European Commission

nuclear science
and technology

Thematic Network on the Role of Monitoring in a Phased Approach to Geological Disposal of Radioactive Waste

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Contract No. FIKW-CT-2001-20130

Final report

2004 EUR 21025 EN

EXECUTIVE SUMMARY

This Thematic Network on the role of monitoring in a phased approach to the geological disposal of radioactive waste has brought together expertise from twelve organisations in ten countries, from within the EU and Associated Countries, to achieve the following objectives:

- to improve both the understanding of the role of and the options for monitoring within a phased approach to the deep geological disposal of radioactive waste; and
- to identify how monitoring can contribute to decision making, operational and post-closure safety and confidence in our understanding of the repository development.

The motivation for this Thematic Network can be described by posing the question: what is the role of monitoring in the phased development of a geological disposal facility? The requirement for monitoring in supporting the implementation of geological disposal has always been recognised and the subject of monitoring is now perceived as one of increasing importance as some repository programmes approach the phase of construction. Furthermore, the topic is suitable for international collaboration.

Chapter 1 of the report introduces the concepts of the safe management of radioactive waste and geological disposal, and identifies the role of monitoring as an important question in the development of a geological disposal programme. The motivation for, and the objective, scope and organisation of this Thematic Network are also introduced.

Chapter 2 outlines previous work that is most relevant to the current project, notably by the IAEA and in a preceding Concerted Action of the European Commission. It also sets down an understanding of the phased development of geological disposal and the principles of monitoring related to geological disposal, which are the starting point for the work described in this report.

Chapter 3 discusses strategic aspects of monitoring. This includes the general reasons for monitoring, the relationship of monitoring to safety and implementation concepts and the role of monitoring in decision making.

Chapter 4 discusses monitoring under the four topics adopted as themes for initial subgroup work during this project. These are: the establishment of baseline conditions, monitoring for compliance, monitoring to support assessments of repository performance and broader aspects of monitoring.

Chapter 5 discusses general monitoring requirements and constraints. This includes discussion of the ability to monitor as specified, the ability to interpret data, monitoring without compromising operational or post-closure safety, monitoring under repository environmental conditions and monitoring over long time periods and/or in remote locations.

Chapter 6 considers monitoring methods and techniques, including the existing experience of monitoring from site investigation programmes and underground research laboratories (URLs).

Chapter 7 summarises the findings, experience and conclusions of the Thematic Network and provides conclusions to the work.

Country Annexes for all the countries that were involved in the Thematic Network are presented in an Appendix. These describe the plans for monitoring in each of these countries and have been prepared by the appropriate organisations in each country.

All the participants of this Thematic Network agree on the importance of monitoring related to establishing baseline conditions, maintaining operational safety, compliance (including safeguards) and in support of model confirmation regarding post-closure safety.

The safety and the implementation strategy adopted, where a spectrum of approaches can be recognised, have implications for the role of monitoring within a disposal programme. There is a range of approaches to monitoring, as demonstrated by the different approaches

followed by the various programmes involved in this Thematic Network. It is important to understand the reasons for these differences and the role played by monitoring within any safety and repository implementation strategy.

The extent of monitoring should be limited to that which could reveal useful results for the decision making process or for the confirmation of safety. That monitoring takes place must be explained to audiences and it is important not to give the impression that such monitoring indicates a lack of confidence in the safety of the disposal system.

This report emphasises that there is already extensive experience of monitoring related to the field of radioactive waste disposal from site investigations, experiments in URLs and relevant experiences from operating other nuclear facilities. Relevant experience also comes from outside this field, for example, from the monitoring of large engineered structures, such as dams and underground openings, which has taken place over many decades.

In summary, technologies exist or are in development, which give good prospects for a level of monitoring that is appropriate for assisting in stepwise repository implementation. The extent of monitoring that it is either appropriate or useful to implement is, however, a sensitive question and depends on implementation strategies. Experience will continue to be gained, especially in those programmes that are approaching site investigations and the construction of repository-related structures – activities which will require the detailed specification of monitoring programmes.

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1 INTRODUCTION

1.1 Radioactive waste, safe management and monitoring

Long-lived radioactive waste exists in most countries of the European Union and it is important that appropriate solutions are developed to ensure the waste is properly managed. The objective of such management is to deal with radioactive waste in a manner that protects human health and the environment now and in the future, without imposing undue burdens on future generations (IAEA 1995).

There is a consensus amongst the organisations responsible for radioactive waste management, regulation and related policy making, that disposal in a deep geological repository is an appropriate means of management of long-lived radioactive waste, e.g. see NEA (1999b). Furthermore, geological disposal has been adopted as the preferred approach in many countries, although alternative strategies for progressing towards this goal are under consideration.

The safety of all nuclear facilities, and other facilities dealing with radioactive material or waste, is ensured through the design of the facility and the operating procedures, where the design is arrived at and tested by safety and performance assessments, and the operational safety of the facility is confirmed by monitoring supported by further assessments. The criteria, techniques and methods for carrying out monitoring in operating nuclear facilities such as power plants and waste treatment and storage facilities are well established, and the principles for achieving safety in such circumstances are well understood.

1.2 Geological disposal and its implementation

The case of disposal for solid radioactive waste and especially the disposal of long-lived radioactive waste, which presents a potential source of hazard for tens of thousand of years or more, is a special problem. The aim of geological disposal is to dispose of the waste such that its long-term safety is assured by the passive functions of the engineered and geological barriers of the repository as specified in the design, without the need for any further actions or monitoring to assure its safety after the closure of the facility. Indeed, it is a principle of the geological disposal of radioactive waste that long-term safety must be established before closure of the facility and cannot depend on any actions or monitoring performed thereafter (NEA 2004, IAEA 2004).

Developing a geological disposal concept, and ensuring its long-term safety, is a challenging task. Typically, such facilities will be developed over a period of many years in a stepwise or phased approach. The means of achieving confidence in long-term safety through a stepwise implementation and the parallel development of a safety case have been widely discussed, e.g. see (NEA 1999a, NEA 1999b, NEA 2004). Technical aspects of the management of phased implementation, and in particular the prospects for reversibility of the implementation and if needed retrieval of the waste, have been addressed in a previous European Commission Concerted Action (EC 2000) and more generally elsewhere (NEA 2001a). In addition a preliminary exploration of the role of monitoring of geological repositories has been carried out under the auspices of the IAEA (IAEA 2001, IAEA 2002).

1.3 Motivation for this Thematic Network

The question at hand, in this Thematic Network, is

What is the role of monitoring in the phased development of a geological disposal facility?

In particular, how do the role, aims and possibilities of monitoring change as the facility moves from the design phase, to construction, to an operating facility in which radioactive waste is being emplaced, towards sealing and closure, and finally after closure.

That monitoring would be required in support of the implementation of geological disposal has always been recognised. The subject of monitoring is now perceived as one of increasing importance in repository programmes and of being suitable for international collaboration. This increased importance arises from:

- the move in several waste management programmes from concept development and research towards more detailed site investigation and implementation stages during which monitoring programmes must be defined;
- the recognition of the need for well-founded decision bases and evidence (to which monitoring will contribute) in progressing phased geological disposal projects;
- issues of confidence and how to develop it, especially in wider stakeholder groups, including the public.

Bringing together expertise in different European programmes under the auspices of the European Commission provides opportunities to:

- understand the approaches to monitoring in each programme and their dependency on national concepts and implementation approaches;
- distil consensus views and recognise alternative approaches to monitoring;
- share technical knowledge and experience amongst the participating organisations;
- communicate these views and experiences more widely, by means of this report.

1.4 Objectives, scope and organisation of the Thematic Network

This Thematic Network has brought together expertise from EC and collaborating countries to achieve the following objectives:

- to improve both the understanding of the role of and the options for monitoring within a phased approach to the deep geological disposal of radioactive waste; and
- to identify how monitoring can contribute to decision making and confidence in our understanding of the repository development.

The scope of work covers potential monitoring strategies and requirements during all phases of the implementation of a disposal system, including site investigation and characterisation, facility construction and operation, steps leading to closure of the facility and any post-closure monitoring that may be carried out.

Twelve organisations from ten European countries have collaborated under the auspices of the European Commission in this Thematic Network, see Table 1. In all ten countries, national concepts for the disposal or long-term management of radioactive waste are under consideration, although the level of advancement of concepts, related research and technical development differs.

Table 1 Participating organisations in the Thematic Network on the role of monitoring in a phased approach to the geological disposal of radioactive waste

Agence nationale pour la Gestion des Déchets radioactifs (ANDRA) France
Deutsche Gesellschaft zum Bau und Betrieb von Endlagern für Abfallstoffe (DBE) Germany
Empresa Nacional de Residuos Radiactivos SA (Enresa) Spain

National Co-operative for the Disposal of Radioactive Waste (Nagra) Switzerland
Nuclear Research and Consultancy Group (NRG) The Netherlands
Organisme national de Déchets radioactifs et Matières fissiles enrichies (NIRAS-ONDRAF) Belgium
Posiva Oy (Posiva) Finland
Radioactive Waste Repository Authority (RAWRA) Czech Republic
Belgian Nuclear Research Centre (SCK-CEN) Belgium
Svensk Kärnbränslehantering AB (SKB) Sweden
Safety Assessment Management Limited (SAM) United Kingdom
UK Nirex Limited (Nirex) United Kingdom

The project has been divided into the following four work packages:

- Information gathering and improving the definition of work to be carried out in the three subsequent work packages;
- Identifying the parameters that could require monitoring, and the reasons for doing so;
- Identifying techniques and strategies for monitoring;
- Compilation of this final report.

Four different types of monitoring were identified at the outset of the project. These provided the basis for initial collaborative tasks carried out by subgroups within the Thematic Network and subsequently presented to all participants and discussed in plenary mode. The types of monitoring considered were:

- the establishment of baseline conditions;
- monitoring for compliance with regulatory and requirements or other criteria and standards;
- monitoring to support evaluations and assessments of repository performance;
- broader aspects of monitoring (which may include, for example, monitoring related to broader areas of science and technical capability, legal matters and societal values).

In addition, more strategic aspects of monitoring were discussed and additional tasks were defined to cover monitoring requirements, monitoring techniques and practicalities and the interpretation of monitoring measurements.

1.5 Structure of this report

This chapter, Chapter 1, introduces the concepts of the safe management of radioactive waste and geological disposal, and identifies as an important question: the role of monitoring in the development of a geological disposal programme. The motivation for, and the objective, scope and organisation of this Thematic Network are also introduced.

Chapter 2 outlines previous work that is most relevant to the current project, notably by the IAEA and in a preceding EC Concerted Action. It also sets down an understanding of the phased development of geological disposal and the principles of monitoring related to geological disposal, which are the starting point for the work described in this report.

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2 PREVIOUS WORK AND BACKGROUND

2.1 IAEA work on monitoring of geological repositories

The International Atomic Energy Agency (IAEA) technical document *'Monitoring of Geological Repositories for High Level Radioactive Waste'* (IAEA 2001) 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. This document establishes several generally important points related to the monitoring of geological repositories.

The document begins by stating:

> *"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."*

The following definition of monitoring is adopted, although it is not binding upon any member state:

> *"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 report recognises that:

> *"The extent and 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."*

The document sets out five key purposes for monitoring in the context of assisting decision making during the phased implementation of a repository, plus three additional 'purely operational reasons' for monitoring, common to any nuclear facility. Monitoring is then discussed in terms of seven 'typical' stages in the development of a geological repository, and also monitoring to establish baseline information, which it is stated "should begin at the earliest time within a repository development programme". Table 2 outlines these divisions.

Table 2 Divisions of purposes for monitoring and stages of repository development defined by the IAEA technical document on monitoring (IAEA 2001)

Purposes for monitoring
'Key objectives' : 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. *'Purely operational reasons during the emplacement of the wastes'* : 1. to determine any radiological impacts of the operational disposal system 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.).
Stages of repository development
1. surface exploration; 2. access construction and underground exploration; 3. construction of the repository; 4. emplacement of waste and near field engineered barriers; 5. disposal tunnel/vault backfilling; 6. backfilling of remaining openings and repository sealing; 7. post closure.

The report concludes

> *"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 and why they might do this. … 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."*

Subsequently the subject of monitoring was discussed at an IAEA workshop (IAEA 2002) which explored issues related to the development of the IAEA safety standard for geological disposal. The IAEA safety standard (IAEA 2004) includes a 'Requirement' related to monitoring as follows:

> *"Requirement 20: Monitoring programmes* [1]
>
> *A programme of monitoring shall be defined and carried out prior to and during the construction and operation of the geological disposal facility. This shall be designed to collect and update the information needed to confirm the presence of the conditions necessary for the safety of workers and members of the public and protection of the environment during the operation of the geological disposal facility and to confirm the absence of conditions that would undermine the safety of the geological disposal facility."*

Supporting text states, inter alia, that

> *"Monitoring programmes will be designed and implemented so as not to reduce the overall level of post closure safety.*
>
> *Plans for monitoring aimed at providing assurance of post closure safety will be drawn up before construction of the geological disposal facility to indicate possible monitoring strategies, but these will need to remain flexible and if necessary revised and updated during the development and operation of the facility."*

2.2 EC work on retrievability of waste in geological repositories

The current Thematic Network was, to some extent, motivated by the importance of monitoring as a subject for further work identified during a previous EC Concerted Action on The Retrievability of Long-lived Radioactive Waste in Deep Underground Repositories' (EC 2000).

The Concerted Action on Retrievability report identifies four reasons for monitoring:

- To provide information (including baseline information) for use in repository design and construction and in the assessment of repository long-term safety.
- To provide information (including baseline information) relating to the impact of the repository on workers, the public and the environment.
- To address the requirements for Nuclear Materials Safeguards (where a repository contains significant amounts of fissile material).
- To assist in the societal decision making process by, for example, monitoring system performance and providing data on conditions relevant to the retrievability of the waste packages.

The report then discusses monitoring in the context of retrievability. The document indicates ways in which monitoring might serve retrievability, for example, by establishing the condition and retrievability of waste packages, providing data related to postponing of closing of disposal areas and access routes, and to demonstrate that systems installed to allow reversibility of operations are fit for purpose. The document also indicates the potential for monitoring related to retrievability in different timeframes defined for the purpose of discussing retrievability.

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[1] At the time of writing the IAEA Safety Standard for geological disposal (IAEA 2004) has been reviewed by IAEA member states, given technical approval by the IAEA WASSC committee, but awaits policy approval. Readers should therefore refer to the actual text as published when this becomes available.

2.3 Principles for monitoring of geological repositories

Monitoring of aspects of a geological disposal system during its phased implementation process is based on a small number of basic principles, which are generally well accepted. For the present work, the following principles are defined. These are based on the existing international consensus, for example as indicated in the IAEA documents summarised above, and are also confirmed as appropriate and achievable by the participants in this Thematic Network.

- The operational safety of a geological disposal facility (both radiological and conventional) must be underpinned and verified by monitoring. This is the case for all nuclear facilities.
- Long-term (post-closure) safety cannot rely on monitoring after closure. This is for reasons of principle – undue burdens should not be placed on future generations – and for practical reasons – it cannot be assumed that future generations will have the technical capability or interest in carrying out monitoring.
- Therefore, long-term safety must be assured by the disposal system design (including the choice of site) and the quality of its implementation. After closure, the disposal system must be passively safe without reliance on monitoring.
- To this end, a convincing long-term safety case has to be developed prior to the emplacement of the waste (i.e. monitoring in the post-emplacement phase is not part of the safety case, although it may provide an opportunity to confirm its conclusions).
- All monitoring must be implemented in such a way as not to be detrimental to long-term safety. That is, no significant detrimental disturbance of the long-term performance should be introduced by monitoring. (Similarly, there must be no compromise with respect to long-term safety in order to facilitate the retrievability of the waste.)
- The societal role of monitoring must be acknowledged. Monitoring may be carried out for non-technical reasons, for example related to public re-assurance. Such monitoring may be continued as long as it is required by future generations, who may not consider this an ‘undue burden’.

2.4 Concepts of phased repository implementation and the implications for monitoring

The development of a geological disposal system for radioactive waste comprises a series of consecutive phases, starting with the definition of the disposal concept, site selection and site characterisation, followed by the phases of detailed repository design, construction and waste emplacement. After waste emplacement, the closure of the repository will proceed in steps that may follow quickly or be delayed, depending on the safety and implementation strategy and the decisions made by future generations.

The principle of phased geological disposal has been endorsed internationally and is being adopted by many national programmes world wide, although the manner of implementation will vary between countries. Two contrasting approaches can be defined for the purpose of illustration.

- One approach to phased disposal emphasises a clear schedule of construction, waste emplacement, repository operation and closure, based on a robust repository design and safety case. Any decisions that may need to be taken to progress through all subsequent phases are expected to follow a pre-defined schedule, and any information that may be required to support such decisions is expected to be available at that time. This approach does not preclude future modifications of the disposal concept and design or of its implementation schedule, nor a potential need for waste retrieval, but it does not explicitly plan for them at the outset.

- Another approach to phased disposal emphasises a flexible schedule of its implementation, taking into account the uncertainties inherent to a long-term project and to important waste management decisions that may lead to closure of a repository, as well as the uncertainties of any information needs in support of such decisions. This approach explicitly plans for the possibility of future developments of an initially robust repository design and safety case, as well as for the possibility of waste retrieval.

The choice between either one of these approaches may depend on such factors as the finality with which operation and closure of a repository is decided upon before construction begins, on the level of input that is expected from stakeholders during the phased approach and before closure, on the need for flexibility imposed by stakeholders, or on the minimum duration that the entire cycle of phased disposal might require.

The US National Research Council (NRC) has termed these approaches 'linear staging' and 'adaptive staging' (NRC 2003). In this report, they will be termed approaches 'A' and 'B' respectively. It should be emphasised, however, that the approaches to implementing phased disposal in different programmes cover a range of intermediate positions between those outlined above.

These differences of implementation strategy have definite implications for the type and extent of monitoring information required to support the decision making process.

- Leaving more options open will tend to increase the need for monitoring to obtain information related to assessing the options.
- Leaving underground disposal and access areas open for longer will increase the need for monitoring related to assuring underground safety and the viability of continuation of an 'open' phase.
- Whether or not the programme includes a separate 'research only' underground research laboratory (URL), a pilot 'research orientated' facility as part of the disposal facility development, or no such research facility, will also affect the type of monitoring that may be carried out in the main disposal facility.

Many technical aspects of monitoring, however, are common to all approaches to implementing phased disposal. These common aspects and differences are discussed in more detail in the succeeding chapters.

3 STRATEGIC ASPECTS OF MONITORING

3.1 Working definition of monitoring

With the considerations of Chapter 2 in mind, it is possible to define monitoring for the purposes of this Thematic Network. The definition of the IAEA technical document (IAEA, 2001), see Section 2.1, is used as a starting point. To this are added two further points identified in Chapter 2 that are relevant to a more complete definition:

- The definition should draw attention to the use of monitoring results to inform future decision-makers on the implementation of successive phases of the disposal concept;
- A consensus definition should permit (but not specify or require) other forms of monitoring in addition to those already included.

The proposed definition of monitoring is therefore:

Continuous or periodic observations and measurements of engineering, environmental, radiological or other parameters and indicators/characteristics, to help evaluate the behaviour of components of the repository system, or the impacts of the repository and its operation on the environment, and to help in making decisions on the implementation of successive phases of the disposal concept.

This definition is made for the purposes of the present report; and it is not intended to be binding upon any participant in this Thematic Network. Extensive discussion between the participants could not resolve the differences between their proposed definitions of monitoring, particularly as some country definitions were decided in regulations, and so the above definition represents a compromise solution.

In addition, two types of monitoring measurement have been identified:

- Continuous monitoring, which is either a process that is continuously checked, such as a radiation area monitor; or where the same measurement is made on a succession of individual items, e.g. the mass and external dose rate of each waste canister or package.
- Periodic monitoring, where a process is checked on an agreed basis, but there are also periods where a process is taking place and not being checked; for example, discrete samples of waste water can be taken for analysis.

In its simplest terms, a monitoring strategy could, therefore, be considered as implementing the proposed definition of monitoring presented above. In order to develop a comprehensive strategy it is, however, necessary to go beyond this and the following sections describe elements that should be considered in developing such a strategy. It should also be borne in mind that any such strategy should be flexible so that it is able to accommodate changes that might take place in a disposal programme as it develops (see Section 2.4).

3.2 Reasons for monitoring

The following reasons for monitoring that relate to the stepwise implementation of a geological repository have been identified in the scope of the present study:

Monitoring as part of the scientific and technical investigation programme, including environmental monitoring

Monitoring that is part of the scientific and technical investigation programme includes the collection of all necessary information related to site selection and site characterisation, design and construction of the facility and for safety assessment (in terms of input parameters and comparison of measured data with model predictions). This also includes monitoring of baseline conditions at potential repository sites to detect any potential negative impact on the environment caused by on-site activities during site characterisation, construction and operation of the underground repository, as well as for reasons of liability.

Monitoring of the acceptable operation of facilities

With regard to operational aspects, regulatory authorities are likely to define specific radiological and non-radiological conditions for the routine operation of the repository as part of the operation licence. Activities related to the development and operation of the repository and related facilities are not allowed to have unacceptable impacts for the operating personnel, the general population and the natural environment. Monitoring may include measurements of emissions, immissions, key features of the facility and of related physical, chemical and rock mechanical processes.

Confirmation of key assumptions of the disposal concept

The safety of the disposal system is usually demonstrated in terms of a safety case. This is defined as a set of arguments and analyses used to justify the conclusion that a specific repository system is safe. It includes a description of the system design and safety functions, illustrates the performance of engineered and natural safety barriers, presents the evidence that supports the arguments and analyses and discusses the significance of any uncertainty or open questions. The safety case also presents the evidence that all relevant regulatory safety criteria can be met. Monitoring is, therefore, a means to assist in confirming that key assumptions regarding the safety-related features of the disposal system are valid.

Maintaining the confidence of future generations

The development of a repository for radioactive waste up to closure is a long-term process, possibly involving several generations. It is important to ensure that future generations will maintain confidence in the adequacy of the disposal system by confirming that the repository does not, at any time, pose a threat to the operating personal and the public, and the disposal system and the surrounding natural environment evolve as expected. Monitoring and the comparison of monitoring results with the predicted evolution of the system is a possible means of fulfilling this requirement. A related aspect is that the available information about the repository should be properly conserved and passed on from one generation to the next.

Nuclear material safeguards

If the repository contains waste with significant quantities of fissile material (spent fuel, plutonium-rich waste) non-proliferation and nuclear material safeguards are likely to be an important issue. It will be possible to declare the waste as "practically irrecoverable", only after the repository has been closed and sealed, when only safeguard operations from the surface will be required. Any safeguard-related monitoring would be aimed at assuring that no unlawful retrieval of material from the repository was taking place. In practice, this could be possible by ensuring that in the post-closure phase no drilling or mining activity (which would be a prerequisite for the retrieval of any nuclear material) was taking place at the site, e.g. by relying on periodic site observation by means of aerial photography or satellite imagery.

3.3 Key indicators to be monitored

As discussed in Section 4.1 regarding the different types of monitoring and further outlined in Section 4.5 (Broader aspects of monitoring) - and also in accordance with the definition and rational of monitoring as adopted for the present Thematic Network - monitoring needs to contribute to the decision making process by providing:

- *site-specific* information on the evolution of the surface and underground environment during all phases of repository implementation, as well as on the short- and long term evolution of the engineered barrier system (EBS);
- overall confirmation of a regular and safe operation of the disposal facility (including the requirements of nuclear material safeguards);

but also by establishing a comprehensive decision basis on technical and non-technical issues, i.e.

- *complementary* information related to science and technology in general and to radioactive waste management in particular; and on
- societal aspects regarding the long-term management of radioactive waste.

The following sections address these issues by focussing on possible requirements on in situ parameters to be monitored (including some examples) and on the monitoring of the broader aspects.

3.4 In situ monitoring

A key aspect of parameters to be monitored concerns their "representativeness" i.e. rock properties tend to vary spatially and with scale, and in some instances may change with time. Therefore, a challenging task regarding the development of a monitoring strategy will be to identify measurable quantities where "point measurements" can be used as a good representation of the status of the disposal system, even in the case of large spatial variability, and which allow for a reliable interpretation to be made, even if only a limited number of measurements (random samples) are carried out.

In general, these "indicators" (i.e. representative processes and corresponding system parameters) that may be monitored, are linked to the physical, chemical and biological conditions. An understanding of these conditions is required to support the adequate engineering of the repository, to analyse the long-term performance of the natural and engineered safety barriers and to clarify the impact of the repository on operating personnel, the general public and the environment.

A large portion of the monitoring will be performed during the early phases of repository development, i.e. during pre-construction and construction, in order to complement the site investigation programme, as well as during repository operation. These monitoring activities normally form part of the licensing procedures.

Before construction of any underground workings, the parameters to be monitored are mainly related to the (undisturbed) geological, hydrogeological and geochemical aspects of characterising the site. Investigations are performed with the aid of boreholes from the surface and later from underground using exploratory tunnels or shafts. Environmental (i.e. radiological and non-radiological) baseline conditions, including natural fluctuations of environmental parameters, will be established at the same time, in order to allow the assessment of any potential impacts of repository construction and operation, and possibly of the post-closure evolution of the waste repository.

Underground activities during repository construction will affect the hydrogeological and geomechanical, and also the geochemical conditions, of the host rock in the vicinity of the openings. Therefore, it will be of interest to monitor the changes in parameters such as the in situ stress field and the hydraulic permeability of the excavation damage zone (EDZ), as well as the extent of the EDZ and the desaturation of the rock mass.

During the operational period, the earlier monitoring programmes will be continued and complemented by new monitoring activities relevant to the emplacement of radioactive materials inside the repository. These measurements and observations, which are aimed in particular at ensuring occupational safety and radiation protection of the personnel and the population near the repository site, are expected to form an integral part of future licensing requirements, and are likely to be similar to those for any other nuclear facility. The results of such monitoring may also have some impact upon the operational procedures of the repository, if it transpires that some of the safety aspects are inadequate.

Monitoring activities performed after waste emplacement will support the societal decision making process, eventually leading to repository closure and will help in building confidence in the safety of the disposal system. The parameters that might be of interest to observe for a repository for high level waste, spent fuel and long-lived intermediate level waste could be, for example:

- the convergence of the rock around underground openings;
- the evolution of the temperature field inside the disposal tunnels and the surrounding rock mass;
- the resaturation rate and swelling pressure of the bentonite backfill material and engineered seals;
- the corrosion rate and gas production; and
- geochemical processes (pyrite oxidation, cement carbonation).

An illustration of possible monitoring activities during the various implementation phases of repository development, including the key indicators that could be monitored, is provided for the situation envisaged by Nirex for the disposal of long-lived I/LLW in the United Kingdom Country Annex (Appendix). The scheme accounts for the stepwise implementation of a repository concept for long-lived waste with an extended period of open disposal vaults to ease the reversibility of the implementation steps.

An important practical issue concerns the development and operation of measuring instruments and transmission lines that will be sufficiently reliable over the potentially long monitoring periods in a relatively hostile environment. Further enhancement to the robustness of instrumentation may be needed here, and practical implementation schemes might be adopted that allow for the maintenance, re-calibration and replacement of defective monitoring equipment.

Two options are conceivable regarding the decommissioning of monitoring equipment. Either the equipment and the transmission lines are removed and the corresponding potential release pathways plugged, or the equipment is left in place in a passive and secured state.

The technical and practical issues of monitoring are discussed in more detail in Chapters 5 and 6.

3.5 The interaction of monitoring and decision making

During the potentially long period prior to repository closure, both future operators and future generations will need to make decisions about how, when and if to implement various steps in the development of the repository system. A primary goal of monitoring is to provide complementary information to assist in making these decisions.

Decision making will be strongly influenced by the societal and political culture of the country in question and will be embedded into its legal and regulatory system. The decision making process will require an adequate organisational framework and corresponding technical and administrative measures. This will be needed, for example, to set out the rights and obligations of the stakeholders (e.g. implementers, regulators, environmental organisations, policy makers, general public), to define the information flows (i.e. who reports to whom on what subject and when), as well as to define the structure of the process within which decisions are to be made.

Some aspects of the decision making process that need particular consideration are addressed in the following sections.

Measurements and observations

The collection of information regarding the site-specific conditions above and below ground, the behaviour of the engineered and natural safety barriers, the prescribed operation of the repository, related information from science and technology at large, and on the values and views of society regarding the management of radioactive waste is intended to provide a sound basis for the decision making in relation to the development of a underground repository for radioactive waste.

Interpretation of monitoring results

A procedure has to be developed that specifies how monitoring results should be interpreted and used. In general, monitoring will be carried out to define the range and normal variability of parameters of interest, to provide data to develop and validate models of system behaviour and to assure that conditions remain within the expected and acceptable bounds. The question of how to respond to unexpected monitoring results must also be considered. Reasons that may call for corrective action could include:

- violation of regulatory requirements or safety objectives, either at present, or with reasonable likelihood in the future;
- a threat to public health (or safety of operation personnel) and/or the environment, in either radiological or non-radiological terms.

Unexpected monitoring results may also occur as a result of instrumental problems, and it is important that a check is first made as to the reason for such results before initiating any corrective action. It may, for example, be sensible to wait for further monitoring results and to investigate the possibility of instrument failure or malfunction. Corrective action of the type referred to above should only be taken in the event of a confirmed and significant deviation, i.e. one that could have an impact on safety or operability.

Corrective actions

A monitoring strategy should be supplemented by the possibility of corrective actions in the situation where unexpected and unacceptable system behaviour occurs. The requirement is not for a plan to deal with every possible eventuality - it is not possible to foresee every possible occurrence. Some provision is needed, however, for responding to unexpected events. The need for a response might be interpreted as a requirement for any anomalous result to be thoroughly investigated and for problems to be identified and dealt with.

Pre-defined "response plans" for a range of conditions and trigger levels may or may not be available at an early stage of the development of a programme for deep geological disposal. Corrective actions may therefore be developed as required and may comprise technical measures as well as administrative measures, even going as far as retrieval of the waste.

Balancing the benefits of monitoring

A common feature of many investigations related to the behaviour of the engineered barriers and the development of the natural repository environment is that these measurements can affect the disposal system in an undesirable manner. Monitoring is therefore a question of balancing the benefits of gaining information on the behaviour of certain components of the disposal system against any detriment that might result from monitoring. The possible detrimental effects of monitoring activities could include:

- the degradation of materials resulting from the delayed emplacement of engineered barriers;

- the formation of pathways through the barrier system leading to the enhanced flow of groundwater within the repository;
- changes in the geochemical conditions due to the extended opening of the underground workings;
- an increased likelihood of human intrusion - especially if the underground structure remains open and society looses interest in institutional control;
- the introduction of additional materials into the disposal areas.

During the development phases, when the waste is directly accessible, the benefits of monitoring must, in particular, be balanced against the additional radiation exposure of the operating personnel and the potential for conventional accidents.

3.6 Extent of monitoring and relation to implementation

Some classes of monitoring, such as establishing the baseline conditions and ensuring compliance with basic radiological and conventional safety requirements, will be common to all geological disposal projects. The extent of other types of monitoring, for example related to decision making and research, will depend on the implementation of the phased disposal concept as outlined in Section 2.4. In particular this will affect the amount of monitoring that is conducted close to and in the waste disposal areas. Three possibilities are described here which are related mainly to the monitoring that may take place following waste emplacement; it should be emphasised, however, that a considerable amount of monitoring will take place before this stage of a repository development programme.

