SKI Report 2004:49

Research

Performance Confirmation for the Engineered Barrier System

Report of a Workshop at Oskarshamn, Sweden, 12 - 14 May 2004

August 2004

ISSN 1104–1374
ISRN SKI-R-04/49-SE

SKi

SKI Report 2004:49

Research

Performance Confirmation for the Engineered Barrier System

Report of a Workshop at Oskarshamn, Sweden, 12 - 14 May 2004

August 2004

Foreword

As part of preparations for review of future license applications, the Swedish Nuclear Power Inspectorate (SKI) organised a workshop on the engineered barrier system for the KBS-3 concept, focused on Performance Confirmation (PC). The workshop was held during 12 - 14 May, 2004 at Oskarshamn. The main purpose of the workshop was to identify key issues relating to the demonstration of long-term safety using a system of engineered barriers.

The workshop began with introductory presentations on Performance Confirmation, on monitoring, and on long-term experiments in underground research laboratories. Working groups were then convened to discuss these topics and identify questions to put to the Swedish Nuclear Fuel and Waste Management Company (SKB) the following day. On the second day, SKB made several presentations, mainly on long-term experiments conducted at the Äspö underground research laboratory. These presentations were followed by an informal session during which the questions identified by the working groups on the first day were discussed with SKB and its representatives.

This report includes the questions identified by the working groups and a summary of the workshop discussions. Extended abstracts for the introductory presentations are included in an appendix. The summery of the workshop disucssions is based on notes taken by David Bennett (Galson Sciences LTD) and Mike Stenhouse (Monitor Scientific LLC). David Bennett made the final editing of the report. The conclusions and viewpoints presented in this report are those of one or several workshop participants. They do not necessarily coincide with those of SKI.

Contents

List of Figures

Contents

List of Figures

1 Introduction

The Swedish Nuclear Fuel and Waste Management Company (SKB) is moving forward with plans for the disposal of spent nuclear fuel. SKB is planning to submit license applications for construction of a waste encapsulation plant in mid-2006 and for construction of an underground waste repository in 2008. The assessment of long-term safety associated with the application for the waste encapsulation plant is known as SR-Can. The assessment of long-term safety associated with the application for the underground waste repository is known as SR-Site. The Swedish Nuclear Power Inspectorate (SKI) and the Swedish Radiation Protection Authority (SSI) are preparing to review SKB's applications.

SKB's concept for the disposal of spent nuclear fuel is known as KBS-3. According to the KBS-3 concept, SKB plans that after 30 to 40 years of interim storage, spent fuel will be placed in copper canisters and that these will be disposed of at a depth of about 500 m in crystalline bedrock. In the KBS-3 concept, the principal engineered barriers comprise an iron insert that will hold and support the spent fuel rods, a copper canister that will encapsulate the fuel and the insert, a layer of bentonite clay known as the buffer that will surround the canister, and a mixture of bentonite and crushed rock that will be used to backfill the waste deposition tunnels. As part of its programme, SKB has conducted a wide range of tests on engineered barriers within its underground laboratory at Äspö (e.g., SKB 2004a). In a sense these tests can be regarded as performance confirmation, even if the concept of performance confirmation has never been used in the programme.

SKI is conducting a series of workshops to consider details of the KBS-3 concept, including the system of engineered barriers. The main objective of the workshops is to prepare for the review of the future license applications by identifying key issues in SKB's strategy for demonstrating engineered barrier performance and long-term safety.

Previous workshops focused on the long-term integrity of the engineered barrier system (the Krägga workshop, SKI 2003) and on engineered barrier manufacturing, testing and quality assurance (the Bålsta workshop, SKI 2004). This report presents the findings from a third workshop that focused on Performance Confirmation and long-term experiments being undertaken by SKB at its underground laboratory at Äspö. The third workshop was held in Oskarshamn during 12 - 14 May 2004.

This report is structured as follows:

- Section 2 describes the objectives and scope of the workshop, and summarises how the workshop was organised.

- Sections 3 to 5 provide brief introductions to Performance Confirmation, the role of monitoring in radioactive waste disposal programmes, and selected long-term experiments being undertaken within SKB's underground laboratory at Äspö that are most closely aligned with Performance Confirmation objectives.

- General and specific issues identified and discussed during the workshop are described in Sections 6 and 7 respectively.

- Conclusions are presented in Section 8.

- The report is supported by a list of references and four appendices, which contain the workshop agenda, the list of workshop participants, extended abstracts for the papers that were presented at the workshop, and the list of questions to SKB that was developed during the workshop.

2 Workshop objectives, participation and structure

The concept of Performance Confirmation as a discrete activity has been developed relatively recently within the US programme for the disposal of radioactive wastes at Yucca Mountain. SKI decided, therefore, to incorporate a consideration of Performance Confirmation within its ongoing workshop series on the engineered barrier system.

The objectives of the workshop were, thus, to:

- Consider international perspectives on Performance Confirmation.
- Evaluate the significance of Performance Confirmation, particularly for the engineered barrier system, as a component in repository licensing.
- Consider components of Performance Confirmation, including relevant long-term tests at Äspö and the role of monitoring.
- Review and discuss SKB's on-going and planned research activities, particularly at the Äspö underground laboratory.
- Identify further work in the area of Performance Confirmation that it might be appropriate for SKI to conduct in preparation for the license application reviews.

The workshop participants had, thus, to consider a wide range of inter-related and overlapping topics (Figure 1).

The workshop involved staff from SKI, the Swedish Radiation Protection Authority (SSI) and SKB, as well as several invited specialists from radioactive waste disposal programmes outside Sweden. The participants list is included at Appendix B.

During the workshop, two working groups were convened to consider issues specifically related to (i) Performance Confirmation and (ii) to key long-term tests at Äspö. The membership of theses working groups is detailed in Appendix B

The workshop schedule is summarised in Table 1. The discussions on the first and last days of the workshop involved SKI and SSI staff and their contractors; SKB and its contractors participated in the discussions during the second day.

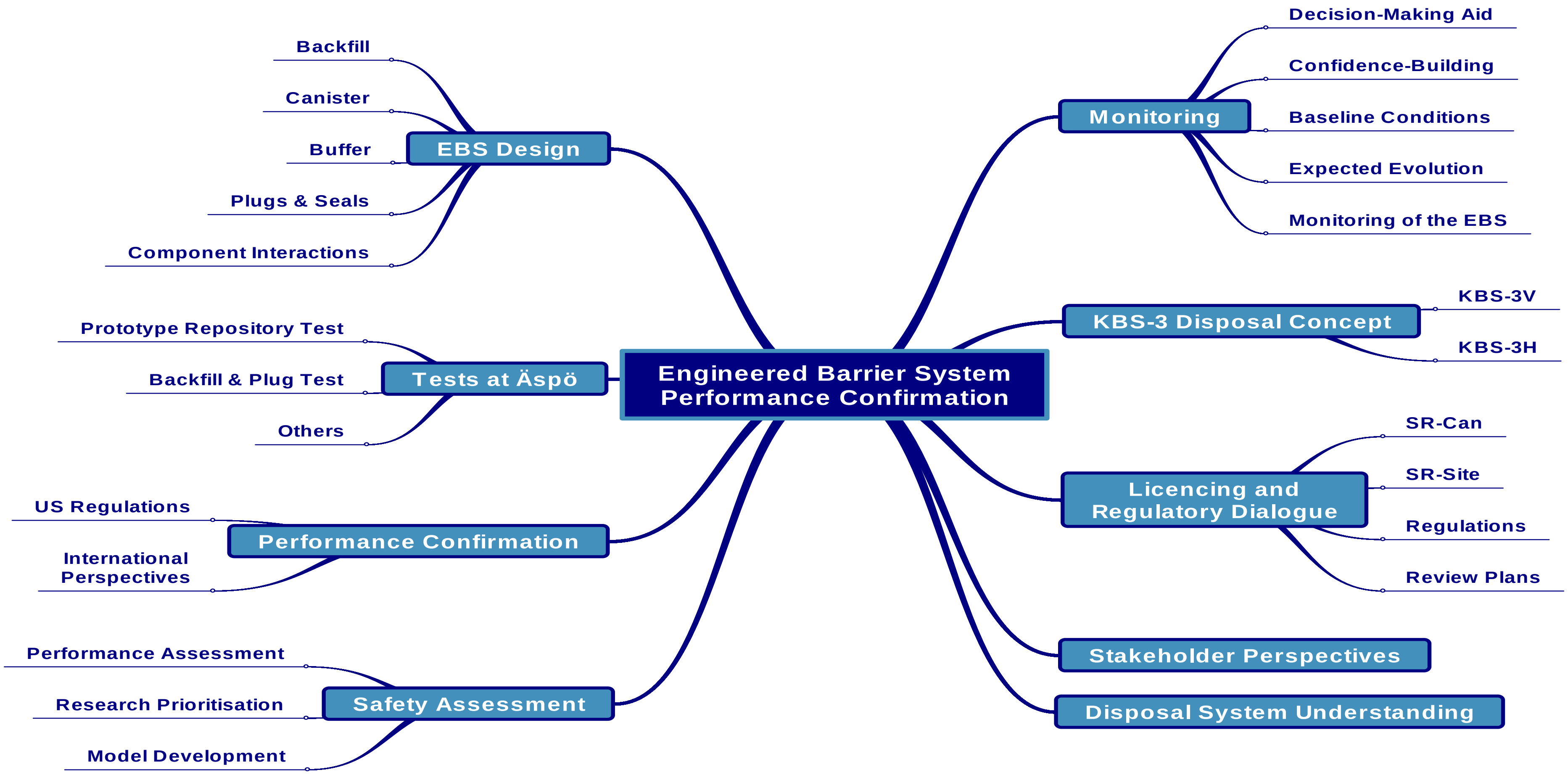

Figure 1 Topics discussed at the workshop.

Table 1 Summary of Workshop Schedule.

Period	Activity
Morning of the first day.	Introduction and workshop objectives.
	Presentations to SKI and SSI staff by invited experts.
Afternoon of the first day.	Summary of previous SKI reviews of SKB's Research, Development and Demonstration (RD&D) programme.
	Summary of conclusions from previous SKI workshops on the engineered barrier system.
	Working group sessions to identify questions to be put to SKB.
	SKB guided tour of the Äspö underground laboratory.
Evening of the first day.	Working group leaders and rapporteurs collate and finalise questions to be put to SKB.
Morning of the second day.	Presentations to SKI, SSI and representatives by SKB and representatives.
Afternoon of the second day.	Questions to SKB.
Morning of the third day.	Discussion of SKB's responses to questions and consideration of implications for SKI's work.

3 Background to Performance Confirmation

As noted above (Section 2), the concept of Performance Confirmation as a discrete activity has been developed relatively recently within the US programme for the disposal of radioactive wastes at Yucca Mountain. The US definition of Performance Confirmation is embedded in US safety regulations, such as US Nuclear Regulatory Commission (USNRC) 10 CFR Part 63:

> *"Performance Confirmation may be defined as the programme of tests, experiments and analyses, conducted to evaluate the adequacy of the information used to demonstrate compliance with long-term safety standards for a geological repository."*

The concept and timing of a discrete Performance Confirmation programme within a radioactive waste disposal programme are, thus, related to the process and schedule for gaining approval for the waste disposal facility (i.e., the licensing or authorisation process).

For example, in the US it is suggested that key interactions between natural and engineered barriers should be monitored during the period from site characterization through repository construction and waste emplacement until repository closure, to identify if any significant changes occur in the conditions assumed in the safety analysis that might affect compliance with the safety standards.

Irrespective of whether a strictly defined Performance Confirmation programme is incorporated within a waste disposal programme, licensing decisions can only be based on the information available at the time, and it is usual for a series of performance and safety assessments to be conducted as new information is gathered throughout the period of repository development and operation.

The types of tests and activities that might be included in a Performance Confirmation programme can overlap to a significant degree with other activities being conducted as part of a radioactive waste disposal programme. For example, activities within a discrete Performance Confirmation programme might include:

- Site characterization.
- Laboratory testing.
- Testing in Underground Research Laboratories (URLs).
- Testing in dedicated demonstration-alcoves, separated from principal repository-construction and waste-emplacement operations.
- Large-scale engineering demonstrations.
- Monitoring.

At least some, and in many cases all, of these activities are undertaken as part of waste disposal programmes in countries that do not use the Performance Confirmation concept or are yet to establish strictly defined Performance Confirmation programmes.

Thus, when establishing a Performance Confirmation programme it is possible to include tests already planned within a waste disposal programme, as well as new purpose-designed tests specifically intended to confirm key safety-assessment data, models and results for the purpose of supporting licensing decisions.

Purpose-designed Performance Confirmation tests can take advantage of the opportunity to conduct and monitor large-scale, long-term testing in underground facilities constructed during the operations and waste emplacement stages of repository implementation. Such tests can address larger spatial scales (meters to kilometers) than are accessible within a surface-based laboratory.

As defined in the US, the Performance Confirmation period extends up to, but not beyond, the time of final license approval for permanent closure of the waste repository. This means that Performance Confirmation tests at Yucca Mountain, for example, could last for several decades or so, during repository construction and waste emplacement. Some of the activities that can form part of a Performance Confirmation programme (e.g., monitoring) might, however, continue beyond the period of Performance Confirmation (Section 4).

Further information on Performance Confirmation, particularly with respect to the different perspectives that stakeholders (including the regulator) may have on Performance Confirmation is provided by Apted *et al.* (2004) in Appendix C.

4 Monitoring and Performance Confirmation

All radioactive waste disposal programmes include monitoring activities. Monitoring is commonly defined as the continuous, periodic or intermittent, measurement or recording of observations.

Most waste disposal programmes have focused the development of their monitoring programmes on the construction and operational phases of repository development, and have mainly considered monitoring of waste and repository conditions, and the impact of repository construction on the properties of the host rock and the surface environment. This is consistent with the International Atomic Energy Agency's definition of monitoring (IAEA 2001), which states:

> "*...continuous or periodic observations or 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.*"

A European Commission (EC) Thematic Network on Monitoring (EC 2004) considered the definition of monitoring and developed a revised definition, which places additional emphasis on the consideration of alternative performance indicators and on the use of monitoring results in decision-making, as follows:

> "*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.*"

Notwithstanding the differences between the definitions, it can be seen that monitoring forms an important part of a Performance Confirmation programme but that the scope of a repository monitoring programme may extend well beyond Performance Confirmation.

EC (2004) indicated that there is good deal of consensus amongst a wide range of countries regarding the principles on which monitoring programmes are being developed and implemented, and the reasons for monitoring. Key principles are that long-term repository safety should not depend on monitoring, and that any monitoring activities and equipment should not compromise disposal system safety. Reasons for monitoring include (Barlow 2004; Bennett and White 2004):

- The provision of "*safeguards*" for fissile materials.
- The development of an understanding of "*baseline*" repository site conditions.
- On-going verification of operational safety.
- Improving disposal system understanding and Performance Confirmation. For example, to improve understanding of the impacts of disposals on the evolution of

the near-field, the geosphere and the surface environment. To build confidence that assumptions, models, and data that support performance assessments are fit-for-purpose.

- Building and maintaining public acceptability and public (societal) confidence.

- As an aid to making decisions on whether and how to proceed to the next stage of repository development and on waste retrievability. The Nuclear Energy Agency provides a discussion of reversibility and retrievability in this context (NEA 2001).

Barlow (2004) and EC (2002, 2004) noted that the type of monitoring activities that will be conducted will depend on the stage of repository development.

Bennett and White (2004) noted that when establishing a monitoring strategy for a particular disposal system or Performance Confirmation test, it is important to consider a realistic system "*expected evolution*", rather than the representation of the system considered in performance assessment, which might be based on conservative assumptions that could suggest greater responses could be observed during monitoring than might actually occur.

All of the studies emphasise the need to consider carefully the feasibility of potential monitoring techniques, including their accuracy and reliability, and the frequency and location of measurements.

