and its associated buffer material.

(3) Near field chemical interactions between introduced materials, groundwater and host rock.

(4) Chemical and physical changes to the surrounding geosphere.

The last two categories coincide with objectives 4 and 5 respectively.

(5) Provision of an environmental database.

(6) Nuclear safeguards.

Using this categorisation, this section describes the parameters that might be usefully monitored in order to help achieve the stated objectives. Consideration is then given to the level of access that would be needed to make the measurements and, finally, the type of equipment that would be required.

All this information is summarised in Table I and discussed in the following subsections.

4.1.1. Degradation of repository structures

This category includes the (mostly mechanical and hydraulic) response of the host rock to the excavations, the emplacement of waste, buffer, backfill and seals (including installation of temporary seals). It would include monitoring of the rock movements around openings and the condition of rock supports. Rock supports encompass rock bolts and (e.g. for low-strength rocks) concrete linings. Monitoring would follow the changes in rock stress, air and rock temperatures, fracture movements and the load on rock support structures. This information would be particularly useful if the repository were to remain open for an extended period. In addition, information would be collected on groundwater ingress or dewatering and the rate of production of rock-derived gases (e.g. radon) from the newly exposed rock.

Some of these parameters could be measured directly using the repository roadways and tunnels for access. However, as the repository is filled with waste and the engineered barriers (buffer, backfill and seals) are emplaced, direct access would no longer be available. Access could be obtained from the repository by drilling boreholes through the barriers or through the rock from adjacent excavations (thus penetrating the natural barrier). However, this might decrease the reliability of the barriers and is to be avoided as far as possible. Instead reliance would need to be placed on remote techniques (e.g. detection of acoustic emissions from propagating fractures). Other possibilities would be the use of geophysical techniques or the installation of remote signalling devices - instruments that transmit information via radio signals or earth currents — though such devices may have relatively short service lives. In addition, the option of constructing, within the confines of the repository or nearby in the same host rock, an extensively instrumented demonstration or 'pilot' facility, avoiding thus any breaching of the real isolation barriers, could be evaluated. If these measurements were effected, or at least started, before the first waste emplacement in the repository proper, they would provide useful advance information and would consist in the demonstration phase anticipated by various geological disposal programmes (see Section 3.1.1.).

4.1.2. Behaviour of the waste packages and buffer material

The behaviour of emplaced waste packages will depend upon degradation phenomena such as corrosion and effects such as waste stack stability, resaturation (e.g. of buffer and waste), and gas production. Also important for many ILW repository designs is the phenomenon of carbonation (by carbon dioxide in air) of cement-based buffers.

TABLE I. PARAMETERS AND MEASUREMENT METHODS

Category/purpose of monitoring	Typical parameters	Access method	Typical measurement methods
DEGRADATION OF REPOSITORY STRUCTURES Monitoring of repository structures/structural stability of openings	Rock temperatures Deformation of openings (orientations and apertures, propagation rates) Rock stress changes close to repository Water infiltration rate Condition of rock supports Repository temperatures, humidity Resaturation of backfill and seal materials	Within repository monitoring including access from boreholes drilled from the repository. Could include the use of devices that are installed in situ but with radio signals or earth currents for transmission of data. In situ/remote monitoring of backfilled openings	Thermocouples etc. Displacement detectors Strain/load sensors Volume measurements Strain/load measurements Various techniques Pressure sensors, moisture detectors, geophysical techniques (seismic wave transmission)
BEHAVIOUR OF WASTE PACKAGES AND BUFFER MATERIALS Monitoring the condition of emplaced waste packages/condition of buffer	Strain, corrosion current Package temperature, humidity close to packages Radioactivity in drainage water Waste-derived gases in repository air Resaturation/swelling pressure in buffer	In situ /remote monitoring of waste packages In situ /remote monitoring of environment close to the package Radioactivity monitoring of repository effluent water Monitoring of radioactive and other gases in repository air In situ/remote monitoring of environment close to the package	Strain gauge, current meter Many techniques available Various e.g. gamma detection Gas analyser Pressure sensors, moisture detectors