Little or no monitoring may be planned close to the waste:

This may be the case if:

- sufficient work has been carried out elsewhere, for example, in a URL (where monitoring of full-scale waste emplacement mock-ups is likely to have taken place) and during any R&D programme at the repository site itself (during an earlier URL phase of investigation and research) that there is confidence in the disposal concept;
- the construction of the repository to that stage (and the monitoring that has accompanied this construction) has not indicated any problems in developing a repository at the site;
- the presence of monitoring equipment close to the waste is thought likely to reduce the efficacy of the engineered barrier system (EBS), especially in the long term, and may cause problems during emplacement of the EBS.

Any monitoring in the repository is, therefore, likely to be on a broader scale and is likely to be a continuation of the monitoring system that was set up before and during the preceding site characterisation phase. SKB and Posiva plan to follow this approach and more details of these organisations' monitoring philosophies and strategies are presented in the country annexes for Sweden and Finland (Appendix).

Monitoring will take place in a pilot facility that is developed at the repository site in parallel with the development of the repository:

In this case, the aim of the pilot facility, which contains a small but representative fraction of the waste, is to provide information on the behaviour of the barrier system and to confirm predictive models. It also serves as a demonstration facility that provides input for decisions regarding closure of the entire facility. In addition, it should allow early detection of any undesirable system evolution.

The Swiss Expert Group on Disposal Concepts for Radioactive Waste (EKRA 2000) has proposed to have such a pilot facility. In addition to such a facility, Nagra suggest to maintain galleries that allow for monitoring, so that it is possible to acquire information relatively close to the waste emplaced in the pilot facility using boreholes drilled from these galleries, but not to monitor directly in the EBS. Nagra’s approach to monitoring is discussed further in the Swiss country annex (Appendix).

Monitoring will take place in the EBS relatively close to the waste itself

In this case, it is planned to install monitoring systems within the EBS and close to the waste, so as to provide confirmatory evidence that the repository is behaving as envisaged. In advance of this monitoring, a URL-phase will have taken place in which R&D work will have been carried out (this will have also required extensive monitoring).

Andra and Nirex plan to follow this approach and more details of these organisations’ monitoring philosophies and strategies are presented in the country annexes for France and the United Kingdom (Appendix).

3.7 Information systems and archiving of monitoring results

Several European waste management organisations have already established systems for the management of monitoring data related to a site, repository or test facility, and in other organisations such systems are presently under consideration or development. Archiving of data and making data available for future generations can be considered as an important aspect of "long-term monitoring" which, from a scientific point of view, could be even more relevant than the actual measurements during the post-closure phase.

The archiving of these data serves several purposes:

(a) In the short term:

- to support the operation of the repository;
- to assist those who may wish to retrieve radioactive waste from the repository, if such a decision is taken, by providing information that may enable the waste to be retrieved more efficiently and safely.

(b) In the medium and long term:

- to ensure a level of information that is sufficient to dissuade or prevent (by administrative means) human intrusion; and
- to permit future generations to perform their safety evaluations, should they so desire.

In addition, archived information would potentially assist society to take appropriate decisions in the medium term following accidental or deliberate human intrusion.

When finally assembled, several copies of this body of data would be transmitted to one or more institutions (the country's national archives for example) for storage. The data are likely to be stored on different media simultaneously, i.e. in decreasing order of durability, on magnetic media (data disks and diskettes), on microfilms and on paper (of low acidity to maximise its durability). Ideally, the data would be copied periodically onto new media before the expiry of each of the media used. A copy of all of the data could also be deposited with the archives of a foreign institution or international organisation.

4 DISCUSSION OF MONITORING FROM DIFFERENT PERSPECTIVES

4.1 Overview

The strategic aim of monitoring, as discussed in Chapter 3, is to provide complementary information for the implementer, the regulator and the public as an input for decision making in a stepwise or phased repository development process. As part of a monitoring programme, an environmental database will be developed on the repository site and its surroundings that will be of use to current and future generations of decision-makers, and there must also be continuous assurance that the operating conditions for repository personnel and the safety of the general population are acceptable. Monitoring aims at confirming the understanding of key aspects of system behaviour that are used for engineering purposes, for confirming the safety case of the repository and for allowing further testing of assessment models. Furthermore, monitoring will provide additional information to give society at large confidence in taking decisions on the major steps of the repository development programme. It will also increase confidence that the repository has no undesirable impacts after its closure. Finally, if the repository contains fissile material monitoring must fulfil the requirements of nuclear safeguards.

The implementation of a repository programme is carried out in a stepwise manner with distinct decision points before the process continues and monitoring will, therefore, cover a broad range of issues related to the different elements of such a programme which will depend on the safety concept that is adopted. Some issues will be monitored from early on over many phases of the programme, whilst others will start later and some others may be of rather short duration.

This Thematic Network identified four cross-cutting and overlapping topics that between them are intended to provide a comprehensive exploration of the topic of monitoring. These types of monitoring and the rationale for each type are described below under these four headings:

- The establishment of baseline conditions – i.e. the conditions that exist on the site before repository and/or URL construction commences. This is important so that later monitoring results can be compared back to these boundary and initial conditions, to indicate any changes due to the repository development.
- Compliance monitoring – which may include monitoring for compliance with regulatory requirements or self-imposed criteria and also monitoring related to quality assurance requirements.
- Monitoring to support evaluations and assessments of repository performance – monitoring data are useful to support performance assessments and to support decisions as whether to move onto the next phase of a repository development programme.
- The broader aspects of monitoring – which includes a range of subjects whilst not necessarily of direct relevance to the technical development of a repository, are of value in implementing a disposal programme. This may include monitoring related to other areas of science and technical capability, legal matters and societal values.

This chapter provides a comparison of the techniques and rationales for monitoring that have been identified by the participating nations. It also analyses the information generated, with a view to establishing the most important parameters to be monitored. In addition to the subject areas listed above, consideration is also given to:

- The relationship between monitoring and safety;

- The relationship between monitoring and regulatory compliance, including non-proliferation safeguards;
- The relationship between monitoring and stakeholder confidence;
- The role of monitoring in the decision making process for a phased repository concept.

As discussed in Section 3.6, there is some variation in the approaches that are being taken to monitoring. The four sections of this chapter that discuss the different types of and reasons for monitoring have been written by representatives from the eleven waste disposal organisations who participated in this Thematic Network. They are based on the experience of these authors and their respective countries' programmes and represent the respective authors' views regarding monitoring, and are not necessarily fully applicable to all countries' disposal concepts and monitoring strategies.

4.2 Establishment of baseline conditions

4.2.1 Purpose and nature of baseline monitoring

The purpose of baseline monitoring is to determine:

- Initial conditions prior to the start of repository construction (i.e. before going underground);
- Initial conditions at the start of any new phase of repository development.

The scope of baseline monitoring includes the determination of conditions and parameters of potential interest for basic earth science, engineering and the environment and the operational and post-closure safety assessment of the repository. The scope of this monitoring should be sufficiently broad to allow issues not foreseen today to be considered in the future.

Baseline monitoring is concerned with the initial values of parameters that will continue to be monitored by either continuous or periodic observations. These may be parameters used in assessing the performance and safety of the disposal system, however several of the parameters that are likely to be monitored will have no direct relationship with such an assessment and will be related more to developing a better understanding of the site. Such assessments are largely carried out by mathematical modelling, and the parameters required for the models will have a considerable impact on what monitoring needs to be done. This monitoring is likely to continue for a long time and will start with baseline monitoring.

The site investigation programme will generate a large body of baseline data, but not all the parameters measured will require monitoring and it is important to emphasise the distinction between these two types of parameter. For example, constitutive properties of the geological materials, such as their density, porosity and permeability, will need to be established, along with their spatial variabilities. However, in many cases no changes in the values of these material properties are expected to be detectable during the timescales over which monitoring will take place, so they will not be monitored.

4.2.2 General rationale and requirements for baseline monitoring

The general ideas of monitoring and the establishment of baseline conditions are to:

- Create a set of reference data, against which the changes caused by repository development can be recognised and distinguished from natural and other man-made temporal and spatial variations in the repository environment;
- Show compliance with any existing requirements, in other words to establish the existing regulatory situation before repository development begins (or moves on to the next phase).

The monitoring of baseline conditions can be put to different uses and needs to be established within a concise monitoring framework, which should include:

- Objectives for the monitoring programme;
- Criteria for selection of parameters to be monitored;
- Identification of the properties, processes, phenomena and observable quantities to be monitored;
- Identification on what methods to be used;
- Identification of the duration and frequency of monitoring, including criteria for when monitoring may terminate;
- Specifications of quality control and reporting of results of monitoring;
- Decisions on trigger levels (if necessary) for actions;
- Decisions on what actions should be pursued in case trigger levels are exceeded.

4.2.3 Scope of baseline monitoring

The scope of baseline monitoring may be conveniently grouped into the following four categories. The purpose of baseline monitoring is, as explained above, to provide data on initial conditions, against which the future monitoring and assessment results can be compared.

On-site engineering, safety and performance

This covers the information deemed necessary to support the engineering and the safety case for the repository. Measurement of the baseline conditions and the subsequent monitoring programme will demonstrate the extent to which the construction of the repository affects the conditions in the rock mass and the associated groundwater and chemical systems. The baseline conditions established should help to confirm the understanding of the geological, physical, chemical and biological processes present on the site, to support decisions on the suitability of the engineering and show that the site is not compromised during the implementation of the repository programme.

Environmental impact

This covers those parameters that are monitored to track environmental impacts and to show compliance with stipulated environmental requirements. The impacts typically include drawdown and diversion of the groundwater table due to repository construction, airborne releases, traffic, noise, visual amenity, etc.

External, local effects on baseline conditions

This covers situations that are not direct consequences of the repository development but may affect the baseline conditions, and so might affect the interpretation of the results of future monitoring. This could include aspects such as new roads, other new construction, or new industries (e.g. quarrying) that may change the infiltration of surface water into the bedrock.

External effects on baseline conditions, in the broader sense

This relates to Section 4.4, which complements the other categories by monitoring the broader setting within which the repository development takes place. Topics for baseline monitoring in this broader sense might include:

- a baseline inventory of the current capabilities of science and engineering in the areas relevant to the repository, e.g. current capabilities for deep mining of large excavations, remote handling of heavy loads, remote sensing of physico-chemical parameters, predictive modelling, probabilistic risk assessment, etc;

- a baseline inventory of the views of stakeholders on various aspects of the project.

As with the other forms of baseline monitoring, the objective is to provide data against which the corresponding future monitoring results can be compared, and thus to identify significant trends and changes.

4.2.4 Requirements for baseline monitoring

The monitoring programme, starting with the baseline conditions, should be tied to the systematic use of the data produced, so that engineering and other activities take account of the results of the monitoring.

To ensure an appropriate quality of the data on baseline conditions, it is helpful to understand the likely changes due to repository construction, the conditions that are likely to be affected, the potential consequences of the changes and how other external changes could affect the baseline. Perturbations caused by the actual investigation activities (drilling, sampling) should also be considered.

It is important that baseline conditions are properly established and fully documented, so that the data are understandable and transparent, even several decades or centuries after their collection.

Baseline monitoring is not a ‘snapshot’ at a single instant in time. It also needs to evaluate the variability of processes and conditions over a sufficiently long period of time so that seasonal, annual and longer-term variations in baseline conditions can be evaluated. Establishing the range of variability is essential in order that it is possible to evaluate later monitoring results in a true perspective. Clearly the time interval over which the ranges of variability are monitored must relate to the period of the natural variations at the site, to ensure that likely maximum and minimum parameter values of relevance to repository behaviour are experienced and measured. Where important parameters show a cyclic, increasing, or decreasing behaviour, baseline monitoring needs to be continued until this trend is established with sufficient confidence.

The longer the time since the original baseline monitoring, the greater is the possibility of changes unrelated to the repository. These changes could be either natural or due to man, such as changes in land use. With the above considerations in mind, it is helpful to establish policies for the interpretation of changes to baseline conditions and the actions that should be taken.

4.2.5 Current example of the definition of baseline conditions

A description of the baseline conditions has been prepared for Olkiluoto, Finland in preparation for the construction of an underground rock characterisation facility at the site in 2004, known as the ONKALO, which is being constructed as a precursor to potential repository development (Posiva 2003a). The main purpose of the baseline description is to establish a reference point for the coming phases of the ONKALO and the whole spent fuel disposal programme. Together with the monitoring system, the ONKALO can also be used as a long-term experiment for which the baseline description defines the initial conditions. Thus, the focus of the Baseline Report (Posiva, 2003a) is:

- to establish the current surface and underground conditions at the site, both as regards the properties for which a change is expected and for the properties which are of particular interest for long-term safety or environmental impact;
- to establish, as far as possible, the natural fluctuations of properties that are potentially affected by the ONKALO in a way that it will later be possible to determine whether such changes are due to natural fluctuations or due to the impact of the ONKALO.

In the same context, an analysis has been carried out to explore to what extent the ONKALO may affect the baseline conditions of the repository, when it is constructed, and thus how it might affect its long-term safety. The baseline description will also form a reference for the subsequent site characterisation activities, and the observations and interpretations from the monitoring activities will largely refer to this description.

The emphasis of the baseline description is on bedrock characteristics that are relevant as regards the long-term safety of the repository, and, hence, include the hydrogeological, geochemical, rock mechanical, tectonic and seismic conditions of the site. With respect to these key areas the main focus is on:

- Hydrogeology, where the main goal is to describe the current understanding of the site-scale flow conditions and to determine the spatial and temporal variation of the groundwater table and the groundwater pressure distribution at depth in the area. The existing monitoring network, which has been in operation for several years, includes several tens of observation holes, some of them open and some completed with multi-packers. This existing network has been extended by drilling new observation holes and by equipping some deep boreholes with multi-packer systems (Posiva 2003c).
- Hydrogeochemistry, where the target is a comprehensive description and interpretation of the hydrogeochemical characteristics of Olkiluoto, giving emphasis to aspects such as the salinity distribution through the main flow paths of the shallow and deep bedrock and the contents of dissolved gases in groundwater at different depths. The characterisation, origin and state of dissolved gas is considered. Consideration will also be given to time-dependent (seasonal and long-term) hydrogeochemical parameters, and the processes determining their evolution. In addition, attention is paid to the hydrogeochemistry of the superficial deposits to improve the current knowledge of the groundwater evolution.
- Rock movements, aiming at compiling background data on the rock mass behaviour in the area, i.e. regional phenomena affecting the stability of the bedrock. Apart from the first metres of rock around the access tunnel to the ONKALO, there will be hardly any observable changes due to rock construction. The role of these observations will be primarily for the evaluation of the long-term stability of the host rock. Slow bedrock movements have already been monitored for several years by the GPS system and also the in situ state of stress of the rock mass has been measured. A seismic station network has also been established at Olkiluoto for monitoring microseismic events (Posiva 2003c).

The construction of the ONKALO and, later the repository will also affect some conditions on the surface, and, therefore, a description of the natural existing conditions in the area and the man-made constructions which are already present at Olkiluoto has also been prepared (Posiva 1999). A more detailed description of the surface environment will, however, be delayed until the existing EIA is updated before the development of the repository takes place.

4.3 Compliance monitoring

4.3.1 Overview of compliance monitoring

The reason for compliance monitoring during each of the stages of repository development is to provide proof that the implementation of the disposal concept is complying with the standards and criteria set by the applicable regulations and site licence. Compliance will in turn give assurance that these criteria for repository behaviour will continue to be met.

Most of the applicable standards will be limits derived from safety and environmental regulations for transport, storage and handling of radioactive material. There will also be limits imposed to meet repository design and operational constraints, as well as to satisfy the concerns of external stakeholders. Examples of such limits include dimensional constraints on waste containers or packages, so that they can be handled in the repository, and the controls of environmental conditions, to limit package corrosion and so maintain the ability to reverse the process.

This section summarises the more comprehensive list of potential compliance monitoring requirements given in the Appendix, under the descriptions of the various countries' programmes for disposal. It identifies the parameters to be monitored and presents the rationale for monitoring those parameters. The list is not linked to any specific regulations or technical specifications, as these will vary from country to country and could potentially change with time. Instead it is intended to form a basis for discussion in each country as to what should be monitored to show compliance with the relevant standards.

Some countries have specific compliance requirements on the host rock for a repository which need to be met as part of the regulations imposed, e.g. in Finland, see Appendix. These requirements are related mainly to the properties of the rock mass, the groundwater flow system and to the chemical environment at depth. Other counties do not have requirements in their legislation for demonstrating such a response of the rock mass and the associated groundwater system, although these may be developed as repository programmes progress.

The main reasons for compliance monitoring are identified as:

- Occupational safety;
- Protection of public and biosphere during repository operations;
- Protection during any extended open period and during closure operations;
- Issues related to liability;
- Nuclear materials safeguards;
- Assurance of continued retrievability.

The following sections examine in more detail these reasons for compliance monitoring.

4.3.2 Occupational safety

To guarantee operational safety and the protection of workers during the operational phase of a repository, it is essential to provide adequate systems for monitoring safety-related parameters in underground spaces. This includes systems for monitoring the stability of these underground spaces, gases (radon, flammable gases etc.), dust, noise, temperature and humidity.

Another important topic is radiation protection, with compliance monitoring including the radiological control of waste canisters and transport containers (dose rates and surface contamination), environmental monitoring of the facilities (dose rates, surface and air contamination) and the individual monitoring of personnel (both external and internal radiation exposure).

The atmosphere in a repository can be affected by several processes. These include the construction activities that could cause an increase in the level of harmful gases underground, especially in a repository located in rock salt, and due to the vehicles used underground. Continuous surveillance of the repository atmosphere is necessary in order to comply with the regulations and site requirements, so that proper working conditions for the repository staff are guaranteed and to prevent the accumulation of flammable gases.

It will also be necessary to make periodic or continuous checks on the performance of all the monitoring equipment.

4.3.3 Protection of the public and environment during repository operations

In a deep geological repository for some types of radioactive waste compliance monitoring of routine gaseous and liquid emissions from the repository site, and also monitoring of the repository environment, is necessary in order to:

- Demonstrate compliance with the emission and dose limits enforced by the regulatory authorities;
- Provide data for assessing the radiation exposure of members of the public resulting from the discharge of radioactive substances from the repository, and thus demonstrate compliance with the dose limits enforced by the regulatory authorities;
- Observe any possible repository-related impacts on conventional issues, such as e.g. hydraulic regime (water springs), surface deformations etc.

In order to assess the exposure of members of the public due to gaseous emissions, the relevant atmospheric dispersion factors must be known, and this requires continuous monitoring of meteorological data at the site. However, for the purposes of demonstrating compliance, the regulatory authorities may require conservative assumptions to be made regarding atmospheric dispersion and other modelling parameters; monitoring of meteorological data may therefore be relevant only to the scientific/technical investigation programme.

Potentially radioactive liquid effluents may arise from decontamination processes and laboratory operations and from wash-out of radionuclides from the surfaces of waste packages or other surfaces within the facility, by initially non-contaminated water. Depending on the levels of radioactivity, the repository environment and the regulatory regime, decontamination of liquid effluents may or may not be required. In either case, monitoring usually consists of measurements on samples from well-mixed holding tanks, the contents of which are not discharged until compliance with radionuclide concentration limits has been demonstrated.

Parallel regulatory regimes exist for non-radioactive contamination of liquid effluents, and similar monitoring facilities are usually required.

Monitoring of the repository environment complements the emission monitoring. Additional monitoring data will be necessary to assess compliance with the dose limits during specified normal operation and to estimate the radiological impact of any unplanned emission events. This compliance monitoring of the local environment of a nuclear facility is the responsibility of the site operator, although regulatory and other agencies may also make independent measurements.

An important additional requirement for environmental compliance monitoring is monitoring of the groundwater. This aspect requires a network of groundwater measurement locations, from which the absence of groundwater contamination caused by the operation of the repository can be fully recorded. The necessary spatial distribution and density of the measurement network would depend on the hydrogeological environment of the repository site. Subsidence, for example, could occur above a repository and would need to be monitored, as any movement could have implications for the transport properties of the host rock or, in extreme cases, could result in flooding of the repository itself. Such subsidence may be an issue where large underground openings are constructed for disposal purposes, as may be required for the disposal of ILW. Microseismic activity will increase due to rock movements and the extent of this activity will supply useful information regarding the stability of the rock mass.

Finally, monitoring of dust and noise nuisance has to be considered. This is of concern particularly in respect of excavated material deposited on the surface or transported off-site.

A distinction needs to be made between monitoring that takes place on the surface and that underground. The extent of underground monitoring during the operational phase depends to a great extent on the approach being taken to repository development, which affects the type and extent of monitoring, as explained in Chapter 3.

Surface monitoring during this phase is likely to be a continuation of the monitoring that would have been set up in advance of repository construction to develop baseline conditions. As soon as construction commences, monitoring of construction-related activities will start, as indicated above. The additional surface-based monitoring that will be required as soon as disposal takes place will be related only to the additional parameters necessary to monitor any radioactive releases or to monitor the processes involved in waste handling, transport and emplacement.

4.3.4 Protection during any extended observation period and during closure operations

The differences in approach to repository development outlined in Section 2.4 lead to differences in monitoring programmes, at least during the pre-closure phase of the repository. In Phased Approach A, monitoring of parts of the repository may cease as soon as each deposition tunnel is backfilled, so any monitoring system in these tunnels would be progressively removed and positioned in the new deposition tunnels as they were constructed. In Phased Approach B the repository could remain open and not backfilled for an extended period, at which stage it is all backfilled in a single operation, and much of the monitoring described above regarding the operational phase would also apply during this phase.

There is also the possibility of setting up a monitoring system to monitor only a small part of the repository in detail, with the majority of the repository having been backfilled and sealed (cf. Nagra’s proposed pilot facility, see Figure 2.2 and Appendix). Access to the repository would still be required, so that the extent of any such monitoring and the time over which it might take place would need to consider the stability of these underground openings and the effect that leaving open an access to the repository might have on its subsequent performance.

Some waste disposal organisations consider that it is necessary to monitor the repository directly during its early evolution and even after closure to test whether the predictions regarding the evolution of, for example, the thermal field, are correct. Such predictive modelling may be included within their safety case, even though the time over which such monitoring is feasible is very short in comparison with considerably longer times of interest in long-term safety. Other organisations make no such predictions as part of the development of their safety cases and, for them, the term prediction is inappropriate here.

4.3.5 Protection provided by post-closure monitoring

Post-closure monitoring may be considered necessary as long as active institutional control is demanded by societal or legal requirements. This time period, which is currently assumed to last a few tens of years to at most a few hundreds of years will, in any case, be short with respect to the timescale over which the emplaced waste represents a radiological hazard, particularly in the case of HLW and SF. Long-term measurements must be designed in such a way that they provide relevant information on the overall system behaviour. The techniques employed must be reliable and measurements should be performed without impairing the safety of the disposal system.

Radiochemical analyses of key nuclides in groundwater and surface water in potential discharge areas, in soil and vegetation samples, or in foods such as milk and meat, are not expected to detect any perturbations attributable to the repository, due to the expected isolation of the radioactive materials for long periods of time and to the small magnitude of any eventual releases of activity. For these reasons, and also because of the recognised impossibility of exact prediction (especially in relation to biosphere evolution), radiochemical analyses at the surface are unlikely to contribute to the validation of models for the prediction of radionuclide release. Such analyses may, however, be useful for public reassurance and may, indeed, be a societal requirement. Another important aspect of post-closure monitoring is to ensure the security of the emplaced waste (i.e. nuclear material safeguards) if the repository contains some fissile material (see below).

4.3.6 Nuclear material safeguards

The basis for any facility-specific safeguards concept is the design information of the facility, including its operating characteristics. In the case of a geological repository, it refers to the design of the entire repository (above ground and underground) as well as to the waste packages and their handling. An IAEA report on the safeguards implications for deep disposal is in preparation that will consider this subject in more detail.

For operational and licensing reasons, the repository operator is expected to check and record the radionuclide and materials inventory of each waste canister or package received, and to record its final location. This operational information would be made available to the national regulatory authorities, and also to the international safeguards agencies, IAEA and Euratom. In addition, the layout and operations of the repository are designed to facilitate material accounting by the inspecting agencies, and to allow simple verification of the provisions made.

In addition, the inspecting agencies have the right to carry out their own totally independent monitoring at locations both above and below ground, even though this may duplicate actions carried out by the repository operator for other purposes. This additional monitoring is expected to include sealed radioactivity detectors and video cameras to monitor package movements; and it could also include the diversion of selected waste packages from the emplacement stream for more detailed independent measurement. The requirement to provide appropriate space and facilities must be foreseen in the repository design.

The type of safeguards monitoring that is required will be determined by whether the waste emplacement areas are backfilled soon after emplacement or whether backfilling is delayed. Due to the possibility of there being a large demand for monitoring activities, it has been suggested that perhaps the safeguards inspectors and the site operator should share monitoring capabilities, such as is the proposed situation at Yucca Mountain.

Using the German and United Kingdom repository concepts as examples, both have been developed in some detail but at present are independent of any specific site. In the German concept, the repository will be divided into two material balance areas (MBAs). MBA1 will be on the surface and MBA2 underground and the waste will be verified exclusively in MBA1, during reception of waste packages. In contrast, in the underground MBA2, the inventory will be determined by accumulating the nuclear data assigned to the waste entering the shaft. Safeguards for MBA2 will consist of accounting and monitoring the shaft transport of casks, as well as periodic verification of the plant design on the basis of the map of the underground excavation. A direct physical inventory is not possible because the casks are emplaced so that they become inaccessible. It has also to be ensured, therefore, that no unaccounted-for waste is retrieved via the shaft.

As a supporting measure, in addition to verifying the underground workings, so-called environmental sampling has been recommended internationally (IAEA, 1997). In a geological repository, environmental sampling would aim at detecting any radionuclides in the underground workings and exhaust air that would indicate reprocessing activities.

The United Kingdom repository concept has similar facilities to those proposed for use in Germany to provide simple, robust materials accounting for both regulatory and safeguards purposes (IAEA 2001). Since the majority of ILW packages would be taken underground in their sealed, reusable, shielded transport containers, this simplifies safeguards accounting because no above-ground facility exists for the routine opening of the massive containers.

To verify the total numbers of packages underground, it is only necessary to count them as they are unloaded from their containers in the underground reception cell, and to verify that the reusable transport containers return to the surface empty.

Provisions for materials accounting and safeguards monitoring underground are otherwise very similar to those in the German concept. Other disposal concepts are likely to have similar materials accounting for both regulatory and safeguards purposes.

4.4 Monitoring to support evaluations and assessments of repository performance

During phased development of geological disposal, a series of progressively more detailed assessments of the long-term (post-closure) performance of the disposal system and its component subsystems will be carried out. These assessments will identify the key features and processes that determine performance and safety and, hence, will guide data collection, including guidance as to the collection of monitoring data to support future assessment phases.

The purpose of the monitoring discussed in this section is:

- To provide information in support of such assessments, in each phase of the system development;
- To support decisions on when (or how; or indeed, whether) to move on to the next phase.

4.4.1 Development of PA/model capabilities

Monitoring data will be used in scientific models of repository performance, partly to provide input data, partly to assess the performance of the models in predicting monitoring observations and partly to allow the models to be updated and refined. In this manner the scientific models of the site and of the repository can be validated, adapted and refined or rejected.

Confidence in the abilities of site-specific models to represent relevant processes is a key in deciding whether to continue the programme, or to modify it. The comparison between modelling predictions and monitoring data is, therefore, a continuous exercise.

The duration of repository phases will vary and so too will the capabilities of the site-specific models. In the majority of areas site-specific monitoring data will be required, such that the purpose of a separate URL will be to develop and test models for use at a disposal site and to demonstrate sufficient confidence in the ability to model key processes in the repository. The models will be developed during the earlier phases of the programme making use of data from URLs and site characterisation, and may continue to be developed as the repository is constructed and at least up to the point at which the waste is emplaced.

This situation will change as the programme progresses. Where Phased Approach B is being followed, some phases of a programme may last many tens of years, so greater reliance may be placed in predictions; especially when deciding whether to commit to backfilling and closure of the repository, which could take place essentially in a single, substantial operation. By the time these decisions have to be made, there will have been ample opportunity to develop and refine the site-specific models and to build confidence in their predictive abilities. This approach requires that predictions are made during the period when the repository is in a transient phase and extensive monitoring is likely to be required in order to follow any such transients.

In Phased Approach A the timescales are likely to be shorter, however, the plan is that waste should not be disposed of until there is sufficient confidence in the results of any safety assessment or evaluation (which is also the situation in Phased Approach B). Some of the modelling is likely to take place before waste emplacement, either in a separate URL and/or in the URL-phase of the characterisation and research programme at the disposal site.

4.4.2 Methodology and assumptions

Section 4.2 makes it clear that some of the initial and boundary conditions of importance in performance assessment will be determined as part of the baseline monitoring programme, and the monitoring of these will not be considered further here. Other important initial conditions of the repository system will be determined as part of the compliance monitoring programme (Section 4.3), for example the initial state of waste containers will be established to ensure compliance with the conditions in the site licence for acceptance of waste packages at the site.

In some ways, monitoring to support performance assessment can be seen as a type of compliance monitoring because, in general, performance assessment is used to show that the long-term regulatory dose or risk limits for the public will be met. However, a useful distinction can be made: compliance monitoring is to show compliance with a regulatory limit, a self-imposed criteria or quality assurance requirements at the time the monitoring is performed, whereas monitoring to support performance assessment is concerned with showing that compliance can be achieved in the future.

The following methodology can be applied to identify the objectives of monitoring in relation to performance assessment:

1. Elaboration of a comprehensive list of processes, boundary conditions, initial conditions and parameters that are of greatest importance in repository performance;
2. For each item in this list, the required monitoring is determined, i.e. which measurement or observation can be made;
3. For each monitoring item defined in the previous step, the requirements can be defined, for example: where the measurement or observation should be made; when and during which period; and the required precision, sensitivity, reliability;
4. Definition of "intervention limits" for the observed parameters.

This type of methodology is not developed further in the report.

4.4.3 Safety goals and reasons for monitoring to support PA

The safety goals for geological disposal concern the operational safety of the repository and the long-term protection of humans and the environment. This section of the report considers mainly the long-term performance of a repository. The limits and regulations that apply are those for nuclear workers and for members of the public (for the latter typically a fraction of 1 mSv/y or 10^{-5} risk per year for programmes with a risk-based approach). In some countries (e.g. the USA) a time cut-off is given over which the fulfilment of the safety goal should be demonstrated; in other countries (e.g. Belgium) no cut-off is specified in the regulations. Performance assessment is applied to give quantitative and qualitative indications on the potential effect of a waste repository on future generations, e.g. NEA, 1997.

In general the ‘multi-barrier concept’ is applied to reach this safety goal, i.e. a combination of several engineered and natural barriers. Depending on the repository design and the host rock, the ultimate safety goal can be fulfilled in different ways. The role of engineered barriers compared with the natural geological barrier, and the time period over which each is important, can be very different from one design to another. For example, in the Belgian reference concept (NIRAS/ONDRAF 2001), the overpacks are only intended to fulfil their containment function during the thermal transient period (about 500 years for vitrified HLW and 2000 years for spent fuel); whereas in the Swedish KBS-3 concept the overpacks should fulfil their containment function over more than 10^5 years.

Table 3 Typical steps in a performance assessment and the contribution that monitoring can make at each step.