A recent review of monitoring plans in a range of radioactive waste disposal programmes (White *et al*., 2003) noted that in most programmes repository monitoring plans are not final but are under active development. In particular, some programmes favour more direct monitoring of the engineered barrier system than others. For example, the in Sweden little or no direct monitoring of the engineered barrier system is planned (e.g., Olsson 2001; SKB 2004b). Olsson (2001) states "…*installations made underground cannot continue in operation after closure*…" and "…*no instruments can be installed in the buffer*…" In contrast, the Japanese programme is considering a range of technical solutions, including placing of sensors within the repository and transmission of monitoring data using through-the-earth-telemetry. Such an approach may allow direct monitoring of the engineered barrier system within the repository itself during the operational and post-closure periods.

Further information on monitoring is provided by Barlow (2004) and by Bennett and White (2004) in Appendix C.

5 Summary of key tests at Äspö

SKB (2004a) summarises the full range of experiments conducted within the Äspö underground laboratory.

The following sub-sections give a brief overview of the three experiments at Äspö that are considered to be of the greatest relevance to Performance Confirmation, namely the prototype repository test, the backfill and plug test, and the long-term test of buffer materials (LOT). More details on these tests are provided by Savage (2004) in Appendix C.

Other experiments at Äspö of potential relevance to Performance Confirmation include the Äspö pillar stability test, the temperature buffer test (TBT), the canister retrieval test (CRT), the gas transport in buffer test (Lasgit), and the horizontal deposition test.

At the workshop, SKB presented summaries of the results from all of these tests.

5.1 Prototype repository test

SKB's Prototype Repository Test is designed to "...simulate part of a future KBS-3 deep repository to the extent possible with respect to geometry, design, materials, construction and rock environment except that radioactive waste is simulated by electrical heaters, and to test and demonstrate the integrated function of the repository components." Additional objectives of the Prototype Repository Test are "...to develop, test and demonstrate appropriate engineering standards and quality assurance methods, and to accomplish confidence building as to the capability of modelling engineered barrier system performance."

The Prototype Repository Test site is a 65 m-long bored drift within the Äspö laboratory, from which six 1.75 m-diameter deposition holes extend vertically downwards to about 8 m depth in accordance with the reference design for the KBS-3 repository (Figure 2).

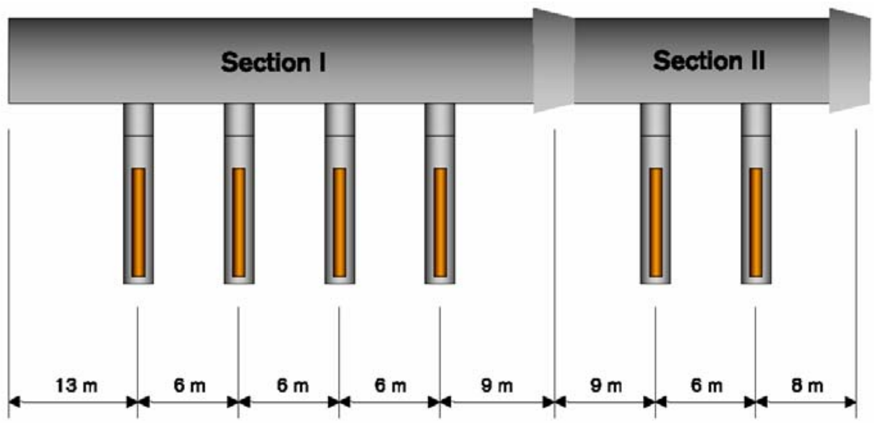

Figure 2 Schematic view of the Prototype Repository Test.

The test comprises two sections. Section I is 40 m long and includes 4 deposition holes. Section II is 25 m long and includes two deposition holes. The sections are separated by a concrete plug. The test is separated from the rest of the underground laboratory by a similar plug. The deposition holes contain electrically heated waste canisters, which simulate the warming that would be caused by radioactive decay of spent fuel. The canisters are surrounded by dense buffer clay consisting of blocks of compacted bentonite powder. The drift above the deposition holes is backfilled (see Section 5.2 below).

Monitoring instrumentation is being used by SKB to record major processes in the rock, buffer and backfill, including:

- Piezometric and pore water pressures.
- Wetting and drying of the buffer and backfill.
- Temperature evolution in the buffer and backfill and the surrounding rock.
- Effective and total pressures.
- Displacements in the buffer and backfill and surrounding rock.
- Gas accumulation in the buffer.
- Chemical and biological processes.

SKB has also developed models of thermal-hydro-mechanical-chemical-biological behaviour of the engineered barriers and the near-field rock and these models will be tested using the experimental data obtained.

5.2 Backfill and plug test

SKB's Backfill and Plug Test is a full-scale test of potential backfill materials, backfilling techniques, and tunnel plug construction methods. According to SKB, the main objectives of the Backfill and Plug Test are to:

- Develop and test different materials and compaction techniques for backfilling of tunnels excavated by blasting.
- Test the function of the backfill and its interaction with the surrounding rock in a tunnel excavated by blasting.
- To develop techniques for building tunnel plugs and test plug function.

A cross-section of the Backfill and Plug Test is shown in (Figure 3). The innermost part of the tunnel is filled with "*drainage material.*" The test itself is ~28 m long and is divided into the following parts:

- An inner part filled with a backfill of 30% bentonite and 70% crushed rock.
- An outer part filled with crushed rock backfill without bentonite, but with a layer of bentonite blocks and pellets at the top.
- A concrete plug with bentonite blocks as an "*O-ring*" seal.

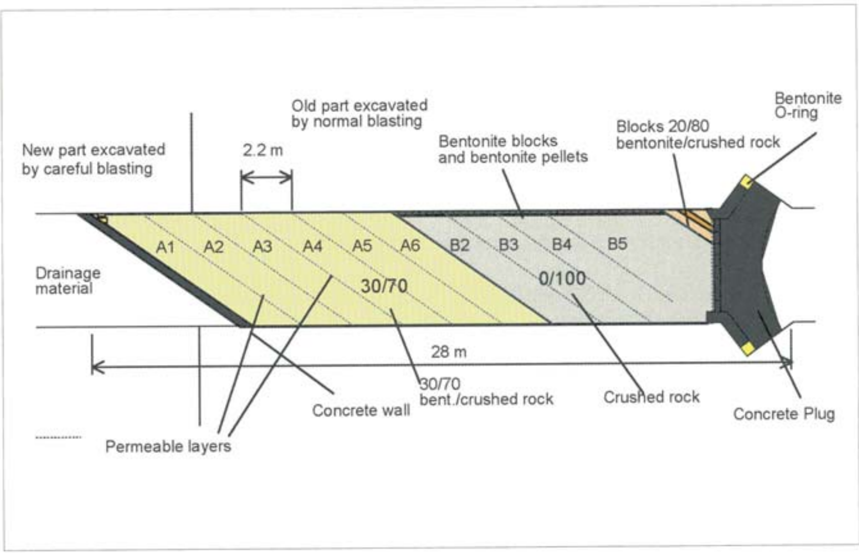

Figure 3 Layout of the Backfill and Plug Test (after Gunnarsson *et al*. 2002).

Permeable mats divide the test volume into 11 test sections (Figure 3). The permeable mats are used for increasing the water saturation rate in the backfill and for applying hydraulic gradients between the layers to allow study of water flow in the backfill and the near-field rock. The permeable mats are installed every 2.2 m, and each inclined layer of backfill is divided into three units in order to measure water flows close to the roof, in the central areas of the tunnel, and close to the floor. The upper volume close to the plug is filled with bentonite pellets and blocks consisting of 20 % bentonite and 80 % sand.

The backfill is instrumented with 34 pore water pressure cells, 21 total pressure cells, 57 sensors for monitoring the water saturation, and 13 gauges for measuring the local hydraulic conductivity. The water pressures in the permeable mats are measured in all sections. Cables and tubes are led through watertight seals in boreholes to the neighbouring "*demonstration tunnel*". Four pressure cylinders, 2 in the roof and 2 in the floor of the tunnel, are installed to measure the mechanical properties of the backfill after saturation. The water pressure in the rock is measured in 75 sections in boreholes. Micro-organisms have been placed in both backfill materials to investigate whether they can survive and multiply under the existing conditions.

The plug is designed to resist the water and swelling pressures that may develop (estimated to be 2-3 MPa). The design includes a 1.5 m deep slot and an "*O-ring*" of highly compacted bentonite in order to cut off the excavation disturbed zone.

The test was installed during 1998 and 1999 and, according to SKB, the monitoring equipment is working well. SKB estimate that the bulk average dry density of the emplaced 30/70 backfill material was between 1650 and 1700 kg/m^3 and that the average dry density of the emplaced crushed rock was 2170 kg/m^3. Hydraulic saturation and flow tests are currently underway.

5.3 Long-term test of buffer materials (LOT)

SKB's "*Long term test of buffer material*" (LOT) comprises a series of experiments aimed at building confidence in understanding and models of bentonite buffer behaviour under conditions relevant to those in a KBS-3 repository. In detail, the objectives of the LOT experiments are to:

- Test models of buffer properties and behaviour after water saturation.
- Study bacterial activity, survival and mobility in the bentonite.
- Study the scope of copper corrosion.
- Determine the bentonite's capacity to pass gas and determine at what temperature this occurs.

The test series comprises seven test parcels, which are exposed to repository-like conditions for 1, 5, and 20 years. The experimental layout is to place parcels containing a heater, a central copper tube, pre-compacted bentonite blocks and various monitoring instruments in vertical boreholes in crystalline rock (Figure 4).

So far, only the 1-year 'pilot parcel' tests have been completed. These parcels were heated at standard KBS-3 conditions (S1 parcel, 90°C), and also under 'adverse conditions' (A1 parcel, 130°C). The higher temperatures of the A1 parcel experiment were used in an attempt to accelerate the experiment.

Temperature, total pressure, water pressure, and water content were measured during the heating period. The two tests were terminated after approximately 12 months of heating, and the parcels extracted by over-coring of the original borehole. The entire 4.5 m long S1-parcel with approximately 20 cm rock cover was successfully lifted in one piece from the rock, whereas the central part of the A1 parcel was lost during drilling. The upper and lower parts were however retrieved.

The physical properties of the bentonite were examined using triaxial, beam and oedometer tests. The mineralogical properties of the bentonite were examined using XRD, CEC, ICP-AES and SEM analyses. All testing followed a defined test programme.

A principal conclusion was that the majority of the buffer material remained in an un-degraded state after one year of water saturation and heating. More detailed observations included:

Some precipitation of minerals, mainly gypsum, was found in the warmest part of the parcels, and the only unpredicted change was minor uptake of Cu into the clay matrix.

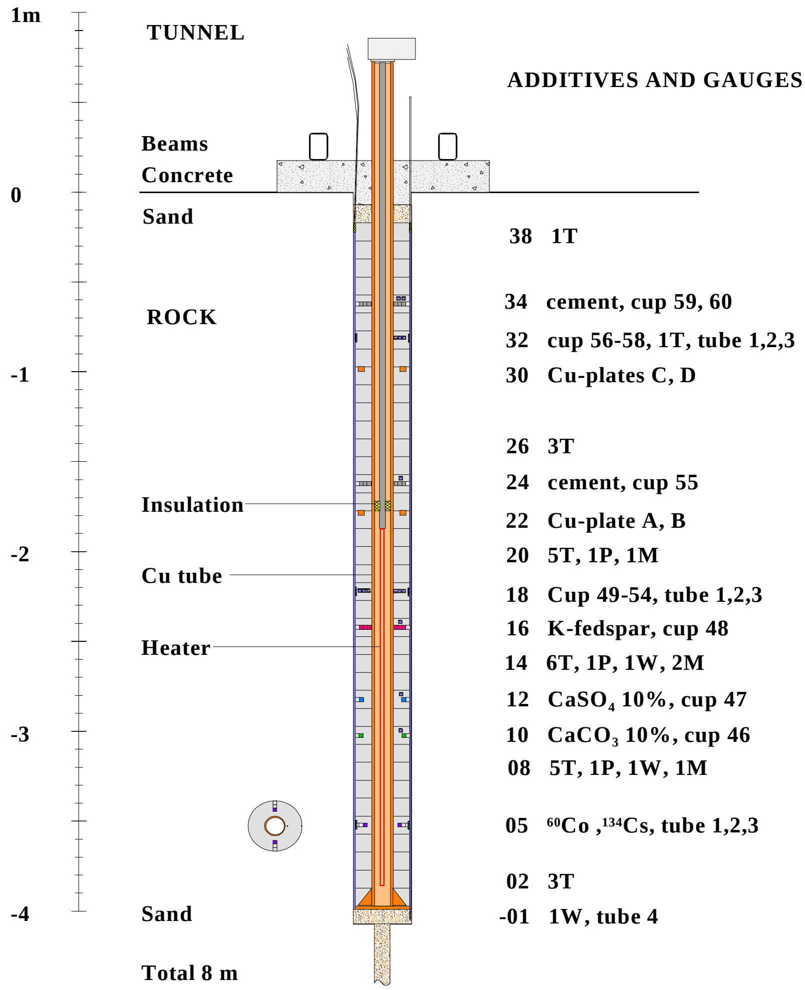

Figure 4 **Schematic diagram of the layout of the LOT test.**

Bentonite plugs containing ^{134}Cs and ^{60}Co, with an activity of 1 MBq were placed at defined positions in the bentonite in order to study radionuclide diffusion. Transport in unsaturated bentonite was confirmed to be minimal. The apparent diffusivity of cobalt in the saturated bentonite was measured to be about 2 x 10-9 cm2 s-1, which is in good agreement with previous experiments. The caesium results could not be fitted to a diffusion profile, and SKB envisages further investigations to ascertain why.

Large numbers of microorganisms were introduced into two of the bentonite blocks. The material was analysed immediately after mixing, after 72 hours, and after termination of the experiment. All bacteria except for spore-forming species were eliminated below the detection limits in the exposed parcel material.

Small well-characterised copper coupons were placed in the bentonite at a few locations. The coupons were of the same copper quality as proposed for the KBS-3 canisters. The mean corrosion rate was calculated to be 3×10^{-6} m per year, which is in accordance with previous modelling results for oxidising conditions. Optical and

SEM analyses did not reveal any signs of pitting. A higher copper content was noticed in the bentonite in the vicinity of the copper coupons.

6 Workshop Discussions - I

The following sections provide a synthesis of discussions at the workshop on a range of general topics related to Performance Confirmation and its relationship with the disposal concept and licensing plans. More specific issues are considered in Section 7.

It is noted that the workshop session in which questions were put to SKB was of an informal nature. The descriptions in Sections 6 and 7 of this report derive partly from SKB's responses to the participants' questions but do not necessarily include all of the details that SKB provided.

In order that the most important questions could be discussed with SKB in the limited time available, and owing to some overlap in the questions proposed by the two working groups, it was decided to consolidate the two lists of questions and consider them under a series of general topic areas. The questions were prioritised according to the overall objectives of the workshop. The final list of questions is contained in Appendix D.

6.1 Performance confirmation

There was considerable discussion of the meaning and use of the term performance confirmation and also its relation to monitoring. SKB does not use the term to label a sub-set of their ongoing programme, but acknowledges that objectives for many experiments are more or less strongly linked to performance confirmation. However, SKB explicitly discusses monitoring (e.g. SKB 2004b) and includes barrier performance tests as one type of monitoring. At present, the Swedish regulations briefly address some aspects of monitoring, but performance confirmation is not explicitly mentioned.

During the workshop, it was argued that in a mature programme, almost all activities are in some way related to performance confirmation (although exceptions exist such as initial site investigation activities). There is no apparent need to describe a subset of activities as part of a performance confirmation programme and, thus, SKB does not use a formal definition for performance confirmation. However, SKB is using data from its range of surface-based and underground laboratory tests in the manner envisaged within US Performance Confirmation programmes.