Category/purpose of monitoring	Typical parameters	Access method	Typical measurement methods
NEAR FIELD CHEMICAL INTERACTIONS Chemical condition of backfill and seals/behaviour of engineered barriers/integrity of concrete structures/changes in near field environment/surface properties of tunnel walls/repository resaturation behaviour	Repository temperature, humidity Mineral, chemical, biological changes on repository surfaces Changes to water content, pressure, chemistry in the near field when dewatering ceases (i.e. following sealing)	Within repository monitoring Periodic sampling within repository Periodic sampling or continuous measurements from within repository	Temperature, moisture (e.g. electrical conductivity), pressure Various analytical techniques Various techniques based on sampling or continuous measurements
CHANGES TO THE GEOSPHERE Changes in surrounding geosphere/interactions between engineered barriers and rock-groundwater system/influence of alkaline plume	Changes in groundwater pressures and pathways Changes in groundwater chemistry e.g. pH, Eh, dissolved solids, radioactivity, microbial activity Changes in mechanical behaviour of important structures in the rock Changes in mineralogy Thermal field Stress field Monitoring of, and response to, seismic events	Access from new or existing boreholes Ditto Ditto Ditto Ditto Ditto plus remote (for microseismic) In-repository, surface and boreholes	Pressure monitoring devices, e.g. piezometers in saturated zone, tensiometers in unsaturated zone Various techniques; borehole sampling, gamma ray detection Electro-mechanical gauges, acoustic emission monitors Sampling Borehole logging Strain/load sensors plus microseismic techniques Seismic wave detectors
ACCUMULATION OF AN ENVIRONMENTAL DATABASE	Meteorology, hydrology, etc. (see main text)	Monitoring at the surface	Various techniques
SAFEGUARDS	Disturbance of engineered barriers	Within repository and/or from the surface	Site inspections Aerial photography Satellite surveillance

The parameters that could be monitored for use as indicators of the condition of waste packages fall into three categories: direct measurements (e.g. corrosion current, strain, swelling pressure for clay buffers); environmental measurements (e.g. temperature, humidity, resaturation pressure); and monitoring of radioactive releases in water and air. All of these methods are likely to require access to the immediate environment of the waste package. This is unlikely to be feasible once the backfill and/or buffer are in place. Again, limited access could be obtained through the use of remote signalling devices or (though this is to be avoided) by running cables through the engineered barriers. As before, a more practical solution would be to carry out parallel tests in a ‘pilot’ section of the repository or in an adjacent demonstration facility where packages could be more highly instrumented without disrupting the engineered barriers.

4.1.3. Near field chemical interactions

The properties of the near field (which includes the engineered barriers and the rock immediately adjacent to the repository) would change over time under the influence of the heat loading, repository aeration/ventilation, groundwater inflow, etc. Chemical, physical and biological changes to surfaces may be important for the effective emplacement of seals. In addition, the long term interactions between the natural groundwater/rock system and the repository materials may be useful in the testing of geochemical models.

Parameters of interest relate to changes in the physical, chemical and biological properties of surfaces (e.g. spalling, mineralogical changes, biofilms) in response to extended exposure to air, to aerated natural groundwater, and to groundwater that has been in contact with repository materials. In general it will be possible to measure these parameters using direct access within the repository.

Of relevance to model testing are the geochemical reactions that occur when the repository resaturates with natural groundwater (i.e. after placement of backfill and seals); of particular interest are the reactions of the groundwater with the buffer. In general, monitoring of these changes will not be possible without intruding into backfilled and sealed areas; since this is to be avoided, a more highly instrumented pilot facility (discussed previously) would be helpful here.

Geochemical changes to the far field are covered in the next paragraph.

Techniques for measuring these changes are widely available and are summarised in Table I.