Typical steps in performance assessment	Contribution of monitoring at each step
1. Definition of assessment context	
2. Scenario development (including the evaluation of features, events and processes (FEPs))	Reassessing the relevance of FEPs Checking observed FEPs against the FEP list Checking the relevance of selected scenarios.
3. Development of conceptual models for different scenarios	Checking model assumptions Checking model boundary conditions Checking included processes and physical or chemical models.
4. Development of mathematical models and selection of numerical tools; parameter selection	Determining model parameters, and/or checking that earlier selected values are valid and representative of actual conditions.
5. PA calculations, uncertainty and sensitivity analyses	Determining model parameter uncertainty, and/or checking that earlier selected uncertainty bands are valid and representative of actual conditions.
6. Evaluation of PA results.	

The relative importance of the natural geological barrier depends strongly on the disposal concept and the type of host rock. For example, disposal concepts in clay or salt tend to rely more on the geological barrier then disposal concepts in hard, crystalline rock (where uncertainties in the natural barrier are compensated by a long-term effective EBS, whose performance is considered easier to defend in a safety case).

The performance assessment process consists of a series of methodological steps on which there is wide-spread international consensus, e.g. see NEA, 1997. Monitoring can contribute at several of the steps as indicated in Table 3.

It should be borne in mind that the process is iterative, so each of the steps will be repeated in subsequent cycles.

4.4.4 Monitoring requirements to assist PA

From the contributions to this Thematic Network, it seems that in most geological disposal programmes it is not yet possible to define quantitative requirements for monitoring in support of PA, e.g. concerning accuracy, precision, sensitivity, durability or reliability of monitoring systems. Some qualitative requirements are available, however, these are in terms of where monitoring should be performed and the time period over which monitoring should take place.

The location of monitoring systems provides an indication as to the extent to which monitoring might have to be intrusive, i.e. whether monitoring would be required close to or inside the repository itself. If intrusive monitoring is considered, it must be demonstrated in advance that it will not have a deleterious effect on long-term safety, e.g. by increasing the possibility of preferential radionuclide migration pathways.

The time over which monitoring can reasonably be expected to be performed (e.g. a few to many tens of years) will severely limit the potential contribution of monitoring to PA, because:

- During the first decades or centuries, the direct monitoring of some processes that are directly linked to safety, e.g. the release of radionuclides from a HLW or spent fuel container, are not likely to be possible.
- In many long-term PA studies the physico-chemical transients occurring during the first decades or even centuries in a repository play a minor role, and may not be modelled in detail (or at all).
- Long-term PA calculations generally consider very much longer timescales, i.e. many thousands of years up to millions of years. This partly reflects the long half-lives of some of the radionuclides involved but, in addition, an important reason in selecting geological environments for disposal is that the expected rates of the geological and physico-chemical processes within these environments are very slow.

The main contribution of monitoring to PA is therefore indirect - an indication that the physico-chemical evolution of the near-field is progressing as predicted. Questions that can usefully be answered by PA, supported by monitoring, include for example: does the backfill become saturated at the expected rate and do the redox conditions evolve from oxidising to reducing at the expected rate? The long-term safety of the repository also depends on the general conditions in the bedrock, where the redox conditions may also be one of the most important factors to consider. In crystalline rock localised changes can take place in far-field chemical conditions close to the vaults and an indication that the evolution of the far-field is progressing as modelled, with regard to, for example, pH, Eh, groundwater geochemistry and groundwater pressures is, therefore, also important. In clays any changes in redox are likely to be limited to the near-field, the anticipated changes in the far-field are likely to be minimal and similar modelling is unlikely to be required.

A compilation of several disposal programmes suggests that current ideas regarding the monitoring that is required to assist PA should concentrate on:

- The physico-chemical conditions of the engineered barriers and their evolution, because those largely determine their long-term containment function;
- The hydrogeological, geochemical and geomechanical conditions in the far-field, because these contribute to the performance of that barrier.

4.5 Broader aspects of monitoring

4.5.1 Introduction

The aim of this section of the report is to consider monitoring in a broader context and to discuss the general categories of monitoring that may be used in long-term waste management and repository development.

Much progress has been made in the development of geological disposal concepts and several underground repositories for low and intermediate level waste are now in operation. No repository has yet been completely developed for high level waste or spent fuel, although from a technical point of view, the geological disposal option is sufficiently mature for implementation. A cautious approach is used, however, because of the novelty of this task. In particular, periodic re-assessment of the appropriateness of the approach chosen and experience show that for judging the adequacy of a specific system for implementation, both technological and societal criteria have to be used. The judgements may be based partially on the results of monitoring and, therefore, both technological and societal issues need to be considered when defining a monitoring programme.

In several countries society requires not only involvement in the judgement of the adequacy of the system before its actual implementation, but also wants to be involved in the decisions during the development and implementation of the repository and its eventual operation and closure. However, society may have broader views than just the repository system under consideration and may want to include other related issues in its decision making. Broad societal considerations may require the surveillance of developments in waste management in general and in other related areas. This implies the need for sufficient flexibility to make changes if these are required (in the most extreme case: retrieval of wastes). Surveillance and flexibility are also ingredients of 'decision making under conditions of uncertainty'.

Monitoring, therefore, covers more than just the measurement of parameters related to the site-specific conditions, the safe operation of the disposal facility and the evolution of the engineered and natural barrier system. It also includes a programme to observe the development of science and technology in general, and in particular in the areas relevant to the management of radioactive waste. This may also include laboratory work and in situ investigations in URLs. Experience gained in other national disposal programmes will also be taken into account for an optimised design, construction and operation of a deep geological repository.

In many countries the public has a strong desire to be involved in the major steps of repository implementation, and the broader aspects of monitoring must, therefore, also include the observation of values and views of society at large regarding the disposal of radioactive waste. Such 'soft' (non-technical) information needs to be understood as an essential input to the decision making process as regards the level of public acceptance.

It is important to recognise that the level of societal involvement and the resulting needs depend upon the specific national framework and, thus, the discussion here is rather general and may not apply to all countries and programmes.

4.5.2 Technical and scientific principles and societal needs

To discuss and define the broader monitoring requirements, it may be useful to discuss and clarify the principles adopted for planning and implementing a repository programme. The following requirements and principles are often considered to be essential (IAEA 1995):

- safety and security now and in future (Principle 1);
- the responsibility of the current generation (that benefits from the power produced) to implement the repository programme (Principle 2);
- the need to consider the rights and interests of current and future generations (Principle 3).

This means, that in addition to safety and security, both intergenerational and intra-generational equity need to be considered and also implies societal involvement in the development of the repository.

Geological disposal provides a system with passive safety (and security) and thus does not place undue burdens on future generations (Principle 1). Step-wise implementation by the current generation ensures that those that benefit take their responsibility and cover the costs (Principle 2). If an adequate approach to implementation and an appropriate design and operational scheme is adopted it also allows involvement of current (and future) generations in the implementation and it provides possibilities for change if required (Principle 3).

In order to identify the need for changes (and to implement them if required), a monitoring programme is needed with a corresponding decision making process. The spectrum of possible changes is broad and is dependent upon the stage of the project: in the phase of screening and defining the system to be implemented it can lead to changes in waste management strategy, changes in siting and changes in design. After a decision has been taken on the system to be developed, the spectrum is still broad: it ranges from changes in the monitoring programme to retrieval of the waste (and choosing an alternative path) and may also result in optimisation of the facility and its operation.

If a monitoring programme has to assist in this process, it needs to be sufficiently broad and may require that monitoring includes not just the repository itself but also other issues.

4.5.3 Monitoring as part of a properly structured programme

The successful stepwise implementation of a repository and the corresponding monitoring programme requires an adequate framework. A programme needs to be designed that, on the one hand ensures proper technical work in all phases (including considerations as to potential improvements of the facility and its operation) and, on the other hand, allows for societal involvement and considers the principle of 'decision making under conditions of uncertainty'. In such a stepwise approach the different phases have very specific goals and in each of the phases explicit surveillance of specific issues is needed.

For each of the issues, potential alternative options must be identified, activities to support decision making must be defined and criteria for decision making must be developed. Furthermore, the decision making process must be clearly defined ("what is decided by whom at what time and on what basis?").

A programme requires a suitable framework which should be embedded within the relevant legal system and may, however, also leave space for ad hoc activities and voluntary actions by the implementer (or others, e.g. the regulator, policy makers, etc.).

The operational components of a structured programme for developing a repository can be divided into 3 broad categories: (1) activities (including monitoring) providing the basis for decision making, (2) decision making itself and (3) provision and maintenance of alternative options for each decision-point.

The broader monitoring aspects included in such a programme are, for example:

- monitoring of the experience with similar facilities or systems in other countries or in other locations;
- monitoring of progress in science in areas relevant to the performance of the repository (e.g. geochemical immobilisation, corrosion of waste package or waste form, longevity of materials for the EBS, etc.);
- monitoring of the context and requirements on the overall waste management concept of a specific country, such as: national energy policy & future of nuclear programme (including fuel cycle strategies & technologies), expected waste arisings (volumes, properties, existing wastes awaiting disposal and their integrity and suitability for disposal, etc.), adequacy of other elements of the waste management concept (e.g. availability of interim storage);
- monitoring of the legal framework and institutional arrangements both national and international;
- monitoring of the adequacy of the institutional programme (participants and their role, monitoring activities performed and analysis tools used to help decision making, etc.);
- monitoring the criteria and their (scientific) bases that are used to judge the acceptability of the performance of the system under consideration (e.g. level of acceptable doses);
- monitoring the status of alternative options (e.g. progress in partitioning and transmutation) and progress in the corresponding technology;

- monitoring of changes in (local, national, international) societal views (e.g. what is considered to be good for society);
- monitoring the adequacy of the framework for developing the repository (e.g. the scientific-technical abilities of the implementer and regulator, financial status, etc.) and actual progress with implementation (is the timetable being kept? changes in the key assumptions and boundary conditions underlying the overall timetable? Any need to revise the original planning?).

This broad spectrum of monitoring issues has to be seen as an example and the specific needs within each country or programme can differ significantly from this list. Furthermore, in several countries analyses of some of the issues mentioned are performed but are not included under the title of monitoring.

The other two items of the programme: decision making and provision of alternative options, are important but outside the scope of this project and are not discussed here.

4.5.4 Current status of the different monitoring activities

In most countries at least some of the different activities mentioned above are already being pursued today. These activities provide information for decision making either in the concept development an /or siting phase, and in the site development and implementation phases

Activities which have been performed include:

- Progress in the area of waste management is monitored in the framework of reporting required as part of the 'Joint Convention' (IAEA, 1997b) to which many countries with a nuclear programme are signatory;
- In several countries there is a need to periodically re-assess the waste management long-term plans. This also includes an assessment of the expected waste arisings;
- Most programmes maintain an active view on the development of science & technology related to waste management, through active Research, Development and Demonstration programmes, through participation in conferences and meetings and through review of the literature. In several countries research institutes exist with the remit to observe developments in science;
- Most programmes observe the attitude of the public (both locally and nationwide) towards their activities, stay actively in touch with developments of the legal framework (including regulatory aspects and the ability of the regulator) and the development of institutional arrangements relevant to their programme. This may also include societal, economical and political stability;
- In some countries alternative waste management technologies are actively investigated while others maintain a watching brief on the developments.

In each country considering the disposal of radioactive waste these activities are embedded in an appropriate framework:

- In most countries some of these activities are required by the national law or the corresponding regulations;
- Some of the activities are part of the reporting for the 'Joint Convention' or for the revision of the national waste management plan;
- Other activities are part of a developing SEA (Strategic Environmental Assessment) or EIA (Environmental Impact Assessment). In other cases these activities are part of the (implicit or explicit) requirements formulated in a licence;
- Some activities may just be an integral part of the company policy and thus be part of the company's work plan.

The evaluation of the results from these activities and the corresponding decisions are often performed within a clearly defined framework which is often defined by national law or regulations, and may also be part of an SEA/EIA. In some countries special commissions have been created for some of these tasks (e.g. CNE in France) and any evaluation may also be part of future licensing steps.

5 MONITORING REQUIREMENTS AND CONSTRAINTS

5.1 Framework

The selection of monitoring techniques and the design of a monitoring system are preceded by the establishment of a list of technical and functional needs, derived from the specified monitoring objectives and strategies, which evolve into a list of requirements and constraints. This list of requirements and constraints will evolve over the various phases of a repository programme, and vary as a function of host rock, design of EBS and waste inventory. In addition, monitoring objectives and strategies are programme-specific, and are in part directed by national rules and regulations. It is, therefore, not possible to provide a universally valid specification of what should be considered when designing a monitoring programme.

To highlight some important considerations when establishing specifications for monitoring, the functional and technical requirements and constraints imposed on a monitoring system are grouped into five broad categories:

1. Ability to monitor as specified;
2. Ability to interpret data;
3. Ability to monitor without compromising operational safety, barrier performance and the post closure safety;
4. Ability to monitor under repository environmental conditions;
5. Ability to monitor over long periods of time in areas which may be remote and where access is difficult.

The requirements and constraints in categories 1 and 2 are common to any monitoring programme. The requirements and constraints in category 3 reflect broad agreement between participating organisations and are fundamental to designing an acceptable monitoring programme, i.e. a guiding principle is that the monitoring system should have only a negligible interaction with the repository components and that it should not jeopardise operational safety, barrier performance or the ability to demonstrate the safety case. Category 4 is more relevant to the situation where monitoring takes place in a URL, or in a repository where it is decided to monitor repository conditions in detail (i.e. perhaps what is proposed in an ANDRA or NIREX repository, see Appendix). Category 5 is also more likely to be associated with Phased Approach B.

Monitoring can also be discussed in terms of the phase of programme and location in which monitoring occurs. Table 4 indicates which requirements and constraints need to be considered when monitoring in different situations or in different phases of the repository development programme, in relation to the five broad categories listed above.

Table 4 Requirements and constraints to be considered for monitoring in different situations or in different phases of the repository development programme, in relation to the five broad categories.

Category	Site characterisation prior to construction	Monitoring from surface (of surface environmental parameters and in boreholes) in pre - and post closure	Monitoring in URL (EBS and near -field, accessible or sealed)	Monitoring pilot facility within repository (EBS and near-field), destined for decommissioning	Monitoring repository, open and accessible EBS and near field	Monitoring repository, sealed EBSs and near - field
Ability to monitor as specified.	X	X	X	X	X	X
Ability to interpret data	X	X	X	X	X	X
Ability to monitor without compromising operational safety, barrier performance and the post closure safety	X	X	X	X	X	X
Ability to monitor under repository environmental conditions			X	X	X	X
Ability to monitor over long periods of time in areas which may be remote and where access is difficult		X	X	X	X	X

Monitoring in the situations listed in Table 4 is likely to be restricted by the requirements and constraints related to compromising, for example, operational safety, barrier performance and long-term safety.

In the remainder of this chapter, each of the five categories is further discussed. In addition, a summary of considerations, describing the characteristics and limits of validity of any component or technique, is provided in Section 5.7. Considering the use of monitoring equipment in such a manner might help to identify which techniques could be adapted to given requirements and constraints, and could be useful if, say, environmental conditions are expected to evolve during the time considered for monitoring, and if monitoring is to be conducted over several phases of a repository programme.

5.2 Ability to monitor as specified

The ability to monitor as specified is limited by the available methods and techniques and by the constraints imposed on these methods and techniques (e.g. the environmental conditions underground, etc.). An inventory of the state of the art of existing sensors and measurement techniques can be used to determine if monitoring requirements can be fulfilled and if the chosen strategy for monitoring can be carried out. Where possible, a sensor or adequate technique to measure the designated parameter needs to be identified. The precision and range of data delivered by the sensor must be compatible with the monitoring needs, for example, to allow for a comparison with model predictions.

Certain types of measurements are easily obtained and an extensive choice of techniques allows monitoring to take place as specified, for example, temperature or strain measurements using vibrating wire or fibre optical techniques are well established. This is not necessarily true for all parameters and measurement conditions. For example, available technology does not allow for the in situ measurements of a number of chemical and radiological parameters.

The ability to monitor as specified implies that the generated data signal can be reliably interpreted. This requires the ability to differentiate between a good signal (related to parameter evolution), a bad signal (related to sensor drift or failure) and a signal that can or cannot be related to a specific parameter and location. It also requires that the influence of monitoring on the component being monitored must be sufficiently small that the observation of the component is comparable to the natural evolution of the component if it were not being monitored (the classical problem of measuring an almost, but not quite undisturbed system).

It is necessary for the correct interpretation of the data signals that all the processes that might affect the signal from the component being monitored are understood. This is of particular concern, because most sensors respond to variations in several parameters. In an environment in which several parameters, for example temperature, pressure and deformation evolve simultaneously, the monitoring system must provide for a method to de-correlate the influence of each, and to trace the signal back to its various sources.

Finally, it is necessary to have set up an appropriate QA system to ensure that the monitoring data are of sufficient reliability and quality.

5.3 Ability to interpret data

To respond to the monitoring objectives, it is necessary to interpret the available data within the context of the sensor environment and applicable process models. The requirements of and constraints on the monitoring system in this category include, for example, the robustness of the monitoring system.

Commonly a comparison will be made between the evolution of parameters inferred from data and those from prior understanding and/or model predictions. Agreement between these two data sets, whilst it could be fortuitous and require further verification as to the accuracy of the monitoring, would tend to confirm prior analysis and model development and is likely to increase confidence in the understanding of repository evolution (at least over the early, transient period). Disagreement will require an analysis of both the quality of the monitoring system and of the models, to understand the reason for the discrepancy.

In a robust monitoring system it should be possible to verify that the received data signals correspond to the evolution of the measured parameter. Sensors may fail or their signals drift over time, and adequate redundancy as well as an understanding of the evolution of sensor behaviour should be used, either to confirm their proper operation to correct for potential drift or to discard data as unusable.

Measurements can be corroborated through the use of several techniques. The use of redundant measurements, either through multiple measurements of the same parameter, or through measurements of several, correlated parameters, is one option. Alternatively, the parallel use of a comparable and controlled installation, dedicated to observe the evolution of sensor behaviour under similar conditions, should allow a distinction to be made between the evolution of the monitoring system properties and the parameter to be observed.

If a measurement cannot be corroborated and, therefore, if a sensor or part of the monitoring system is found to be in error, the options are to replace or recalibrate the sensor (if it is accessible) or to decommission the sensor (if the data are no longer needed or if the sensor is inaccessible).

Where the measured data can be corroborated, then the observed difference with the prior model predictions suggests that the latter should be revised. It is hoped that data will be sufficient to allow re-examination of initial assumptions and update corresponding models to match the observed evolution of the component and/or parameter. The potential implications of such revised model predictions on the performance of engineered or natural barriers and on the evaluation of long-term safety need also to be considered.

Such updating of the understanding of repository evolution and in the corresponding models can be of two types: the *anticipated type*, which can be easily justified by prior uncertainties, and the *unexpected type*, following which the understanding of the system and perhaps the way in which it is represented in models would need to be updated. It is common practice to place assumptions made whilst developing a process model within the context of limited knowledge and parameter, as well as model uncertainty. The required evolution of models is in fact a good test of how prior uncertainties were taken into account, were documented and then accommodated as part of the development of a model. Ideally, only the anticipated type of evolution of both the repository and the models will be required within this framework, whereas the unexpected type would inevitably raise questions about the level of prior understanding of the repository system. This may be a concern, if the updated model has implications for updating a safety case and if it lowers the estimated overall performance of the repository. In the context of a phased approach to repository development it may damage stakeholder confidence and suggest longer observation periods before decisions to move to the next phase are made.

5.4 Ability to monitor without compromising operational or post-closure safety

A guiding principle is that the monitoring system should have only a negligible interaction with the repository components and that it should not jeopardise operational safety, barrier performance or the ability to demonstrate the safety case. Site monitoring in boreholes may have an impact on flow and transport, and a demonstration of adequate borehole sealing will be required in this case. Where the monitoring of engineered components is part of the objectives of the monitoring programme, then several strategies are available to avoid compromising performance and safety, as discussed in the section on compliance monitoring (Section 4.3).

There are no such concerns if monitoring is to be carried out on a distinct, but comparable facility (for example, in a URL emulating the evolution of the operating repository), unless the URL itself is at or sufficiently close to the repository site. If it is to be carried out in a component of the repository dedicated to this purpose and scheduled for decommissioning (i.e. perhaps a pilot facility), care should be taken that such monitoring has no negative impact on other nearby components. The question needs to be thoroughly addressed in the context of monitoring a repository component that is intended to assume its normal function and performance over the long term. Monitoring should, in itself, neither constitute an operational danger nor a threat to long-term safety.

These types of requirements and constraints apply to sensors and signal transmission, as well as to potential power sources and other monitoring system components. The presence and operation of these components could be of concern for operational safety; for example by accidentally igniting flammable gases, or causing an explosion. Their hydrogeological, mechanical or chemical footprint could have implications for barrier performance and long-term safety. Void spaces left by degrading sensors and transmission cables could create preferential flow paths, and chemical pollution resulting from the degradation, say, of a power source could alter groundwater geochemistry.

It is also necessary to ensure that the ability to demonstrate barrier performance and long-term safety is not lost by the presence of a monitoring system. The influence of such a system on process models should therefore be negligible, or comparable to what had already been taken into account during the development of those models. The incorporation of sensors into engineered components that are themselves expected to degrade, resulting in comparable long-term effects, may be an option in addressing this concern. For example, the degradation of the hydrogeological properties of a concrete lining to a tunnel may mask the additional degradation due to the presence of an optical fibre that had been installed to monitor some aspect of the performance of this liner.

The monitoring of the interior of sealed repository components may present a particular threat to performance and safety. The choice as to whether this type of monitoring is necessary or even desirable is programme-specific, and the advantages and disadvantages of leaving monitoring equipment inside inaccessible components need to be weighed against each other. Depending on the choice, the potential impact of such a monitoring objective would either be avoided altogether, or would need to be considered in detail.

To estimate the potential impact of monitoring the interior of sealed components, the available monitoring techniques and signal transmission requirements should be compared with the repository design and the potential implications of such monitoring on performance and safety need to be assessed. In practical terms, this requires a comparison to be made between two applied design issues: the design (and realistic construction) of the engineered barrier or component that is being monitored and the design and implementation of the monitoring sensors and transmission system (cables or wireless). Whether the monitoring of a sealed and remote repository component is or is not acceptable depends not only on the available monitoring techniques, but also on a direct comparison with the design elements of that component. The potential impact of such a monitoring system can be estimated by comparing, for example, the practical short- and long-term considerations of its evolution (i.e. the footprints of the retrieved equipment, equipment degradation products…) with an idealised view of an engineered repository component (perfect geometrical shapes, no degradation products…).

This category of requirements and constraints can thus be addressed by a judicious choice of detailed monitoring objectives and monitoring techniques to be used. In addition, it is possible that certain impacts of a monitoring system on performance could be alleviated once the monitoring objectives have been reached. For example, it has been suggested that certain wires or optical fibres could be retrieved and the remaining void space filled and sealed.

5.5 Ability to monitor under repository environmental conditions

The monitoring system, the sensors and the data transmission technology, must operate under specific, at times potentially extreme repository environments. Their ability to fulfil all requirements should not be affected by exposure to:

- temperature;
- groundwater pressure;
- mechanical constraints (pressure and shear);
- chemical environment; or
- radiation.

These requirements may restrict the ability to monitor certain parameters. For example, most sensors do not operate at high temperatures, which may conflict with the need to measure a parameter at temperatures nearing 100°C. Cables are known to conduct water over long distances, with the potential to destroy connected sensors; ensuring that connectors and cables are water tight is, therefore, essential to prevent destruction of monitoring devices. Converging or swelling deformations could shear transmission cables and a converging host rock raises the pressure to lithostatic, possibly resulting in damage to sensors.

An aggressive chemical environment may cause the early corrosion of sensors, as a repository presents an active environment in which materials that are bought into contact are prone to interact. A significant cause of the deterioration of sensors is corrosion, prompting a special interest in any long-term experience as to the resistance to corrosion under comparable conditions. To reduce such deterioration through corrosion, replacing metal parts of a sensor by ceramic or glass-based materials would present an advantage to ensure their long-term operation.

Polymers are susceptible to deterioration caused by radiation, and cable insulation should be mineral based (e.g. using aluminium or magnesium powder). Any residual gas within sensors or transmission systems which is susceptible to ionisation under radiation will result in a false signal.

5.6 Ability to monitor over long time periods and/or in remote locations

This category is included to emphasise that monitoring of repository construction, operation and closure may call for monitoring over very long time frames, as well as monitoring of remote, inaccessible areas, and under changing environmental conditions. The requirements and constraints imposed on suitable techniques are thus related to their lifetime, reliability, resistance to a range of environmental conditions and absence of maintenance needs. At the same time, these requirements may evolve during repository development, for example, monitored areas that are originally close to a data acquisition station may become increasingly remote and inaccessible and local environmental conditions may change.

This category of requirements and constraints is mainly concerned with the longevity and robustness of monitoring techniques. In some circumstances it may be possible to design a system where corrective maintenance is allowed for the installation of sensors without losing excessive data or disturbing the conditions. For example, sensors may drift and their re-calibration during operation must be planned for. In general, however, it is preferable if sensors do not have to be maintained.

The longevity of data acquisition (several programmes may monitor over a period up to one or more centuries) invariably leads to a deterioration of sensor and transmission reliability. The ability to predict the lifetime of monitoring systems is an important asset in their design, and existing experience is invaluable. Techniques with adequate, long-term field experience and demonstrated reliability are, therefore, likely to be given preference over new techniques. If the monitoring system cannot be accessed and maintained, or sensors and cables be replaced at the end of their lifetime, the duration of monitoring will be limited by the reliability of the initial installation.

Sensors will become increasingly remote from data acquisition stations, especially in situations where monitoring of closed or sealed components is planned. The lack of direct access may be due to operational safety requirements, irradiated repository components, evolution and closure of components or a preference for sampling data at the surface. The distance between a sensor and a directly accessible part of a repository could increase from tens of metres to several kilometres in a typical repository setting, and signal attenuation and possible interference with signal transmission must be taken into account.

The installation of required sensors and transmission systems during all phases of the repository operation must be planned when designing a monitoring system. For example, if monitoring is to be performed in areas that will become inaccessible during the operation of the repository, the monitoring equipment must be installed before closure of the areas to be monitored.

A lack of access requires a choice of robust sensor technology, with known and predictable evolution over time and without the need for maintenance or re-calibration. Available field experience suggests that such a technology (vibrating wire, certain types of fibre optical techniques) is available to provide for the reliable measurement of certain parameters over several decades. If the monitoring objectives require such a maintenance-free operation over a longer time, in the order of centuries, then R&D leading to robust techniques which are reliable over that time frame may become a priority to support the monitoring programme.

5.7 Choice of instrumentation

Meeting specific monitoring objectives may result in variations in the densities of monitoring equipment, depending on the repository component that is to be monitored. Such variations can be due to the potential needs of performing redundant measurements, of measuring spatial distributions of a parameter, and/or of measuring a more or less extensive list of parameters. Three categories of such measurements can be identified, related either to the density and frequency of sensors used to monitor a given component or to the requirement to investigate the behaviour of the sensors themselves and the way they respond to an evolving repository environment.

Lightly-instrumented repository component

The choice of instrumenting a component with a few sensors could be motivated by a desire to:

- Limit the overall effect of monitoring;
- Measure the evolution of only the most significant, or representative model parameters, which could be correlated to more thorough monitoring in comparable, heavily-instrumented components. A single sensor, for example a temperature gauge, could be sufficient to check that the overall evolution in an emplacement tunnel is consistent with other locations, including more heavily-instrumented tunnels;
- Enhance knowledge of a very specific aspect of component evolution. For example, to verify the hypothesis of initial waste canister defects, or to check convergence rates to predict tunnel stability.

An advantage of such an approach is the limited perturbation imposed on the system, compared with any more heavily-instrumented components. The main obstacle to instrumenting a large number of such locations in a repository would be the requirement for long distance data transmission systems. In any event, monitoring for operational safety throughout the repository would require the comparatively light instrumentation of components to ensure safety in disposal tunnels, access tunnels, etc.

Heavily-instrumented repository component

The decision to instrument a component with a large number of sensors could be motivated by a desire to gain detailed information on some or all of the main model parameters and their evolution. Typically, parts of URLs are heavily instrumented to gain comparable knowledge of the evolution of a repository prior to its actual construction. This type of component instrumentation has the potential to offer:

- A detailed comparison with model predictions;
- Information on the spatial variability of a parameter within a component;
- A benchmark for the observed phenomenological evolution to which the results of sparsely-instrumented, but otherwise similar components can be compared.

The requirement for instrumentation in this case might range from a moderately to a very high density of sensors, depending on the number of chosen parameters and on decisions regarding the level of redundancy and the spatial distribution of monitoring equipment. The need to monitor coupled processes would typically require a higher sensor density.

Care must be taken that such a heavily-instrumented component meets the important requirements of not having any significant impact on barrier performance or on the safety case. It may otherwise be necessary to decommission it.

Analysis of sensor behaviour and its evolution

Sensor and transmission techniques used for monitoring could be embedded in reference components, either under controlled environmental conditions or under conditions that were as close as possible to those expected in the repository. In the former case, any deviations of sensor measurements from controlled conditions could be analysed and, if possible, any drift inferred. If found to be predictable, this drift could then be used to correct for a similar drift in any real data. In the latter case, a choice might be made to retrieve the sensor and to examine its characteristics and evolution after being subjected to repository conditions.

Inventory of sensor/transmission properties

To assist in the design of a monitoring programme, it may be useful to establish an inventory of existing, proven or promising techniques. Because adequate techniques must meet with all requirements and constraints, especially those related to repository operational and long-term safety, repository environmental conditions, operational lifetime and reliability, it may also be useful to include relevant information with such an inventory. Information summarised on such an inventory sheet might include:

Overall characteristics: measured parameter; measuring principle; device description; external dimensions; weight…
Measurement characteristics: measuring range; measuring error; full range accuracy and precision?…
Operating characteristics: installation needs; calibration needs; maintenance needs; expected lifetime; access needs; power supply needs; additional needs (parts, connectors…); tolerated temperature range; tolerated pressure range; tolerated mechanical constraints; tolerated chemical environment; tolerated radiological environment…
Signal characteristics: signal output; signal range…
Signal transmission: transmission type; transmission range; transmission precision; transmission distance; cable description…
Tolerance to interference
Relevant prior experience: field experience; working reference; manufacture; applicable norm…
Interaction with the safety case: potential hydrological footprint; potential mechanical footprint; potential chemical footprint…
Costs: Purchase of equipment, installation, operational and maintenance cost.

6 MONITORING METHODS AND TECHNIQUES

6.1 Introduction

The emphasis of this chapter is on methods and techniques related to monitoring in the context of a phased approach to disposal. The choice of adequate methods and techniques will need to be adapted to the choice of specific objectives and strategies and these may evolve during the different phases of a repository programme. They may also vary as a function of programme-specific choices and preferences, as well as in response to national standards and regulations.

Monitoring is an integral part of all phases of repository development, and specific objectives include site investigations, monitoring environmental conditions, testing design and host rock properties in URLs, operational safety and post-closure monitoring. In addition, some programmes (for example that envisaged by Nagra) plan pre-closure monitoring in a pilot disposal area (i.e. instrumented disposal cells receiving waste to enhance prior knowledge on the evolution of the engineered barriers and the near-field). Other programmes (for example as envisaged by Nirex or Andra) plan to include such a monitoring objective in parts or all of the progressively built repository, and to use the information to assist the decision making process as part of the stepwise repository development programme.