Some workshop participants noted that confirmation of long-term performance is in many cases not strictly possible for radioactive waste disposal systems, and that the term could thus be misleading. Others noted that, in this context, the word confirmation did not imply a requirement for absolute proof or validation but, rather, was aimed at ensuring that at least certain types of data and models are fit-for-purpose. Although it will not be possible to access the very long timescales (i.e., thousands of years) by experiment or monitoring, monitored URL experiments do offer a considerable opportunity for performance testing over extended periods (e.g., one or two decades, possibly longer). These timescales are still much longer than those commonly used to derive data for performance assessment modelling. Performance confirmation or long-term monitoring may also provide the opportunity to reveal any unexpected behaviours or interactions between key repository components

It was noted that, unless it is clearly explained, a performance confirmation programme might be seen by stakeholders as a means of allowing positive licensing decisions to be made, even when important R&D work remains to be completed. It was emphasised that this was not the intended purpose of performance confirmation programmes. Conversely, stakeholder might view the establishment of a performance confirmation programme that required all aspects of long-term safety to be confirmed by practical experiment as a way of preventing licencing. Again, it was emphasised that this was not the intended purpose of performance confirmation programmes.

Several questions were discussed regarding the appropriate breadth, duration and components of a performance confirmation programme, and the nature of any confirmation criteria that might be established. Overall the workshop felt that performance confirmation activities should be integrated within the wider programme of R&D, repository development and safety analysis, which is in agreement with current planning.

It was suggested that a regulatory organisation should have a key role in evaluating the sufficiency of performance confirmation activities, but that it might be unwise to establish tightly prescriptive confirmation criteria. There might be several alternative routes to obtaining a sufficient basis for licensing steps, and the implementing organisation should be able to develop its own strategy with performance confirmation activities as one of several components.

It was also noted that some performance confirmation tests might be conducted solely in response to stakeholder concerns that did not affect safety. The workshop felt that in such cases it was important to communicate that this is indeed the main objective and that information on disposal system safety would not be expected.

6.2 Regulatory dialogue

The dialogue between SKB and the Swedish regulators has to a large extent been based around reviews of the SKB RD&D programme that are published every third year. Additional dialogue is ongoing in the areas of system/safety analysis as well as site investigations. These components of the dialogue have been initiated as a result of a government decision made in 2001.

It was noted that the tracking of review comments has been more systematic and thorough in some areas (e.g. related to the canister) than others, and that more stringent requirements regarding the documentation of the dialogue would be needed in the run up to licensing. A specific suggestion that arose from the workshop discussions between SKI and SKB was that it could be beneficial to establish a working group to discuss buffer and backfill related issues[1].

---

1 A workshop on the long-term stability of the buffer and backfill was held in Lund in November 2004.

6.3 Use of performance and safety assessments in prioritization

It is essential that long-term experiments are designed and optimised to give relevant results in the context of performance assessment. Within SKB it is the performance assessment modellers as end-users, who suggest a need for a particular experiment and define what needs to be done.

The structure of SKB's RD&D programmes is/will be closely related to the structure of performance assessments, which should illustrate how performance assessment is used to prioritise research and long-term testing. However, there will always be some investigations aimed at understanding of processes, which need not be explicitly included in performance assessments. SKB plans to use the process report to document the links between experimental results, process understanding and performance assessment. The process report, which was first published as a main reference to SR 97, and will be updated and modified during the development of forthcoming safety assessments.

It was suggested that it would be helpful if SKB could document a clear and systematic assessment of whether the existing experimental/performance confirmation programme is suitably comprehensive and informed by safety assessment. Given the long time scales for large-scale tests to confirm e.g. barrier performance, it is essential that any need for complementary tests are identified. There should be a traceable link between unresolved issues in performance assessment and prioritisation of any new experiments that are considered.

6.4 Experimental and licensing timescales

The workshop discussed the relative timing of SKB's experiments and data collection activities, and plans for license submissions. General time plans have been developed for the Äspö experiments covering 20 years, but they are not always tailored to exactly fit in with licensing applications, such as SR-Can. However, in some cases experiments may be decommissioned on a schedule to assist licensing applications. For example, part of the Prototype Repository Test (Section 5.1) may be decommissioned before full hydrological saturation is reached, in order to provide information for use in SKB's 2008 SR-Site license application. SKB suggested that the added value of continuing an experiment has to be balanced against the information needs at specific occasions.

SKI recognises the need for a certain degree of flexibility in programme management but emphasise that future decisions will require a sound basis and clear strategies for resolution of remaining issues. SKI would welcome sight of SKB's detailed planning regarding the timing of experiments, and suggests that such plans should be continually updated and modified depending on experimental results and the status of the programme.

6.5 Data applicability and model development and testing

No decision has yet been made as to the preferred site for the Swedish radioactive waste disposal repository. SKB is currently investigating candidate areas at Forsmark in Östhammar and at Laxemar and Simpevarp in Oskarshamn (e.g., SKB 2004b).

SKB's planning is not yet firm regarding the need for performance confirmation testing and monitoring at whichever site is selected. The workshop discussed the applicability of data obtained at Äspö to the candidate areas that are currently considered. SKB noted that some data might be transferable between sites but that the Äspö data would obviously more directly applicable to a repository in the Oskarshamn area than at Forsmark, where initial site characterisation data suggest that the host rock is less fractured with in general a higher level of rock stresses. The off-site experiments would always have some usefulness for demonstration of technology feasibility, but the need for on-site verification could vary depending on site selection. Certain types of experiments would be more sensitive than others to specific conditions at a future repository site, e.g., the pillar-stability experiment.

SKB noted that in addition to the tests at Äspö, it has participated in experimental programmes in several underground research laboratories in other countries. Process modelling provides a means of extrapolating between sites and evaluating the implications for Swedish conditions. Even URL experiments in clay media could in certain cases be used in the SKB programme. Participants suggested that it would be valuable if SKB could describe which experiments will provide direct input to KBS-3 performance assessment and which experiments provide process understanding in general.

The workshop suggested the need for a systematic evaluation of the implications of the differences between the conditions encountered during the experiments at Äspö (and in other URL experiments if data from those will be used to support SKB's applications) and those of the selected repository site. It was noted that the differences between sites might influence the choice between the reference KBS-3 repository design with vertical waste deposition holes and the KBS-3H design (see Section 6.7).

Performance confirmation often involves the application of formal procedures for building confidence in models that include testing the predictive capability of models. SKB indicated that its approach is to develop a hypothesis and undertake predictive modelling at the experimental design stage, prior to conducting the experiments. Sensitivity analysis is carried out to identify important parameters. SKB finalise and publish the predictive modelling work before the experimental results are obtained. Later the experimental data may be tested to calibrate and refine the models, but the primary aim of the experiments is demonstration of process understanding rather than model refinement. SKB does not establish explicit criteria against which to judge the acceptability of model prediction, but confidence is enhanced where the utilised approximations appear to give acceptable agreement. The workshop suggested that efforts should be made to evaluate specific examples of SKB's conduct/management and publication of experiments and modelling work aimed at demonstrating predictive modelling capabilities and confidence-building.

The issue of using alternative/multiple conceptual models was discussed. The workshop participants regarded this to be an important work component for generating confidence in predictive modelling. Improved confidence can be obtained if several modelling groups, who address the same modelling task with slightly different methods, obtain similar results. For instance, SKB used four independent modelling groups to support the prototype repository experiments. An example of alternative conceptual models is whether the reduced microbial viability in a buffer with fully developed swelling pressure depends on desiccation or mechanical squeezing. This may be important since desiccation might be reversible, whereas mechanical squeezing leading to rupture is irreversible.

The workshop discussed the statistical validity of the experimental data obtained from the Äspö tests. SKB noted that although there had been only a small number of tests, a wide range of conditions (e.g., water inflow rates – see Sections 7.2.1 and 7.4.1) had been observed and this variability was carried forward to performance and safety assessments. Predictions of temperature evolution have generally been good, while predictions of resaturation times have been fair. Development of swelling pressure has been more difficult to predict. Workshop participants acknowledged the practical problems of conducting large number of experiments, but suggested that SKB should develop a strategy for handling the limited representativeness of the prototype repository. This strategy may include additional long-term experiments (on-site or off-site) and different monitoring activites during repository construction. Such a strategy would be an essential element in the planning of the detailed site characterisation phase.

6.6 Monitoring

SKB plans to conduct monitoring (i) before construction to establish a baseline of information on the characteristics of the repository site, (ii) during construction and (iii) during repository operation. SKB has no plans at present to conduct monitoring after repository closure once all of the spent fuel has been emplaced, i.e., probably in the latter part of the 21st century. The KBS-3 concept is designed with the intention that institutional control should not be necessary. On the other hand, legal responsibility for the repository will be transferred to the Swedish State after repository closure and the state might decide to carry out some post-closure monitoring. The possible need for institutional control in connection with the planned SFL35 repository for long-lived L/ILW was also discussed, since a previously published report (SKB TR-99-28) indicated that such control would be maintained. SKB's plans for monitoring of the repository are discussed in SKB 2004b (this report was not available during the workshop).

SKB has no plans at present to conduct large-scale experiments to demonstrate the feasibility of closing the main repository tunnels. However, SKB acknowledged that no detailed strategy had been worked out for the closing parts of the repository other than the deposition tunnels. Repository programmes in other countries have not addressed this problem in any detail either. SKB believes that it has a large enough "toolbox" of techniques and materials to be able to establish such a strategy.

SKB is proposing an initial phase of repository operation, during which 200–400 canisters of spent fuel would be emplaced in the repository and the deposition tunnels where these waste are located would be backfilled (SKB 2004b). Assuming continued regulatory approval for disposal, the initial operational phase would then be followed by a phase of "*regular operation*" during which detailed characterisation, construction of the repository and further waste emplacement would occur. SKB is seeking to gain general approval of its concept through implementation of the initial operational phase. SKB does not envisage the need to retrieve the wastes deposited during the initial phase and does not have explicit monitoring criteria that would trigger waste retrieval. The only reason envisaged for retrieval is if the disposal concept initially approved was later rejected.

SKB (2004b) indicates that during the initial phase of repository operation, monitoring might be made of temperature, of micro-seismic events, of the hydraulic regime and of re-saturation or pressure build up in the backfill. Monitoring instruments would not be placed in the buffer. SKB (2004b) notes that monitoring during the initial phase of repository operation would likely shed more light on transient processes, rather than on the conditions that will prevail in the closed repository, when groundwater pressure is completely restored, free oxygen is consumed, and a large-scale rock mass is moderately heated.

The workshop suggested that SKB should specify in more detail the type and intensity of the future monitoring that will be conducted during repository construction and the initial phase of repository operation. Among other things it is important that results from this monitoring could confirm early site descriptive models and inform any decision on whether to proceed to the regular operation phase (see also Section 7.4.1). Regulatory approval of regular operations would require a substantial body of favorable measurement results etc.

In a previous workshop (SKI 2003), the idea of using a demonstration tunnel for evaluating EBS performance during repository operation was discussed. A demonstration tunnel containing canisters with real fuel, buffer and backfill would be dismantled to gain information prior to the sealing of the repository. SKB suggested that so far no clear objective of such a test has been identified, but agreed that this option can be considered in the context of performance confirmation and monitoring.

6.7 Horizontal waste canister deposition, KBS-3H

SKB (2004a) describes a possible alternative way of implementing the KBS-3 concept in which the waste disposal canisters would be emplaced into horizontal rather than vertical deposition holes as considered in SKB's reference repository design. The scheme involving horizontal waste canister deposition is known as KBS-3H.

In the KBS-3H scheme, waste canisters would be emplaced into 300 m long deposition holes drilled from the transport tunnels. Each waste canister and the associated rings of compressed bentonite forming the buffer would be held in a perforated steel deposition cylinder, forming a deposition parcel. Once in the deposition hole, these parcels would be separated by vertical disc shaped bentonite end plugs (SKB 2004a).

SKB (2004a) suggests that the KBS-3H scheme would necessitate less excavation of the host rock and less backfill. During discussions at the workshop it was noted that the lower reliance placed on the backfill in the KBS-3H scheme might be one way of addressing some concerns about the backfill (see Section 7.3).

The relevance to KBS-3H of the data from the tests performed at Äspö was discussed. SKB suggested that although some specific results from the Backfill and Plug Test would be less relevant to the KBS-3H scheme, the process understanding developed as a result of the investigations at Äspö would be generally relevant to both the vertical and horizontal waste deposition schemes. The relevance to KBS-3H of parts of the Prototype Repository Test was questioned by workshop participants. SKB indicated that the primary scientific objective of the Prototype Repository Test - the investigation of bentonite-rock interactions and the development of a calibrated thermo-hydro-mechanical model for the period to saturation - would still be relevant to KBS-3H. Re-saturation might be different, but thereafter the processes would essentially be the same. SKB suggested that there is a good set of data for the horizontal concept from the NAGRA and ENRESA disposal concepts, albeit on different rock types.

SKB suggested that if the KBS-3H scheme was adopted, further underground tests would be more urgent in the area of demonstrating engineering feasibility, rather than for performance confirmation for long-term safety. SKB is considering whether there would be a need for a long-term test of the KBS-3H, akin to the Prototype Repository Test, but currently is not convinced of the need for such a test.

The expected evolution of a repository constructed according to the KBS-3H scheme was discussed. SKB does not consider that there will be significant differences between the expected evolution of the horizontal and vertical waste deposition schemes, but has not undertaken or documented a thorough analysis to demonstrate that this is the case. The workshop noted that even if the expected evolutions were similar, the differences when representing the KBS-3H scheme in performance assessment might be significant. The workshop participants discussed some of the potential effects on performance assessments for the KBS-3H scheme of longer horizontal radionuclide transport pathways, gas generation and migration, and earthquakes. Moreover, one difference that needs to be evaluated is that vertical emplacement involves only one canister per deposition hole, whereas there is a possible domino effect (e.g. on buffer properties) with horizontal emplacement of several canisters in a tunnel.

SKB confirmed that the forthcoming license applications will be based on the reference design with vertical deposition holes. SKB considers that the KBS-3H scheme would require further investigation before it could be considered as a serious contender for implementation. An important component will be the POSIVA safety assessment for horizontal deposition that will be published in 2007.

7 Workshop Discussions - II

The following sections provide a synthesis of discussions at the workshop on a range of specific topics related to Performance Confirmation and the main engineered barrier system components and their interactions.

As noted above (Section 6), the descriptions that follow derive partly from SKB's responses to the participants' questions but do not necessarily include all of the details that SKB provided. They should be regarded as the participants' interpretation of the issues based on SKB's answers.

7.1 Canister issues

Discussions at the workshop related to performance confirmation for the canister (Figure 5) focused on the consumption of oxygen present initially within the disposal system, and the implications for rates of canister corrosion.

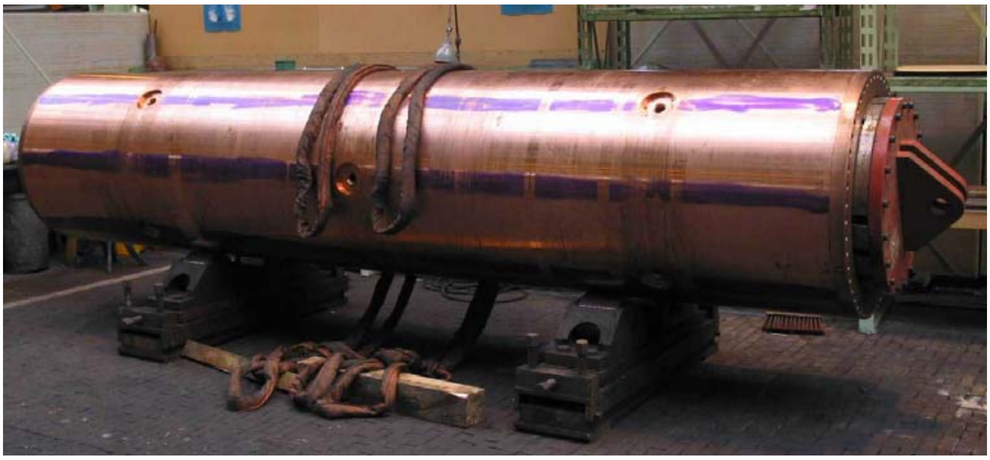

Figure 5 A modified copper canister used in the prototype repository.