4.1.4. Changes to the geosphere

The geosphere surrounding a repository will respond in a number of different ways to the presence of the repository, e.g. mechanically, hydraulically, chemically. Relevant measurable parameters are temperature, stress, groundwater chemistry, groundwater pressure, solute chemistry and mineralogy. These parameters will often be measurable using boreholes drilled during the site characterisation and underground investigation phases. A wide range of techniques exists (Table I). Many mineralogical changes in response to repository ventilation are likely to be confined to the immediate vicinity of the repository.

Of particular interest are changes to the hydraulic and mechanical behaviour of rock structures that may have a direct bearing on the long term performance of the isolation system e.g. the connectivity of major water conducting fractures. Again, investigation of these features is likely to be by boreholes drilled during the site characterisation and underground investigation phases.

For repositories in the saturated zone, groundwater flow will be towards the repository while the repository remains open. However, following repository resaturation (or perhaps resaturation of part of the repository) groundwater will flow through the repository back into the geosphere. This will produce geochemical changes in the geosphere. For some repository concepts e.g. those that make extensive use of cement, the changes may be profound. Monitoring of these effects may be difficult, in part because of problems of access to the affected rocks, but mostly because the monitoring timescales are likely to extend into the post-closure period. Nonetheless, these issues may be relevant, both to model testing and to a societal decision to close a repository.

At some repository sites, the monitoring of, and the responses to, seismic events will also form an important part of model testing.

4.1.5. Accumulation of an environmental database

The accumulation of environmental data over a period of several decades may be of great assistance in assessing the suitability of the land above a repository for alternative land uses. Parameters of potential relevance are:

- meteorology;
- hydrology, drainage, water usage, water quality;
- concentration of radionuclides and other pollutants in various environmental compartments including biota, sediments and waters;
- local ecology;
- geomorphological processes, such as denudation, localized erosion, slope evolution;
- tectonic activity such as vertical and lateral earth movement rates, seismic events;
- geothermal heat flow;
- land use in the surrounding region.

All these parameters may be measured from the surface. The data should be continuous and extend over many years.

4.1.6. Nuclear safeguards

The application of nuclear safeguards (for repositories that contain significant quantities of fissile material) will require a level of surveillance that is sufficient for the early detection of unauthorised movement of fissile material. A probable indicator of unauthorised movements would be the unexpected disruption (e.g. excavation) of engineered and/or natural barriers. Such disruption could be detected by:

- site inspections,
- aerial photography,
- satellite imagery and
- microseismic surveys.

4.2. QUALITY ASSURANCE

Quality assurance and quality control procedures are intended to provide a framework within which work is planned, performed, reviewed and recorded to give an adequate level of confidence that the work is fit for purpose.

In the context of a repository monitoring programme, it is expected that the application of quality assurance will require that:

- monitoring programmes are planned to an appropriate level of detail, including the identification of suitable methods, locations, equipment and procedures;
- monitoring programmes are followed;
- sampling, analytical and inspection methods comply with defined protocols and standards;
- sampling is adequately documented to permit tracking of a sample;
- appropriately qualified and trained staff carry out the defined tasks;
- decisions are made by the appropriate persons or body;
- information is disseminated and consultation is undertaken as required;
- inter-laboratory comparisons and peer review processes are carried out as required;
- adequate records are kept of all activities for the time and in the form defined;
- data are documented in such a way that their origin is transparent and traceable, that there significance is clear and that data uncertainty is defined;
- procedures are reviewed and updated to take account of continually developing standards and measurement techniques;
- staff carrying out defined tasks remain qualified and have up-to-date skills and the required knowledge and skills, e.g. a qualified staff member remains competent and meets any continuous professional development requirements;
- special attention is given to the question of what monitoring data records should be archived, and how the archive should be preserved (see Section 4.4).

4.3. RELIABILITY

When long term monitoring is required, facilities will have to be provided to allow instruments to be maintained and/or replaced when failures occur. The opportunity for instrument replacement and maintenance inside the repository will be limited because of the potential safety hazard once the emplacement of waste has begun. In the event that such monitoring were deemed appropriate, the provision of instrument redundancy would give some extension of the period over which the instrumentation continued to provide usable data. Instrumentation should be designed to ensure that the installations themselves do not provide preferential release paths through the isolation barriers.