Developing a monitoring programme in response to any of these objectives could benefit from extensive prior monitoring experience, as outlined in Section 6.2. For example, monitoring techniques related to operational safety have been widely used in nuclear facilities and mining operations, as well as in operating URLs and underground ILW or LLW disposal facilities.

An important first step is identifying all requirements and constraints imposed on the monitoring system. These vary in response to the specific objectives and monitoring environment, and may evolve with the phases of the programme and steps of repository operation and closure. An overview of requirements and constraints to be considered is given in Sections 5.3 –5.6. It is important to remember that many of the techniques required for monitoring are well established and are, in many cases, those that have been employed in site characterisation programmes. The majority of these techniques are not covered here, as they are described and documented in great detail elsewhere; the techniques that are covered in this chapter are those that are directly related to monitoring the in situ properties of the repository environment.

For convenience, parameters considered for monitoring have been grouped into five broad categories: thermal, hydrogeological, mechanical, chemical, and radiological (THMCR). The ability of monitoring techniques to fulfil the requirements of repository monitoring and to respect the constraints that may exist underground is determined by the generated signal and related transmission techniques employed (see Sections 5.4-5.6 and 6.4), as well as by the sensor properties (see Section 6.4 for a limited overview of possible techniques).

The possible implications for monitoring in the context of following either Phased Approach A or B to repository development are discussed in Section 4.3.4. It is emphasised that neither approach relies on monitoring to ensure long-term safety (whilst both approaches rely on monitoring to ensure operational safety).

6.2 Experience of underground and related monitoring

There is extensive experience from decades of monitoring related to nuclear waste repository research, development and operation, as well as from engineering projects with shared monitoring interests and techniques. Examples of the use of monitoring techniques, that can be applied during one or several phases of a repository programme, are provided by site investigations, experiments in URLs, hydroelectric dams, bridges, roads and railways, tunnels, existing nuclear disposal facilities, nuclear power plants and mining operations. It needs to be remembered, however, that some of the requirements that may exist for monitoring within the repository and for long-term monitoring in the post-closure phase could impose considerable requirements on monitoring equipment, particularly with regard to their longevity. This implies that, although many of the required monitoring techniques may already be available, there is still a need for further development in other areas.

Many national programmes have either conducted site investigation studies to identify suitable sites and/or to obtain more detailed site characteristics of candidate sites. The objectives are to obtain site specific information on regional and local flow and transport properties, as well as thermal and rock mechanical properties. Such investigations are tied to drilling programmes and monitoring is performed either in situ (i.e. in boreholes) or relevant parameters are determined on extracted fluid and rock samples. Monitoring methods and techniques that are used for site investigations from the surface tend to be well established. A thorough description of site investigation methods and techniques is presented for example in a report issued in the context of the Swedish site investigations (SKB, 2001b). It should be noted that some of the monitoring performed during site investigation can be continued during future repository construction and operation phases (as planned, for example, by Posiva at Olkiluoto, where it is proposed to develop a repository for spent fuel disposal, and where construction of the first underground access to the ONKALO is scheduled to begin in 2004) (Posiva, 2003c). The development of the ONKALO will allow Posiva to monitor the evolution of some of the site characteristics due to the presence of what is intended to be effectively the first phase of repository construction.

Extensive monitoring experience has also been gained in the large number of operating URLs. The Radioactive Waste Management Committee (RWMC) of the NEA, in an overview of the use and purpose of URLs within repository development programmes, highlighted that the "accumulated experience of all existing URLs exceeds 250 years of operation" (NEA 2001b). The Asse mine in Germany was converted into a generic (i.e. not site specific) URL, and operation began as early as 1965. Site-specific URLs allow underground investigations to be performed in the host rock considered for a potential repository. The first site-specific URL was created in 1980 in the Konrad mine in Germany (NEA 2001b). A significant number of additional URLs have since allowed national and international experiments and related monitoring to be conducted related to, for example, underground site characterisation, geotechnical measurements, thermal experiments, transport experiments, sealing experiments, etc. Examples of such URLs are the Tono mine (Japan), Stripa mine (Sweden), Grimsel Test Site and Mt. Terri (Switzerland), Olkiluoto (Finland), Hades (Belgium), Whiteshell (Canada), Äspö (Sweden) and Busted Butte and the Exploratory Studies Facility (USA). The experience of monitoring in environmental conditions similar to those of a repository is gained from the use of instrumentation in underground conditions and from the evaluation of experiments. In addition, some of the URL experiments are specifically dedicated to the research and development of reliable monitoring methods and techniques, and take into account the needs of a repository programme and the constraints of its environment through all its phases. New URLs are also under construction, e.g. in France (Meuse/Haute Marne) and in Japan (Mizunami).

Monitoring experience can also be gathered from existing and operating underground repositories. For example, a variety of waste has been either disposed of, or emplaced for research purposes, at Morsleben (Germany) since 1971. In particular, the heat generating HLW that was emplaced into boreholes under a R&D licence is being closely monitored. Commensurate with the licence requirements, one of the monitoring objectives is related to the evolution of the EBS, to ensure waste retrievability. LLW disposal sites (for example the experimental tunnel adjacent to the VLJ repository at Olkiluoto, Finland) are being monitored for operational safety. Such operational safety monitoring may overlap with the monitoring objective of observing site response and evolution in the presence of a repository, for example as related to geotechnical safety (convergence of host rock, stability of tunnel liner, resaturation…). The I/LLW repository in Sweden (the SFR) has been in operation since 1988 with a comprehensive monitoring programme in force since the start of operation, with the objective of collecting information so that operational and long-term safety analyses can be updated as required and so that the repository can be operated and closed successfully. Continued confidence building through monitoring may also be required by the original licence for construction and operation. For example, monitoring over a specified period is a licence requirement for the operation of the Waste Isolation Pilot Plant (WIPP) in the USA.

Finally, relevant monitoring experience has also been obtained in non-repository related projects, such as the monitoring of road and railway tunnels (geotechnical stability, stress/strain conditions of tunnel liners …), dams (permeability, pressure…), nuclear power plants (structural and radiological considerations), or mining operations (operational safety of underground activities, geotechnical measurements…). Some of this experience is directly transferable to monitoring in a repository environment. Depending on national rules and regulations and the waste inventory to be considered, monitoring related to repository construction and operation may be required over time frames on the order of decades to centuries. Techniques that have been in use and proven over such long time frames are, therefore, of particular interest.

6.3 Examples of sensors for repository monitoring

Extensive prior experience is available with monitoring methods and techniques in the context of monitoring engineered components, which may be directly relevant to repository programmes. All such monitoring is tied to the availability of adequate sensors and (unpublished) reviews have been carried out by several waste disposal organisations of such sensors, as well as the technical factors that need to be taken into account when choosing and developing adequate monitoring techniques for use in a URL, a pilot facility or an actual repository.

6.4 Categories of sensors and transmission properties

To allow in situ measurements, sensors transform the parameter to be measured into a usable and transmittable electrical, optical, or electromagnetic signal. The nature of the generated signal can be of significant importance for implementation in a repository environment and signal attenuation and possible transmission distances are important factors in the design of a monitoring system.

Sensors can be used to monitor any or all of the THMCR (Thermo, Hydraulic, Mechanical, Chemical (including biological) and Radiation) type parameters (for example, to measure pressure in a multi-packered borehole test to support hydrogeological site investigation, or hydrogen concentration to support operational safety). In contrast, what are referred as deported measurements (i.e. sampling and transfer of the sample for remote analysis) require the transmission of the physical/chemical parameter to be measured to a remote sensor location. Deported measurements are commonly used in the context of site investigations (e.g. sampling in boreholes) and may also be useful where in situ measurement techniques in engineered components or in the near-field are not sufficiently developed (for example, for chemical or radiological measurements).

Electrical signal and transmission properties

A distinction can be made between active and passive sensors. Active sensors transform the measured signal and generate an electrical signal (charge, potential or current); the most common variety being thermocouples. The typically weak signal needs to be amplified within 1 to 10 m of the sensor, which presents an added difficulty if the sensor needs to be installed in a remote location. These types of sensors are also sensitive to temperatures above 50°C.

Passive sensors come in several categories; one type modifies an impedance (resistance, conductance, capacitance), commonly within a Wheatstone bridge. Distances from the sensor to signal conditioning systems range from 1 to 10 m, which limits their usefulness in the context of remote monitoring.

Sensors that are better adapted to the requirements of repository monitoring include (passive) vibrating wire sensors and inductive sensors. Both generate signals that can be interpreted even after substantial attenuation, allowing for transmission distances of 2 km and several hundred metres, respectively. Vibrating wire sensors have been in continuous, maintenance-free operation for several decades, up to approximately 70 years (for example in the monitoring of dams).

Electrical signals are transmitted via electrical cable (copper core…), with transmission being better at higher current or voltage levels. The common failure mode over the long term is related to the water tightness, corrosion, and mechanical resistance of the cable (for example to pressure and shear exerted by the engineered barrier or the host rock).

Optical signal and transmission properties

Fibre optical sensors generate a signal related to light intensity, spectral information or fringe interference, which is barely attenuated over great transmission distances. A distinction is made between intrinsic and extrinsic optical sensors - the extrinsic variety includes one or several sensors added to the fibre, typically through some local modification of the fibre properties. This is achieved, for example, through localised micrograting (Bragg), light reflector (Michelson), or optical cavity (Fabry-Pérot). In the intrinsic variety, the optical fibre has the distinct advantage of fulfilling both the function of sensor and transmitter (using the Brillouin or Raman technique), and is thus amenable to measuring a distribution of thermal and mechanical parameters over the length of the fibre.

Fibre optical sensors tend to be robust and promise to operate reliably over long periods. In general, either light intensity or spectral information can be transmitted over several kilometres. Depending on the techniques, the use of high power light sources, detectors and low attenuation fibres, transmission distances can be as much as 85 km. Available long-term experience with optical fibres used for signal transmission is that normal types of fibres, such as single mode acrylate–coated fibres, are specified for use in normal environmental conditions for more than 20 years. Their continued use as sensors in the intrinsic version in normal environmental conditions is, therefore, also at least 20 years. Extrinsic sensor types can have life times limited to less than 10 years, mainly depending on the mechanical transduction mechanism.

Optical sensors have a number of distinct advantages compared with conventional sensors (e.g. distance, immunity to electromagnetic interference, application in explosive areas, etc.). In addition, the interrogation equipment is continuously improving, whist the fibre itself can be considered as a static glass rod which can, in principle, be used for centuries. This is of particular significance for long-term monitoring, because continuous technological improvements allow systems to be adapted to the latest state-of-the-art technology which, in turn, can be connected to the fibre sensors that have already been installed in situ. This means that the precision and reliability of a monitoring system can be improved over its lifetime.

Electromagnetic signal and (wireless) transmission properties

Wireless signal transmission through open tunnels is an accessible technique, which has the advantage of avoiding the installation and future removal of cables for that purpose. Cables are subject to deterioration and may interfere or complicate repository operation and design (e.g. in relation to the transfer and emplacement of waste packages).

Of greater interest may be the wireless signal transmission through the ground, which is currently at the R&D and prototype phase for applications in the petroleum industry, notably for the transmission of pressure and temperature measurements. If such techniques were to be improved and found useful in the context of repository monitoring, they could allow for a direct signal transmission from the repository to the surface. They could also remove the need for cables forming a link between open and closed repository areas. Avoiding the use of such cables through backfill, buffer or sealing material might help ensure that barrier performance is not impaired.

A significant disadvantage of this technique lies in the need for a local power source to transmit remote signals, and this is of particular significance where a closed component is being monitored. In this case evaluations of both the barrier performance and its impact on long-term safety should, therefore, be carried out, taking into account the space required by the sensor, signal emitter and power source, as well as any long-term degradation products resulting from these components.

Remote monitoring and sampling

Certain measurement techniques may not be well adapted to in situ environmental conditions. They may also require frequent maintenance and calibration, thus prohibiting their use in remote, inaccessible areas. To accommodate such measurement requirements and combine them with the need to observe the evolution of remote properties, it may be possible to sample the data remotely and to transfer the data to an accessible measurement station, where environmental conditions are easier to control and maintenance of the equipment is possible.

This is routinely done, for example in the context of site investigation, where fluid samples are extracted from boreholes to perform a chemical analysis of their composition. In the context of underground investigations, for example remote pressure measurements can be transmitted through a capillary tube and the actual pressure measured at the accessible end of the tube. Similarly, fluid or gas samples can be taken remotely and transmitted through tubes, to allow for chemical analysis.

Such measurement techniques, where the measured value is transmitted to a sensor, are sensitive to false modifications of the transmitted physical or chemical properties. For example, care must be taken not to alter the chemical composition of fluid samples.

Such techniques may not be adequate under certain repository conditions. For example, the need to install one or several tubes to allow for the transmission of the information may interfere with the desired performance of local repository components.

7 SUMMARY AND CONCLUSIONS

7.1 Motivation for this Thematic Network

The question at hand, in this Thematic Network, is:

What is the role of monitoring in the phased development of a geological disposal facility ?

That monitoring would be required to support the implementation of geological disposal has always been recognised. The subject of monitoring is now perceived as one of increasing importance in repository programmes and also suitable for international collaboration. This increased importance arises from:

- the move in several waste management programmes from concept development and research towards actual site investigation and implementation stages, during which monitoring programmes must be defined;
- the recognition of the need for well-founded decision bases and evidence (to which monitoring will contribute) in progressing phased geological disposal projects;
- issues of confidence and how to increase it, especially in wider stakeholder groups, including the public.

Bringing together expertise in different European programmes under the auspices of the European Commission, has provided opportunities:

- to understand the approaches to monitoring in each programme and their dependency on national concepts and on the approaches followed to safety and repository implementation;
- to distil consensus views and recognise alternative approaches to monitoring;
- to share technical knowledge and experience amongst the participating organisations;
- to communicate these views and experiences more widely, by means of this report.

7.2 Established principles and consensus for repository monitoring

The monitoring of aspects of a geological disposal system during its phased implementation is based on a small number of basic principles which are themselves based on the existing international consensus and are also confirmed as appropriate and achievable by the participants in this Thematic Network.

- The operational safety of a geological disposal facility (both radiological and conventional) must be underpinned and verified by monitoring. This is the case for all nuclear facilities.
- Long-term (post-closure) safety cannot rely on monitoring after closure. This is for reasons of principle – undue burdens should not be placed on future generations – and for practical reasons – it cannot be assumed that future generations will have the technical capability or interest in carrying out monitoring.
- Therefore, long-term safety must be assured by the disposal system design (including the choice of site) and the quality of its implementation. After closure, the disposal system must be passively safe without reliance on monitoring.

- To this end, a convincing long-term-safety case has to be developed prior to the emplacement of the waste (i.e. monitoring in the post-emplacement phase is not part of the safety case, although it may provide an opportunity to confirm its conclusions).
- All monitoring must be implemented in such a way as not to be detrimental to long-term safety. That is no significant detrimental disturbance of the long-term performance should be introduced by monitoring. (Similarly, there must be no compromise with respect to long-term safety in order to facilitate the retrievability of the waste).
- The societal role of monitoring must be acknowledged. Monitoring may be carried out for non-technical reasons, for example related to public re-assurance. Such monitoring may be continued as long as it is required by future generations, who may not consider this an 'undue burden'.

There is also an established consensus that monitoring is essential:

- to the control of a facility (e.g. ensuring that safe conditions exist and that construction and operations are carried out according to correct procedures and required quality); and
- to decision making (e.g. establishing that required conditions are present, sufficient information is available to move to a next phase and technical ability exists to maintain safety in a phase or subsequent phase).

Four issues have been identified that have formed the basis for initial work in this project:

- The importance of establishing a baseline;
- The importance of monitoring as a QA and regulatory compliance tool;
- The inability to monitor long-term safety directly and, therefore, the importance of monitoring to underpin understanding and models on which long-term assessments are based;
- Monitoring as an aid in wider confidence building.

7.3 Main findings and experience from this TN

The main findings of this Thematic Network are presented and discussed below. Confirmation is required that monitoring can be carried out in line with the above principles and, if possible, that the consensus referred to above is real.

All the participants of this Thematic Network are in agreement on the importance of monitoring related to establishing baseline conditions, maintaining operational safety, compliance (including safeguards) and in support of model confirmation. Any differences in approach to such monitoring relate mainly to the extent to which monitoring is seen as confirming processes related to evolution of the repository and its long-term safety.

The importance of safety and the implementation strategy, where a spectrum of approaches can be recognised, have implications for the role of monitoring within a programme. Factors that need to be considered here include:

- waste type and EBS properties and expected performance, which affect the extent to which parameters related to long-term performance can be measured;
- implementation strategy, including plans for progression from one step to the next, including periods of observations in (open) underground structures;
- regulatory regime and requirements;
- degree of concept flexibility;
- political and/or public expectations.

There is, therefore, a range of approaches to monitoring, as demonstrated by the different approaches followed by the various programmes involved in this Thematic Network. It is important to understand the reasons for these differences and the role played by monitoring within any safety and repository implementation strategy.

Minimal monitoring may be preferred if the purpose is limited to confirming constant properties and if uncertainties about barrier and near field evolution are small. More detailed monitoring may be foreseen if potential degradation of the repository is more complex or such that early measurement will confirm a satisfactory, or otherwise, evolution. Specially instrumented test or pilot facilities may be used in a research mode if this is thought desirable.

The extent of monitoring should be limited to that which could reveal useful results for the decision making process or for the confirmation of safety. That monitoring takes place must be explained to audiences and it is important not to give the impression that such monitoring indicates a lack of confidence in the safety of the disposal system.

The technology that is necessary for much of the monitoring, e.g. of the surface environment and operational radiological parameters, is standard and is not discussed here. The technology required for monitoring parameters which are specifically relevant to repositories has been and will continue to be developed in URLs and in relation to mining and hydrocarbon exploration. It needs to be emphasised that there is already extensive experience of monitoring related to radioactive waste disposal that comes from site investigations and experiments in URLs. Experience also comes from outside this field, for example, from the monitoring of large engineered structures, such as dams and underground openings, which has taken place over many decades. Compliance monitoring is also standard practice within the nuclear industry.

Limitations exist, however, especially with regard to the longevity and reliability of monitoring equipment, especially under harsh environmental conditions, and calibration drift in remote locations may be a problem. False expectations should not be raised either with respect to what is practical over long timescales, or the utility of measurements and the ability (or need) to respond to the results of monitoring. That a parameter can be measured is not, however, a good reason for its measurement. Its measurement is justified only if it contributes to an increase in understanding or confidence in safety, and where it is possible to interpret the measurements.

There are also issues to consider over the gradual discontinuation of different types of monitoring during decommissioning, closure and post-closure phases of a repository, and also over the preservation, continued access to and use of monitoring databases compiled over many years. Such questions may only be answered many years in the future in the light of future scientific, regulatory or public interest.

In summary, technologies exist or are in development, which give good prospects for a level of monitoring that is appropriate for the issues at hand. The extent of monitoring that is either appropriate or useful to implement is, however, a sensitive question and depends on implementation strategies. Experience will continue to be gained, especially in those programmes that are approaching site selection and the construction of repositories – activities which will require the detailed specification of monitoring programmes.

Monitoring can be seen in a broader sense than just in situ measurements of the (key) phenomena of the disposal system under consideration. If monitoring is seen in the broader sense as periodically determining the status of important issues to long-term waste management, then many issues may need to be considered; included in these are issues related to science, technology and society. Such “broader monitoring” may be an important part of decision making and should be integrated within a repository development programme.

The "broader aspects" of monitoring include a large potential range of activities and monitoring in this area may vary considerably between different countries – in several countries some of the issues often mentioned within this description are not included under the title of monitoring. Much of this type of monitoring, the evaluation of the results of such activities and the corresponding decisions are often performed within a clearly defined framework, which may be part of an SEA or EIA or may be an integral part of the steps towards licensing. Several of the “broader monitoring” activities discussed in this report are already being carried out in most disposal programmes, with some of them being arranged within a formal legal or institutional framework (e.g. the IAEA Joint Convention).

8 REFERENCES

(The references related to the Country Annexes are at the end of each description of a country's monitoring programme.)

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9 APPENDIX - COUNTRY ANNEXES

9.1 BELGIUM

9.1.1 Definition

No official definition of monitoring exists in the Belgian Radiation Protection Regulation. In the SAFIR 2 report [1] the following working definition was used:

“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.”

9.1.2 Context (including legal framework)

Belgium has a federal state structure, which means that certain competences are exercised on a central (federal) policy level, while other competences are partially or completely designed on the decentralised (regional) policy level, constituted by the Flemish and Walloon Regions and the Brussels-Capital Region. Since the State Reform of 1980 (completed with those of 1988 and 1993) the competences in the field of the Protection of the Environment are exercised by the Regions, including the control of operational activities which, in general, may be harmful to man and environment (by issuing environment protection licences) and the waste management policy. The regulation of the nuclear activities is actually an exception to this regional competence. The protection of the population and of the environment against the danger of ionising radiation has indeed remained exclusively a federal matter. Furthermore, the management of radioactive waste, of whatever origin, is also a federal competence (see Special Law of 8 August 1980 on Institutional Reforms).

Since 1 September 2001 the control of nuclear activities is performed by the ***Federal Agency for Nuclear Control (FANC)***. For the execution of certain tasks, the Agency may call upon the assistance of specialised control organisations such as **A.V.N**. and **A.V.C**., a.o. for inspections in nuclear facilities.

Since September 2001, the regulations concerning nuclear safety and radiation protection have been modified thoroughly. Up to this date, the regulations were governed by the law of 29 March 1958, and the accompanying Royal Decree of 28 February 1963, known as the General Radioprotection Regulation for the Protection of the Workers, the Population and the Environment (GRR-1963). These regulatory texts have been abolished since 1 September 2001 and respectively been replaced by the Law of 15 April 1994 and the Royal Decree of 20 July 2001. No specific requirements for monitoring are given in these regulatory texts, with exception of the obliged organisation of a physical and medical control system. Specific regulatory guidance for disposal of radioactive waste is in preparation.

Nuclear Emergency Planning is a competence belonging to the Federal Minister of Internal Affairs and his administrative services (Federal Public Service Internal Affairs, General Direction Civil Security and General Direction Crisis Centre).

Next to the safety regulations mentioned above, the management of radioactive waste and of excess fissile materials in Belgium is subject to a specific legal framework, specifying the competences and tasks of the **Belgian Agency for Radioactive Waste and Enriched Fissile Materials** (ONDRAF/NIRAS). ONDRAF/NIRAS was created to fulfil a task of general interest and general utility reconciling the interests of the community with those of the waste producers. The regulation was established at the end of the seventies and has since been adapted and completed a few times, in particular in the beginning of the nineties. In the table below, the legal framework is summarised.

	Legal texts
ONDRAF/NIRAS-law	Art. 179, §2 and §3 of the law of 8 August 1980 on budgetary propositions 1979-1980, as modified and completed by: The law of 11 January 1991 art. 9 of the Law of 12 December 1997
ONDRAF/NIRAS – Royal Decrees	Royal Decree of 30 March 1981, on the missions and functioning of ONDRAF/NIRAS, as modified by the Royal Decree of 16 October 1991
Other legal elements	Ministerial letter of 10 February 1999 concerning General Rules for the establishment of acceptance criteria by ONDRAF/NIRAS for conditioned and non-conditioned waste Royal Decree of 18 November 2002 regarding the qualification of equipment for the storage, processing and conditioning of radioactive waste

In general terms, ONDRAF/NIRAS is responsible for the management of all radioactive waste on the Belgian territory, generated by nuclear power plants, industrial applications using ionising radiation, medical activities, or research. The task laid down for it by law is to outline a policy for the coherent and safe management of radioactive materials covering the following aspects:

1. Compiling an inventory of radioactive materials (and enriched fissile materials), and assessing the decommissioning and remediation costs of all sites containing radioactive materials;
2. Collection and transport of the waste to the site of Belgoprocess (ONDRAF/NIRAS's industrial daughter company) for a centralised management;
3. Processing and conditioning in the Belgoprocess facilities (some waste producers have their own processing and conditioning facilities and they transfer conditioned waste to ONDRAF/NIRAS and Belgoprocess);
4. Interim storage of all conditioned waste at the Belgoprocess site;
5. Long-term management (disposal as the option under investigation);
6. Tasks relating to the management of enriched fissile materials.

For the long-term management, a distinction is made between the category A (low and intermediate short-lived waste) programme on one hand, and the category B (long-lived waste) and C (high-level waste) programmes on the other. The category A programme is currently in a pre-project phase; sites have been chosen for studying site specific disposal designs with the active participation of the local municipalities (Dessel, Mol, Fleurus / Farciennes) via local partnerships between the municipalities and ONDRAF/NIRAS. In this pre-project phase for category A waste the two technical options ‘surface disposal’ and ‘deep disposal’ are looked at in parallel.

For the waste from categories B&C, the programme is still in a methodological research and development phase, preceding the pre-project phase. Methodological research and development prime aim is to establish if it is feasible, both technically and financially, to design and build on Belgian territory a deep disposal solution for category B and C waste that is safe, without prejudging the site where such a solution would actually be implemented. Recently, on 15 July 2002, the SAFIR-2 report – Safety Assessment and Feasibility Interim Report 2 –, presenting the research and development work during the period 1990-2000 was submitted and presented to the supervising authority (Secretary of State for Energy and

Sustainable Development). During the second half of the year 2002 the report was submitted to a Peer Review by NEA/OECD on demand of the Belgian Government. The final report of the NEA/OECD Peer Review has been published in May 2003.

9.1.3 Reasons for monitoring

A repository cannot be closed until there is sufficient confidence that the disposal system will function as intended. Therefore, it is important to understand the role of monitoring during the various stages in its life.

The purpose of monitoring a radioactive waste repository is four-fold:

1. To determine the undisturbed state of a disposal site and its immediate environment before disposal commences, so that the baseline conditions are known, and to acquire information during the design phase that can be used in the design of the facility and in safety assessments;
2. To provide information during the construction phase, the operational phase and the phase of institutional control about the impact of the repository on personnel, the public and the environment as a means of verifying continuing compliance with the relevant standards, to verify the behaviour predicted by the safety and other assessments and to achieve a better appreciation of the processes that are involved;
3. To comply with the requirements of the ‘Nuclear Materials Safeguards’ of the IAEA in the case of a repository that holds substantial amounts of fissile material;
4. To help to support the decision-making process for the disposal of radioactive waste through its various stages, and to gather data about conditions for the retrievability of waste packages.

9.1.4 Monitoring strategy

The perspectives and limitations of monitoring of a geological repository of radioactive waste have been outlined in Minon (2002) [2].

As the project of the underground disposal of high level waste is a first of a kind activity, it has to go through all the steps necessary to develop a new activity: conceptual development, feasibility studies, modelling, laboratory observations and experiments, demonstration and pilot facilities, construction, operation and finally closure. In each of those steps monitoring is needed as for any other scientific and industrial development.

In determining the monitoring strategy, three axes need do be defined:

- The monitoring purposes (see paragraph 3.) (Why?)
- The parameters related to the information requirement (What?)
- The methods and techniques allowing the measurement of the parameters (How?) need to be defined;
- The system and its components to be monitored;
- The time periods.

The disposal system needs to be carefully defined. A distinction is made between the waste form, the engineered barriers and the host rock on the one side and the environment, i.e. the geosphere and the biosphere on the other side. The rationale for that distinction is that we intend to have some control, by our decisions and choices, on the disposal system and its behaviour within a rather long period of time while our influence on the environment is very limited or even non-existent.

The time periods considered for monitoring are as follows:

- Before construction (or pre-operational);

- Construction;
- Operation and waste emplacement;
- Before closure;
- After closure or institutional control.

The main conclusions of this paper [2] are that monitoring can be a key activity before closure as decision aiding tool, and that if necessary, corrective and protective actions can be taken. Post closure monitoring and monitoring in the environment are believed to be limited to indirect observations; the environment cannot be controlled or corrected. At that time only global protective actions to be taken at the disposal level solely – e.g. retrieval of the waste – are possible, probably based on very indirect monitoring data.

In developing a monitoring programme, it is recognised that certain boundary conditions will influence the programme chosen:

- The aim of disposal is to evolve to a passive system, in which it is foreseen that monitoring will "fade away" (evolution from active control towards passive control and eventually towards a passive system).
- Regulatory constraints *e.g.* the dose to the personnel executing the monitoring.
- The possible generation of preferential migration routes through a particular barrier as a result of installing monitoring equipment.
- An increased likelihood for human intrusion.
- Replacement of monitoring devices and the possibility in certain conditions of measurement errors that cannot be verified.

9.1.5 Key processes to be monitored

9.1.5.1 Determining the baseline conditions

This aspect of monitoring is part of the site characterisation exercise.

Its primary aim is to determine the characteristics and processes at the site that exist *before* disposal and to acquire a thorough insight into these natural "undisturbed" processes and characteristics.

Parameters that can be monitored for this purpose include:

- Groundwater flows in the host and surrounding geological formations;
- Geochemical characteristics of the groundwater;
- Natural radioactivity in the groundwater, surface water and geological formations and background radiation at the site;
- The hydrology of surface waters, with special attention to recharge and rates of infiltration;
- Meteorological and climatological conditions;
- Land use in the surrounding area;
- The ecology of natural habitats and ecosystems.

9.1.5.2 Information about the changes caused by disposal

Changes can take place in the various components of the disposal system due to:

1. Evolution of the waste package and the overpack;
2. Physical/chemical interactions in the near field;
3. Chemical and physical changes in the geological barrier;
4. Changes in the aquifers and biosphere.

The phenomena and processes that can occur in each of these components and which are relevant to long-term safety must be understood. In many cases these are transitory phenomena (e.g. increase in temperature, resaturation of the backfill material, pressure build-up etc.) that eventually reach equilibrium. This transient phase is less relevant to the long-term safety of the repository for vitrified waste and spent fuel, as the overpack or container provide physical containment during this period. The understanding of the safety relevant processes and characteristics will provide an important basis for the design of the actual monitoring programme which is still to be developed in a further phase of work.

9.1.5.3 Nuclear Materials Safeguards

Nuclear Materials Safeguards will apply to a repository containing waste with a high level of fissile radionuclides, such as spent fuel. These safeguards specify that adequate controls must be carried out to verify that there is no proliferation of fissile material.

During the operational phase of the repository safeguards can be applied directly but application becomes more difficult when the post-closure phase is considered. Before a Safeguards regime can end, the material must be ‘practically irrecoverable’. In order to be able to meet this requirement human intrusion in the form of boreholes or mining operations at the site must be prevented. It should be possible to verify this by regular inspections of the site, aided by aerial and satellite photography.

9.1.5.4 Monitoring as a decision-making instrument

In practice, monitoring can be used both technically and socially as an instrument of decision-making. Technical decisions that can be taken on the basis of monitoring include:

- Modifying certain aspects of the design of the repository in the latter phase of its operation based on the measurement of long-term stress regimes and groundwater flows;
- Identifying or changing the ideal time to backfill and seal off main galleries after observing the long-term stability of the excavations.

Such decisions are, of course, taken during the design phase, but several decades of experience operating a repository will yield valuable information which can be used to further optimise certain aspects of its operation and design.

One of the decisions which will need public support will be the decision to seal and close the repository. This can only happen when two crucial conditions have been met:

- Sufficient confidence has been established in the proper operation of the disposal system during the operational phase (by the continuous monitoring of the facilities);
- Sufficient technical elements and arguments exist to show that the repository will continue to function properly after closure.

After closure the method of monitoring will become far less direct, since it is one of the fundamental principles of the disposal design that the efficacy of the various barriers must not be impaired by monitoring.