The availability of oxygen, particularly in the buffer, will influence the rate and overall amount of canister corrosion that occurs.

SKB indicated that is it not possible to determine or monitor redox conditions (or oxygen levels) within the buffer, for example during the Prototype Repository Test, but that mineralogical examination of the buffer materials after the test had been decommissioned might provide indications of the conditions that had developed during the test. SKB noted that in the prototype repository monitoring plan, provisions exist for gas analysis, and that pore-water analyses would be done on decommissioning. Some of these data might help towards characterisation of redox conditions and SKB is working on a sampling protocol for such measurements. Some workshop participants felt that the duration of the Prototype Repository Test might be too short for any clear redox effects to be discerned. However, some data on corrosion rates may become available from SKB's LOT tests where on-line measurement is being carried out (see Savage 2004 in Appendix C).

The workshop discussed whether oxidation of pyrite in the buffer would help to lower oxygen levels and thereby limit canister corrosion. SKB noted that although pyrite oxidation might occur in the repository, the performance assessments did not take credit for the consequent consumption of oxygen because the presence of pyrite in the buffer could not be guaranteed. However, SKB would still consider the corrosion influence of sulphide in the buffer.

7.2 Buffer issues

Discussions at the workshop focused on the following issues related to Performance Confirmation for the buffer:

- Buffer wetting times and re-saturation rates.

- Alternative buffer materials.

Figure 6 A ring of compressed bentonite clay that will form the buffer.

7.2.1 Buffer wetting times and re-saturation rates

SKB suggested that important results from the prototype repository test relate to an understanding of rock-bentonite interactions and the development of a calibrated THM model of repository re-saturation. An additional benefit is the experience gained from establishing QA procedures for all of the work related to the experiment.

SKB suggests that a good understanding of the re-saturation process has been obtained. SKB's understanding of the re-saturation process has been helped by considering and comparing results from underground experiments at Grimsel, in Switzerland, and at Äspö. The host rock at Grimsel has a porosity of 0.1, whereas the porosity of the host rock at Äspö is 0.02. At Grimsel, the relatively high porosity of the rock means that the zone of partially-saturated rock around the repository excavations will re-saturate relatively quickly and the supply of water to the bentonite will be relatively plentiful from an early stage. In this case the rate of buffer re-saturation will largely be determined by the hydration properties of the bentonite. At Äspö the relatively low porosity of the host rock means that the zone of partially saturated rock around the repository excavations will re-saturate more slowly and the supply of water to the bentonite will be both reduced in magnitude and delayed in time. In this case the rate of buffer re-saturation will largely be determined by the hydraulic properties of the host rock.

SKB has observed both differential (spatially heterogeneous) wetting of the buffer materials within single deposition holes, and different rates of water ingress to different deposition holes. The Prototype Repository Test, in particular, has demonstrated that the magnitude of differences in the rates of water ingress to different deposition holes can be quite marked and difficult to predict by modelling, with the buffer materials in some deposition holes showing signs of significant increase in hydraulic saturation after just a few years, while other holes remain essentially dry. The workshop considered that consequences of SKB's observations on buffer wetting rates should be evaluated in detail.

The workshop participants expressed concern over the fact that individual deposition holes might remain essentially dry for a much longer period than previously envisaged as part of the KBS-3 concept. Questions were raised as to whether there could be negative effects associated with the buffer failing to hydrate and swell. An example identified by workshop participants was that the dryer buffer material might have a lower thermal conductivity than a fully saturated buffer, and that this might lead to higher thermal gradients and possibly mineral alteration in the vicinity of the canister. An irreversible transformation of the bentonite close to the canister surface could influence the physical properties of buffer and its performance in time periods much longer than the repository thermal phase.

A second example identified by the workshop was the possibility that microbial populations might remain viable before full swelling pressure has developed. Even if SKB's research suggests that microbes cannot remain viable under the pressures that develop within the saturated bentonite buffer, conditions in an unsaturated buffer might be less detrimental for the microbial populations.

The workshop noted SKB's view that differences in buffer re-saturation times of between a few years and a few thousand years were not significant to the calculated performance of the disposal system. SKB expect a trend of gradual increase in water saturation but expressed the view that even completely dry conditions would not harm the bentonite. Nonetheless, the extreme case of a series of alternating wetting and drying cycles (e.g., in response to ventilation) would not be acceptable. Introduction of an open ended time scale for saturation of the buffer is a potentially critical assumption for which SKI would expect SKB to provide a detailed justification for in connection with the planned safety assessments. The use of very dry deposition holes could indeed be advantageous from a transport perspective, but it could introduce difficulties in the prediction of the buffer evolution. The workshop participants concluded that SKB should undertake a systematic review of the assumptions that support the performance and safety analyses to determine whether differences in buffer wetting rates might have any effects on long-term safety.

SKB presented an analysis of the effects (e.g., on canister movement) of differential wetting of the buffer within a single deposition hole in support of the SR-97 safety analysis. This analysis indicated that even for extreme cases of differential wetting, the effects on safety would not be significant. While uneven swelling has been observed in the prototype repository test, the effects are nothing like the worst case evaluated. Nevertheless, SKB should be able to compare the observations of differential wetting with the properties of the walls of the deposition holes with the aim of being able to identify deposition holes where uneven wetting might occur in the repository.

7.2.2 Alternative buffer materials

SKB has indicated that it is considering the use of alternative buffer materials, in particular the use of commercially available bentonite other than MX-80. The commercially available Wyoming MX-80 bentonite has been specified as SKB's "*reference*" buffer material for many years, and virtually all of SKB's testing work on the buffer has been performed on this material.

The workshop discussed the potential need for further long-term performance confirmation tests associated with the potential adoption of alternative buffer materials. SKB indicated that although some tests are envisaged, the bulk properties are expected to be similar to that of MX-80, in spite of differences in the mineralogy of the alternative bentonite materials. SKB indicated that the primary reasons for considering alternative buffer materials were cost and security of supply, and were not related to long-term performance or safety.

The workshop noted that accessory minerals within the alternative buffer materials, as well as the smectite composition and content, might differ from those of MX-80. These differences might influence the long-term chemical behavoiur and transformations of the bentonite and affect the long-term physical properties of the buffer. SKI suggested that it would not be sufficient to judge the acceptability of new bentonite materials based solely on simple criteria such as smectite content. SKI recommended that SKB should review available experimental results from testing of MX-80 and justify the scope and ambition level for the corresponding testing of alternative buffer materials. Confirmation of performance from large scale tests would most probably also be needed. SKB acknowledged this and noted that additional LOT-type experiments were under consideration for the alternative buffer materials.

7.3 Backfill issues

Discussions at the workshop focused on the following issues related to Performance Confirmation for the backfill:

- The feasibility and practicalities of backfill emplacement.
- Whether the backfill will meet the requirements for good hydrogeological performance and low permeability.

7.3.1 Backfill emplacement

SKB has experimented with different methods for backfill emplacement. The method for the Backfill and Plug Test involved use of a digger fitted with a vibrating compaction plate to emplace the backfill in a series of layers sloping at ~35º (Figure 7).

Figure 7 Backfill emplacement

Use of the compaction plate is designed to ensure that the dry density of the backfill mixture is sufficiently high so that, as it hydrates and the bentonite clay swells, the backfill develops a sufficiently low permeability.

In setting up the Backfill and Plug Test, SKB had to cope with a considerable range of water inflow rates to the tunnels at different locations within the Äspö laboratory. SKB has tested the use of cement grouts for sealing fractures where the greatest water inflow to the tunnels occurs but, in practical terms, there is a limit as to the flow rates that these methods can cope with. One section of tunnel within the Äspö laboratory had to be abandoned during a backfill emplacement trial because high rates of water inflow caused the backfill mixture to become wet and, once wet, the clay hampered the mobility of the backfill emplacement vehicle. Determining whether these issues will be significant at the repository site will require further site-specific investigations.

7.3.2 Backfill hydrogeological performance

Results from SKB's Backfill and Plug Test (Section 5.2) suggest that the permeability of the backfill comprising crushed rock alone is high at ~10^{-7} m/s. This is significantly higher than would be required in the repository and SKB has concluded that pure crushed rock is not a suitable backfill for the disposal tunnels, although it might be used in other parts of the repository (e.g., the shaft). In addition to hydrological performance, cost is a key parameter influencing the selection of the backfill material and, thus, there is a desire to use the cheaper crushed rock where possible, as long as safety is not compromised.

Results from SKB's Backfill and Plug Test for the backfill comprising a 30:70 mixture of bentonite to crushed rock are not yet conclusive and there is uncertainty as to whether this backfill can meet its performance requirements. Although the Backfill and Plug Test investigated the performance of a 30:70 mixture of bentonite to crushed rock, alternative backfill mixtures (50:50 mixtures of bentonite to crushed rock) and mixtures including alternative swelling clays (e.g., the natural Friedland clay) are also under investigation, and the backfill composition may be further optimised.

SKB's upcoming safety assessments may include a poor backfilling variant but SKB has no plans at present to relax the present requirement for the backfill, which states that the permeability should be similar to that of the surrounding bedrock.

SKB does not foresee significant long-term change in the properties of the backfill. The workshop participants noted, however, that it is necessary to specify a backfill material that will meet its performance objectives not just for the present day but also into the future (e.g., allowing for potential increases in groundwater salinity).

Overall it is recommended that SKB identifies and considers a range of risk management solutions for the apparent difficulty of emplacing a backfill that will achieve the performance requirements.

7.4 Integrated engineered barrier system issues

Discussions at the workshop focused on the following issues related to Performance Confirmation for the engineered barrier system as a whole:

- Buffer/backfill interface interactions.
- Plans for future testing.

7.4.1 Buffer/backfill interface interactions

SKB plans to backfill the tunnels above filled waste deposition holes shortly after canister deposition and buffer installation has been completed. One of the reasons for this is so that the backfill will be able to resist upward pressure that develops as the bentonite clay comprising the buffer becomes saturated with water from the surrounding rocks and swells.

One of the uncertainties discussed at the workshop, which had been identified previously but which was highlighted by recent results from the Äspö tests described in Section 5, related to the relative rates of buffer and backfill wetting and saturation. The workshop participants noted that the ranges of wetting and saturation rates observed for the buffer in the Prototype Repository Test and for the backfill in the Backfill and Plug Test suggest that a wide range of behaviours might occur within the repository in terms of movement at the backfill/buffer interface.

Although there may be practical difficulties in measuring such movements, data from monitoring of the backfill/buffer interface during the initial phase of repository operation might be one type of monitoring result that could assist a decision to move to the regular operation phase (see Section 6.6).

7.4.2 Plans for future testing

Discussion of the decommissioning of the Prototype Repository Test (e.g., see Section 7.1) led to the identification of a recommendation to examine SKB's plans and procedures for excavating and decommissioning the range of tests being conducted at the Äspö laboratory. Workshop participants also felt that the forward testing plans and future optimisation studies should be developed bearing in mind the need for the components of the engineered barrier system to function as parts of an integrated disposal *system*.

8 Conclusions

SKB has reached an important stage in developing the programme for disposal of Sweden's spent nuclear fuel. SKB is commencing the transition from an idealised, theoretical disposal concept to a practical engineering programme for constructing a repository and disposing of spent fuel in a manner that can be demonstrated to be safe for the long-term.

SKB has conducted a wide range of tests within an underground laboratory at Äspö. Some of the Äspö tests can be viewed as addressing Performance Confirmation objectives but SKB's testing programme has also addressed wider objectives. For this reason SKB does not have a discrete Performance Confirmation programme. Although the workshop identified the need for further testing in some areas, the workshop felt that Performance Confirmation activities should probably continue to be integrated within the wider programme of repository development and safety analysis.

The experience gained from the Performance Confirmation and other testing within the underground laboratory at Äspö has been very valuable in increasing understanding of processes that may occur in a waste repository, and has also enabled the development and demonstration of engineering techniques (e.g., for tunnel construction, and for canister and backfill emplacement).

Testing at Äspö has, however, also shown that moving from a concept to engineering reality is not always straightforward and that several potentially important uncertainties remain, including:

- A wide range of water inflows to tunnels and waste deposition holes has been observed. Some parts of the Äspö laboratory were considered too wet to be backfilled. Within other parts of the Äspö laboratory, some deposition holes may be dryer than would be ideal for buffer saturation. The range of wetting and saturation rates at different locations within the repository may also lead to a range of backfill/buffer interface behaviours. Determining whether these issues will be significant at the site selected for the repository will require further site-specific investigations and possibly direct monitoring of the engineered barrier

- Whether it will be possible to demonstrate that the reference backfill material will meet its performance objectives remains an open question. Results from SKB's Backfill and Plug Test for a backfill comprising a 30:70 mixture of bentonite to crushed rock are not yet conclusive, but initial indications are that the requirement for the backfill to develop and maintain a very low permeability might be hard to meet with this material. It is recommended that SKB identifies and considers a range of engineering and risk management solutions for the apparent difficulty of emplacing a backfill that will achieve the performance requirements.

As might be expected, the practicalities that have to be faced when moving from a concept to an engineering reality are causing SKB to re-evaluate some aspects of the KBS-3 disposal concept and enhance plans for its implementation. For example, SKB is continuing to work to optimise materials selection, design of the bentonite blocks comprising the buffer, and may also revisit backfill emplacement techniques. With regard to the KBS-3 concept, SKB has confirmed that the forthcoming license applications will be based on the reference repository design with vertical waste deposition holes. The alternative design involving horizontal waste deposition holes would require further investigation before it could be considered as a serious contender for implementation.

An important conclusion from the workshop is that it would be beneficial for SKB to develop closer and more explicit links between plans for data gathering (e.g., during site characterisation and experimental work), safety analyses conducted to support licence applications, and disposal concept design optimisation. A need for gathering data during the initial operations phase in order to justify a transfer to regular operations was also identified.

With regard to further preparations for license application reviews, the workshop suggested:

- Developing comprehensive detailed plans tailored to the review of each particular application.

- Establishing a working group devoted to issues related to the buffer and backfill.

- Assessing in more detail specific examples of SKB's conduct and publication of experiments and modelling work aimed at demonstrating predictive modelling capabilities and confidence-building.

9 References

Apted, M., Arthur, R. and Stenhouse, M. (2004) *Perspectives on Performance Confirmation*, see Appendix C this volume.

Barlow, S. (2004) Thematic Network on the Role of Monitoring Within a Staged Approach to Geological Disposal of Radioactive Waste, see Appendix C this volume.

Bennett, D.G. and White, M.J. (2004) Monitoring of Radioactive Waste Disposal Systems: International Perspective, see Appendix C this volume.

EC (2002) Concerted Action on the Retrievability of Long-Lived Radioactive Waste in Deep Underground Repositories, EC Report No. EUR 19145 EN. European Commission.

EC (2004) Thematic Network on the Role of Monitoring in a Phased Approach to Geological Disposal of Radioactive Waste. EC Report No. EUR 21025 EN. European Commission.

Gunnarsson, D., Börgesson, L., Hökmark, H., Johannesson, L.-E., and Sandén, T. (2002) *Installation of the Backfill and Plug Test*. In: Clays in Natural and Engineered Barriers for Radioactive Waste Confinement: Experiments in Underground Laboratories, Reims, France, pp. 94-107.

IAEA (2001) *Monitoring of Geological Repositories for High-Level Radioactive Waste*. IAEA Report No. TECDOC-1208, International Atomic Energy Agency.

NEA (2001) Reversibility and Retrievability in Geologic Disposal of Radioactive Waste, Reflections at the International Level, OECD Nuclear Energy Agency.

Olsson, O., Svemar, C., Papp, T., Hedman, T. (2001). The Potential for Retrievability and Application of Monitoring within the KBS-3 Concept for Final Disposal of Spent Nuclear Fuel. In: Proceedings of Waste Management 21001 (WM'01) Conference, 25 February– 1 March 2001, Tuscon, Arizona.

Savage D. (2004) Long-Term Tests Relevant to the Performance Confirmation of the engineered barrier system Design in the KBS-3 Concept, see Appendix C this volume.