In general, currently available instrumentation is sufficiently accurate and precise for the monitoring requirements envisaged. However, when instrumentation is not accessible a key issue is the verification of the sensor signal. For long term monitoring the interpretation of measurement results may involve significant uncertainties. Nonetheless, it should be remembered that measurement techniques, especially those using non-intrusive remote surveying, are being developed continuously.

4.4. PRESERVATION OF RECORDS AND REPORTING

Monitoring data represent a valuable source of information that should be rationally managed and safely stored on various media (magnetic, electronic, paper, plastic, etc). Databases should be sorted by category in order to be readily usable for interpretation and tracking of any trends. Systems of quality control for the recording and storage of data should be put in place in order that the continuous integrity of the data can be demonstrated to regulatory authorities even after, in some cases, prolonged periods of time.

Monitoring data will be very useful for future comparison with closure and possible post-closure monitoring. Therefore, records should be updated and maintained in such a form that they can be used in the long term. These records may also include detailed information such as the rationale for the design of the monitoring programme, the location and the frequency of measurements, the sampling and analytical procedures and data.

The results of monitoring are expected to be submitted to national safety authorities in the form of periodic reports documenting the performance of the repository, to meet regulatory requirements and to reveal any discrepancies with anticipated behaviour. Operators may need to establish a programme of repeat analyses and corrective actions to fulfil regulatory requirements.

5. CONCLUSIONS

It is widely accepted that the long term safety of geological disposal should not rely on a continued capability to monitor a repository after it has been sealed and closed. Although future generations may wish to monitor, it would be presumptuous to speculate how or why they might do this. On ethical grounds, they should have no monitoring burden placed upon them. However, there are several more immediate applications of monitoring information, obtained from the outset of a development programme, which the repository designers and operators can, and should, be required to consider.

Monitoring a deep geological repository and its environment would be carried out principally as an aid to decision making. There are several objectives for carrying out monitoring and a range of applications for monitoring information. Some of these objectives require monitoring to be carried out throughout the operational life of a repository and the majority of them also require the clear establishment of baseline information related to the “undisturbed” conditions of the site.

The main types of decision that will make use of monitoring data in the period up to repository closure, are those concerned with moving from one operational stage to another in the management of the facility. These may be small steps, such as decisions on the eventual inventory and backfilling for a specific section of the repository. Some of these decisions, particularly the decision to close a repository, have wider significance and may need to be taken by means of a consultative process involving various sectors of society.

As repository closure approaches, it may become progressively more difficult to retrieve the wastes. Consequently, by the time of closure, confidence in the capability of the disposal system to contain the wastes safely must be sufficient in the relevant community of decision makers. Thus, an important aspect of monitoring during the operational phase and any subsequent pre-closure period, is to enhance understanding of those aspects of the safety case that it is feasible to address over a period of several decades.

After closure of the repository, there may be a continued demand for monitoring of the site and the surroundings, even if there is no control over land use. The needs of future generations can be helped if a comprehensive and continuous, time series environmental monitoring database is passed on to them.

It is clearly preferable that any monitoring system, whether devised for use during operation or after closure, should not intrude into the barriers designed to contain radionuclides. This could be approached by allocating a part, (or possibly parts) of the repository as a demonstration facility, ensuring that it is broadly representative of the range of conditions found within the repository. This demonstration section could be heavily instrumented and monitored up to repository closure, when it would need to be decommissioned safely. If it was to have a use after closure, then it would need to be isolated from the sealed repository.

Broadly speaking, monitoring techniques are available for all types of surface and underground data acquisition that can currently be envisaged. Instrumentation and technology will improve over the decades of repository life, and monitoring systems will need to be replaced, as far as feasible.

Surveillance and monitoring for nuclear safeguards purposes is clearly feasible using available methodology, both during operations and after repository closure.

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