9.1.6 Monitoring techniques

A broad experience with monitoring techniques exists from the Mol-Dessel research site for deep disposal in the Boom Clay. Two types of monitoring are carried out:

1. Hydrogeological and environmental monitoring based on drillings from the surface or surface based monitoring or sampling;
2. Monitoring in the HADES underground laboratory.

At the end of the seventies and the early eighties a hydrogeological network was developed in the framework of the R&D on the possible geological disposal in the Boom Clay. This network is not limited to the Mol-Dessel nuclear site but extends over the whole north-east of Belgium, i.e. in total an area of about 3000 km², and includes both the phreatic aquifer and the deeper aquifers to a depth of about 500m. The network is dense close to the site and for the phreatic aquifer and sparse at its edges and for the deepest aquifers. In total it includes well over a 100 measuring points. The network is exploited by SCK•CEN and a digital database with monthly measurements over the last 20 years is available.

In the framework of SCK•CEN's nuclear license and its research on radio-ecology, SCK-CEN performs environmental monitoring since the late 50’s. As for both the hydrogeological network and the environmental monitoring standard techniques have been applied, no further attention will be given to them in the context of this report.

The HADES URL is operational since 1984 and by consequence signifies a broad experience in monitoring in clay. Typical problems related to monitoring in the HADES URL are related to the plasticity of the clay (leading to important displacements), the high porewater pressure and lithostatic stress. Hereafter a brief overview is given of the main monitoring techniques by parameter or type of parameter to be monitored.

Hydraulic pressures:

- For the measurement of hydraulic pressures SCK•CEN developed a special type of stainless steel multifilter piezometer, on such a piezometer each filter has its own chamber with minimal dead volume and connected to the gallery by instrumentation tubing. The hydraulic pressure is measured in the gallery by standard pressure transducers (“Wheatstone bridge” type). To install these piezometers the plastic properties of the Boom Clay are used, i.e. they are installed in a borehole with minimal oversizing and the borehole seals around the instrument by creep of the clay. Some of the piezometers in the HADES URL are now about 20 years old and still function perfectly. Also the pressure transducers are very reliable and precise: a calibration after 10 years of operation showed a deviation of only 0.1%. Over the years many variants of these piezometers were developed such as fully plastic piezometers and a system suitable for hard clays that was successfully used at Mount Terri.
- In the framework of backfill and sealing tests, pore water sensors were directly installed in situ. In almost all cases the sensor producers were required to modify the sensor housing to increase the water tightness over long term. In general no major problems were encountered.

Temperature:

- Temperature was found to be easy to measure by using for example thermocouples such as used in nuclear research reactors; such thermocouples have a protection by a stainless steel instrumentation tube. The latter showed to be reliable and precise over a period of more than 10 years (CERBERUS project [3]).
- Currently SCK•CEN is working on the application of optical fibre based sensors for distributed temperature measurements over long distances. Also in this case there is a protection by a stainless steel instrumentation tube. Currently the system is being tested around the CORALUS in situ tests in a combined heat and radiation field.

Total or lithostatic stress

- Total stress has been measured either by using Glötzl, piezoelectric or vibrating wire sensors with relative large sensitive surface or by miniature pressure sensors. Especially in the beginning leaks often occurred in the oil filled cells or problems at the connection between the cell and the cable. The measurements were often difficult to interpret due to the disturbance in the geomechanical stress field caused by making the instrumentation drilling. Miniature pressure sensors installed in direct contact with the Boom Clay regularly suffered from puncture of the sensitive membrane by pyrite or sand particles in the Boom Clay. However the experience is very positive for miniature sensors in contact with bentonite.

Displacement

- Some types of dilatometers can be reliably applied to measure displacements in the Boom Clay around excavations were the displacements are relatively important (several centimetres). For the measurement of small displacements (millimetres) currently an instrumentation based on a magneto restrictive sensor is being tested in the frame of the RESEAL in situ shaft sealing experiment.

Radiation dose or dose rate

- The radiation dose around the CERBERUS experiment was measured using standard replaceable TLD dosimeters. Currently SCK•CEN is working on a fibre-optic sensor that could measure radiation dose in a combined heat and radiation field.

Chemical parameters

- Chemical parameters are measured by using the above mentioned piezometers either by sampling the water or by circulating the water through a measurement cell e.g. equipped with pH, E_h or other chemical sensors or by introducing optical fibre chemical sensors. The correct measurement of E_h requires the use of a non-metallic piezometer and an anaerobic box (all contact with oxygen needs to be avoided) for installing the sensors. Recently it has been demonstrated that reliable pH and E_h measurements are possible.

Transport parameters

- Transport parameters as such cannot be measured directly but are derived from tracer tests. In the HADES URL the piezometer technique is applied to perform tracer test. The so-called CP1 tracer test with HTO is monitored successfully since 1987 and can in principle still a hundred years being monitored.

All results of the electronic sensors since the mid-eighties are stored in the HADES databank were they are continuously on line available.

Although the experience gained in the HADES URL has a large value, monitoring of a real repository will pose extra problems mainly related to the distance over which the signals need to be transported, the limitations in accessibility of the monitoring locations, the time over which the parameters need to be monitored and the presence of the waste itself.

9.1.7 Availability, required development

Not yet developed. The main developments required are related to the problems cited above.

9.1.8 How to react on unexpected monitoring results?

Not yet developed.

9.1.9 References

1. SAFIR 2 – *Safety Assessment and Feasibility Interim Report 2*. NIROND 2001-06 E, December 2001.

2. Minon, J P 2002. *Monitoring of geological disposal of radioactive waste: perspectives and limitations. In "Issues relating to safety standards on the geological disposal of radioactive waste"*, Proceedings of a specialists meeting held in Vienna, 18 – 22 June 2001, IAEA-TECDOC-1282, June 2002.

3. Noynaert, L., Volckaert, G., De Cannière, P., Meynendonckx, P., Labat, S., Beaufays, R., Put, M., Aertsens, M., Fonteyne, A. and Vandervoort, F., *The Cerberus project – Demonstration test to study the near field effects of an HLW canister in argillaceous formation*, Final Report, European Commission, EUR 18151, 1998.

9.2 CZECH REPUBLIC

9.2.1 Definition

RAWRA does not have any definition of the monitoring in the broader sense, even in the Czech legislation there is no definition of monitoring in general. A general definition of radiation monitoring were formulated for all types of workplaces with the ionising radiation sources in the Regulation of the State Office for Nuclear Safety (SUJB) No. 184/ 1997 on Radiation Protection Requirements. This Regulation has been replaced with the Regulation No. 307/ 2002 in June 2002 and the definition of monitoring has been changed.

Radiation monitoring

- Reg. No. 184/ 1997, before June 2002: Monitoring is a measurement and an evaluation of exposure of exposed workers and other persons, and the contamination of workplace and its vicinity by the ionising radiation or by the radionuclides.
- Reg. No. 307/ 2002, after June 2002: Monitoring is measurement of quantities characteristic of radiation field or radionuclides and evaluating of results of these measurements with the purpose of optimisation of the exposure.

9.2.2 Context (including legal frame work)

In January, 1997, the Czech Parliament approved Act No. 18/1997 Coll., the Atomic Act, on "Peaceful Utilisation of Nuclear Energy and Ionising Radiation". The Act came into force on 1st of July, 1997. The Atomic Act is based on the internationally adopted principles of nuclear safety and radiation protection which are implemented in recommendations of the IAEA, ICRP and WHO. The Atomic Act is very important from the point of view of radioactive waste management because it defines new principles in the radioactive waste management, among others:

- The State guarantees the safe final disposal of all radioactive waste and spent fuel conditioning before its disposal.
- The owner of radioactive waste (waste generator) is responsible for safe radioactive waste management including its conditioning into a form acceptable for its final disposal, except for the conditioning of spent fuel.
- Radioactive waste generators shall cover all expenses connected with management of waste generated and/or waste expected to be generated during their future activities, including its final disposal and the post-closure monitoring of the repositories.
- The State may contribute to cover expenses of management of radioactive waste resulting from past practices.

- The Radioactive Waste Repository Authority (RAWRA) and a fund for the collection of resources from waste generators for radioactive waste disposal (so called Nuclear Account) shall be established.
- All existing radioactive waste repositories in the Czech Republic shall be ceded into the property of the State within 3 years, it means till the year 2000.
- Radioactive waste shall become the property of the State in the moment of its acceptance by RAWRA for its disposal or conditioning.
- The licensee is responsible for its nuclear installations and workplaces with sources of ionising radiation decommissioning including the processing of generated radioactive waste.
- The licensee shall create a special financial reserve to cover the expenses of future decommissioning of its installation(s) or workplace.

9.2.2.1 Radioactive Waste Management in the Czech Republic

The Radioactive Waste Repository Authority (RAWRA) was established by the Czech Ministry of Industry and Trade, according to the Atomic Act, in June 1997. RAWRA's mission is to ensure the safe disposal of existing and future radioactive waste in compliance with the requirements for nuclear safety and protection of the population and environment.

The scope of its activity includes:

- siting, development, construction, operation, closure of radioactive waste repositories, including a deep geological repository for high level waste and spent nuclear fuel
- radioactive waste management
- conditioning of spent fuel before its final disposal
- registration of waste generators and disposed waste
- co-ordination of R&D Programme in the field of radioactive waste management
- control of financial reserves of licensees for decommissioning of their installations and workplaces
- services for waste generators

In compliance with the Atomic Act, RAWRA took over the radioactive waste repositories from private companies in January 2000. Since this time, the State guarantees the disposal of radioactive waste and only the State, represented by RAWRA, can dispose the radioactive waste.

9.2.3 Reasons for Monitoring

- to ensure radiological and non-radiological safety of the repository,
- to ensure protection of the workers, the population and the environment,
- to monitor behaviour of the repository site,
- to assess the repository impact on environment,
- to show compliance with international and national guidelines and regulations.

9.2.4 Monitoring Strategy

A strategy for monitoring has not been firmly defined in the Czech Republic, however,

- for near surface facilities it is supposed to carry on monitoring during the whole institutional period (approx. 300 years),

- for a deep repository the strategy has not been discussed yet,
- but for any new facility the monitoring programme will be planned from the very beginning of the field activities (to have a base-line for observation of the particular parameters).

Basic requirements on radiation monitoring have been formulated for all types of workplaces with the ionising radiation sources in the Regulation of the State Office for Nuclear Safety No. 307/ 2002 on Radiation Protection Requirements. The Regulation deals in detail requirements on monitoring, procedures for evaluation of quantities measured within the framework of monitoring and defining of the reference levels. To license a workplace with the ionizing radiation sources the Monitoring Programme has to be approved by the State Office for Nuclear Safety.p

According to the Regulation No. 307/ 2002:

(1) The monitoring programme has, according to the way and the scope of handling with the ionising radiation sources, as a rule the following parts:

a) the monitoring the workplace with the ionising radiation sources,

b) the personal monitoring,

c) the monitoring the discharges,

d) the monitoring the vicinity.

(2) The monitoring programme shall include for both the normal operation and also for the foreseen deviations from the normal operation, including the radiation accidents and if need also the radiation emergencies:

a) the definition of quantities that will be monitored, the way, the scope and the frequency of measurements,

b) the instructions for the evaluation of results of measurements,

c) the values of reference levels and the overview of relevant measures in the case of their exceed,

d) the specification of methods of measurements,

e) the specification of parameters of used types of measuring instruments and aids.

(3) The monitoring programme shall be proposed by a such way and in a such scope, to enable during the operation of workplace the verification of requirements for the limiting the exposure, the proof that the radiation protection is optimised and the assurance of other requirements for the safe operation of workplaces with the ionising radiation sources, especially the early detection of the deviations from the normal operation. The monitoring is proposed according to the nature of object and implemented either systematically (routinely), namely continuously or regularly (periodical) when in the defined terms there is repeated, operationally during the determined activity with the aim to evaluate and to ensure the acceptance of this activity from the viewpoint of system of limits. If there come into origin changes in the arrangement of workplace, in the ionising radiation sources, in the way and conditions of handling with them, or changes of monitoring methods, the monitoring programme is adapted.

9.2.5 Key processes to be monitored

The results of monitoring should give the representative information about repository behaviour over the whole period of operation and post-closure control. It is necessary to observe physical and chemical parameters of disposed waste, barrier system and surroundings important from point of view of workers and population radiation protection and consequently to assess the repository impact on environment during any stage of repository operation. The selection of monitored key processes has to reflect these aspects.

Since this study deals with monitoring for case of geological disposal, we consider reasonable to mention Czech repositories for LLW and ILW located in subsurface. At present, the Czech Republic operates three repositories of low-level (LLW) and intermediate-level (ILW) radioactive waste. One repository for LLW is already closed. The repository was in operation in 1959 – 1965, it is situated in an abandoned stone quarry at Hostím (near the town of Beroun) in the central part of the country. It was filled with concrete in 1997 and closed. Now, total alpha and beta activity and activity of selected radionuclides (^{3}H, ^{14}C, ^{90}Sr) is measured in surface waters and groundwater sampled from three boreholes in the vicinity of repository once per year.

9.2.5.1 Richard Repository

The Richard repository was built in a former limestone mine, Richard II (beneath the hill Bídnice) near Litomerice town in northern part of the Czech Republic. The repository has been used since 1964 to store institutional waste. The total volume of adapted underground chambers exceeds 16,000 cubic meters, waste repository capacity making up about half this volume (the rest being service corridors). As mentioned above, all monitoring activities are given by the monitoring programme.

The following list contains sensitive parameters monitored:

- Radiation monitoring: workplace (γ - dose rate, surface contamination, concentration of selected radionuclides in the air); mine water (total alpha and beta activity, activity of selected radionuclides); discharges (water; total alpha and beta activity, activity of selected radionuclides); environment (γ - dose rate, total alpha and beta activity, activity of selected radionuclides in underground and surface water; personal monitoring)
- Degradation of waste
- Degradation of EBS
- Chemical form of released radionuclides
- Migration parameters in EBS
- Ventilation of disposal area
- Humidity and water condensation in the disposal chambers
- Hydraulic parameters
- Hydrological parameters: mine waters, groundwater, rainwater
- Geodynamical stability

9.2.5.2 Bratrství Repository

The repository is situated in western part of country at Jachymov town. This repository is designed only for waste containing naturally occurring radioactive material. It was adapted from a mining adit in a former uranium mine where five repository chambers with a total volume of almost one thousand cubic meters were built. The repository was put into operation in 1974.

The monitored sensitive parameters are similar to the previous case of Richard repository:

- Radiation monitoring: workplace (concentration of short-lived radon daughters, volume activity of long-lived radionuclides of the uranium-radium series emitting alpha radiation); mine water (total alpha and beta activity, activity of selected radionuclides); discharges (water; total alpha and beta activity, activity of selected radionuclides); environment (total alpha and beta activity, activity of selected radionuclides in surface water); personal monitoring.

- Degradation of waste
- Degradation of EBS
- Chemical form of released radionuclides
- Migration parameters in EBS
- Ventilation of disposal area
- Humidity and water condensation in the disposal chambers
- Hydraulic parameters
- Hydrological parameters: mine waters, rainwater
- Geodynamical stability

9.2.5.3 The Melechov Massif

The Melechov Massif is characterised as common Varisean granitic body in Bohemian Massif with the geological position very close to the main area of study site selected for site characterisation of HLW repository concept. This locality was selected as the testing site, nevertheless, it is unacceptable as a study site because part of it is situated in a protected drinking water source. Thus, it is not expected to build any disposal facility on this site.

The following work is carried on in the western part of Melechov Massif:

- Geological mapping on the scale 1:10,000
- Hydrogeological investigation
- Airborne gamma-spectrometry and magnetic measurement
- Ground gravimetric survey
- Petrology of individual granite types
- Fracture measurement and characterization of individual fracture system

The results from work above mentioned will help to select testing polygons with characteristic geological conditions for the verification and sensitivity testing of individual techniques and methods.

The Melechov Massif represents primary phase of development of deep geological repository for high level radioactive waste and spent fuel.

9.2.5.4 Management of High Level Waste and Spent Fuel

In the Radioactive Waste Management Concept that was approved by the Czech Government, a long-term strategy of high level waste and spent fuel management was formulated. According to it high level waste and spent fuel will be disposed into a deep geological repository. At present, RAWRA initiates a site-selection process of the deep geological repository of HLW and spent fuel.

9.2.6 Monitoring techniques

The Czech Republic has years of experience with LLW and ILW disposal in the geological repositories. The repositories are situated in abandoned mines and are operated for more than 20 years. From that reason all techniques used for monitoring of sensitive parameters are standard radiochemical, spectrometric and integral techniques. Nevertheless, we assume the techniques used in HLW deep repositories should be more advanced and complex as wider spectrum of parameters will be needed to be monitored.

9.2.6.1 How to react on unexpected monitoring results?

In case of unexpected monitoring results the tools are follows:

- to take measures to protect the workers, the population and the environment (according to the Monitoring Programme and Emergency Plan),
- to carry on repeated measurement of the respective quantity,
- to carry on measurement on nearby points,
- to report to the State Office for Nuclear Safety.

9.2.7 References

1. Act 18/ 1997 (Atomic Act)
2. Regulation No. 184/ 1997 of the State Office for Nuclear Safety on Radiation Protection Requirements
3. Regulation No. 307/ 2002 of the State Office for Nuclear Safety on Radiation Protection Requirements
4. Woller, F., Nachmilner, L., *Progress Towards a Deep Geological Repository in the Czech Republic, in monography* Witherspoon, P.A., Bodvarsson, G.S., *Geological Challenges in Radioactive Waste Isolation*, Third Worldwide Review, Earth Science Division, Lawrence Berkeley National Laboratory, LBNL-49767, 2001, p. 97-104

Czech Documents on Monitoring

5. Královcová, E., *Monitoring of Radioactive Waste Repositories in the Czech Republic in 2000 XXIII.* Days of Radiation Protection, 28.11. – 1.12. 2000, Jáchymov, Czech Republic (in Czech)
6. Královcová, E., *Monitoring of the Radioactive Waste Repositories Richard and Bratrství in 2000*, RAWRA, February 2001, (in Czech)
7. Královcová, E., *Monitoring of Discharges from Radioactive Waste Repositories, RAWRA,* May 2001, (in Czech)
8. Královcová, E., *Personal Doses in Radioactive Waste Repositories in 2000, RAWRA*, May 2001, (in Czech)
9. Ferjencik, M. et al., *Safety Analysis of Bratrstvi Repository*, 2001, (in Czech)
10. Dusilek, P. et al., *Safety Analysis of Radioactive Waste Repository*, 2000, (in Czech)

9.3 FINLAND

9.3.1 Definition

Several expressions are used in the Finnish language to denote *monitoring* in different contexts. For the monitoring system of the ONKALO underground rock characterization facility the following working definition applies: *“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”.*

For the operational and post-closure phases of the repository this definition may be extended to include changes taking place in the repository system itself (in relation to the time of construction, emplacement of waste or closure of the facility).

9.3.2 Context (including legal framework)

According to the Finnish Nuclear Energy Act the nuclear waste generated in connection with or as a result of the use of nuclear energy in Finland shall be handled, stored and permanently disposed of in Finland. The nuclear electricity producers, Teollisuuden Voima Oy and Fortum Power & Heat Oyj, are solely responsible for the whole management of their nuclear waste. The responsibility for practical implementation of the disposal of spent fuel lies with Posiva Oy, which is owned by the two nuclear power companies. The power plant companies themselves take care of the low- and intermediate-level waste from the power plants.

The waste generator's responsibility for nuclear waste ceases "when the Radiation and Nuclear Safety Authority (STUK) has confirmed the nuclear wastes to be permanently disposed of in an approved manner". Thereafter the "rights of ownership" to the waste are transferred to the State. According to the nuclear energy act, "should it become necessary, after disposal, the State has the right, at the disposal site, to take all measures required for the control of the nuclear wastes and for ensuring the safety of the repository".

According to the general safety requirements for final disposal of spent fuel (Government decision of March 1999) "disposal shall be planned so that no monitoring of the disposal site is required for ensuring long-term safety and so that retrievability of the waste canisters is maintained to provide for such development of technology that makes it a preferred option". According to the YVL Guide 8.4 by the Radiation and Nuclear Safety Authority (STUK, May 2001), "facilitation of retrievability or potential post-closure surveillance activities shall not impair the long-term safety."

The law for the Environmental Impact Assessment (EIA) was enacted in 1994. The instructions for the practical implementation of EIA require that the implementer also formulate a programme for monitoring of the actual potential impact. In the case of spent fuel disposal, Posiva has described possible monitoring activities in the final EIA report (1999), but restricted mainly to the period before the final closure of the repository. In their statements on the EIA report the Ministry of Trade and Industry have stated that the principles for the monitoring programme should be clarified by the time of discussion of the construction license of the spent fuel repository.

Posiva selected Olkiluoto in the Eurajoki municipality as the site of the spent fuel repository in 1999 and the decision was officially endorsed by the Parliament in 2001. Posiva is planning to start the construction of the underground rock characterisation facility, ONKALO, at the Olkiluoto site in 2004. The need for establishing the baseline and implementing a monitoring system before the start of construction has been recognized by both Posiva and STUK. The description of the Olkiluoto baseline conditions and the related monitoring system are reported in Posiva (2003a and 2003b).

The implementation of spent fuel disposal will include the following phases:

- construction and operation of an underground research facility and other necessary research, development and planning work
- construction of the disposal facility (encapsulation facility, repository and auxiliary facilities)
- encapsulation of spent fuel bundles and transfer of waste canisters into their deposition positions
- closure of emplacement rooms and other underground rooms
- post-closure monitoring, if required.

These phases, which can be partly parallel, shall be scheduled and implemented with due regard to long-term safety. In doing so, i.e. the following aspects are considered:

- reduction of the activity and heat generation in waste prior to disposal
- introduction of the best available technique or a technique that is becoming available
- acquisition of adequate experimental knowledge of the disposal site and other factors affecting long-term safety
- potential surveillance actions related to ensuring the long-term safety or to non-proliferation of nuclear materials
- need for preserving the retrievability of the disposed waste canisters
- aim of preserving the natural features of the host rock and other favourable conditions in the repository
- aim of limiting the hazards and other burdens to future generations due to long-term storage of waste.

In the post-closure phase, retrieval of the waste canisters from the repository shall be feasible during the period in which the engineered barriers are required to provide practically complete containment for the disposed radioactive substances. The disposal facility shall be designed so that the retrieval of waste canisters, if needed, is feasible with the technology available at the time of disposal and with reasonable resources.

9.3.3 Reasons for monitoring

In the construction phase of the ONKALO the monitoring activities aim primarily at

- observing possible changes in the repository host rock that can be of importance for the long-term performance of the repository and its assessment
- obtaining data that can help in understanding the features and processes in the repository host rock and the surface environment
- obtaining information about the response of the host rock to the construction activities that can be used in the further planning of the construction and operational activities.

The same reasons are likely to be valid for the later phases of the repository development as well. In the post-closure phase there may be interest to know whether the long-term evolution of conditions on surface, in bedrock and in the repository itself takes the form anticipated in the EIA and the repository performance assessments.

In broader terms the monitoring may also be understood to include the observation of social and technological changes that can potentially affect the implementation of waste management. Pursuant to the discussion of the Decision-in-Principle, Posiva is required to follow up such developments.

9.3.4 Monitoring strategy

Posiva's plans for disposal of spent fuel are based on a KBS-3 type concept. In the next phase an underground rock characterisation facility, ONKALO, will be built. The construction of the disposal facility will follow in the 2010's and the operations will start in 2020. Closure of the facility and the sealing of the repository will take place in the 2040's at the earliest.

Before starting the construction of ONKALO Posiva must establish the baseline (undisturbed) conditions at Olkiluoto on the basis of data and information from surface investigations and deep boreholes. After baseline conditions have been determined the changes will be monitored through the underground construction phases. Since the design of ONKALO allows for the possibility of using at least some parts of it for the actual repository, the monitoring system related to ONKALO will be enlarged for monitoring the host rock of the repository until the end of the repository operation, possibly even longer. Whether monitoring activities are later (during the operational period) also applied to the engineering barrier system and to the waste itself is still to be determined. It is understood that the requirements and possibilities for post-closure monitoring will be considered by the generations who are active when that time is approaching and will also depend on social conditions and development of technology.

The most likely use of the information collected from the monitoring system is for the further characterisation and understanding of the Olkiluoto site. New information can lead to changes in existing structural, hydrogeological, geochemical or rock-mechanical models of the site and should they be important, changes in designs or construction methods might be considered. To enable such use to be made of the data from the monitoring system, the data will be regularly assessed and compared to parameters derived from existing models and from predictions from models developed to test their validity against monitoring data. In this process of assessment attention will be paid to natural fluctuation in the ambient conditions as well as to the measurement uncertainties. To make comparison easier, baseline characterisation data are used to set bounding values for the natural range of variation for the most important parameters. These boundary values will be considered as “action levels”: and values beyond these levels will trigger a more thorough analysis of the monitoring data and may result in modifications to the existing models and designs.

The system for safeguards monitoring is currently under discussion both nationally and internationally. Some of the systems established by Posiva may be used to supplement the information provided by the independent safeguards system operated by the authorities.

9.3.5 Key processes to be monitored

Monitoring during the whole life cycle of the repository may address:

- changes in relation to the baseline conditions (after starting underground construction; both on surface and in bedrock)
- compliance of human activities with the given rules and instructions
- technical performance of repository materials and engineering barrier system
- safety performance of the whole disposal system
- changes in social context of nuclear waste management, including technology change

During the construction and operations phase of the repository monitoring may include

- surface environment
- natural levels of radioactivity in the air, soil, water, animal and plant life
- meteorological conditions
- surface hydrology
- characterization of natural habitats and ecosystems
- rock temperature
- hydrogeological parameters
- in-situ geomechanical/ rock stresses
- groundwater chemistry (pH, Eh, rock-water interaction products)
- presence of gases

As an example, the summary of the hydrological monitoring system planned for ONKALO is given in Tables 1 and 2.

9.3.6 Monitoring techniques

Monitoring will be based on similar techniques that are used in site investigations and environmental impact assessment work. As an example, possible techniques for hydrological monitoring are mentioned in Tables 1 and 2.

9.3.6.1 Availability, required development

Technology is available for the needs of monitoring the response of bedrock and groundwater to the construction work. Experience has been obtained from operation practices in the VLJ-repositories and is used for planning of the ONKALO monitoring system. Currently there are no reliable methods that would enable long-term monitoring of the repository performance.

9.3.7 How to react to unexpected monitoring results

The principles of the use of the monitoring information are explained in Chapter 4 (Monitoring strategy).

9.3.8 References

Posiva Oy. 1999. The final disposal facility for spent nuclear fuel – Environmental impact assessment report.

Posiva Oy. 2003a. Baseline conditions at Olkiluoto. Posiva Oy, POSIVA 2003-02.

Posiva Oy. 2003b. Programme of Monitoring at Olkiluoto During Construction and Operation of the ONKALO. Posiva Oy, POSIVA 2003-05.

YVL-guide 8.4.2001. Long-term safety of disposal of spent nuclear fuel. Radiation and nuclear safety authority (STUK).

Table 5

ISSUE	PROCESS / FEATURE	PARAMETERS TO BE MONITORED	METHOD	MEASUREMENT CYCLE	LOCATION	EXPECTED VARIATION
Hydrology	Variation of precipitation	Amount of water	Rain gauge and snow course measurements	-Once a day or continuous (rainfall) -Once a week/month (snow)	-Rain gauge and weather station at Ulkopäänniemi -Snow course at Olkiluoto island	<100 mm/day <1000 mm/year
	Infiltration (recharge of groundwater)	Water level or amount of water	Water level measurements in boreholes and amount of water in lycimeters	Continuous/once a week	-Boreholes and groundwater tubes selected for long-term monitoring -Lycimeters	<5 mm/day
	Surface water run-off	Water level and/or flow rate	Measuring weirs	Once a week	Four measuring weirs	<1 m (water level) <5000 l/min (flow rate)
	Evolution of groundwater table	Water level	Water level observations in shallow boreholes and groundwater tubes	Once a week/month	Boreholes and groundwater tubes selected for long-term monitoring + new ones based on the location of access ramp	<3m (natural fluctuation)
	Evolution of hydraulic head	Fresh water/environmental head/ groundwater pressure	-Head measurements in packed-off boreholes -Flow logging in open boreholes	-Continuous (e.g. 1/hour) in packed-off boreholes -Twice a year for flow logging	-Packed-off (around 10) boreholes and seven permanent piezometers -Selected (around 10) open boreholes for flow logging	<3 m (natural fluctuation)

Table 6

ISSUE	PROCESS / FEATURE	PARAMETERS TO BE MONITORED	METHOD	MEASUREMENT CYCLE	LOCATION	EXPECTED VARIATION
Hydrology	Evolution of groundwater flow	Flow rate	-Transverse flow meter -Dilution of tracers in packed-off sections	Continuous for some selected sections/Once a year at selected depths	-Continuous at two or three selected borehole sections -Selected borehole sections (around 50) at different distances from ONKALO	<500 ml/h at a distance of 500 m from ONKALO
	Evolution of hydraulic network and fracture properties	Transmissivity	Flow logging + HTU (double packer test)	Once a year	Selected boreholes near tunnels	variation and changes can not be estimated
	Ingression of water	Water level and/or flow rate	-Measuring weir -Water collector	Once a week	Weirs at tunnel + individual leakage points	<100 l/min
	Egression of water	-Air flow rate and humidity -Amount of water used for construction and investigations	-Ventilation and hygrometer (moisture meter) -Water balance	Continuous	Outlets of tunnels and shafts	variation can not be estimated
	Evolution of saline water interface	Electric conductivity of water	Groundwater sampling + flow logging + geophysical measurements	Once/twice a year	Selected open boreholes and ground surface measurements	will be based on numerical calculations (will be published during 2003)

9.4 FRANCE

9.4.1 Context

The long-term management of high level, long-lived waste (HLW) is at a research state in France. The French law (1991) related to this research provides for the study of reversible or non-reversible disposal concepts. This law addresses both environmental and human health protection, as well as the right to choose of future generations. In other words, it emphasizes the right of future generations to act upon the evolution of a HLW disposal process. In December 1998, the French Government made a strong recommendation that the research on HLW management should be performed according to a logic of reversibility.

Choosing a reversible approach to managing the disposal process may be motivated by considerations of:

- Modesty imposed by current limits of scientific knowledge
- Modesty imposed by the involved time scales
- Freedom of choice in waste management offered to future generations in light of potential evolutions in waste management solutions
- Open and flexible approach to long term HLW management
- Need for long term confidence building measures, partially supported by long term monitoring and phenomena analysis

The logic of reversibility was translated into a phased approach of the disposal process during pre-closure, from receipt of the first waste package to closure of the repository (Dossier 2001 Argile). The process was divided into five main steps, as illustrated in Figure 1:

Step 1: The cell is being filled: Receipt and emplacement of the waste packages into the repository. At this stage, all operations are reversible and the access installations to the cell are open. A removable plug (operational phase) allows the emplacement of waste packages.