SKB (1999) *SR97 – Identification and Structuring of Process*, SKB Report No. TR-99-20, Swedish Nuclear Fuel and Waste Management Co.

SKB (2004a) *Experiments at the Äspö Hard Rock Laboratory*. Swedish Nuclear Fuel and Waste Management Co.

SKB (2004b) Monitoring During the Stepwise Implementation of the Swedish Deep Repository for Spent Fuel. SKB Report No. R-04-13, Swedish Nuclear Fuel and Waste Management Co.

SKI (2003) Long-Term Integrity of the KBS-3 Engineered Barrier System, Report from Workshop at Krägga Herrgård, Bålsta, Sweden, 6-8 November 2002, Synthesis and Extended Abstracts, SKI Report No. 2003:29, Swedish Nuclear Power Inspectorate.

SKI (2004) The Engineered Barrier System - Manufacturing, Testing and Quality Assurance, Report from Workshop at Bålsta, Gässtgivaregård, Sweden, 12-14 November, 2003, Synthesis and Extended Abstracts, SKI Report No. 2004:26 Swedish Nuclear Power Inspectorate.

White, M.J., Bennett, D.G., Crawford, M.B. and Emsley, S. (2003) *Techniques for Post-Closure Monitoring*. Galson Sciences Limited Report No. 0358-1.

APPENDIX 1: WORKSHOP AGENDA

engineered barrier system Workshop Oskarshamn 12-14 May, 2004

Agenda

Wednesday, May 12

9.00	- 9.20	Welcome and introductory remarks (Ö. Toverud) Purpose of the workshop (S. Wingefors)
9.20	- 10.00	Review of international Performance Confirmation (PC) programs (M. Apted)
10.00	- 10.30	Coffee break
10.30	- 11.30	A summary of the international perspective on monitoring (D. Bennett) Thematic network on monitoring in a staged approach to disposal (S. Barlow) Findings from a review of SKB-reports related to long-term tests at Äspö HRL (D. Savage)
11.30	- 12.30	Lunch
12.30	- 12.40	SKI review of Äspö HRL tests in SKB RD&D programs (Ö. Toverud)
12.40	- 12.50	Conclusions from earlier SKI engineered barrier system workshops (C. Lilja)
12.50	- 13.00	Introduction to work in groups (Ö . Toverud)
13.00	- 15.00	Parallel working group sessions start preparing questions to SKB. Chairs & rapporteurs for group 1 and 2 are representatives from Monitor, Quintessa and Galson Sciences (M. Apted and D. Savage / D. Bennett)
15.00	- 15.20	Coffee break
15.20	- 16.20	Presentations from working groups and general discussion on questions
16.30	- 17.00	Transport by car to Äspö HRL
17.00	- 19.00	Visit at Äspö HRL
19.00	- 19.30	Transport back to Hotel Corallen

20.00		Dinner at Corallen
22.00		Working group chairs & rapporteurs and SKI staff finalise questions to SKB

Thursday, May 13

9.00	- 9.15	Introduction and purpose of the workshop (Ö. Toverud)
9.15	- 10.00	SKB presentation on ongoing long-term tests and some other experiments at Äspö HRL
10.00	- 10.30	Coffee break
10.30	- 12.00	SKB presentation cont'd
12.00	- 13.00	Lunch
13.00	- 15.00	Questions from working groups (working group chairs)
15.00	- 15.30	Coffee break
15.30	- 16.30	Questioning cont'd
16.30	- 17.00	Summation - outstanding issues (working group chairs)
19.00		Dinner at Corallen

Friday, May 14

9.00	- 10.00	Discussion of outcome from questioning of SKB (working group
10.00	- 10.30	Coffee break
10.30	- 11.45	Discussion on implications for SKI work (B. Strömberg)
11.45	- 12.00	Conclusions (Ö. Toverud)
12.00		Lunch

Appendix 2: Workshop Participants

Performance Confirmation Working Group

Mick Apted (chair)	Monitor Scientific, US.
Mike Stenhouse (rapporteur)	Monitor Scientific, US.
Steve Barlow	United Kingdom Nirex Limited.
Bo Strömberg	SKI
Benny Sundström	SKI
Stig Wingefors	SKI
Shulan Xu	SSI

Äspö Working Group

David Savage (chair)	Quintessa, UK.
David Bennett (rapporteur)	Galson Sciences Limited, UK.
Jussi Heinonen	STUK, Finland
Fritz Kautsky	SKI
Christina Lilja	SKI
Öivind Toverud	SKI
Anders Wiebert	SSI

SKB Staff and Contractors (present on 13 May 2004 only)

Tommy Hedman	SKB
Patrik Sellin	SKB
Karsten Pedersten	Göteborg University
Ola Karnland	Clay Technology AB
Lennart Börgesson	Clay Technology AB
Christer Andersson	SKB
Christer Svemar	SKB

APPENDIX 3: EXTENDED ABSTRACTS

Perspectives on Performance Confirmation
Mick Apted, Randy Arthur and Mike Stenhouse
Monitor Scientific LLC

Monitoring of Radioactive Waste Disposal Systems: International Perspective
David Bennett & Matthew White
Galson Sciences Limited

Thematic Network on the Role of Monitoring Within a Staged Approach to Geological Disposal of Radioactive Waste
Steve Barlow
United Kingdom Nirex Limited

Long-Term Tests Relevant to the Performance Confirmation of the engineered barrier system Design in the KBS-3 Concept
David Savage
Quintessa Limited

Perspectives on Performance Confirmation

Mick Apted, Randy Arthur and Mike Stenhouse, Monitor Scientific LLC

Introduction

Performance confirmation (PC) is defined here as the program of tests, experiments and analyses, conducted to evaluate the adequacy of the information used to demonstrate compliance with long-term safety standards for a geological repository. In addition, key interactions between natural and engineered barriers should be monitored during the period from site characterization through repository construction and waste emplacement, to identify if any significant changes occur in the conditions assumed in the final safety analysis that may affect compliance with the safety standards. The basic concept of PC is specifically embedded in safety regulations (e.g., US Nuclear Regulatory Commission (USNRC) 10 CFR Part 63), and has been the subject of technical workshops (e.g., EPRI, 2001, "*Performance Confirmation for the Candidate Yucca Mountain High Level Nuclear Waste Repository*", TR-1003032, Electric Power Research Institute, Palo Alto, California) and advisory reports by various international regulatory agencies.

Activities of a broad-based PC program might include:

- site characterization,
- laboratory testing,
- underground research laboratories (URLs).
- dedicated demonstration-alcoves, separated from principal repository-construction and waste-emplacement operations,
- large-scale engineering demonstrations,
- monitoring, and
- other tests.

It is important to note that the types of tests included in a PC program overlap to a significant degree with other key activities of a repository program that are conducted for purposes other than PC. Thus, site characterization tests can contribute to both objectives related to repository layout, site suitability, etc., as well as to PC objectives. Tests on engineered barrier system components can contribute to objectives regarding optimization of costs, operational safety, long-term performance, etc., as well as to PC objectives. Monitoring is needed to assure worker safety during repository construction and waste emplacement, but can also be extended to meet PC objectives. Thus, a PC program, can include ancillary tests already planned by a repository program, as well as purpose-designed tests specifically intended to confirm key safety-assessment models and data. It is this latter type of PC tests that is the focus of this presentation.

Perhaps the primary purpose-designed tests for a PC program arise from the opportunity to conduct and monitor large-scale, long-term testing in underground facilities constructed during the operations and waste emplacement stages of repository implementation. Note that the PC period extends up to, but not beyond, the time of final license approval for permanent closure of a repository. This allows for a maximum PC-test duration of several decades during repository construction and waste emplacement. Purpose-designed PC tests conducted and monitored over long time periods (years to decades) and over extended spatial scales (meters to kilometers) within underground repository facilities are the primary foci of this review, with the recognition that many other tests and demonstrations planned for other purposes within a repository program can and will contribute to an overall PC program.

Different stakeholders have different perspectives and expectations with respect to PC, which are briefly summarized below.

Regulator perspective

In most countries, the regulator will be the primary advocate, co-analyst, and arbitrator for PC. The regulator needs to be assured that the safety analyses/ safety case submitted by the implementor is scientifically defensible, that uncertainties and variabilities have been taken into account, and that credible alternative conceptual models, consistent with available data, have been considered.

The PC program provides an opportunity for information to be collected that challenges and evaluates the robustness of assumptions, models and data that supports continued permitting and development of the repository. For example, example, collecting information on minerals in the geological host rock to reduce uncertainties regarding the uncertainty in assumptions regarding the retardation of radionuclides in the far field could be beneficial, whereas, simply repeating a standard column or batch test used to determine a distribution coefficient would provide very little further confidence in safety assessments that rely on retardation.

Regardless of the type of Performance Confirmation tests that may be possible, regulators recognize that PC must be based on what tests are practicable. The regulator also recognizes that not all sub-models (and associated data) of the safety analysis are amenable to PC. Furthermore, the regulator often adopts a risk-informed perspective on proposed PC tests, emphasizing tests on models or data that have a significant impact of the safety case and compliance.

Finally, the regulators must provide clear and unambiguous definitions of terms. Most importantly, the concepts of "*confirmation*" and "*validation*" must be specifically defined within a regulatory context. Such definitions must be identified by the regulator as distinct from the more restrictive "*refutable hypothesis*" meanings of these terms, as commonly applied within the scientific community. Within a regulatory perspective, a model is considered "*confirmed*" and "*valid*" by demonstrating it is fit for the purpose used in the safety assessment.

Concerned stakeholder/ affected communities perspective

Local citizens and their elected representatives desire an extended, thorough checking of the technical basis and supporting data for assurance of the safety of a repository to be sited within their community. An extended period of PC, including monitoring, during underground construction will allow the potential discovery of any surprises (e.g., undetected features over a portion of a site), that may adversely impact long-term isolation. The extended PC period will also allow the implementor, in consultation with the regulator and local community, to adapt repository and engineered barrier system designs to accommodate any such surprises, as well as to take advantage of new information that may further contribute to assuring long-term isolation.

Of course, it is also possible that a PC program may find evidence that seems to contradict existing models or assumptions underpinning safety assessments, thus possibly necessitating changes in the repository design concept, or leading to more detailed site characterization. Extreme care must be applied to any such evidence, however. Test are conducted in underground facilities in rock having highly variable properties, with limited control of experimental boundary conditions (e.g., small earth movement leading to temporarily high increase in water inflow). This may lead to spurious results that only seem to contradict models and data used in the safety analysis. It will be necessary for non-technical concerned stakeholders to understand that confirmation criteria (see later discussion) should be carefully defined and interpreted.

Lastly, an extended PC period of several decades will permit society to further educate itself about the merits of geological disposal and re-affirm if this remains the preferred option to assure public health and safety. However, it is important that the approach of extended PC tests not be misused as the basis for indefinitely postponing a decision on repository closure. A decision for permanent closure by the regulators will be based on a sufficiency of understanding and confirmation of long-term safety.

Implementor perspective

The implementor is tasked with planning, building, conducting, analyzing, and reporting the results and interpretations of a PC testing program. Early development of a Performance Confirmation Plan by the implementor was a key recommendation from the EPRI Performance Confirmation Workshop (EPRI, 2001). The PC Plan can set forth objectives, testing philosophy, screening criteria, available resources, long-term schedule, coordination between the implementor and regulator, and links between PC and related data-collection activities by the implementor. As with parallel research, development and design plans, the PC Plan would be expected to be updated on a regular basis, as reviewed by the regulator and available to other stakeholders.

Within the wide range of possible tests that could be performed within an underground PC program, the implementor must consider how to prioritize and select a PC testing program. As the EPRI PC Workshop (EPRI, 2001) concluded, screening criteria should be developed as early as possible, jointly between the regulator and the implementor. The purpose of the screening criteria is to exclude tests and expectations that are not be relevant or sensible for a long-term PC program, including:

- tests that are impractical or not feasible (e.g., creating continental ice sheets),
- tests on well-accepted models (confirmation of Darcy's Law or Fourier Law, Fick's Law, etc.).
- tests of coupled processes if the repository design (e.g., containment for >1000 years) obviates or mitigates their occurrence or impact on long-term safety.
- tests for process models that sensitivity analyses show do not significantly impact repository safety for a wide range of credible conditions.
- tests for which the larger scale or extended time period within a PC program will not assure a better understanding of the process. (e.g., radioelement solubility, corrosion of corrosion-resistant container materials, container sinking in buffer).
- tests on models for transient processes that are not specifically included in the main chain of safety assessment models.
- tests that might compromise the long-term isolation features of a site (such tests could be conducted at an analog site or in a satellite demonstration alcove at the actual site).

In addition, the implementor is confronted with practical concerns and questions regarding the design and operation of PC tests, including

- Do devices exist to measure and monitor parameters that are intended for confirmation?
- Do devices exist that are sensitive enough to measure and monitor expected changes in parameters that are intended for confirmation?
- Might the measurement/monitoring devices or data collection perturb the site (e.g., introduction of fluoro-carbon compounds, growth of microbe colonies)?
- Might the measurement/monitoring devices unduly restrict or disrupt the parallel construction and emplacement operations?
- Can the measurement/monitoring devices be calibrated and re-calibrated over the expected duration of the PC tests?
- Can multiple, redundant measurement/ monitoring devices be emplaced to avoid the potential for false-positive signals, and how many such devices are needed to be confident that false-positive results will not occur?
- Is there a potential for common mode failure of measurement/ monitoring devices, and how can this be prevented?

- How might natural variability in rock properties complicate the measurement or interpretation of monitored results?

- How might transient effects, induced by repository construction, affect planned measurements/ monitoring (e.g., spurious release of natural radioactivity due to stress cycling on minerals)?

- Are all factors affecting variability and uncertainty in measurement/ monitoring included in establishing error bars in model predictions that will be compared against PC tests?

- Do PC tests help to distinguish between viable alternative conceptual models?

- How can later refinements to models be accommodated?

Finally, the implementor must be careful in deciding confirmation criteria. The key question is "*What constitutes confirmation of a model prediction*?"

For example, does the magnitude of change between the model prediction and the measured value of a parameter need to be matched? Might it be sufficient to compare measured vs. predicted initiation time of change, the rate of change, or duration of change? Or might confirmation be shown simply by agreement between a model and a PC test with respect to the direction of change in a parameter? Different approaches to confirmation criteria for individual PC tests will need to be negotiated on a case-by-case basis between the implementor and regulator, and documented in the Performance Confirmation Plan. The standard for deciding the appropriate confirmation criteria for a given PC test, however, must be "*fitness for purpose*" with respect to the final safety analysis.

Monitoring of Radioactive Waste Disposal Systems: International Perspective

David Bennett & Matthew White, Galson Sciences Limited

Introduction

The Swedish Nuclear Power Inspectorate (SKI) is making preparations for the review of license applications related to the disposal of spent nuclear fuel. The Swedish Nuclear Fuel and Waste Management Company (SKB) refers to its proposals for the disposal of spent nuclear fuel as the KBS-3 concept.

In the KBS-3 concept, SKB plans that after 30 to 40 years of interim storage, spent fuel will be placed in copper canisters and that these will be disposed at a depth of about 500 m in crystalline bedrock, surrounded by a system of engineered barriers.

The waste will be held by an iron insert within a copper canister. The canister will be placed in a deposition hole, drilled into the host rock from a repository tunnel, and surrounded by a buffer of bentonite clay. The waste deposition tunnels will be backfilled using a mixture of bentonite and crushed rock, and sealed soon after waste canister deposition has been completed. Waste deposition will then continue in an adjacent tunnel.

Thus, parts of the repository will be operational while other sealed tunnels are in a transient phase. This situation may last for 50 years or so before the whole repository is backfilled and sealed (SKI 2003).