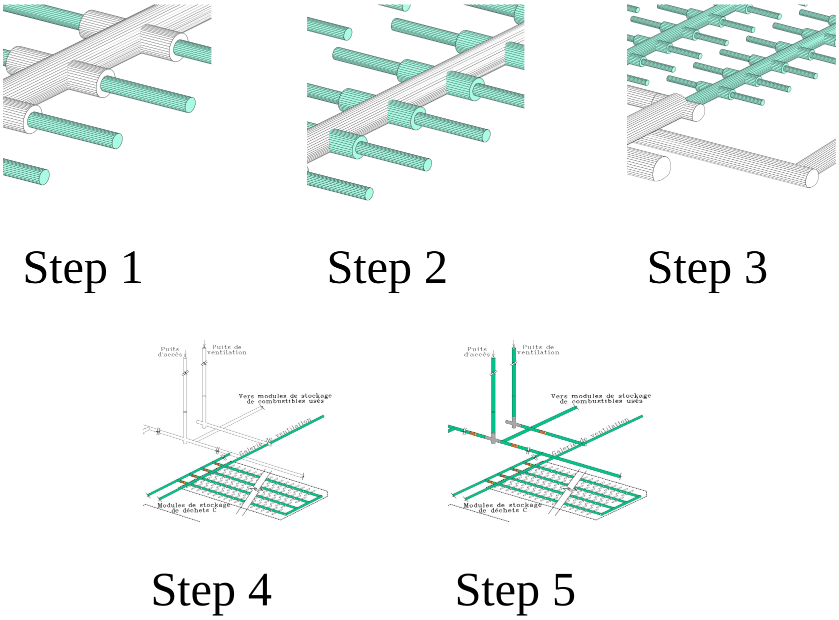
Step 2: The cell is full and closed with a permanent plug. Packages can still be retrieved, by destroying the permanent plug and by re-using a temporary plug.

Step 3: The disposal area is backfilled (cells and handling drift have all been closed), and the underground access is limited. It is still possible to regain access to the package by removing the backfill.

Step 4: Disposal modules have all been closed, and their access drifts (haulage drifts) may also have been sealed.

Step 5: All modules are sealed, and all access drifts and shafts to the repository are also closed: The repository is in post-closure configuration.

Figure 1 Stepwise approach to a reversible disposal process



With each step, the level of reversibility is reduced (it is easier to retrieve a waste package from an open and accessible, rather than a sealed and remote drift). Therefore, decisions to proceed through the steps of the disposal process and to reduce the level of reversibility must be supported by a progressive increase in confidence and sufficient knowledge and data, which are in part provided by monitoring.

9.4.2 Monitoring objectives

Monitoring is an integral part of the reversible management approach. The overall monitoring objective is to support continuous management decisions to proceed, hold, or reverse the disposal process. Specific monitoring objectives respond to the considerations that motivated a reversible disposal process. They are to:

- Provide knowledge on the major phenomena which control the state and the evolution of the components of the disposal system, characterize this state at each step of the disposal process
- Compare these data with existing knowledge of the evolution of the repository, modeling as well as potential future requirements
- Contribute to the stepwise management (decision making) of the facility :
    - assess the knowledge of phenomena that occur in the current disposal phase, increase the confidence in this knowledge : thermal, mechanical, hydraulic, chemical, radiological processes, at various scales and in different locations ;
    - assess the practical conditions in which the disposal process might be reversed and the disposed packages retrieved ;
    - model the future evolution of the system, as a function of the decision to be taken (keep the facility at the present stage, go through the next step of the disposal process, or reverse the process)

In addition, the facility will be monitored during its construction and operation with regard to :

- industrial availability and maintenance of the structures and operating equipment,
- safety and protection of workers and environment: fire detection, air quality, temperature, dose rates etc.

9.4.3 Monitoring in a reversible disposal process

The evolution of the process (the five steps) can be related to the generic time zones identified in the “EC Concerted Action on Retrievability” (Euratom 2000), as shown in Table 1. Note, however, that neither the time zones, nor the steps in the disposal process correspond to an *a priori* defined duration. The logic of reversibility thus provides for a freedom of choice to the next generations, and allows process decisions to be taken whenever the information obtained through either monitoring or other venues is deemed sufficient.

Table 7 Comparison of monitoring during reversible management to the "EC Concerted Action on Retrievability" generic time zones

Time Zone	Description	Monitoring during successive steps of disposal process
1	Interim storage at or near the surface	Site characterization – Baseline information
2	Design and construction of the repository and completion of the first disposal cells	Baseline information
3	Period of filling one disposal cell with waste packages	Step 1 (monitoring of process)
4	Period of keeping the package accessible before backfilling	Period of monitoring while in step 1 (until decision to proceed)
5	Backfilling and sealing of the disposal cell	Step 2 (monitoring of process)
6	Period of keeping the backfilled and sealed disposal cell accessible before backfilling the depositing tunnel	Period of monitoring while in step 2 (until decision to proceed)
7	Backfilling the depositing tunnel	Step 3 (monitoring of process)
8	Period of keeping the access tunnel open, after having backfilled the depositing tunnel	Period of monitoring while in step 3 (until decision to proceed)
9	Backfilling of the access tunnel	Step 4 (monitoring of process)
10	Period of keeping the access shafts open, after having backfilled the access tunnel	Period of monitoring while in step 4 (until decision to proceed)
11	Backfilling and sealing of the shafts	Step 5
12	Post-closure phase with institutional control	Period of post-closure monitoring
13	Post-closure phase without institutional control	

While the monitoring objective (support the decision making process) is independent of repository evolution, the monitoring strategy, as well as methods and techniques, must be adapted to the physical configuration of the observed repository components (accessible, backfilled, sealed, or remote). Therefore, specific solutions must be adapted to each of the steps in a phased approach.

9.4.4 Defining the monitoring program

To respond to the monitoring objectives, a monitoring program is developed taking into account the system to be monitored (i.e., the configuration of the observed repository components), operational and environmental needs, the models and simulations describing the evolution of this system, and available methods, sensors, and transmission systems.

At a given step (i), defining a specific monitoring program requires to:

- Identify those phenomenological parameters controlling the state and evolution of the repository
- Develop models and simulation tools of repository evolution

- Determine a list of relevant indicators (representative parameters that can be monitored)
- Define a monitoring system (architecture, sensors, transmission…)
- Ensure that the monitoring system is adapted to environmental conditions
- Ensure that the monitoring system responds to operational needs (lifetime, access, reliability…)
- Ensure that the monitoring system does not interfere with operational and long term safety

If the decision is taken to evolve towards a different step, the monitoring program is to be updated. This requires to identify:

- If the list of relevant phenomenological parameters has evolved
- If the list of relevant indicators has evolved, either due to representative parameters or to the ability to monitor
- The impact of a changed configuration (areas have been sealed, remote locations, signal transmission…)
- The impact of modified environmental conditions
- The evolution of operational needs (monitoring without access…)
- The impact on long term performance (cables through sealed area?…)

9.4.5 Status of monitoring program in France

A preliminary identification of phenomenological parameters to be observed at each step has been completed. A preliminary inventory of available sensors and transmission cables has been obtained. Preliminary monitoring concepts are being developed based on ongoing analysis of relevant phenomena, process models and parameters.

Specific monitoring goals are identified based on the understanding of the evolution of physical processes in and near repository components. The choice of which parameters and phenomena are most relevant for monitoring is related to the step wise approach and is geared to support decisions of a reversible management. By way of example, a number of important phenomena to monitor during each step are:

Step 1: Re-saturation of the near field and the buffer zone, the relative humidity and temperature near the waste packages, mechanical loads and damage zone near the planned sealing area.

Step 2: Hydrological, mechanical and thermal evolution of the disposal cell seal and of environment behind seal

Step 3: Thermal, re-saturation, and host rock deformation evolution in and near a sealed disposal module

Step 4: Mechanical and hydrological evolution of access tunnel seals

Step 5: Mechanical and hydrological evolution of access shaft seals

The details of a monitoring program have not yet been defined. The ability of sensors and transmission systems to operate under repository conditions, and possibly from inaccessible, remote locations, is under investigation. The ability to perform chemical and radiological monitoring is also under investigation. Specific questions, addressing for example the ability to observe phenomena in a sealed repository component, and analyzing potential implications on the safety case, are being discussed.

ANDRAs research plan between now and 2005 includes following studies related to monitoring :

- Phenomena analyses, modelling of disposal phases and component evolution
- Identification of potential ties to and influence on the level of reversibility and on safety
- Choice of model parameters to be monitored
- Definition of a monitoring program
- Inventory of techniques
- Inventory of requirements
- Analysis of phase-dependant, physical configuration of repository components
- Choice of techniques and instrumentation
- Integration of monitoring program in the design of the disposal concepts

The objective of the research program is to provide a feasibility report on reversible disposal in 2005, including a description of its strong ties to monitoring, as well as a first suggestion for a monitoring program. It has been structured in iterative phases between different research processes, in particular knowledge acquisition, design, modeling and safety assessment.

9.4.6 References

Dossier 2001 *Dossier de synthèse 2001 Argile*, ANDRA, 2001

Euratom 2000 *Concerted Action on the Retrievability of long-lived radioactive waste in deep underground repositories*, European Communities, EUR 19145 EN, 2000

French Law 1991 Loi n° 91-1381 du 30 décembre 1991 *relative aux recherches sur la gestion des déchets radioactifs* (Journal officiel de la République française du 1er janvier 1992) - Code de l'environnement, articles L542-1 à L542-14, 1991

9.5 GERMANY

9.5.1 Context

9.5.1.1 Definition of Monitoring

"Continuous or periodic measurements of properties considered important to safety."
but DBE also supports the definition of the IAEA which is given as follows:

"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."

Legal Framework

Relevant Laws, Ordinances, and Regulations

In the Federal Republic of Germany, laws and ordinances does not specifically deal with HLW or LILW disposal, but with disposal of radioactive waste in general.

The basis of the German regulatory framework is the:

1. *Fundamental Law for the Federal Republic of Germany (Grundgesetz für die Bundesrepublik Deutschland) /4/.*

The Fundamental Law, which entered into force in 1949, is the constitution of the country. Pursuant to this Fundamental Law Germany has a federal organization, with the Federal States being given strong competencies in all aspects of public life. In principle, the Federal States have all competencies not explicitly assigned to the Federal Government. Art. 74 of the Fundamental Law, in its section 11a, assigns to the Federal Government the jurisdiction to regulate:

"The generation and use of nuclear power for peaceful purposes, the construction and operation of facilities to this purpose, the protection against the hazards associated with these activities or with ionizing radiation as well as the disposal of radioactive waste".

This assignment of jurisdiction to regulate radioactive waste disposal has a direct influence onto the distribution of roles and responsibilities between the different authorities and parties working in the field of licensing a repository for radioactive waste.

The Regulatory framework ruling Radwaste in the Federal Republic of Germany includes the following laws and ordinances:

2. *Law on the Peaceful Use of Nuclear Energy and the Protection Against its Dangers, - Atomic Energy Act (Gesetz über die friedliche Verwendung der Kernenergie und den Schutz gegen ihre Gefahren – Atomgesetz, AtG) of December 23, 1959, last amended on July, 2002.*

The most important articles with regard to final disposal are §§ 9a, 9b, 23 and 24 /2/. The Atomic Energy Act rules only general aspects of the licensing procedure and the licensing requirements for a LILW repository. It contains no technical or scientific regulations concerning the design, location, construction, operation, closure, and monitoring of a final repository for radioactive waste.

3. Law on the Establishment of a Federal Office for Radiation Protection (Gesetz über die Errichtung eines Bundesamtes für Strahlenschutz) of October 9, 1989, last amended on May 3, 2000 /5/.

The Law on the Establishment of a Federal Office for Radiation Protection defines BfS's duties. With this law all tasks related to safekeeping of fissile Materials, supervision and licensing of radioactive materials transportation, and disposal of radioactive waste including disposal site development, which until then had been entrusted to PTB, were transferred to BfS.

4. Ordinance on the Protection Against Damage by Ionizing Radiation – Radiation Protection Ordinance (Verordnung über den Schutz vor Schäden durch ionisierende Strahlen – Strahlenschutzverordnung StrlSchV) of October 13, 1976, last amended on July , 2001 /6/.

The Radiation Protection Ordinance rules all aspects of protection against damage caused by ionizing radiation. It is fully applicable, without exception, to the operation of a radwaste repository. It contains no special regulations for repositories.

5. Federal Mining Act (Bundesberggesetz, BBergG) of August 13, 1980, last amended on August 21, 2002 /7/.

The Federal Mining Act is applicable to the establishment of repositories for final disposal in Germany because this act not only rules the mining of natural resources but also the construction and operation of underground facilities for storage of goods and disposal of waste.

In addition to the mentioned laws and ordinances, the responsible authority for regulating radioactive waste management and disposal, at that time the Federal Minister for Internal Affairs, published in 1983 the

6. Safety Criteria for the Final Disposal of Radioactive Waste in a Mine (Sicherheitskriterien für die Endlagerung radioaktiver Abfälle in einem Bergwerk) of January 5, 1983 /8/.

This is the main rule dealing with siting, construction, operation, and closure of a repository for geological disposal of radwaste. As previously stated, the Federal Government, represented by the then competent Federal Ministry for Internal Affairs, promulgated the "Safety Criteria for the Final Disposal of Radioactive Waste in a Mine" in a memorandum of April 20, 1983, to the licensing and regulatory authorities directing them to take the Safety Criteria into consideration in future licensing procedures. Whenever the licensing authorities of the Federal States do not interpret the Safety Criteria as intended by the Federal Government, the Federal Government can force compliancy by issuing directives. The safety criteria are in the process of being revised to be adapted to the most recent state-of-the-art.

Geological final disposal of radioactive wastes is defined by these criteria as maintenance-free, temporally unlimited, and safe isolation of such wastes from the human environment, without a-priori intention of retrieval. The criteria are rather generic, in order to provide a flexible framework that can be adapted to different site conditions.

Although this set of criteria was published in 1983, i.e. after selecting the sites Konrad and Gorleben, it formalizes in a generic manner all aspects actually considered in the site selection processes. Moreover, it also sets up guidelines for the further steps of site development and later repository construction and operation.

The Safety Criteria qualitatively specify measures to be taken to achieve the protection objective of disposal, and define the principles by which to demonstrate compliance with the objectives. The basic idea is that safety is ensured by a series of technical measures and by methods and/or procedures adjusted to one another. The importance of the site selection and the use of state-of-the-art technology are emphasized.

9.5.1.2 Regulatory Authorities in Respect to LILW Disposal and their Advisory Organizations

Germany is a country with a Federal structure. This has a strong influence on the structure of the regulatory, licensing, and supervisory bodies in the field of nuclear waste management and disposal. The regulatory scheme in Germany is therefore significantly different than in other countries.

The Fundamental Law assigns the competence for nuclear matters, and hence for radioactive waste management, to the Federal sphere. The German Parliament, in turn, assigned in 1976 by the fourth amendment of the Atomic Energy Act the responsibility for providing installations for radioactive waste final disposal to the Federal Government.

Pursuant to § 23 of the Atomic Energy Act BfS, which is a body of the federal administration directly subordinated to BMU, is responsible for construction and operation of final repositories. It is the applicant for a license on behalf of the Federal Government, and legally responsible for the repository operation and its supervision in regard to nuclear matters. This supervision begins after the end of the licensing procedure. The legal supervision monitors the construction, operation and decommissioning of the repository in accordance with the regulatory content of the operational license.

The *Federal Institute for Geosciences and Natural Resources (Bundesamt für Geowissenschaften und Rohstoffe, BGR)*, the German Geologic Survey is heavily involved in the site exploration, which shall lead to a site suitability statement before starting the repository licensing procedure, and later to a substantiated safety case for the repository. In these respects parts of the site exploration data are used as input data for baseline monitoring purposes.

Under contract with BfS, DBE carries out the repository planning, including preparation of the license application and of the supporting body of documents. DBE constructs the exploration mine and performs the site survey in cooperation with BGR so as to compile the body of data for baseline monitoring and information necessary to substantiate the repository safety case respectively.

In regard to all radiological and nuclear aspects, the repository operator in the legal sense is BfS. Although DBE carries out the task of running the site on behalf of BfS, it is not the operator in the sense of the Atomic Energy Act. As previously stated, the regulatory body carrying out the nuclear and radiological supervision in the case of the Morsleben deep geological repository is a special organizational unit of BfS, the internal supervision (Eigenüberwachung). For the Konrad repository the supervision scheme will be the same. With regard to the future HLW repository necessary arrangements have not yet been made for they are not needed at present. But on the basis of today’s valid laws and ordinances the scheme will be the same.

Giving a great degree of autonomy to the internal supervision ensures independence of the supervisory function from the role as operator. Internally, this unit reports to BfS’s Vice-President, the unit responsible for the operation to the President.

In regard to the licensing procedure for radioactive waste repositories, the Atomic Energy Act rules that such a repository must undergo a so-called “Planfeststellungsverfahren” (Plan Approval Procedure). The “Verwaltungsverfahrensgesetz” /9/ (Administrative Procedures Act) states that the body responsible for the project (BfS) must submit the plan to the competent authority under the law of the respective Federal State. The authority responsible for issuing the approval to the plan (license) is pursuant to § 24 of the Atomic Energy Act the authority designated to this respect by the *Government of the Federal State* hosting the repository.

Once in operation, the supervision of repositories for radioactive waste in Germany is twofold. On the one hand there is the day-to-day supervision by the mining authorities, which is aimed at ensuring the operational safety of the repository in its condition as a mine. The responsible *Mining Authority of the Federal State* where the repository is located carries out this mining supervision. On the other hand there is the supervision with regard to radiological safety and nuclear matters. This supervision is the responsibility of the Federal Government, and is carried out by the BfS.

The relationship with the Mining Authority carrying out the conventional and mining safety supervision is very fluent, since this authority’s mission is also to advise the mine operator on all safety-relevant aspects. The operator may only carry out any activity potentially affecting the miners' safety, as, e.g., excavating new drifts or disposal chambers, upon approval by the Mining Authority. Inspections, e.g. at the Morsleben repository are carried out on a regular basis

Based on the described legal framework the following regulations have to be considered with regard to repository monitoring:

- Atomic energy act
- Federal Mining Act (BBergG)
- Federal Emission Protection Act
- Act for the order of water regime
- Mining Ordinance for Health Protection (GesBergV)
- Ordinance for Mine Ventilation (KlimaBergV)
- General Ordinance for the storage of dangerous waste
- Radiation Protection Ordinance (StrlSchV)
- Safety criteria for the final disposal of radioactive waste in a mine
- Guidelines for shaft backfilling and monitoring
- Guideline for Emission and Immission Monitoring at Nuclear Facilities (REI), Part C2: Repositories for Nuclear Waste, 12-20-1995.
- DIN 25423: Sampling for Monitoring of Radioactivity in Air, Dec. 1999.
- KTA Safety Rule 1503.1: "Monitoring of the Release of Gaseous and Aerosol Bound Radioactive Substances, Part 1: Monitoring of Radioactive Substances Releases via the Stack During Normal Operation", Issue 6/93.
- KTA Safety Rule 1503.2: "Monitoring of the Release of Gaseous and Aerosol Bound Radioactive Substances, Part 2: Monitoring of Radioactive Substances Releases via the Stack During Normal Operation", Issue 6/93.
- KTA Safety Rule 1504: "Monitoring of the Release of Radioactive Substances with Water", Issue 6/94.

9.5.2 Reasons for Monitoring

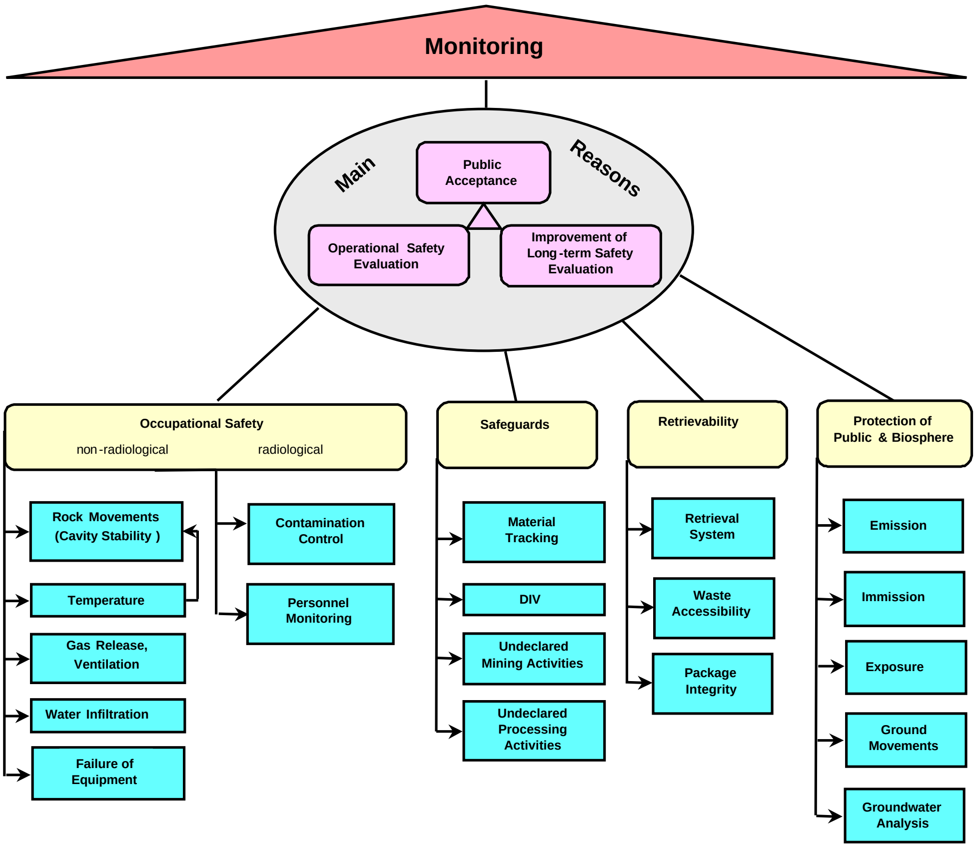
The main reasons for monitoring are the improvement of the long-term safety evaluation, the operational safety evaluation and the public acceptance for a repository implementation. Thus, monitoring shall provide the opportunity to increase confidence in the safety of the disposal system by verifying that the repository evolves in the manner predicted [1].

Taking this as monitoring fundamentals more specific reasons have been derived by defining protection objectives and the societal requirements:

- Occupational safety (radiological, non-radiological)
- Protection of public and biosphere
- Safeguards
- Retrievability

Each of them requires monitoring tasks as shown in Figure 1.

Figure 2 Monitoring – reasons and tasks



The strategy and thus all monitoring activities are based on the defined reasons for monitoring. Monitoring starts with the characterization of conditions at the undisturbed site (baseline conditions) and lasts during repository construction, operation, closure and institutional control. With regard to the given definition of monitoring, all processes and parameters important to safety shall be addressed. This includes the safety for all mining operations and for the waste disposal activities.

The mentioned safety criteria require applying state-of-the-art technologies. Prior to any equipment installation an approval from the authority has to be achieved. Monitoring systems shall be transparent to inspections. That means the measurement system should be as easy as possible with regard to system structure, handling and documentation. At present, a data base system to keep monitoring data (all kind of monitoring data) is under construction at DBE. This is to provide all the information to people who have to work with these data at DBE, BfS and BGR (if required) and for proof keeping reasons. These data are used to evaluate the operational safety and to provide input data for predictive calculations of the system evolution.

With respect to cost efficiency systems shall be used which have proven their reliability and which need less maintenance. R+D projects have been launched to improve existing measuring techniques and to develop new techniques to meet these requirements as good as possible. Quality assurance is to be applied to all monitoring activities

9.5.3 Key processes requiring special attention are:

- Waste emplacement: – correct emplacement, backfilling and sealing procedures
- Safeguards monitoring

Due to experiences concerning shaft and drift sealing obtained from corresponding research projects / in-situ tests, the correct installation of a sealing construction to ensure the proper work of the sealing is a very difficult task. Thus, to prove the proper work of the construction by monitoring without reducing the isolation function is a critical area.

With regard to safeguards monitoring [2] the design information verification and the detection and identification of undeclared mining activities are main objectives. Due to the fact that no monitoring strategies and methods have yet been identified as really suitable, this seems to be a critical area.

9.5.4 Monitoring techniques

With regard to monitoring techniques the following instructions are to be considered:

- The applicability of monitoring systems shall be independent of the geological environment. Any adaptation shall only be a question of specification, housing, etc.
- All systems to be applied shall be based on the state-of-the-art technology.
- Where ever possible a sufficient redundancy of measurement systems shall be implemented.
- Measurement frequency depends on how the individual process can be representatively recorded taking data handling efficiency into consideration.
- Raw data and processed data shall be independently recorded.
- Result evaluation shall consider local effects as well as regional system evolution.
- A regular reporting to the authorities („Jour-fixe“) is to be performed.
- A catalogue on fault reporting shall continuously be updated (distinction between mining law and atomic law).

9.5.5 How to react on unexpected results

Currently there is no action plan available which directly relies on monitoring data. The monitoring results are evaluated by experts and if the need arises, safety measures are discussed and implemented.

9.5.6 References

Biurrun, E., Bundrock, G., Engelhard, J., Horlbeck, B., Jobmann, M., Teichmann, L., Walther, C., Weidenbach, J. 2001: *Repository monitoring in Germany,* Internal Report, 107 pages, editor: M. Jobmann, DBE, Peine, Germany.

Richter, Bernd 1998: *International nuclear material safeguards for the direct final disposal of spent-fuel assemblies*, Nuclear Technology, Vol. 12.

9.6 THE NETHERLANDS

9.6.1 Definition

Monitoring is not defined by legislation or regulation. The normal dictionary meaning is 'maintaining supervision over a (technical) process'.

Monitoring, with the normal dictionary meaning given above, is mentioned in some policy statements:

a) The Dutch policy with respect to underground disposal distinguishes three principles: (1) isolation of the waste, (2) control over the waste facility, and (3) surveillance of the facility. Surveillance will be closely related to monitoring.

b) Legal demands (mining, nuclear, and environmental acts) will require monitoring.

c) Institutional control (e.g. IAEA for non-proliferation) will require monitoring

9.6.2 Context

9.6.2.1 Waste Management

Radioactive waste must be stored in the only Dutch (surface) storage facility near Borssele, operated by COVRA NV, which is a part of the Ministry of Housing, Spatial Planning and the Environment The facilities are designed to store the waste for 100 years, but extension of that period is being studied. After the temporary storage, waste has to be disposed in an underground repository. The site-selection process is not foreseen in the coming (tens of) years. Also no Dutch underground research facility is planned.

Apart from the conventional requirements in the mining act, no specific laws and regulations requiring monitoring for a deep underground facility exist. General requirements for industrial activities are given in the Environmental Law. General requirements for operation of nuclear facilities are given in the Nuclear Energy Law/Radiation Protection Decree. Retrievability is considered essential in any Dutch repository concept.

The Netherlands has ratified (on April 26, 2000) the Joint Convention on the Safety of Spent Nuclear Fuel management and on the Safety of Radioactive Waste Management [1] which entered into force on 18 June 2001. The ratification implies a number of high level monitoring activities (e.g. maintaining a national waste inventory).

9.6.2.2 Research

The most recent national research programme (1996-2000) was steered by the CORA commission: commission for disposal of radioactive waste. Several research reports have been published during this programme. In 2001 the commission published its final report [2].

With respect to monitoring, the commission concluded:

- that allowing surveillance and supervision of retrievable disposal may decrease the societal resistance against disposal.
- that future technical research should focus amongst others on the development, construction and testing of monitoring-systems to be used during the retrievability-period, for surface and for underground facilities.

Of further interest is the NRG report 'Retrievability of Long Lived Radioactive Waste in Deep Underground Repositories - Monitoring & Safety aspects' [3] that has published under a contract of the Dutch Ministry of Housing, Physical Planning and Environment.

9.6.3 Reasons for monitoring

The reasons for monitoring depend on the point of view. Here the government policy, the CORA conclusion, and NRG's reasons for monitoring are given.

Government policy:
Surveillance (and thus monitoring) is one of the three principles of the Dutch waste management policy.

CORA commission:
The CORA report states that surveillance and supervision is a societal requirement for acceptance of disposal.

NRG report on Monitoring &Safety aspects:
In [NRG 26767] the following reasons have been given:

- Monitoring for radiological protection (of facility workers);
- Monitoring for environmental protection (and protection of the general public);
- Monitoring for operational safety (includes non-radiological safety);
- Monitoring for operational control (includes condition of the waste and the disposal cell, especially with respect to retrieval);
- Monitoring for safeguards purposes;
- Monitoring to enhance confidence in the predicted behaviour of the repository system.

9.6.4 Monitoring strategy

No monitoring strategy has been developed yet. It should be mentioned that, with respect to the Dutch principles for disposal, the monitoring strategy would be incorporated in a surveillance plan.

9.6.5 Key processes to be monitored

Monitoring for radiological protection (of facility workers):

- Radiation levels

Monitoring for environmental protection (and protection of the general public):

- Chemical, biological, and radiological characteristics of gas, groundwater and soil.

Monitoring for operational safety (includes non-radiological safety):

- Deformation of excavations
- Deformation of backfill material
- Moisture contents
- Ventilation
- (emplacement) System status
- Fire/smoke detectors
- Access of personnel

Monitoring for operational control (includes condition of the waste and the disposal cell, especially with respect to retrieval):

- Status of waste confinement
- System status of disposal cell
- System status of access tunnels

Monitoring for safeguards purposes:

- Incoming and outgoing colli
- Sealing of waste packages
- Access of personnel
- External inspections of waste management organisation and facilities

Monitoring to enhance confidence in the predicted behaviour of the repository system

- Temperature (versus prediction)
- Deformations and stresses (versus prediction)
- Moisture content (versus prediction)
- Ground water flow patterns (versus prediction)

9.6.6 Monitoring techniques

For most of the processes to be monitored a large variety of techniques is available. A list is given in [3].

9.6.7 Availability, required development

With the introduction of retrievability into the disposal strategies, a need for monitoring of the system status of the waste and the disposal cells has arisen. Because the waste is isolated by one or more barriers in the disposal cell, it is difficult to 'measure' the system status without affecting the barriers.

This is reflected in the conclusion of the CORA commission: 'that future technical research should focus amongst others on the development, construction and testing of monitoring-systems to be used during the retrievability-period, for surface and for underground facilities.'

Examples of remote monitoring are ultrasonic inspection and geo-electric monitoring.

9.6.8 How to react to unexpected monitoring results?

The causes and consequences of the unexpected results have to be analysed. The potential for corrective actions must be determined. It makes sense to develop in advance a strategy for dealing with unexpected results or deviations from the expected results.

9.6.9 References

Euratom, *Nuclear Safety Convention for Spent Fuel Management and the Safety of Radioactive Waste Management*, Official Journal of the European Communities, C51 E/260, 26 February 2002.

CORA commission, *Retrievable disposal of radioactive waste in The Netherlands; Summary,* Ministry of Economic Affairs, February 2001.

F. van Gemert and J.B. Grupa, *Retrievability of Long Lived Radioactive Waste in Deep Underground Repositories; Monitoring and Safety Aspects*, NRG report 20220/00.36767/P, 18 June 2001.

9.7 SPAIN

9.7.1 Definition

ENRESA has previously dealt with a definition of monitoring specifically aimed to radiological monitoring. However, monitoring should be defined in a more general way including all the processes whereby the quantity and quality of factors that can affect the environment and/or human health are measured in order to regulate and control future potential impacts. Thus monitoring could be defined as:

> *"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"*

9.7.2 Context (including legal framework)

In Spain, ENRESA is responsible for the implementation of the waste management system. Nuclear Safety Council (CSN) is the regulator for nuclear safety and radiation protection. Currently there are not any national monitoring requirements, regulations or legislation for the deep geological disposal concept. Anyway, some regulations (in terms of laws & regulatory guides) exist about nuclear & radioactive installations as well as technical instructions relating working activities in mines.

Regarding El Cabril, a facility for disposal of Low & Intermediate Level Waste, the Environment Radiological Surveillance Plan essentially regulates the monitoring activities which will affect the environment (water and air quality and flora and fauna) in a radius of 10 Km around the repository and the quality of the water collected from the disposal cells, for the operational phase.

Spanish Regulators

Nuclear Safety Council (Nuclear Safety)
Nuclear Energy Sub-Directorate within the Ministry of Economic Affairs (Safeguards).
Mining Sub-Directorate within the Ministry of Economic Affairs (Non-radiological Safety).

Spanish Regulations

Legislation:

Among the most important legislation with implications for monitoring they could be mentioned the following:

- Nuclear Energy Act (Law 25/1964)
- "Real Decreto 783/2001 Reglamento sobre Protección Sanitaria contra Radiaciones Ionizantes": Royal Decree which incorporates Council Directive 96/29/EURATOM, 13 May 1996, laying down basic safety standards for the protection of the health of workers and the general public against the effects of ionising radiation.
- "Real Decreto 1836/1999 Reglamento sobre instalaciones nucleares y radiactivas": Royal Decree with regulations about nuclear & radioactive installations and licensing procedures.

Regulatory Guides (Spanish Nuclear Safety Council):

The regulatory authority (Nuclear Safety Council) issues Regulatory Safety Guides for specific purposes related with nuclear installations. Some of them deal with monitoring aspects, but not dedicated to waste disposal facilities:

- GSG 01.04 Radiological control and surveillance of liquid & gaseous radioactive effluents arising from NPP's

- GSG 04.01 Design and development of an Environmental Radiological Surveillance Programme for NPP's
- GSG 05.03 Control of encapsulated radioactive sources

Technical Instructions (from Spanish Law of Mines)

- ITC 04.7.02 Limit values for gas concentrations, temperature, humidity and climate conditions.
- ITC 04.7.04 Ventilation: inspection and surveillance
- ITC 04.8.01 Environmental conditions: dust

9.7.3 Reasons for monitoring

The main reasons for monitoring are to:

- show compliance with international and national guidelines and regulations,
- evaluate the behaviour of system barriers,
- demonstrate understanding of the behaviour of system barriers and
- assist in the decision-making process.

9.7.4 Monitoring strategy

Monitoring strategy could be defined as "determination of basic monitoring objectives, the adoption of courses of action and the allocation of resources necessary for carrying out these objectives". Although up to now a monitoring strategy has not been developed, some ideas have arisen from the development of conceptual designs.

As monitoring objectives clearly depends on the repository phase, different strategies should be implemented for these phases. For every repository phase or "time zone", the monitoring strategy could be developed following three main stages: preliminary studies, conceptual plan and implementation plan. These stages are previous to the beginning of monitoring itself.

Herein it can be found a proposed set of activities to be included in the framework of each stage:

Stage 1: Preliminary studies.

- *Definition of specific monitoring objectives* (e.g. show compliance with regulations, guidelines or technical specifications; evaluate the behaviour of system barriers; etc.)
- *Identification of processes and parameters to be monitored* (processes and parameters that monitor the fulfilment of the specific objectives defined for each time zone). These processes & parameters should be "monitorable" and relevant.
- *Identification of available technologies* (to monitor those processes and/or parameters*).*

Stage 2: Conceptual plan.

- *Analysis and evaluation of available technologies and feasibility studies* (analysis in terms of availability, functionality, accuracy, cost, etc. Evaluation of available technologies against functional requirements)
- *Selection of techniques* (selection of the "best" technique to monitor each of the processes/parameters)
- *Definition of monitoring programme* (duration of the monitoring regime, frequency of sampling or measurements, limit setting etc.)

- *Definition of modelling tools for data analysis* (methods and/or tools to derive relevant data from sampling or measurements)

Stage 3: Implementation plan

- *Definition of detailed instrumentation (architecture and sensors).* Definition of monitoring scheme architecture, location of sensors, redundancies, etc. Installation, calibration, operation, maintenance, intervention (in case of failure) and dismantling procedures.
- Definition of control scheme (data acquisition and transmission).
- *Data analysis and resulting actions.* Simulation of foreseen evolution, Assessment of compliance, Criteria for non-compliance conditions, How to react to unexpected results?.
- *Reporting of monitoring data.* Audience & users, type of information, feedback, frequency, etc.

These three stages should be implemented for each one of the repository phases or "time zones" (site characterisation, excavation, construction, operation, closure, post-closure, etc.).

This strategy will be different in terms of scope, objectives and implementation depending on the time zone, as specific features will require not affording some of the steps within each time zone.

9.7.5 Key processes to be monitored

During site characterisation phase, key processes to be monitored are geological, hydrogeological and geochemical processes as well as environmental processes to establish baseline conditions.

Within construction phase, geomechanical processes are of major interest and in-situ surveillance of hydrogeological and geochemical conditions is also important.

Key processes to be monitored during operational phase are those related to environmental aspects (radiological and working conditions), safeguards, equipment operation, implementation of barriers and system behaviour during this phase.

Within closure phase, material characterisation and installation are key processes.

Finally, during post-closure phase, key processes are those relevant to support assessment of repository performance, and safeguards control.

9.7.6 Monitoring techniques

The development of mining technologies as well as underground research laboratories leads to gather experiences in different monitoring techniques. Depending on the monitoring objectives these techniques will require further developments.

ENRESA has experience in some kinds of monitoring, in particular in monitoring for site investigations (El Cabril Project, El Berrocal Project, FEBEX Project, etc.) and for barrier performance (FEBEX Project, ASPO Backfill & Plugging Test).

Some examples of experience in site monitoring are:

- Climatological & radiological monitoring of nuclear sites.
- Geophysical studies (helicopter airborne geophysics, geophysical borehole testing, radar survey and seismic tomographies).
- Lithological and mineralogical characterisation.
- Hydrochemical and isotopic characterisation of groundwater.
- Hydrogeological characterisation (packers and pressure sensors).

Other examples of experience in monitoring of non-radiological underground environmental conditions:

- Temperature (thermocouple)
- Deformation/Displacement (strain gages)
- Pressure (vibrating wire & piezoresistive)
- Water content (capacitive, psycrometer, TDR)
- Gas pressure (magnetic)
- Velocity of ventilation air (hot wire)
- Drift inflow (absorbent material on the walls)

9.7.7 Availability, required development

Although different feasible methods for use during site investigation and barriers performance have been investigated, it is foreseeable that current monitoring methods will experience great advances in the future, as well as the development of new monitoring techniques through technology innovation processes.

In the long term, post-emplacement monitoring (radiological & non-radiological) is the issue of major concern and maintenance/longevity of monitoring equipment could be a critical area, so increasing efforts in developments will be required.

9.7.8 How to react on unexpected monitoring results?

The reaction on unexpected monitoring results is an issue that cannot be addressed in a general way and requires a case-by-case analysis. Response plans should be specifically defined for every process or parameter to be monitored.

9.7.9 References

ENRESA. EL BERROCAL project. *Characterisation and validation of natural radionuclide migration processes under real conditions of the fissured granitic environment.* Madrid, July 1996.

ENRESA. FEBEX project. *Full-scale engineered barriers experiment for a deep geological repository for high level radioactive waste in crystalline host rock*. Publicacion tecnica 1/2000. Madrid, March 2000.

9.8 SWEDEN

9.8.1 Definition

The following definition of monitoring applies:

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.

9.8.2 Context (including legal frame work)

The nuclear industry has the responsibility for managing and disposing of all radioactive wastes from its plants. The owners of the nuclear power plants jointly formed Swedish Nuclear Fuel and Waste Management Co. (SKB) for this purpose. SKB is responsible for the implementation of the waste management system. Several laws and regulations govern the work. Swedish Nuclear Power Inspectorate (SKI) and the Swedish Radiation Protection Agency (SSI) are the main authorities for safety issues related to built and planned nuclear facilities and radiation protection respectively. SSI is e.g. responsible for reporting in accordance with the EURATOM Treaty (Article 35 – 37) stating that: (Article 35) "*Each Member State shall establish the facilities necessary to carry out continuous monitoring of the level of radioactivity in the air, water and soil and to ensure compliance with the basic standards. The Commission shall have the right of access to such facilities; it may verify their operation and efficiency",* (Article 36) "*The appropriate authorities shall periodically communicate information on the checks referred to in Article 35 to the Commission so that it is kept informed of the level of radioactivity to which the public is exposed",* (Article 37) *"Each Member State shall provide the Commission with such general data relating to any plan for the disposal of radioactive waste in whatever forms will make it possible to determine whether the implementation of such plan is liable to result in the radioactive contamination of the water, soil or airspace of another Member State."*

The spent nuclear fuel will be disposed of in a deep repository. The legal responsibility for the deep repository will be transferred to the state after closure of the repository. The comprehensive program for implementation of the waste system is accordingly to the Act on Nuclear Activities, reviewed every third year based on the R&D program prepared by SKB. The fee levied on the producers of the electricity by nuclear power is by law decided yearly according to the Act on the Financing of Future Expenses for Spent Fuel etc. More details on the current (2004) programme can be found in SKB, 2001a, 2001b.

General restraints on environmental impact etc. are stipulated in laws and regulations and are also established as a part of the licensing process. There are no specific laws and regulations requiring monitoring for the deep repository besides the data collected for any major industrial plant. However SKI states in the regulations and general recommendations (SKIFS 2002:1, 8§) launched Oct 24, 2001 that *"the impact on safety of such measures that are adopted to facilitate the monitoring or retrieval of disposed nuclear material or nuclear waste from the repository, or to make access to the repository difficult, shall be analysed and reported to the Swedish Nuclear Power Inspectorate".* The regulations also advise that actions taken *"should show that these measures either have a minor or negligible impact on repository safety, or that the measures result in an improvement of safety, compared with the situation that would arise if the measures were not adopted".*

The implementation of the deep repository is executed in stages with intervening permits at major decision points. A major recurrent issue is the work to confirm the long-term safety of the repository. The evaluation work is based on the results of the comprehensive research, development and demonstration programme for a broad number of issues. The scientific approach is followed, so independent researchers can confirm the results by SKB. Repeated measurements or observations during a longer period of time, generally extending over several stages of repository development will generate data to meet a range of objectives.

9.8.3 Reasons for monitoring

Monitoring is executed of several reasons, mainly to:

- describe the Primary Baseline conditions of the repository site,
- develop and demonstrate understanding of the repository site and the behaviour of engineered barriers,
- assist in the decision-making process,
- show compliance with international and national guidelines and regulations.

Specific rationales are to:

- obtain knowledge of undisturbed conditions in nature and their seasonal variations (baseline) in order to identify and evaluate the impact of activities related to the deep repository during different phases,
- obtain a better understanding of the function of the deep repository system to support the safety account and to test models and assumptions,
- monitor the environmental impact of the deep repository,
- provide evidence that the working environment is safe with regard to radiological and non-radiological effects,
- show that requirements on radioactive waste verification (safeguards) are fulfilled.

9.8.4 Monitoring strategy

A basic strategy for monitoring is that monitoring of the site conditions and other conditions should be closely tied to the general implementation programme. The monitoring programme is not viewed as an independent activity but as a well-integrated task in the site-specific programme of investigations from the surface and from the underground and in the construction, operation and preparations for closure of the repository.

SKB has prepared a monitoring strategy (Bäckblom & Almén 2004), that in appropriate detail will include:

- objectives for the monitoring programme,
- criteria for selection of issues to be monitored,
- identification of the properties, processes, phenomena and observable quantities to be monitored,
- identification on what methods to be used,
- identification of the duration and frequency of monitoring, including criteria for when monitoring may terminate,
- specifications on quality control and reporting of results of monitoring,
- decision on trigger levels (if necessary) for actions and
- decisions on what actions should be pursued in case trigger levels are exceeded.

9.8.5 Key processes to be monitored

Key processes to monitor are physical, chemical and biological conditions of importance to support the engineering of the repository, to analyse the long-term safety and to clarify the environmental impact. Possible processes and parameters that may be monitored are outlined in Table 1.

9.8.6 Monitoring techniques

SKB has experience from many kinds of monitoring from study-site investigations, from the construction of SFR (final disposal for short-lived, low- and medium-level waste from operation of nuclear facilities), CLAB (interim storage for spent fuel) and the construction and operation of Äspö Hard Rock Laboratory. Techniques in potential use for site characterisation and site monitoring are described in SKB, 2001b.

9.8.7 Availability, required development

SKB has feasible methods for use during the site investigation phase. It is foreseen that further developments – not possible to specify now – are needed for instruments to be used during the construction and operation of the repository.

9.8.8 How to react on unexpected monitoring results?

Procedures for monitoring are described in the SKB Quality System including data check, calibrations etc. The observational method will be applied during construction and operation of the repository, meaning that there are pre-established action plans for a range of unexpected conditions.

9.8.9 References

SKB reports are downloadable from www.skb.se

Bäckblom, G., Almén, K.-E., 2004. *Monitoring during the stepwise implementation of the Swedish deep repository for spent fuel*. SKB R-04-13. Svensk Kärnbränslehantering AB, Stockholm.

SKB, 2001a: *RD&D-Programme 2001. Programme for research, development and demonstration of methods for the management and disposal of nuclear waste*. 355 p. Svensk Kärnbränslehantering AB, Stockholm. ISSN 1104-8395.

SKB, 2001b: *Site investigations. Investigation methods and general execution programme.* SKB Technical Report TR-01-29. 264p. Svensk Kärnbränslehantering AB, Stockholm. ISSN 1404-0344.

Table 8 Possible need for monitoring in different implementation stages

Site investigation phase	Construction and detailed characterization phase	Initial operation, regular operation, closure phases	Post-closure phase during institutional control
Environmental monitoring programme - disturbance of surface investigations	**Environmental monitoring programme** - disturbance of supplementary surface investigations - impact of repository construction (soil, groundwater, gas, noise)	**Environmental monitoring programme** - disturbance of supplementary surface investigations - impact of repository construction (soil, groundwater, gas, noise)	**Environmental monitoring programme** - impact of rise of groundwater level **Documentation is preserved**
Climate - temperature, atmospheric pressure, precipitation, evaporation, runoff, sea level changes **Biosphere** - flora, fauna, soil layer land use etc.	**Climate** - temperature, atmospheric pressure, precipitation, evaporation, runoff, sea level changes **Biosphere** - flora, fauna, soil layer land use etc.	**Climate** - temperature, atmospheric pressure, precipitation, evaporation, runoff, sea level changes **Biosphere** - flora, fauna, soil layer land use etc.	**Climate** - temperature, atmospheric pressure, precipitation, evaporation, runoff, sea level changes **Biosphere** - flora, fauna, soil layer land use etc. **Documentation is preserved**
Boreholes from the ground surface - groundwater chemistry and pressure, temperature	**Boreholes from the ground surface** - groundwater chemistry and pressure, temperature	**Boreholes from the ground surface** - groundwater chemistry and pressure, temperature	**Documentation is preserved**
	Boreholes from underground - groundwater chemistry and pressure, temperature - deformations in the rock	**Boreholes from underground** - groundwater chemistry and pressure, temperature - deformations in the rock	**Documentation is preserved**
Seismic events - time, location and type of local earthquakes	**Seismic events** - time, location and type of local earthquakes - micro-seismic events **Surveillance of the repository** - fire, - floods, seeping water, pumped-out water (quantity, quality) - ventilation (temperature, quantity, quality) - noise - monitoring of conditions for preventive maintenance - stability of underground openings	**Seismic events** - time, location and type of local earthquakes - micro-seismic events **Surveillance of the repository** - fire, - floods, seeping water, pumped-out water (quantity, quality) - ventilation (temperature, quantity, quality) - noise - monitoring of conditions for preventive maintenance - stability of underground openings - radiation monitoring - safeguards	**Seismic events** - time, location and type of local earthquakes - micro-seismic events **Documentation is preserved** **Surveillance of the repository** - safeguards **Documentation is preserved**

9.9 SWITZERLAND

9.9.1 Definition

In Switzerland, no official or formal universal definition for monitoring does exist. Two options have been used in the past:

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."*

9.9.2 Context, legal framework and disposal concept

According to Swiss law, the producers of nuclear waste are themselves responsible for its safe management. Hence, in 1972 the electricity supply utilities, which operate five nuclear power plants (with a total capacity of 3'200 MW_e), and the Federal Government (responsible for the wastes from medicine, industry and research) formed the National Cooperative for the Disposal of Radioactive Waste (Nagra). Nagra is responsible for preparing for the disposal of all categories of waste.

In the Swiss disposal concept, two types of repository are foreseen, namely

- the repository for low- and intermediate-level waste (L/ILW) arising from the operation and decommissioning of Swiss nuclear power plants and from medicine, industry and research, as well as for low-level technological waste from reprocessing. The repository will consist of mined caverns located in a suitable geological formation;
- the repository for vitrified high-level waste (HLW), long-lived intermediate-level waste (ILW, primarily resulting from fuel reprocessing) and for direct disposal of spent fuel (SF) elements. The repository will be located in a deep geological formation and will consist of a drift system for in-tunnel emplacement of HLW and SF and drifts or silos for long-lived intermediate-level waste, with access via a vertical shaft or ramp.

Following a long a systematic evaluation procedure and a comprehensive investigation phase, Wellenberg has been proposed as the site for a L/ILW repository. The general license application was submitted to the Federal Government in 1994, and subsequently the Wellenberg site was judged as being suitable for more detailed investigation by the Swiss safety authorities and by experts in relevant fields (BFE 1998). In 1995, the project was blocked by a cantonal veto on the utilisation of underground spaces. However, as a result of intensive dialogue, a concession for an exploratory drift has been issued by the local government. A public referendum on drift construction was subsequently held on the 22 September 2002 and was rejected by the people of the canton. Consequently, Wellenberg was abandoned, and a formal programme for further L/ILW work is currently under development.

For the siting of the SF/HLW/ILW repository, the sediments - where Opalinus clay is the primary option and the Lower Freshwater Molasse a reserve option - and the crystalline basement in Northern Switzerland are under consideration. In addition to the possibility of disposing of these wastes within Switzerland, the option of disposal within the framework of multinational projects is also kept open. The repository for HLW and SF will not be required before the middle of this century.

9.9.2.1 Legal framework

As of the end of 2003, the present nuclear legislation in Switzerland poses no explicit requirements on monitoring:

- Atomic Law of 23rd December 1959
- Federal Government Act on the Atomic Law of 6th October 1978
- Radiological Protection Law of 22nd March 1991
- Radiological Protection Ordinance of 22nd June 1994

However, the new Nuclear Energy Law (KEG 2003) - which has passed parliamentary debate in the Spring of 2003 and will get into force without any public referendum once the corresponding Federal Ordinance is finalised (most likely in 2005) - explicitly defines an 'observation phase' as a 'longer time period during which a deep geological repository will be monitored and the radioactive waste would be retrievable without substantial effort'. The law requires the owner of the repository to present a state-of-the-art project for the observation phase (and subsequent closure) after the radioactive waste has been emplaced. After the observation phase, the Federal Council shall order the closure of the repository, when permanent protection of man and the environment is ensured. After closure, the Federal Council may require a prolonged (but time-limited) surveillance of the repository.

Guideline R-21 (HSK & KSA 1993) of the Swiss nuclear safety authorities requires that any special measures taken for monitoring may not (significantly) degrade the barrier functions of the repository. The long-term safety of the repository shall be based on a multi-barrier system (safety principle 4), and "*any measures which would facilitate surveillance and repair of a repository or retrieval of the waste shall not impair the functioning of the passive safety barriers*" (safety principle 5). Furthermore, the guideline requires that no undue burden is put on future generations (safety principle 6).

Safety principles 4, 5 and 6 were eventually converted into Protection Objective 3: *"After a repository has been sealed, no further measures shall be necessary to ensure safety. A repository must be designed in such a way that it can be sealed within a few years."*

Protection objective 3 specifies the boundary conditions for monitoring (and retrievability) of the waste. It states clearly that there must be no necessity to carry out active measures (monitoring and maintenance) in order to ensure safety – after it has been sealed a repository has to be safe without any further active measures being taken. It is not, however, specified whether, and for how long, the repository should be monitored and maintained. Neither is it specified when the repository may be sealed – sealing could therefore take place immediately after waste emplacement, or years or decades later (provided long-term safety is not compromised).

Requirements on waste characterisation (and interim storage) are described in Guideline R-14 (HSK 1988).

9.9.2.2 Concept of monitored long-term geological disposal

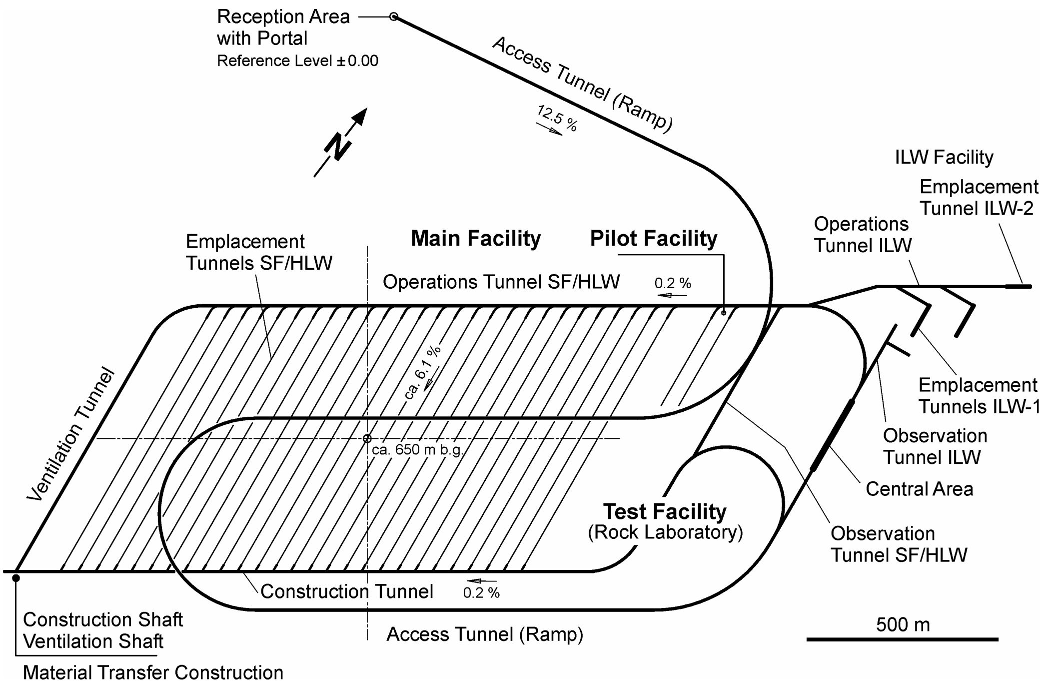
The new version of the Nuclear Energy Law (KEG 2003) has adopted the concept of monitored geological disposal as proposed by EKRA (Swiss Expert Group on Disposal Concepts for Radioactive Waste). It foresees the disposal of radioactive wastes in a deep geological disposal facility where, after the emplacement, a period of monitoring will take place before the facility is closed (EKRA 2000).

The concept specified by EKRA combines the need for passive safety, as ensured by disposal at depth in a stable geological environment, with a cautious, stepwise approach to implementation, which is intended to address not only scientific and technical issues but also societal concerns. The approach involves an extended period of monitoring, during which retrieval of the waste is relatively easy, and the emplacement of a representative fraction of the waste in a pilot facility to test predictive models and to facilitate the early detection of any undesirable behaviour of the system, if this should occur. Opportunities are, thereby, provided for the review and possible reversal of decisions, including the retrieval of the emplaced waste.

The concept of monitored long-term geological disposal has been considered for the proposed repository for spent fuel (SF), vitrified high-level waste (HLW) and long-lived intermediate-level waste (ILW) in Opalinus Clay, located in the potential siting area of the Zürcher Weinland (Nagra 2002a-c). The elements of the disposal system are illustrated in Figure 1 and include:

- the main facility where the majority of the waste will be emplaced
- the test facility to provide the information required before the main facility starts operation
- the pilot facility containing a small but representative fraction of the waste, to provide information on the behaviour of the barrier system and to check predictive models
- a tunnel system providing access and connecting the different system components, including tunnels for the near-field and environmental monitoring programmes.

Figure 3 **Plan view of the repository for spent fuel (SF), vitrified high-level waste (HLW) and long-lived intermediate-level waste (ILW) in Opalinus Clay**



9.9.2.3 Construction and operation

Implementation and closure of a geological repository proceeds in a stepwise manner: Once the investigations from the surface are complete, a test facility (rock laboratory) is constructed at the planned disposal level to obtain additional information for the construction of the main facility and for confirming the parameters that are important for long-term safety assessment.

Construction of the repository involves the completion and installation of all components of the disposal facility that are required for the emplacement of radioactive waste. This is followed by the emplacement of SF and HLW in the pilot facility and of ILW in the corresponding emplacement tunnels. The disposal operation also includes backfilling and successive sealing of the disposal units. At the same time, the first emplacement tunnels are constructed in the main facility. This work is carried out using the construction and ventilation shaft. Further emplacement tunnels are constructed in parallel with emplacement operations in the main facility. Once emplacement has been completed, all tunnels are sealed and monitoring is concentrated a) on the pilot facility, and b) on the near field and the geological environment of the main facility by means of observations from the still open observation tunnels.

Special seals are installed when the main facility is closed. Access still remains possible to the test facility and by means of the observation tunnels to the pilot facility. After an extended monitoring phase, a decision is made to close the entire facility and the remaining open access routes are backfilled and sealed.

9.9.2.4 Monitoring

Monitoring activities will change with regard to objectives and location during the stepwise implementation of the geological repository: Monitoring during site investigations from the surface and later from underground will primarily be done for establishing baseline conditions and later either to confirm the expected behaviour or to detect any unexpected changes above ground and in the geological media during the construction of the exploratory/access tunnel.

During the design and construction phase (and continued for some parts during waste emplacement) monitoring will be focused around activities in the test facility in order to optimise the design, construction, operation and closure of the repository.

During the operational period, the earlier monitoring programmes will be partially continued and complemented by some new monitoring activities relevant to the emplacement of radioactive materials inside the repository. These measurements and observations, which are aimed particularly at ensuring occupational safety and radiation protection of the personnel and the population near the repository site, are expected to form an integral part of future licensing requirements, and are likely to be similar as for any other nuclear facility.

Monitoring of the pilot facility after the waste has been emplaced and the emplacement tunnels are backfilled and sealed supports the decision-making process leading to closure of the repository. This facility provides ample possibilities for a broad instrumentation of basically all components of the disposal system which will allow for a comprehensive long-term monitoring of the hydraulic, chemical and mechanical conditions of the waste, the engineered barriers and the surrounding host rock. Measurements will also be possible in boreholes drilled from the observation tunnels of the pilot facility and from the access tunnel (ramp) above the main facility which allow for environmental monitoring. Additional observation tunnels may be constructed from the ramp above the main facility if needed.

After the repository has been closed, any monitoring will most probably be done from the surface, in order not to impair long-term safety, and will be continued as long as it is thought beneficial to society. Any direct radiological evidence for the validation of predictive modelling results is very questionable; due to the high efficiency of the engineered (and natural) barrier system, the potential release of radioactivity into the biosphere will only occur a very long time after the waste has been emplaced, and it will be very small. Nevertheless, measurements made from the surface may provide a good basis for public reassurance, and may even be a societal requirement.

In-situ activities will be complemented by activities off-site, which may include work in generic rock laboratories, general laboratory work and studies and (in general) keeping an eye on the development of science and technology in the relevant areas. Hence, a whole spectrum of surveillance and monitoring activities will ensure that, for the different milestones regarding stepwise repository development, the necessary scientific information basis will be available.

In view of the long time frames involved until a decision will be taken on the construction of a repository for SF, vitrified HLW and long-lived ILW a complete and detailed monitoring strategy has not been developed yet. However, the role of the different facilities in the different phases of repository implementation has been elaborated for a geological repository for low- and intermediate-level waste (L/ILW) at the (meanwhile abandoned) Wellenberg site (GNW 2000, HUGI et al. 2001). A similar approach will be adopted in due time for the SF/HLW/ILW repository.

9.9.3 Reasons for monitoring

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

- to provide supplementary information for making management decisions in a stepwise programme of repository construction and operation;
- to confirm and strengthen the understanding of some aspects of system behaviour used in developing the safety case for the repository and to allow further testing of models of these aspects;
- to provide supplementary 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 after closure;
- to accumulate an environmental database on the repository site and its surroundings that may be of use to future generations;
- 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 maintaining and establishing confidence in the long-term ability of the repository to isolate the wastes properly, monitoring will also be carried out in the operational phase in order to demonstrate compliance with requirements common to any operating nuclear facility. This will include monitoring to determine any radiological impacts of the operational disposal system on personnel and on the general population, to determine non-radiological impacts on the environment surrounding the repository and to ensure compliance with non-nuclear industrial safety requirements for an underground facility (e.g. dust, gas, noise, radon gas, etc.).

9.9.4 Monitoring strategy

Monitoring is part of the Nagra programme since more than 20 years. Key monitoring aspects are:

- Monitoring objectives
- Repository development phases
- Elements of "surveillance strategy"
- Boundary conditions

9.9.4.1 Monitoring objectives

Five broad areas have been identified where monitoring is important in the process of the development of a repository

- monitoring as part of the *scientific/technical investigation programme* (e.g. information for site selection and characterisation[1], design and construction of the facility and for safety assessment); this also includes monitoring of baseline conditions at potential repository sites;
- (radiological, non-radiological) monitoring of the *acceptable operation* of facilities (as prescribed by authorisation), i.e. activities related to the development/ operation of the repository and related facilities (without unacceptable impacts for operating personal, general population, natural environment, e.g. emmissions, immissions, key features of the facility/process);

- *confirmation* that key assumptions/conclusions still hold (e.g. PA incl. underlying information base is still adequate, waste management option under development still appropriate, ...). Here also societal needs are considered (e.g. implementation of a programme to stay involved with the issue of long-term waste management, incl. monitoring of possibilities for alternative options);
- *non-proliferation* (nuclear safeguards - although this might be integrated in one of the other categories);
- *maintain the confidence* of future generations in the adequacy of the repository.

[1] *no one-time measurements related to site characterisation are included*

9.9.4.2 Repository development phases

Monitoring is very dependent upon the phases of the repository development. The following broad phases are distinguished for discussing monitoring needs

- *pre-implementation phase* - phase of Research, Technical Development & Demonstration: concept development (including basic research), site selection, site characterisation from surface and underground, etc.
- *implementation phase* - phase of construction and operation of the repository (emplacement of wastes)
- *post-emplacement pre-closure phase* - phase of observation after emplacement of the wastes
- *post-closure phase* - phase of observations after closure (institutional control)

Monitoring is not looked at in isolation: It is part of a more general surveillance strategy connected to the available options and the criteria for decision-making. Thus, the strategy is related to the available alternatives (e.g. reversibility) and the corresponding decision-making.

9.9.4.3 Elements of "surveillance strategy"

Major elements of the surveillance strategy in relation to the stepwise implementation for deep geological repositories are:

- monitoring activities (with corresponding objectives, boundary conditions, time frames)
- options of how to proceed with repository development
- criteria for decision-making (to be defined!)
- decision-making process (who? - what? - when?)