The most important initial processes are probably the saturation of the bentonite buffer, a process which will depend strongly on the thermal evolution of the system and the mechanical influences of bentonite swelling on the canister and near-field rock. Backfilling soon after canister deposition may be important to minimize the potential for canister movement as a result of bentonite saturation and swelling. Another process likely to begin immediately after canister deposition during the repository operational phase is re-equilibration of groundwater chemistry. This will include a gradual return from oxidizing to reducing chemical conditions in the buffer, backfill and near-field bedrock. Hydraulic re-saturation will also begin soon after canister and buffer deposition, and is likely to continue throughout the operational phase and into the post-closure phase. The pattern and sequence of backfilling and sealing is likely to cause hydraulic re-saturation to be spatially variable.

This paper is a contribution to an SKI-sponsored workshop on how to gain assurance that the Engineered Barrier System (engineered barrier system) will perform as required. The paper draws on a range of sources, including a recent review by White *et al*. (2003) of repository monitoring programmes in 14 disposal programmes around the world. The paper begins by discussing briefly the relationship between Performance Confirmation and monitoring, before proceeding to discuss some more detailed aspects and examples of engineered barrier system monitoring.

Performance confirmation and monitoring

The US Nuclear Regulatory Commission described Performance Confirmation for Yucca Mountain in terms of an integrated programme of tests, experiments and analyses (US NRC 1999). The objectives of such a programme include:

- Verifying assumptions data and analyses that support performance assessments (PAs) made to support initial licensing decisions.

- Identifying significant changes to initial PA assumptions and data based on observations and monitoring during the subsequent repository development and operation phases.

- Providing support for later regulatory decisions - for example on repository closure.

All radioactive waste disposal programmes include monitoring, which is commonly defined as the continuous, periodic or intermittent, measurement or recording of observations. Since most of the programmes have focused the development of their monitoring programmes on the construction and operational phases of repository development, monitoring has mainly been considered in relation to the waste and repository conditions, in addition to the impact of construction on the properties of the host rock and the surface environment. This is consistent with the IAEA (2001) definition of monitoring, *"...continuous or periodic observations or 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."* It can be seen, therefore, that monitoring may form one part of a wider Performance Confirmation programme (which, for example, may include other R&D activities aimed at reducing uncertainties and building further confidence in models).

The rationale for monitoring

The rationale for monitoring of radioactive waste disposal systems has been discussed widely (e.g., IAEA 2001, OPG 2003). Long-term safety does not depend on monitoring but monitoring may be required for several reasons (White *et al*. 2003), including:

- Safeguards.

- To determine a "*baseline*" knowledge of site conditions.

- To ensure operational safety and assess any operational impacts.

- To understand the evolution of the near-field.

- To determine the evolution of the geosphere.

- To evaluate the impacts of the repository on the surface.

- Confirmation of performance assessment assumptions.

- As an aid to decision-making, for example to retrieve the waste or to end the institutional control phase.

- Public acceptability and public confidence.

Given the relatively recent adoption by many waste disposal programmes of so-called "*step-wise*" repository development processes, more emphasis is now being placed on the use of monitoring data as an aid to decision-making on moving from one step of the process to another (Nirex *et al.* 2003; NRC 2003).

Monitoring strategies and timescales

A range of considerations needs to taken into account when establishing a strategy for monitoring, and there is a clear need for any particular monitoring strategy to be developed on a site-specific and disposal system specific basis. Constraints on the strategy adopted are likely to include:

- The need to ensure that the monitoring does not compromise disposal system safety.

- The need to take account of stakeholders' views and desires regarding the purpose of monitoring.

- The need to consider the different stages of repository development, for example from site characterisation to the period after repository closure. All of the disposal programmes reviewed by White *et al* (2003) accepted the need for monitoring, extending throughout the phases of investigation, repository development, operation and into the post-closure period. Indeed, it is likely that monitoring in boreholes will continue throughout. The US WIPP programme envisages monitoring "*...until no more meaningful data are being collected*." The Swiss programme envisages that monitoring will continue "*…as long as it is thought beneficial to society*". Nirex *et al*. (2003) discuss schemes by which the development of a repository can be characterised in terms of a series of stages, as well as a range of programmatic approaches that govern how a programme might progress from one stage to another. Obviously the detail of the monitoring that will be undertaken in the different stages will vary, but often the changes are relatively gradual.

- The need for the strategy to be suitably informed by an understanding of the expected evolution of the repository and of the features, events and processes (FEPs) that may affect that evolution (e.g., see Crawford and Wilmot 1998). It is important to realise that the expected evolution of the repository may differ from the central-scenario modelled in performance assessments because modelling simplifications may introduce additional conservatisms. It is also important to consider the uncertainties associated with the occurrence and magnitudes and rates of processes in the disposal system.

- A range of more detailed but nonetheless essential factors including the feasibility, accuracy and reliability of monitoring techniques, and the frequency and location of measurements.

- A strategy for responding to unexpected monitoring observations. Possible strategies include undertaking further measurements, perhaps using complementary monitoring techniques, revising models of disposal system performance, dialogue with regulators and other stakeholders, and undertaking risk management activities, including considering waste retrieval.

Monitoring of the engineered barrier system

The response of the disposal system to repository construction and waste disposal can be characterised broadly in terms of thermal, mechanical, hydraulic and chemical responses (e.g., OPG 2003). These responses are likely to be of a highly coupled nature and will also vary spatially, in response to disposal system geometry and variations in engineered barrier system and host rock material properties.

Parameters that have the potential to be monitored in the longer-term, therefore, include:

- Temperature.
- Rock convergence, canister movement, buffer swelling, movement of the interfaces between the engineered barrier system components, development of an engineering disturbed zone (EDZ), ground surface elevation2.
- Groundwater pressure, hydraulic saturation, water table elevation.
- Water chemistry.

The following sub-sections present examples of concepts and approaches under investigation for monitoring engineered barriers both within repositories and URLs. It is recognised that at the current time, most of the disposal programmes' monitoring plans are yet to be finalised[3], and that few can be regarded as mature. Rather, the majority of the monitoring plans are under active development, and this may be expected to be the case for some years to come, not least so that stakeholder views can be continuously taken into account.

It is noted that the need to ensure that the passive safety provided by the disposal system, and particularly by the engineered barrier system, is not compromised has been interpreted in different ways in different disposal programmes. The snapshot of the status of monitoring plans provided by White *et al*. (2003) indicates that some programmes are considering much more direct and intimate monitoring of the engineered barrier system than others. Such direct monitoring would involve the placement of sensors and communication devices (cables, transmitters) within or close to the engineered barriers, and has been described as being "*invasive*" (e.g., OPG 2003).

---

2 Surface elevation changes may provide indirect evidence on the behaviour of the repository. For example, uplift is expected as a consequence of heating in the Canadian system (Thompson and Simmons 2003), and subsidence may occur associated with closure of the US WIPP repository, which is hosted in salt and does not contain heat-producing waste.

3 The US WIPP programme may be regarded as an exception.

The Finnish and Swedish programmes seem to favour little or no invasive monitoring of the repository engineered barrier system (e.g., Olsson *et al*. 2001), even though Olsson *et al*. (2001) identify plans for a pilot facility as part of the Swedish programme. In contrast, the Canadian and Japanese programmes seem to place relatively more emphasis on direct monitoring of the engineered barrier system, at least within Underground Rock Laboratories (URLs), experimental parts of the repository, or pilot facilities, where the opportunities for monitoring of the engineered barrier system are increased.

Data Transmission

Developments in the capabilities of wireless data transmission technologies are opening up further possibilities for monitoring of the engineered barrier system without compromising barrier integrity or passive safety. Information presented by Malan *et al*. (2000) suggests that although infrared radiation and conventional radio transmissions systems may offer little real potential for remote communication of monitoring data, even while the repository is open, through-the-earth (TTE) telemetry has significant potential for use during both the pre-closure and post-closure periods.

TTE telemetry is based on the transmission of data using very low-frequency electromagnetic waves (e.g., 2-3 MHz). Tests conducted in South African mines indicate that wireless TTE communication can be effective between depths of 500 m and the surface, and have included the successful transmission of data from remote mine-closure sensors (Malan *et al*. 2000; Malan *et al*. 2003). Further tests are investigating the use of TTE telemetry for transmission of data within mines in conjunction with wired systems for transmission of data to the surface.

Testing and development of similar technologies is under way in Japan, where through-rock transmission of data has been shown to be feasible over a distance of 115 m. Long-term (10-year) tests of the system are scheduled for the monitoring of subsidence at Kansai International Airport. The French waste disposal organisation, ANDRA, is also understood to be testing TTE telemetry systems for use in sealed boreholes.

According to Kononov and Smit (1997) and Kononov (1998), the main factors that control the performance of TTE telemetry include:

- Surface and underground electromagnetic background noise.
- Rock attenuation.
- Surface and underground transmission power.
- Antenna parameters.

With regard to the supply of power, the Japanese organisation RWMC estimates that 50-year battery lifetimes are achievable. Protocols can be developed for prolonging battery life, that include, for example, only transmitting information at pre-determined times, or when the rate of change of a measurement exceeds a trigger value. In addition, signals can be transmitted regarding the status of battery life so that the time at which the data stops being received can be predicted in advance. An alternative approach to the use of batteries would be to provide some form of power generation in the sub-surface, perhaps based on a local heat source. Further research and development would be needed to explore the possibilities for providing long-term power supplies in repositories.

Figure 1 illustrates a Japanese concept for remote monitoring of a disposal system that includes sensors within the engineered barrier system and wireless data transmission along a series of relay stations. The Japanese programme is also considering an idea to use mobile "*self-moving*" monitoring equipment for data gathering within a repository (Figure 2).

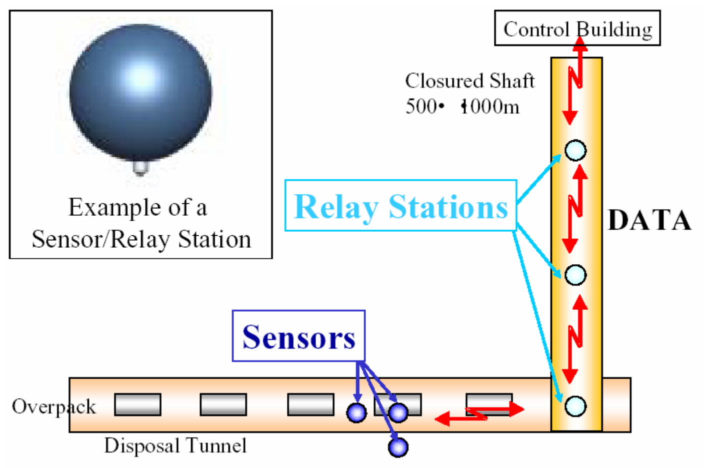

Figure 1 Japanese concept for remote monitoring of a HLW repository.

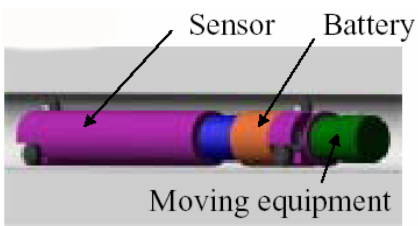

Figure 2 Japanese concept for a mobile sensor device which could form part of a remote monitoring system for a HLW repository. The device would run in tunnels above the waste deposition holes collecting telemetry data from sensors closer to the waste.

Monitoring of the canister

With the exception of monitoring for canister movement or settlement, the opportunities for monitoring of the waste canister itself after manufacture, sealing and emplacement within the deposition hole appear to be rather limited.

In most HLW/spent fuel disposal programmes, radionuclide releases are not expected to occur in the first few thousands of years or longer (e.g., Olsson 2001). Any monitoring for radionuclide release from the waste canister is, therefore, most likely to be of most benefit in enhancing stakeholder confidence in canister integrity.

As an example of potential approaches, the Japanese programme has considered monitoring the radionuclide content of any drainage waters collected within the repository during the operational phase. The Japanese programme has also included work aimed at using a detector placed close to the canister within the buffer, together with optical fibers or optical stimulated luminescence systems, to make measurement of radiation around waste overpacks.

Monitoring of the buffer

A prime example of monitoring the buffer is provided by the European Commission-sponsored Full-scale Engineered Barriers Experiment (FEBEX) project. FEBEX included monitoring of the behaviour of bentonite buffer materials in tests designed to approximate closely a system for the disposal of HLW in granitic host rocks (e.g., ENRESA *et al*. 2000). The FEBEX "*in-situ*" test was conducted over a period of several years in the URL at Grimsel in Switzerland. Full size waste containers were simulated using cylindrical heaters and these were surrounded with blocks of highly compacted bentonite clay. Some 632 sensors were installed in the heaters, the clay barrier, the surrounding rock and a service zone, a region at the end of the tunnel separated from the heaters and clay barrier by a concrete plug (Table 1). These sensors were used to monitor temperature, humidity, total pressure, displacement and water pressure. In addition, a system of porous ceramic pipes was installed to allow monitoring of gas pressure and composition.

The FEBEX project demonstrated the feasibility of installing a range of different sensors in the buffer and operating them over a several year period with a lower percentage of failures than was originally expected by the manufacturers. The FEBEX project also included a significant component of coupled thermo-hydro-mechanical and thermo-hydro-geochemical process modelling and was successful at improving confidence in understanding of buffer mineral transformation processes, buffer permeability and buffer swelling, in response to hydration and heating, and in highlighting certain geochemical uncertainties (ENRESA *et al*. 2000).

Although it would probably not be appropriate to apply the type and level of invasive monitoring performed during the FEBEX experiments within a real repository because this might compromise the passive safety provided by the engineered barrier system, the use of suitable telemetry systems might enable at least some direct monitoring of the engineered barrier system without compromising passive safety.

Monitoring of seals

The Canadian programme has considered a range of seals for use in waste emplacement rooms, access tunnels, shafts and boreholes, and has assessed the performance of seals composed of cement-based and clay-based materials. The Canadian programme has also undertaken a number of significant tests, most notably the Tunnel Sealing Experiment, involving monitoring of seals and engineered barriers in the Canadian URL. Details of the instruments and systems used for monitoring the performance of repository seals during the Canadian URL tests are described and discussed in OPG (2001).

Monitoring the performance of a repository seal may necessitate instrumentation of the rock mass around the seal, of the interfaces between the seal components and the rock, as well as the seal itself (Table 2).

General conclusions from the Canadian seal studies (OPG 2001) include:

- The need to plan not only for the installation of sensors but to ensure that due consideration is also given to the associated equipment (e.g., signal conditioners, amplifiers, cables junction boxes, dataloggers).

- The need to protect instrumentation to the extent possible from the effects of moisture, dust and lightening.

- That although some success was achieved using remote sensing technologies to monitor mechanical effects, further research and development work would be necessary to extend the use of these technologies to the monitoring of strain, hydraulic or other monitoring parameters.

Table 1 Sensors installed during the FEBEX “*in-situ*” test (ENRESA *et al.* 2001).

Variable (or instrument)	Type of sensor	Area (*)				Total
		G	**B**	**C**	**S**	
Temperature	Thermocouple	62	91	36		189
Total pressure in borehole in rock (3-D)	Vibrating wire	4				4
Total pressure on rock surface	Vibrating wire	30				30
Total pressure on heater	Vibrating wire		6			6
Hydraulic pressure in borehole in rock	Piezoresistive	62				62
Packer pressure in borehole	Piezoresistive	62				62
Pore pressure in bentonite	Vibrating wire		52			52
Water content	Capacitive		58		1	59
Water content	Psychrometer	28	48			76
Water content	Time Domain Reflectometer	4	20			24
Extensometer in rock	Vibrating wire	2x3				6
Heater displacement	Vibrating wire		9			9
Expansion of bentonite block	Vibrating wire		8			8
Displacement within the bentonite barrier	Potentiometer		2x3			6
Clinometer	Linear Variable Differential Transformer		6x2			12
Crack meter	Linear Variable Differential Transformer	1x3				3
Gas pressure in the bentonite barrier	Magnetic		4			4
Gas flow	Manual measure		6			6
Atmospheric pressure	Piezoresistive				1	1
Velocity of ventilation air	Hot wire				1	1
Resistor intensity	Electric converter				6	6
Resistor voltage	Electric converter				6	6
TOTALS		**261**	**320**	**36**	**15**	**632**

(*) G: granite; B: bentonite; C: heater; S: service zone

Table 2 Monitoring components of repository seals (OPG 2001)

Seal Component	Feature Monitored
Rock	Excavation damage Rock mass displacement Stress change Temperature Pore Pressure
Interfaces between seal components	Contact pressure Hydraulic pressure Interface aperture displacement Acoustic emission Temperature
Cement-based seal components	Strain Displacement Acoustic emission Temperature
Clay-based seal components	Pressure Moisture content Displacement

Conclusions

Some disposal programmes are considering much more direct and intimate monitoring of the engineered barrier system than others. Such direct monitoring would involve the placement of sensors and communication devices within or close to the engineered barriers, and has been described as being "*invasive*". The Finnish and Swedish programmes seem to favour little or no invasive monitoring of the repository engineered barrier system. In contrast, the Canadian and Japanese programmes seem to place relatively more emphasis on direct monitoring of the engineered barrier system, at least within Underground Rock Laboratories (URLs), experimental parts of the repository, or pilot facilities, where the opportunities for monitoring of the engineered barrier system are increased. Developments in the capabilities of wireless data transmission technologies are opening up further possibilities for non-intrusive monitoring of the engineered barrier system without compromising barrier integrity or passive safety.

This paper has touched on a few selected issues associated with repository monitoring and its role in Performance Confirmation. Examples of monitoring approaches and techniques have been discussed. The authors are not proposing that any particular techniques are necessarily more appropriate than others, and firmly believe that the development of an appropriate monitoring strategy is something that needs to reflect the particular national context as well as site-specific and disposal system specific issues.

Given the context of the SKI workshop, this paper may serve to help identify relevant regulatory questions such as the following:

- Does the Performance Confirmation (PC) plan include the relevant components?
- Does the plan include relevant monitoring techniques across the stages of repository development?
- Is the plan flexible so that it can take account of societal (e.g., in stakeholder views) and R&D developments (e.g., telemetry)?
- Are the PC plan and the monitoring strategy adequately informed by understanding of the FEPs that will affect the disposal system and its expected evolution? How are uncertainties accounted for?
- How are key parameters (or FEPs) prioritised?

References

Crawford M.B. and Wilmot R.D. (1998) Normal evolution of a spent fuel repository at the candidate sites in Finland. Posiva Oy Report 98-15.

ENRESA, AITEMIN, ANDRA, CIEMAT, CSC-Zaidin, G.3S, GRS, NAGRA, SGS Tecnos SA, ULC, UPC-DIT, and UPM (2000) FEBEX project. Full-scale engineered barriers experiment for a deep geological repository for high-level radioactive waste in crystalline host rock. Final Report. ENRESA Technical Publication 1/2000.

IAEA (2001) Monitoring of geological repositories for high-level radioactive waste. IAEA-TECDOC-1208, IAEA, Vienna.

Kononov, V.A., and Smit, J.J. (1997) Global Mine Warning and Monitoring System, Proceedings of the 27th International Conference of Safety in Mines Research Institutes, February 20-22 1997, New Delhi.

Kononov, V.A. (1998) Developing a trapped miner location system, an adequate rescue strategy and associated technologies. SIMRAC Final Project Report GEN502. Pretoria: Department of Minerals and Energy, 36p.

Malan, D.F., Kononov, V.A., Coetzer, S.J., Janse van Rensburg, A.L., and Spottiswoode, B.S. (2000) The feasibility of a mine-wide continuous closure monitoring system for gold mines. Final Project Report GAP 705, Safety in Mines Research Advisory Committee, South Africa.

Malan, D.F., Grave, M., Napier, J.A.L., Piper, P.S. and Lawrence, L.E. (2003) Experimental validation of a mine-wide continuous closure monitoring system as a decision tool for gold mines. Final Project Report GAP 852, Safety in Mines Research Advisory Committee, South Africa.

Nirex, ANDRA, DBE, ENRESA, NAGRA, NRG, ONDRAF/NIRAS, Posiva, RAWRA, SCK/CEN, SKB and SAM (2003) EC Thematic Network on the Role of

Monitoring in a Phased Approach to Disposal. EC Report: EC-TN-Monitoring-Rep-11.

NRC (National Research Council of the National Academies) (2003) One Step at a Time: The Staged Development of Geologic Repositories for High-Level Radioactive Waste. Washington, D.C: The National Academies Press. ISBN 0-309-08708-2.

Olsson, O., Svemar, C., Papp, T., Hedman, T. (2001). The Potential for Retrievability and Application of Monitoring within the KBS-3 Concept for Final Disposal of Spent Nuclear Fuel. In: Proceedings of WM'01 Conference, February 25 – March 1, 2001, Tuscon, Arizona.

Ontario Power Generation (2001) Instruments and systems for monitoring the engineering performance of repository seals. OPG Report No: 06819-REP-01200-10072-R00.

Ontario Power Generation (2003) An approach to long-term monitoring for a nuclear fuel waste repository. OPG Report No: 06819-REP-10106-R00.

SKI (2003) Long-term integrity of the KBS-3 engineered barrier system. Report from Workshop at Krägga Herrgård, Bålsta, Sweden, 6-8 November 2002. Synthesis and Extended Abstracts, Swedish Nuclear Power Inspectorate Report 2003:29.

Thompson, P.M. and Simmons, G.R. (2003). An approach to long-term pre-closure and post-closure monitoring for a nuclear fuel waste repository. In: Myrvoll (ed.) Field Measurements in Geomechanics, Swets and Zeitlinger, 799-809.

US NRC (1999) Disposal of high-level radioactive waste in a proposed geologic repository at Yucca Mountain, Nevada. Proposed Rule, Federal Register, 64(34), 8640-79.

White, M.J., Bennett, D.G., Crawford, M.B. and Emsley, S. (2003) Techniques for post-closure monitoring. Galson Scienecs Limited Report to United Kingdom Nirex Limited. 0358-1, SC3030/008.

Thematic Network on the Role of Monitoring within a Staged Approach to Geological Disposal of Radioactive Waste

Steve Barlow, United Kingdom Nirex Limited

Background

It has always been recognised that monitoring will be required in support of the implementation of geological disposal of long-lived radioactive waste. The issue has become of increased importance with the adoption of a phased, or step-wise approach to development and implementation of disposal, that is now a feature of many national programmes.

Monitoring has already been the subject of several different international studies and these have been reviewed by a Thematic Network set up in 2001. 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.

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.

The EC Concerted Action on The Retrievability of Long-lived Radioactive Waste in Deep Underground Repositories (EC 2000) 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.

Against this background the Thematic Network was established under the auspices of the European Commission, to bring together waste management organisations from ten European nations to explore the role of monitoring in geological disposal and in particular within a phased, or step-wise approach.

As of May 2004, the Thematic Network has submitted its final report to the European Commission, which proposes to publish the report within the EUR report series. Participants within the Thematic Network represented waste management organisations from UK, Belgium, France, Germany, the Netherlands, Spain, Czech Republic, Switzerland, Finland and Sweden. The "*Country Annex*" supplied by SKB (the Swedish Waste Management Organisation) is appended to this paper in the Annex.

Introduction

The safe management of 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 facing many nations. 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 (IAEA 2004; NEA 2004)].

Notwithstanding the above, it has always been recognised that monitoring will have an important role to play in supporting the implementation of geological disposal, and with moves towards a phased implementation approach, the importance of monitoring was seen to be even more important. The Thematic Network agreed that the following points should be considered when defining the role of monitoring in a geological disposal facility:

- the strategy for monitoring should be developed within the full context of the problem;
- it should be accepted that monitoring will be different between stages;
- the reason for monitoring should be explicit and stated;
- the limitations of the technology that exists must be understood;
- when developing the strategy the broader aspects must be acknowledged.

The following sections consider each of these in turn and why they are important.

Development of the strategy for monitoring

From the outset of the Thematic Network, it was clear that there could be no one single monitoring strategy applicable to all programmes as it would be dependent upon many factors, often determined by the nature of the project, the types of waste or the specific national requirements. Different approaches have been identified as outlined below.

Definition

Monitoring covers a number of aspects so it is important to have a clear definition. The IAEA technical document (IAEA 2001), proposes a definition but this was not considered comprehensive by the Thematic Network members. Therefore the proposed definition of monitoring adopted by the Thematic Network was:

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.

However, it is recognised that this is also a compromise, which may not be applicable to all approaches.

Implementation

The development of a geological disposal system for radioactive waste comprises a series of consecutive phases whose implementation will be different between concepts. For the purpose of illustration two contrasting approaches can be defined.

- One approach, based on a robust repository design and safety case, assumes that any decisions that needs to be taken to progress through subsequent phases will follow a pre-defined schedule. 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. This approach has been termed "*linear staging*" in some programmes (NRC 2003).

- Another approach to phased disposal emphasises a flexible schedule of its implementation, taking into account the uncertainties inherent to a long-term project and 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. This approach has been termed "*adaptive staging*" (NRC 2003).

These differences have definite implications for the type and extent of monitoring information required to support the decision making process. In particular this will affect the amount of monitoring that is conducted close to and in the waste disposal areas. The Thematic Network considered that this could develop into three alternative strategies:

- Little or no monitoring may be planned close to the waste where sufficient work has been carried out elsewhere, there are no adverse indicators and the presence of monitoring equipment close to the waste is thought likely to reduce the efficacy of the engineered barrier system;

- Monitoring will take place in a pilot facility that is developed at the repository site in parallel with the development of the repository, the aim of the 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.

- Where there is time in the programme monitoring will take place in the engineered barrier system relatively close to the waste itself so as to provide confirmatory evidence that the repository is behaving as envisaged.

Parameters to be monitored

One of the key aspects of monitoring is how representative the results are, 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 is 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.

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 now to assist them in making these decisions.

Monitoring will be different between stages

The monitoring requirements will vary between implementation stages because of the data required and the information that can be obtained.

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 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.

The differences in approach to repository development outlined in Section 3.2 lead to differences in monitoring programmes, which can be clearly seen in the pre-closure phase of the repository. In the linear approach, 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 the adaptive approach, 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 (c.f. Nagra's proposed pilot facility). 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.

Some programmes are also considering the need for long-term post-closure monitoring: this may be considered necessary as long as active institutional control is demanded by societal or legal requirements. 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. such long-term monitoring programmes may 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.

Reasons for monitoring should be explicit

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.

Limitations of technology should be understood

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 engineered barrier system 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). Category 5 is also more likely to be associated with the "*adaptive staging*" approach.

The broader aspects must be acknowledged

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 conclusions of the Thematic Network were by nature rather general and may not apply to all countries and programmes.

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 engineered barrier system, etc.);

- monitoring of the context and requirements on the overall waste management concept of a specific country, such as: national energy policy and 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 analysis 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 considered to be outside the scope of the project and were not addressed.

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 1997) 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.

Conclusions

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 the 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.

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.

References

EC (European Commission) (2000) Concerted Action on the Retrievability of Long-lived Radioactive Waste in Deep Underground Repositories, European Commission Report EUR 19145 EN.

IAEA (1997) Joint Convention on the safety of spent fuel management and the safety of radioactive waste management. IAEA document INFCIRC/546, 24 December 1997.

IAEA (2001) Monitoring of geological repositories for high-level radioactive waste. IAEA-TECDOC-1208. ISSN- 1011-4289.

IAEA (2002) Issues related to safety standards on the geological disposal of radioactive waste, IAEA-TECDOC-1282, International Atomic Energy Agency, Vienna 2002.

IAEA (2004) Geological Disposal of Radioactive Waste, IAEA Safety Standards Series, Safety Requirements, International Atomic Energy Agency, Vienna, 2004.

NEA (2004) The Nature and Purpose of the Post-closure Safety Case in Geological Disposal, Nuclear Energy Agency, OECD, Paris.

NRC (2003) One step at a time. The staged development of geologic repositories for high-level radioactive waste. National Research Council, National Academic Press, Washington DC, 201pp.

Annex 1

The Thematic Network Country Annex for Sweden (supplied by SKB)

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.

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 formas 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, b).

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.

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.

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.

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.

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).

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.

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.

References

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.

Figure 1 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. **Boreholes from the ground surface** - groundwater chemistry and pressure, temperature	**Climate** - temperature, atmospheric pressure, precipitation, evaporation, runoff, sea level changes **Biosphere** - flora, fauna, soil layer land use etc. **Boreholes from the ground surface** - groundwater chemistry and pressure, temperature	**Climate** - temperature, atmospheric pressure, precipitation, evaporation, runoff, sea level changes **Biosphere** - flora, fauna, soil layer land use etc. **Boreholes from the ground surface** - groundwater chemistry and pressure, temperature	**Climate** - temperature, atmospheric pressure, precipitation, evaporation, runoff, sea level changes **Biosphere** - flora, fauna, soil layer land use etc. **Documentation is preserved** **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	**Seismic events** - time, location and type of local earthquakes - micro-seismic events	**Seismic events** - time, location and type of local earthquakes - micro-seismic events **Documentation is preserved**
	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	**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	**Surveillance of the repository** - safeguards **Documentation is preserved**

Long-Term Tests Relevant to the Performance Confirmation of the engineered barrier system Design in the KBS-3 Concept

David Savage, Quintessa Limited

Introduction

SKB are carrying out a number of tests at the Äspö HRL, principally "*to demonstrate the technology required for key functions of a deep repository for high-level radioactive waste*" (Börgesson, 1997), namely:

- prototype repository;
- technology demonstration;
- retrieval test;
- backfill and plug test;
- long term tests;
- tests of adverse conditions.

A number of reports and papers have been published regarding the planning and operation of the backfill and plug test (Börgesson, 1997; Börgesson and Hernelind, 1999; Gunnarsson *et al*., 2001, 2002; Goudarzi *et al*., 2003), the prototype repository (Svemar and Pusch, 2000, Pusch and Svemar, 2003; Goudarzi and Johannesson, 2003), and the long-term test of buffer material (Karnland *et al*., 2000). These publications are reviewed here.

Backfill and plug test

SKB envisage that the Backfill and Plug Test is a full-scale test of backfill material, backfilling techniques, and construction of a tunnel plug. According to SKB, the main objectives of the Backfill and Plug Test are to:

- develop and test different materials and compaction techniques for backfilling of tunnels excavated by blasting;
- test the function of the backfill and its interaction with the surrounding rock in a tunnel excavated by blasting;
- to develop techniques for building tunnel plugs and to test the function thereof.

SKB completed the installation of this test at the Äspö Hard Rock Laboratory (HRL), in l999. The inner part of the tunnel is not used for the test but is filled with 'drainage material'. The test volume, which is about 28 m long, can be divided into the following three parts (Figure 1):

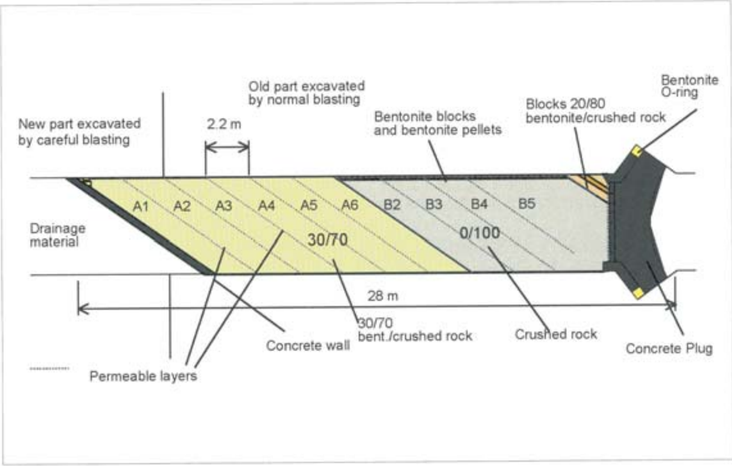

Figure 1 Layout of the Backfill and Plug Test at the Äspö Hard Rock Laboratory. From Gunnarsson *et al*. (2002).