9.9.4.4 Boundary conditions

Furthermore, preliminary boundary conditions and criteria have been defined to develop a monitoring strategy, e.g.:

- duration of monitoring in comparison with the time scales (life time) of the different features, events and processes of the repository
- the need for passive safety without reliance on monitoring
- no compromises with respect to safety to enhance monitoring possibilities

- a convincing safety case has to be developed prior to the emplacement of wastes: monitoring in the post-emplacement phase is not part of the safety case, however, it is part of confirming it
- the societal component of monitoring (e.g.: continue with monitoring as long as there is a societal need for it)

9.9.5 Key processes to be monitored

The broad operational aims of monitoring and the corresponding key processes/parameters that require monitoring typically are:

- *Monitoring of wastes* (characterisation/confirmation, quality assurance) for all wastes that are produced; determination of variability of key properties; periodic analyses of different samples during pre-implementation phase (monitored parameters and frequency depend upon waste type)
- *Establishing of base line conditions* is done (or will be done) on each site where significant perturbations might occur due to e.g. drilling of deep boreholes, exploration gallery, repository construction and operation; monitoring of those properties used to define the baseline (also for reasons of liability); environmental measurements to define the "unperturbed conditions" (including variability) for later measurements to detect any systematic deviations
- *Confirming of "unperturbed conditions"* is done (or will be done) on each site where significant perturbations might occur, for instance by "Quellen- und Grundwasserüberwachungsprogramm" (German name for well established Nagra programme)
- *Characterisation of natural environment* (especially geology and hydrogeology but also issues like meteorology and climatology): long-term observations e.g. of hydraulic head, periodic analyses of water samples are (or have been) made in a significant number of existing boreholes. Additionally, other geological (especially neotectonic) monitoring is performed that comprises micro-seismics, geodesy, etc.; determination of variability or evolution of key properties: "Langzeit - Überwachungsprogramm Nordschweiz - Tiefbohrungen - Erdbeben - Geodäsie" (German name for well established Nagra programme)
- *Confirmation of adequacy of properties of materials:* characterisation and confirmation (quality assurance) of key materials to be used in the repository (e.g. container material, backfill, sealing material); monitoring of key properties; periodic measurements of different samples to ensure that they correspond to the specifications (during implementation phase)
- *Monitoring of operational conditions* as prescribed by authorization (personal, population, environment) during site characterisation, repository construction and operation
- *Monitoring as part of long-term experiments*: monitoring of dedicated experiments in underground rock laboratories and research laboratories at the surface (construction and operation of a rock laboratory is planned at the selected repository site)
- *Confirmation monitoring* as discussed by EKRA in the context of monitored geological disposal requires several specific features; these features have been (GNW 2000) or are currently (NAGRA 2002a) being defined and evaluated on a conceptual level. Confirmation monitoring may include:
  - continuation of (long-term) field observations as part of the site characterisation process
  - long-term experiments in underground rock laboratories

- a "dedicated" pilot facility is foreseen where measurements (monitoring) will be done in order to test the adequacy of performance assessment models (as far as possible) and also to be able to detect early any undesirable evolution.

- These in-situ observations will be combined with an "institutional programme" that includes monitoring of science in general and experiments etc. in other places.

9.9.6 Monitoring techniques

In Switzerland practical experience with monitoring covers a large range of applications e.g. from major engineering infrastructures (dams, bridges, tunnels), environmental monitoring (air, water, soil) to various surveillance activities of the nuclear industry, including some preparatory actions for the geological disposal of radioactive waste.

Monitoring related to the site investigations for geological repositories for radioactive waste was performed by Nagra for many years e.g. for the (abandoned) project for the disposal of L/ILW at Wellenbeg and the HLW/ILW regional investigations of the crystalline basement and the sediments in Northern Switzerland - including current activities in Opalinus clay at the Zürcher Weinland. Deep groundwater conditions were (and in active projects still are) continuously monitored in boreholes using multipacker well completions for aquifers and low-permeable geological formations. Water sampling was (and still is) periodically done for hydrochemical and isotope analyses. At Wellenberg - until withdrawal from the site - a long-term record of meteorological data has been assembled (meteorological station "Bettelrüti") and surface water and shallow groundwater conditions have been periodically analysed. A monitoring programme for neotectonic processes based on micro-seismic monitoring, high-precision levelling and position monitoring (GPS) is active in Northern Switzerland, as it has also been at Wellenberg before the project was abandoned.

Site monitoring was done during construction and continues now during operation of both underground laboratories (Grimsel and Mont Terri) sited in Switzerland. Monitoring activities include e.g. the observation of the ambient and hydrogeological, geo-chemical and rock-mechanical conditions and are accompanying measures for several long-term experiments. Radiological monitoring is required when radioisotopes are applied. Underground rock laboratories are particularly well suited for the development of monitoring systems and surveillance strategies.

Radiological monitoring (NADAM and MADUK network) is done nation-wide and especially in the vicinity of nuclear facilities, to measure environmental radioactivity and background radiation. Furthermore, the Swiss digital seismograph network (SDSNet) and the seismic telemetry network measure the frequency and intensity of earthquakes and micro-tremors in Switzerland.

Waste monitoring is performed in terms of volumes and arisings of the different waste types, physical, chemical and radiological properties of waste and by periodic measurements on raw waste samples as part of the producer's waste characterisation programme.

Finally, Nagra's institutionalised programme related to some "broader aspects of monitoring" supports the waste management organisation and other stakeholders in their decision-making process. This programme keeps a watching brief on the development of science and technology, especially nuclear technology and waste management strategies, changes of legal requirements, public perception, societal/ethical aspects of nuclear waste management etc.

The applied monitoring techniques are described in detail in the corresponding technical reports as part of the Nagra documentation system.

9.9.7 Availability and required development

Feasible methods are presently available for site investigations, establishing baseline conditions and various long-term observations (see section 16.6). Technical and methodological developments to satisfy future monitoring needs are anticipated (and possible) throughout all phases of repository implementation.

9.9.8 How to react to unexpected monitoring results?

A monitoring and surveillance strategy is only sensible if it is complemented by the possibility for corrective measures and actions in case of unexpected (i. e. unpredicted and unacceptable) system behaviour.

Corrective actions are based on a decision-making process and may comprise technical (for instance during repository design and construction) as well as administrational measures (during repository operation) and could go as far as to waste retrieval. Under the assumption that the surveillance plan confirms adequate evolution of the disposal system, repository development will proceed according to the original implementation plan.

A pre-established "response plan" as part of the afore-mentioned "institutional programme" is at present not available; however, the feasibility of waste retrieval has been investigated for both L/ILW (Nagra 1998) and SF/HLW/ILW repository concepts (Nagra 2002a).

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9.10 UNITED KINGDOM

9.10.1 Introduction

This Country Annex states the definition of monitoring adopted by United Kingdom Nirex Limited, and subsequent sections explain the rationale for that definition.

9.10.2 Definition of Monitoring

The definition of monitoring adopted by Nirex is:

> *"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."*

9.10.3 Context

The United Kingdom (UK) holds significant stocks of long-lived radioactive waste, which are the product of fifty years of investigation and the exploitation of nuclear technology. The role of Nirex is to provide the UK with safe, environmentally sound and publicly acceptable options for the long-term management of radioactive materials.

Figure 1 shows how the UK has been undertaking research on waste management options for several decades and that this will continue even after a preferred waste management strategy has been developed for the UK[2]. Monitoring the ongoing work on options other than the chosen option(s) will be used to support the environmental impact assessment process that will be required prior to implementation of a facility. The objective of this work will be to keep the research on other options up to date in order to ensure that the decisions that have already been made are robust to any changes that have occurred.

Nirex has developed its Phased Disposal Concept as an option for the long-term management of ILW and some LLW, and this development work has given Nirex a clear view of the many technical requirements that future transport, handling, storage and disposal of radioactive waste would entail. This annex presents how monitoring can be applied now and in the future within the Nirex Phased Disposal Concept. Although it is recognised that many of the approaches would be applicable to other options if they were selected.

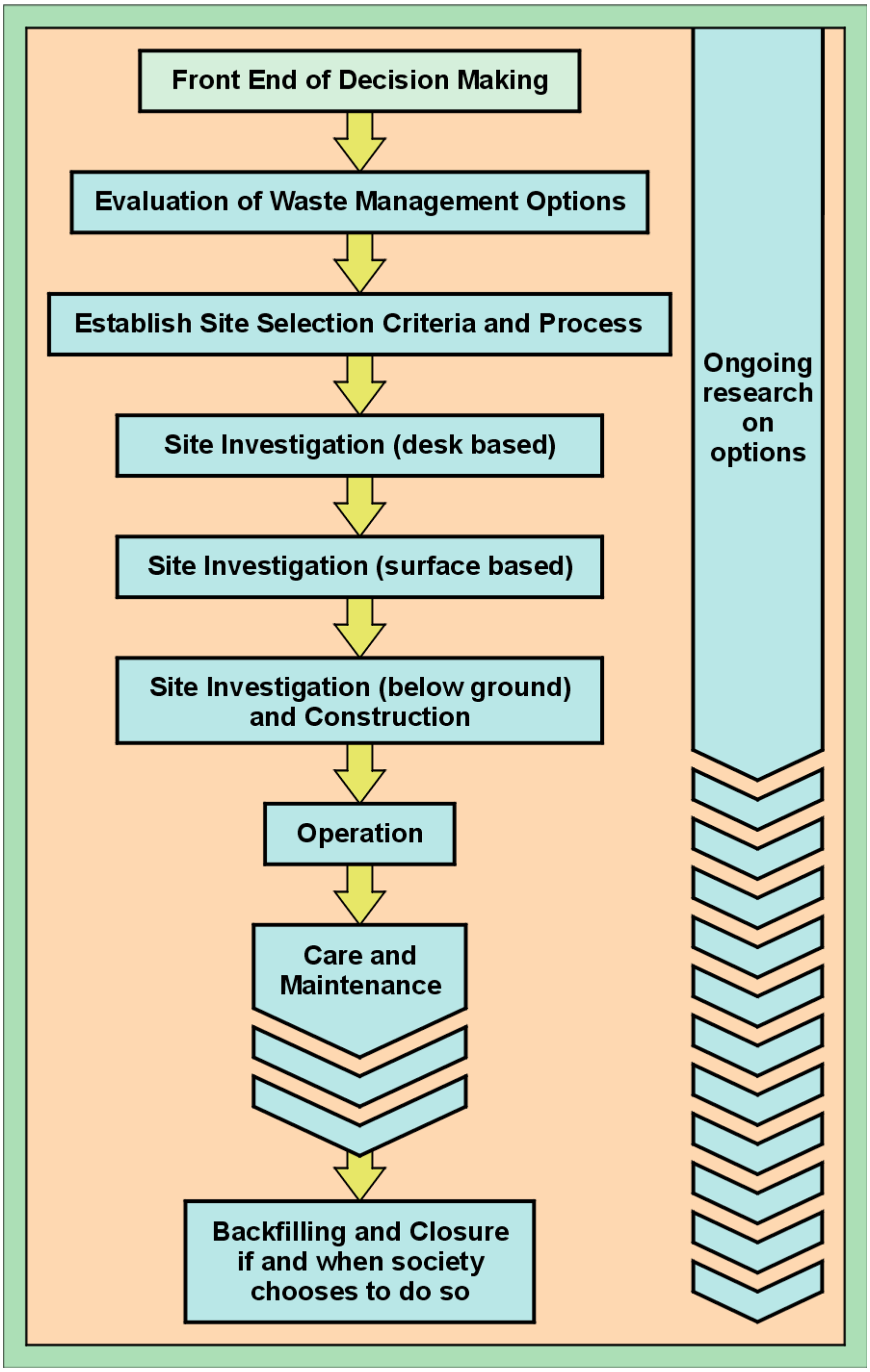
9.10.4 Reasons for Monitoring

The Nirex Phased Disposal Concept is a long-term waste management concept that progresses in a series of phases, briefly:

- **Packaging**. Packaging of wastes to Nirex standards and specifications, is already being carried out;
- **Surface storage**. Continued storage of packaged waste, generally at its site of origin or site of packaging;

[2] For presentational purposes figure 1 assumes that deep disposal is the preferred option.

Figure 4 Steps Needed to Implement a Waste Management Facility



- **Transport**. Transport to a centralised phased disposal facility;
- **Operation**. On receipt at the phased disposal facility, transport containers would be unloaded and the waste packages would be emplaced in large purpose-built vaults excavated at depth within a suitable geological environment;
- **Monitoring**. Monitoring would be initiated as part of the control of the waste facility. After all waste has been emplaced the option would be available to backfill, seal and close the repository or to keep it open for a further period under 'care and maintenance'. This phase – which is, in effect, continued underground storage – could, with

maintenance, be extended for a period of up to several hundred years during which time the waste packages could be retrieved if deemed necessary;

- **Backfilling**. When sufficient confidence is obtained in the disposal system, the vaults could be backfilled with a cement-based material (the Nirex Reference Vault Backfill – NRVB). The decision whether to proceed to backfilling, and the timing of such a step will be made by future generations, based on evaluation of a number of technical and societal factors;
- **Closure**. After backfilling, at an appropriate time, the repository could be sealed and closed;
- **Post-closure**. In the post-closure phase, the multiple barriers created by the disposal concept would provide long-term containment of the radioactivity in the repository, without the need for continued maintenance, and would thus protect human health and the accessible environment. This does not mean, however, that the repository would be forgotten about, as it is envisaged that it would continue to be monitored from the surface using a variety of non-intrusive methods.

The operational steps are illustrated in Figure 2 (next page).

Each step of the Nirex Phased Disposal Concept is designed to be reversible, and the retrievability of the waste in this concept has already been examined in some detail. Nirex is now building on this earlier work to consider the role of monitoring within a Phased Disposal Concept, and the options for carrying this out. This will take account of input from three stakeholder dialogue workshops organised by Nirex at which issues related to retrievability and monitoring were identified and discussed.

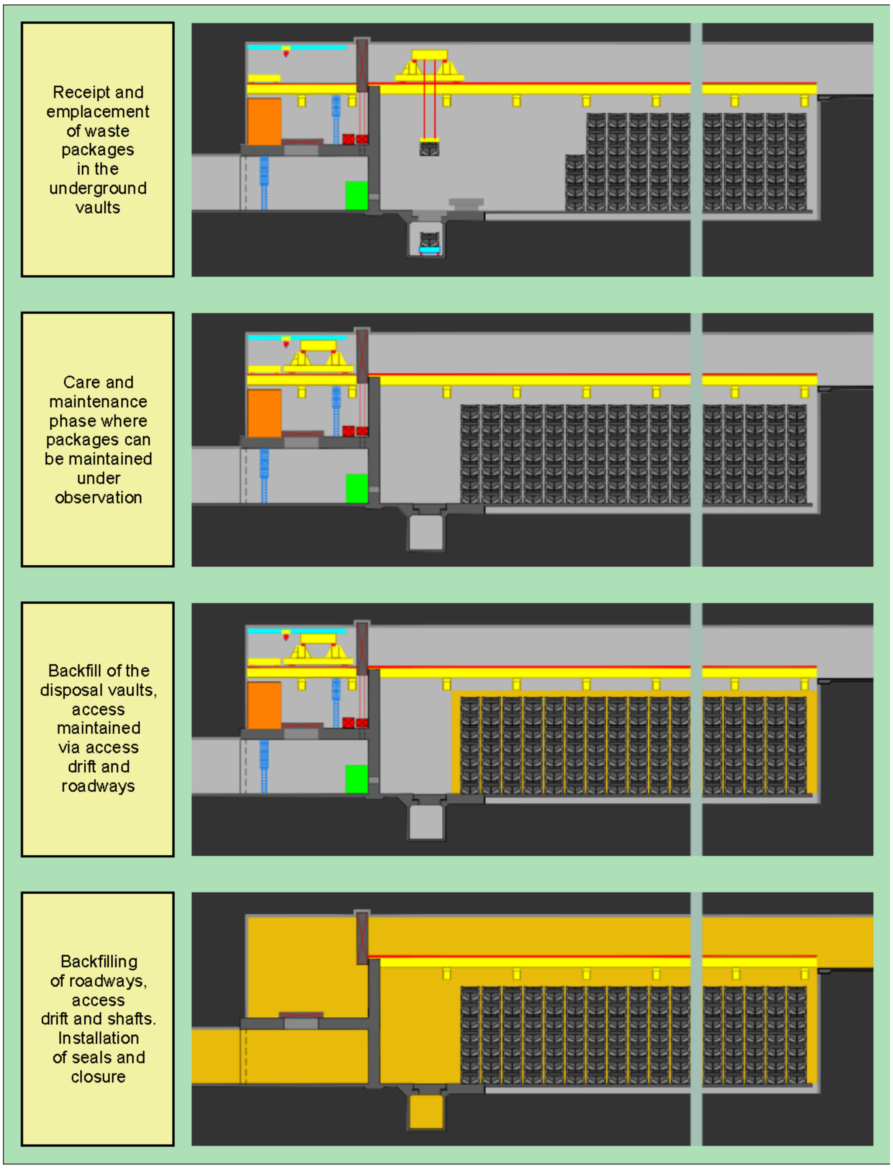
Results from monitoring will be key factors in providing the confidence needed to progress from one stage to the next. At each decision-point, the Nirex Phased Disposal Concept would offer future generations the options to:

- remain at the current stage for a longer time;
- proceed to the next stage;
- proceed, but with a different strategy from the original plan;
- reverse the process by one or more steps, to return to an earlier stage; or
- retrieve the waste packages and start again with a different management concept.

Since each decision-point is largely an issue of confidence, the justification for monitoring needs to consider the contribution to public acceptability as well as the purely technical requirements.

The technical justifications for monitoring are to obtain a continuing record of the actual condition of the waste packages, the waste management facility and its environment, so that successive decisions can be made on the basis of accurate information, and the best possible predictions of the future evolution of the system.

Figure 5 Phases of the Disposal Concept



In addition the late 20th century has shown that scientific and technological initiatives must pay more attention to the social and political context within which they operate. In particular, Nirex has learned that radioactive waste management cannot make progress in isolation from the stakeholders who are concerned in its safety – which potentially includes the entire population of the UK.

One objective is therefore to understand the social and political context in which the successive decisions are to be made, and to ensure that all stakeholders in the process are provided with adequate information to enable them to be participants in the debate and make their own judgements.

Nirex research has found that the public do not want to make decisions on radioactive waste management, but they want the opportunity to raise their issues and concerns and have them influence the decision made. In order to satisfy these viewpoints, the Nirex programme envisages that a broad interpretation is applied to monitoring such that it also includes processes aimed at:

- understanding the issues that are of concern to various groups of stakeholders;

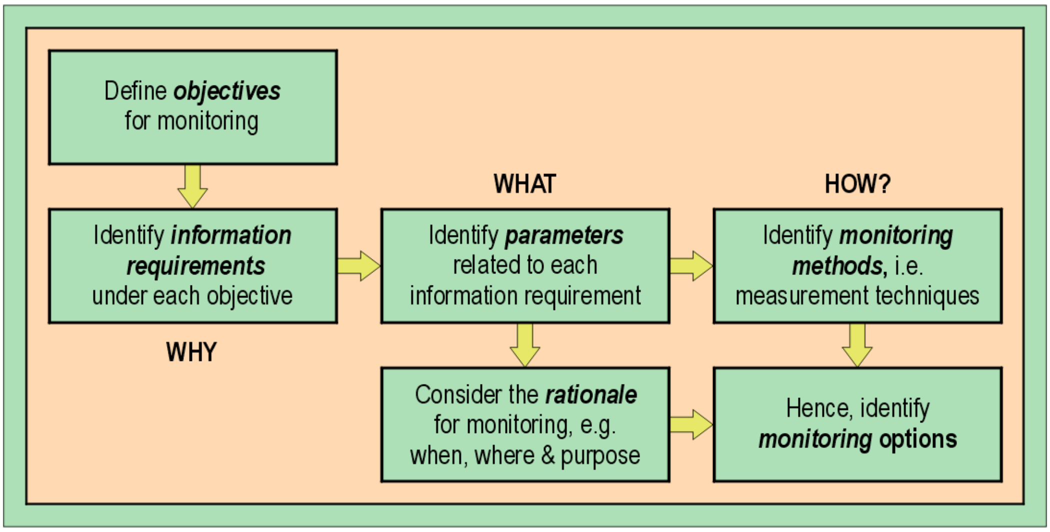
- addressing questions that stakeholders ask;
- undertaking research to address stakeholder issues and concerns; and
- ensuring that appropriate monitoring data are collected over a sufficient period of time to produce reliable answers.

9.10.5 Monitoring Strategy

Figure 3 below illustrates the strategic methodology applied by Nirex to structure its monitoring plans, starting from a definition of objectives and leading on to the identification of parameters to be monitored, followed by identification of the detailed methods and options.

Sub-sections discuss the three major stages in the strategy: Why, What and How.

Figure 6 Strategic methodology for the identification of monitoring options



9.10.5.1 Why – objectives and information requirements

The objectives and information requirements arise directly from the need to make informed decisions at each stage of the stepwise process, figure 1. For ease of reference these are grouped under eight headings, which cover both technical and non-technical aspects. The headings are allowed to overlap to some degree, because the main priority at the strategic level is to be sure that the list will be comprehensive, as judged from the different viewpoints of all stakeholders.

For any long-term waste management process, the associated monitoring programme must support all of the following objectives, by providing the relevant information at the times when it is needed:

1. UK national policies and needs
   Monitoring of the UK nuclear energy and radioactive waste management policies, current scientific and technological capabilities, and social acceptability will allow a facility to be developed with a suitable capacity, and at an appropriate time and location. An example of this is the regular update of the UK Radioactive Waste Inventory which Nirex project manage.
2. Facility design and construction
   During the site selection process monitoring of conditions, such as, host rock and geological environment will allow optimisation of the design and construction.

3. Long-term safety case
   A major function of monitoring is to support the models used to underpin the long-term safety case. In the early stages the models are based on generic information and can only indicate the prospects of meeting long-term safety requirements. Because of the timescales involved for the long-term safety case, the models cannot be fully tested by monitoring; but testing over shorter timescales can build confidence. Nirex is currently looking at how long these timescales could be extended. This confidence would have to be sufficient so that when a decision was taken to close and seal the facility the long-term safety case could be "demonstrated" to the satisfaction of the authorities and general public.

4. Operational safety case
   Operations will be monitored to demonstrate on-going compliance with the operational safety case approved by the regulatory authorities.

5. Environmental impact
   The environmental impact of the facility will be monitored to show ongoing compliance with aspects, such as, regulatory conditions on radioactive and non-radioactive emissions. Whilst it is anticipated that there would be no unexpected events identified early detection would allow mitigation measures to be put in place. Monitoring the environmental impacts will continue through out the construction and operation of the facility, continuing into the post-closure phase.

6. Reversibility and retrievability
   The waste packages, the facility and its environment will need to be monitored to ensure that all necessary systems for waste retrieval can be safely maintained and operated to facilitate the option to reverse any or all of the previous steps.

7. Policy, legal and regulatory framework
   The facility must be implemented such that all policy, legal and regulatory requirements are met, e.g. international, national and local requirements under conventional and special legislation. In particular the requirements for an Environmental Impact Assessment and a Strategic Environmental Assessment, European Directive 2001/42/EC, which requires the assessment of the effects of certain plans and programmes upon the environment, and will certainly apply to the proposed waste management facility. This will require an ongoing programme of monitoring of these policies and frameworks to show compliance and predict future changes.

8. Public acceptability and wider confidence issues

   The facility must be implemented such that public acceptability and wider confidence issues are satisfied, e.g. the social equity of the decision process, social acceptability at a given site and safety. To ensure continued satisfaction these aspects need to be monitored, and the results fed back into all other aspects of the programme. For example, Nirex have received feedback from the public that they would want monitoring to continue after closure of the facility. Therefore Nirex has started to investigate what form this monitoring could take and for how long it could continue.

9.10.5.2 What should be monitored?

Having identified the information requirements related to each objective, it is then necessary to identify the parameters that should be monitored in order to satisfy the information requirements. In some cases the parameter required may be measured or obtained directly, whereas in other cases several measurements and/or some analysis, interpretation or derivation may be necessary.

The rationale for monitoring of each parameter or group of parameters can then be considered in more detail, for example in terms of when and where a parameter should be measured. This consideration will later guide the definition of monitoring options.

When deciding what should be monitored consideration needs to be given to establishing a reference set of monitoring data against which future data can be compared. This classic example of baseline monitoring is to establish the initial conditions before any of the changes that will follow from facility construction and operation. However, Nirex also recognises that the phased nature of its programme will require a new reference set of monitoring data on several future occasions, and accordingly uses 'baseline monitoring' in a broader sense.

For example, newly excavated tunnels are expected to undergo significant changes in the short term, but should then reach a condition that will change much more slowly. Here, the purpose of baseline monitoring is to supervise the initial transitional period, and then to establish a set of reference data that form a baseline for the much more gradual changes to follow.

Another reason for extending the meaning of baseline monitoring beyond the pre-construction stage is that the value of this data diminishes with time. Environmental conditions can be expected to change independently of the facility development (e.g. due to climate changes) so from time to time it may be necessary to establish a new baseline in order to identify any further changes that are due to the facility development.

9.10.5.3 How should monitoring be done?

Having established what parameters need to be monitored, the methods to obtain the required data can be established. This includes the measurement techniques, instruments and schemes necessary to obtain values of the required parameters.

Knowledge of the practical capabilities of monitoring methods, together with a clear understanding of the rationale for monitoring of each parameter or group of parameters, should enable practical, useful and cost-effective monitoring options to be defined.

The measurement uncertainty associated with each option should be considered, and especially its effects on predicted performance parameters. If the uncertainty is too great to allow a demonstration of compliance, or to support the necessary decision making for the future, then a more accurate monitoring method should be sought.

Figure 3 and the above discussions summarise the strategic methodology that connects the basic justifications and objectives for monitoring to the identification of specific parameters to be monitored, and ultimately to the techniques to be used.

9.10.6 Key Processes to be monitored

Based on experience gained in the 1990's, with the rejection of proposals for development of the Rock Characterisation Facility at Longlands Farm, Sellafield, a key lesson learned was that technical development must be accompanied by the development of social and political acceptance. The issues and concerns of importance to stakeholders will also change when progressing along the stepwise process. Partly because the people involved will change. At the beginning of the process radioactive waste management will be debated at a national level as the overall strategy and direction of the process is set. In the UK we are about to start a national programme to debate and research options. This will involve national debate and a wide range of stakeholders. Once an option(s) has been selected the implementation process will begin.

Nirex has developed its Phased Disposal Concept and has identified the generic technical processes to be monitored. Nirex has also made progress in monitoring the social processes that will just as strongly affect the development of the disposal system.

9.10.6.1 Key technical processes

Before construction and operation	
Surface environment	Natural levels of radioactivity in the air, water, soil, animal & plant life
	Meteorological conditions
	Surface hydrology
	Characterisation of natural habitats and ecosystems
Underground	Temperature
	Hydrogeological parameters – groundwater flow in the host formation & main surrounding aquifers; permeability & porosity of the formations considered; fracture geometry & apertures; changes in stress state control on groundwater flow.
	Groundwater chemistry – geochemical characteristics (pH, Eh, rock-water interaction products); background levels of radioactivity, presence of radiogenic gases, natural colloids & microbe populations
Waste characteristics	Radionuclide content of the waste.
	Physical & chemical properties of waste & their evolution with time
	Integrity of the waste packages
During construction, operation and closure	
Performance of barriers	
Waste characteristics	Package integrity - dummy packages, corrosion coupons, package temperature, induced strains; removal of selected packages for inspection & testing
Near Field	Geotechnical response to excavations
	Groundwater flow & chemistry; changes in stress state control on groundwater flow.
	Thermal effects & gas generation
	Backfill condition
	Sealing systems
Far field	Hydrogeological parameters – groundwater pressures, permeability & porosity, flow patterns including disturbances caused by presence of the facility
	Geochemical parameters - pH, Eh, rock-water interaction, radioactivity, gas generation
	Seismic and tectonic activity
Confirmation of ability to reverse previous steps and retrieve packages	Waste emplacement & retrieval systems (e.g. cranes & other waste handling systems)
	Integrity of packages/ lifting features
	Rock support systems, groundwater management, vault environment particularly during any extended 'care & maintenance' period
Safeguards	Surveillance & tracking of waste packages to verify emplacement in disposal vaults & check that nuclear material is not being diverted
Safety and environmental impact	
Occupational	Monitoring the workplace for surface contamination

safety	Monitoring the workplace for airborne contamination
	Personnel monitoring
	Environment: ventilation, chloride levels, humidity, etc.
Public safety and environmental Impact	Airborne discharge monitoring; air sampling in the site environment
	Liquid discharge monitoring; monitoring of rivers, lakes, sea & subsurface aquifers
	Monitoring of soil, sediments, crops and other biological indicators
	Dosimetry around the site
	Monitoring of noise, dust, traffic levels & other environmental impacts
After closure (using non-intrusive methods)	
Surface environment	Contamination, radionuclides and gas originating from the facility, climatic conditions, ice and permafrost, surface water, flora & fauna
	Surveillance for safeguards purposes
Groundwater	Hydrogeological conditions; changes caused by seismic events

9.10.6.2 Key social processes

The above technical monitoring will contribute to a better understanding of the technical aspects of the facility; but as noted above, technical development must be accompanied by the development of social and political acceptance. Nirex has instituted monitoring programmes to develop its own awareness of these issues.

Nirex recognises that it needs to promote dialogue and debate as a step towards building a consensus as to how to manage the UK's radioactive waste. This means talking and listening to as many organisations and individuals with a stake in the discussion as possible. To this end, Nirex has made a commitment in its corporate transparency policy to give stakeholders access to and influence on the work programme.

Nirex has found that each group of stakeholders comes to radioactive waste management with different levels of direct experience and knowledge. Therefore stakeholders want to engage in the debate at different levels. To recognise this, Nirex tries to use a variety of dialogue techniques, tailored to the current understanding of the needs of various groups. That understanding is derived from a proactive monitoring programme of the social and political context within which Nirex operates.

A major group of stakeholders includes the regulatory agencies and government departments that have a traditional role in radioactive waste management, and Nirex maintains a continuing dialogue with those bodies. But in addition, Nirex has proactively broadened its contacts to include NGOs and the media, and has actively sought out others whose judgement and opinions may be valuable. All the information obtained through these contacts allows Nirex to monitor the regulatory and political environment within which it must operate.

The political environment is also affected by social attitudes to the Nirex Phased Disposal Concept. Political representatives convey the attitudes of their constituents; and they also react as individuals. Therefore Nirex has commissioned research on public attitudes. Focus groups have been found more informative than simple opinion polling, because the group structure allows members of the public to ask questions, discuss the answers, raise their own issues and articulate their own opinions. This largely avoids preconceptions about what the public 'want' or 'need' to know.

The results of these focus groups have profoundly affected the way that Nirex presents the Phased Disposal Concept. They have also affected the course of future development work, and through this, will affect the Concept itself. Therefore it is important to repeat the focus groups from time to time in a controlled manner so that results can be compared – in other words, to make public concerns the subject of ongoing monitoring.

9.10.7 How to react on unexpected monitoring results?

As can be seen a programme of work is in progress to develop a strategy for monitoring and identify the options for performing the monitoring required within a phased approach to disposal . The time being invested by Nirex in this is to build a robust basis upon which future decisions can be taken. To this end any result should not be seen as 'unexpected' but as additional information upon which those decisions have to be based. This does not mean that results are blindly accepted, they need to be verified, but if they are verified then they have to be acknowledged and used. Ultimately this could result in the need to modify the concept, possibly by repackaging or retrieving wastes. However, this is being built into Nirex's plans now through the implementation of the phased approach so that current and future generations have the time and ability to take the necessary decisions.

9.10.8 References

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