- an inner part filled with backfill consisting of 30 % bentonite and 70 % crushed rock;
- an outer part filled with crushed rock backfill without bentonite, but with bentonite blocks and pellets at the roof;
- a concrete plug with bentonite blocks as an 'O-ring' seal.

Permeable mats divide the test volume into 11 test sections. The permeable mats are used for increasing the water saturation rate in the backfill and for applying hydraulic gradients between the layers for studying the flow of water in the backfill and in the near field rock. The permeable layers are installed every 2.2 m and each layer is divided into three units in order to measure the flow close to the roof, in the central areas of the tunnel, and close to the floor.

The outer part ends with a wall of prefabricated concrete beams that were used for temporary support of the backfill during the casting of the plug. The upper volume close to the plug is filled with bentonite pellets and blocks consisting of 20 % bentonite and 80 % sand. The backfill is instrumented with 34 pore water pressure cells, 21 total pressure cells, 57 sensors for monitoring the water saturation, and 13 gauges for measuring the local hydraulic conductivity. The water pressures in the permeable mats are measured in all sections. All cables and tubes are led through watertight seals through boreholes to the neighbouring 'demonstration tunnel'. Four pressure cylinders, 2 in the roof and 2 in the floor of the tunnel, are installed to measure the mechanical properties of the backfill after saturation. The water pressure in the rock is measured in 75 sections in boreholes. Microorganisms have been placed in both backfill materials to investigate if they can multiply under the existing conditions.

The plug is designed to resist the water and swelling pressures that may develop (estimated to be 2-3 MPa). The design includes a 1.5 m deep slot and an 'O-ring' of highly compacted bentonite in order to cut off the excavation disturbed zone.

According to SKB, the installation as a whole worked well. SKB estimate that the bulk average dry density is between 1650 and 1700 kg/m3 for the 30/70 backfill material and the average measured dry density of the 0/100 material was 2170 kg/m3. After the installation of the test, the water saturation of the backfill started. The water saturation was expected to be completed at the beginning of 2003 with flow testing starting thereafter.

Prototype repository

According to SKB, "the main objectives of the Prototype Repository Project are to simulate part of a future KBS-3 deep repository to the extent possible with respect to geometry, design, materials, construction and rock environment except that radioactive waste is simulated by electrical heaters, and to test and demonstrate the integrated function of the repository components. Additional objectives of the prototype repository, which will be operated for up to 20 years, is to develop, test and demonstrate appropriate engineering standards and quality assurance methods, and to accomplish confidence building as to the capability of modelling engineered barrier system performance. The latter is effected by providing data for predicting the performance of the system by use of models that are available or will be developed".

The Prototype Repository test site is a 65 m long TBM-bored drift at the Äspö HRL from which six 1.75 m diameter deposition holes extend downwards to about 8 m depth in accordance with the KBS-3 concept (Figure 2).

The outer 25 m long part has two holes and is separated from the inner 40 m long one, which has 4 holes, and from the rest of the underground laboratory by stiff and tight plugs. The deposition holes contain genuine copper/steel canisters with heaters for simulating the warming caused by the radioactive decay. The canisters are embedded in dense buffer clay consisting of blocks of compacted bentonite powder, and the drift will be backfilled. The instrumentation makes it possible to record major processes in the rock, buffer and backfill, like piezometric and pore water pressures, wetting/drying of the buffer and backfill, temperature evolution in the buffer and backfill and surrounding rock, effective and total pressures and displacements in the buffer and backfill and surrounding rock, gas accumulation in the buffer, and chemical and biological processes in the system.

Models have been derived for predicting and describing the thermal-hydro-mechanical-chemical-biological (THMCB) functions of the near-field rock and engineered barriers and they will be applied and evaluated by use of the experimental data. According to SKB, further major purposes of the project are to define how practical characterisation and modelling of the rock can be made at various planning and construction stages, and to apply and evaluate a number of construction and transportation issues.

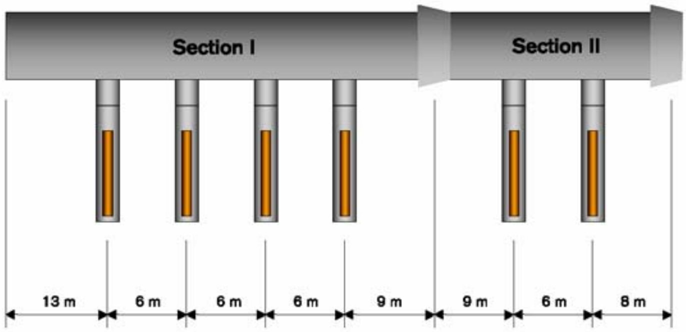

Figure 2 Schematic view of the layout of the Prototype Repository. From Goudarzi and Johannesson (2003).

In theory, the Prototype Repository test will make it possible to investigate a number of processes over relatively long periods of time, particularly with regard to issues such as:

- application on site of buffer and backfill under real conditions with consideration of drainage problems.
- Construction of plugs.
- Emplacement of full-scale canisters.
- Long-term evolution of the wetting/drying of the buffer and backfill in differently structured and water-bearing rock.
- Mechanical response of the near-field rock to heating.
- Chemical processes in both the water saturation phase and after saturation of the buffer and backfill, comprising salt accumulation, cementation, and mineralogical changes. Microbial processes over longer periods of time.

Long-term test of buffer material

The "*Long Term Test of Buffer Material*" (LOT) series of experiments at the Äspö HRL aims at checking models and hypotheses for a bentonite buffer material under conditions similar to those in a KBS-3 repository. The test series comprises seven test parcels, which are exposed to repository conditions for 1, 5, and 20 years. The experimental layout is to place parcels containing heater, central copper tube, pre-compacted bentonite blocks and instruments in vertical boreholes in crystalline rock (Figure 3).

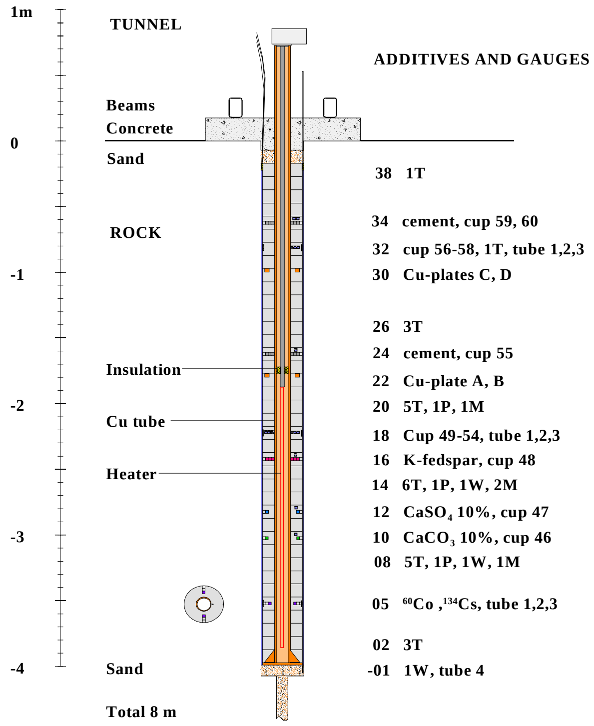

Figure 3 **Schematic diagram of the layout of the 'adverse conditions' long-term test at Äspö HRL. From Karnland *et al*. (2000).**

So far, only the 1-year 'pilot parcel' tests have been completed. These parcels were heated at standard KBS-3 conditions (S1 parcel, 90°C), and also under 'adverse conditions' (A1 parcel, 130°C). The latter was used in order to accelerate possible processes. Temperature, total pressure, water pressure, and water content were measured during the heating period. The two pilot tests were terminated after approximately 12 months of heating, and the parcels extracted by over-coring of the original borehole. The entire 4.5 m long S1-parcel with approximately 20 cm rock cover was successfully lifted in one piece from the rock, whereas the central part of the A1 parcel was lost during drilling. The upper and lower parts were however retrieved.

Reference and exposed bentonite material were analysed with respect to physical properties (triaxial, beam and oedometer tests), and to mineralogical properties (XRD, CEC, ICP-AES and SEM analyses) according to a defined test programme. Some precipitation of minerals, mainly gypsum, was found in the warmest part of the parcels, and the only unpredicted change was minor uptake of Cu into the clay matrix. A principal conclusion was that no degrading processes with respect to buffer performance were found in the major part of the bentonite as a consequence of the water saturation process and heating for one year.

Bentonite plugs containing 134Cs and 60Co, with an activity of 1 MBq, respectively, were placed at defined positions in the bentonite in order to study cation diffusion. Transport in unsaturated bentonite was confirmed to be minimal. The apparent diffusivity of cobalt in the saturated bentonite was measured to be about 2 10-9 cm2 s-1, which is in good agreement with previous experiments. The caesium results could not be fitted to a diffusion profile, and SKB envisage further investigations to ascertain why.

Large numbers of microorganisms were introduced into two blocks as starting concentrations. The material was analysed immediately after mixing, after 72 hours, and after termination of the experiment. All bacteria except for the spore-forming species were eliminated below the detection limits in the exposed parcel material.

Small well-characterised copper coupons were placed in the bentonite at a few locations. The coupons were of the same copper quality as proposed for the KBS-3 canisters. The mean corrosion rate was calculated to be 3 10-6 m per year, which is in accordance with previous modelling results for oxic conditions. Optical and SEM analyses did not reveal any signs of pitting. A higher copper content was noticed in the bentonite in the vicinity of the copper coupons.

Conclusions

SKB has reached a critical stage in the development of its programme for the eventual construction of a repository for HLW, namely the transition from an idealised theoretical concept to a practical engineering programme which can be demonstrated to be safe in the long-term. Since the tests at the Äspö HRL are being conducted in ‘real time’, even test durations of 20 years are short in light of timescales for long-term safety. Consequently, it is unlikely that many topics of relevance to long-term performance can be investigated by such tests. However, issues relating to the practicality and quality of emplacement of the engineered barrier system materials and consequent implications for long-term safety can be pursued through these tests and should be a focus for SKI’s concern.

References

Börgesson, L., Äspö Hard Rock Laboratory. Test Plan for Backfill and Plug Test, Progress Report HRL-98-08, Swedish Nuclear Fuel Management Company Limited, Stockholm, Sweden, 1997.

Börgesson, L., and Hernelind, J., Äspö Hard Rock Laboratory. Preparatory modelling for the backfill and plug test. Scoping calculations of H-M processes, International Progress Report IPR-99-11, Swedish Nuclear Fuel Management Company Limited, Stockholm, Sweden, 1999.

Goudarzi, R., Gunnarsson, D., Johannesson, L.-E., and Börgesson, L., Äspö Hard Rock Laboratory. Backfill and Plug Test, Sensors data Report (period 990601-030101) Report No: 6, International Progress Report IPR-03-14, Swedish Nuclear Fuel Management Company Limited, Stockholm, Sweden, 2003.

Goudarzi, R., and Johannesson, L.-E., Äspö Hard Rock Laboratory. Prototype Repository, Sensors data report (period 010917-030901) Report No: 7, International Progress Report IPR-03-46, Swedish Nuclear Fuel Management Company Limited, Stockholm, Sweden, 2003.

Gunnarsson, D., Börgesson, L., Hökmark, H., Johannesson, L.-E., and Sandén, T., Äspö Hard Rock Laboratory. Report on the installation of the Backfill and Plug Test, International Progress Report IPR-01-17, Swedish Nuclear Fuel Management Company Limited, Stockholm, Sweden, 2001.

Gunnarsson, D., Börgesson, L., Hökmark, H., Johannesson, L.-E., and Sandén, T.: Installation of the backfill and plug test. In Clays in Natural and Engineered Barriers for Radioactive Waste Confinement: Experiments in Underground Laboratories, Reims, France, pp. 94-107, 2002.

Karnland, O., Sandén, T., Johannesson, L.-E., Eriksen, T. E., Jansson, M., Wold, S., Pedersen, K., Motamedi, M., and Rosborg, B., Long term test of buffer material. Final report on the pilot parcels, SKB Technical Report TR-00-22, Swedish Nuclear Fuel Management Company Limited, Stockholm, Sweden, 2000.

Pusch, R., and Svemar, C., Äspö Hard Rock Laboratory. Prototype Repository, Predictive modelling of the engineered barrier system performance in the Prototype Repository Project, International Progress Report IPR-03-26, Swedish Nuclear Fuel Management Company Limited, Stockholm, Sweden, 2003.

Svemar, C., and Pusch, R., Äspö Hard Rock Laboratory. Prototype Repository, Project Description FIKW-CT-2000-00055, International Progress Report IPR-00-30, Swedish Nuclear Fuel Management Company Limited, Stockholm, Sweden, 2000.

APPENDIX 4: QUESTIONS TO SKB

During the workshop the working groups identified a set of questions for SKB. The questions were derived on the basis of:

- The workshop objectives.
- The presentations to SKI and SSI staff by SKI contractors and overseas experts.
- The results of previous SKI reviews of SKB's research, development and demonstration (RD&D) programme.
- The conclusions from previous SKI workshops on the engineered barrier system.
- The tour of the Äspö underground laboratory.

The questions are presented below grouped according to a few broad topic areas.

General Questions

1. Is Performance Confirmation part of SKB's long-term testing programme? If so, how does SKB define, and how would SKB like to use, Performance Confirmation?

2. In which areas would input from SKI be helpful to SKB regarding long-term testing?

3. How has SKB used its safety assessments and understanding of disposal system evolution to prioritize its plans for long-term testing?

Questions on Performance Confirmation

4. How will SKB reconcile the timescales for the licencing programme with the production of results from Äspö?

5. What data from Äspö will be used in SR-Can?

6. How much long-term testing is planned for the Äspö and how much is planned for the selected site?

7. How relevant are the data from Äspö to another site?

8. What long-term tests from other international programmes is SKB currently planning to use?

9. What is the role of predictive model testing (as opposed to calibration) in the Äspö programme? Does SKB have alternative conceptual models for different processes? If so, has SKB considered how a testing RD&D programme might

be used to distinguish between alternative conceptual models, where they exist?

10. How statistically relevant are the data from Äspö?

Questions on Monitoring

11. What is SKB's plans for a monitoring programme?

12. Does a demonstration need to be undertaken of closing the main repository tunnels?

13. What monitoring results would require canister retrieval?

Questions Relating to the Prototype Repository Test

14. What is the single most important lesson/key issue likely to be learnt from the Prototype Repository?

15. Will REDOX in the buffer be measured during the Prototype Repository test?

16. What are the implications of differential wetting of deposition holes?

17. What can be measured during/after excavation of the Prototype Repository?

Questions Relating to the Backfill

18. How do available results from Äspö compare to the specifications-/requirements of the buffer & backfill?

19. Has SKB decided on the suitability of the crushed rock backfill? And of the 30:70 backfill?

20. If the performance of the emplaced backfill is less than expected in performance assessment, what are the implications for the requirements on the plugs and for risk/safety?

Questions Relating to KBS-3H

21. If a horizontal concept is adopted:

    (a) What data from the existing Äspö experiments will still be relevant?

    (b) What additional experiments are necessary to support KBS-3H?

    (c) Is the expected evolution of the KBS-3H disposal system different from the KBS-3V, in that case how?

Additional Questions

22. Does SKB anticipate the need for carrying out subsurface tests using real fuel elements, rather than simulated engineered barrier system components? e.g. radiation effects vs. electric heater

23. Does SKB have any long-term laboratory tests addressing creep of copper?

24. SKI and SSI are concerned about the range in resaturation times. What are the implications of differential wetting of deposition holes?

25. Is SKB considering alternative bentonites? Is there a need for long-term testing of alternative bentonites?

www.ski.se

STATENS KÄRNKRAFTINSPEKTION
Swedish Nuclear Power Inspectorate

POST/POSTAL ADDRESS SE-106 58 Stockholm
BESÖK/OFFICE Klarabergsviadukten 90
TELEFON/TELEPHONE +46 (0)8 698 84 00
TELEFAX +46 (0)8 661 90 86
E-POST/E-MAIL ski@ski.se
WEBBPLATS/WEB SITE www.ski.se