Radioactive Waste Management
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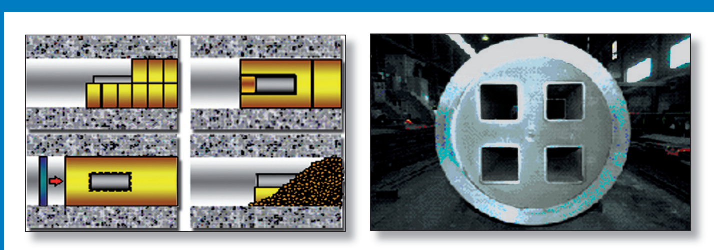
Engineered Barrier Systems (EBS) in the Safety Case: Design Confirmation and Demonstration

Workshop Proceedings
Tokyo, Japan
12-15 September 2006



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NEA No. 6257

NUCLEAR ENERGY AGENCY
ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

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NUCLEAR ENERGY AGENCY

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The mission of the NEA is:

- to assist its member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally friendly and economical use of nuclear energy for peaceful purposes, as well as
- to provide authoritative assessments and to forge common understandings on key issues, as input to government decisions on nuclear energy policy and to broader OECD policy analyses in areas such as energy and sustainable development.

Specific areas of competence of the NEA include safety and regulation of nuclear activities, radioactive waste management, radiological protection, nuclear science, economic and technical analyses of the nuclear fuel cycle, nuclear law and liability, and public information. The NEA Data Bank provides nuclear data and computer program services for participating countries.

In these and related tasks, the NEA works in close collaboration with the International Atomic Energy Agency in Vienna, with which it has a Co-operation Agreement, as well as with other international organisations in the nuclear field.

EXECUTIVE SUMMARY

Deep underground disposal is the option favoured internationally for the long-term management of heat-generating radioactive wastes (spent fuel and high-level waste), and other radioactive wastes with significant contents of long-lived radionuclides. Countries that possess these waste types typically have significant, active programmes aimed at developing suitable underground waste repositories. Individually, the various national programmes are at different stages of advancement, and some are approaching repository licensing.

Deep underground radioactive waste disposal systems typically include a system of barriers that acts to isolate and contain the wastes and, thereby, protect the environment and human health. The presence of several barriers with complementary safety functions is designed to enhance confidence in the protection that will be provided. The barriers include the natural geological barrier and the engineered barrier system (EBS). The EBS may itself comprise a variety of sub-systems or components, such as the waste form, container, buffer, backfill, and tunnel seals and plugs.

The Integration Group for the Safety Case (IGSC) of the OECD Nuclear Energy Agency (NEA) Radioactive Waste Management Committee (RWMC) is co-sponsoring a project with the European Commission (EC) to develop a greater understanding of how best to design, construct, test, model and assess the performance of engineered barrier systems, and how to integrate these aspects within the safety case for disposal.

This report presents a synthesis of information and findings from the fourth NEA-EC workshop on EBS, which dealt with the topic of EBS design confirmation and demonstration. The workshop was held on 12-15 September 2006 in Tokyo, Japan.

EBS design and optimisation is necessarily an iterative process that follows from an initial step of defining the basis for disposal system safety (the safety strategy). The optimisation process involves a range of studies to:

- Define the requirements of the disposal system and of the EBS and its components, and to take account of waste-specific and site-specific constraints that will influence the design.
- Understand the materials of the EBS components and the processes that may affect them as the disposal system evolves.
- Model the behaviour and assess the performance of the EBS components and of the disposal system as a whole under the range of conditions that may occur.
- Confirm and demonstrate that the EBS can be manufactured, constructed and installed satisfactorily.
- Provide reasonable assurance that the disposal system will provide an acceptable level of safety during repository operations and for a long period after repository closure.

This approach to EBS design and optimisation has provided a structure for the NEA-EC EBS project and several, if not the majority, of the waste management organisations are actively following this approach. The approach is considered to be very useful. It not only enables EBS design, but may also play a central role in safety case development.

Experience shows that over the course of a repository development programme, changes in repository and EBS design are to be expected for many reasons. It is important for a disposal programme to put in place clear and well-defined processes and procedures for making decisions on EBS design, and for recording the rationale for those decisions.

Design decisions need to be based on consideration of a wide range of factors, such as:

- Long-term safety.
- Operational safety.
- Environmental impact.
- Engineering feasibility.
- Cost.

The relative weighting given to the factors considered should take account of the uncertainties involved and the views of the stakeholders, as appropriate.

It is essential to develop a good understanding of the processes and effects that may occur within the disposal system after EBS construction and emplacement. The use of formal safety and performance assessment methods helps to integrate the various different types of information to be considered (such as scientific understanding, site characterisation data, engineering and materials knowledge, and stakeholder perceptions).

Many useful, large-scale experiments have been conducted (in underground laboratories for example) that have enabled an assessment of the feasibility of methods for waste package fabrication, tunnel construction, waste emplacement, buffer and backfill emplacement, and tunnel sealing, among others. In general, these demonstrations have been successful and have shown that the necessary techniques for manufacturing and installing EBS components are feasible and available. However, further trials of some methods (including backfill emplacement, supercontainer construction and emplacement) are still required, particularly at the repository or industrial scale. Further experiments are also likely to be required to increase understanding of the long-term behaviour of the EBS after installation.

The national radioactive waste disposal programmes are currently conducting and planning a wide range of further experiments and modelling programmes, ranging from tests and demonstrations of manufacturing and emplacement techniques, to scientific experiments aimed at improving understanding and modelling capabilities. As the disposal programmes further mature, and repository implementation is approached, work will also be required on the process of demonstrating the application of quality assessment and quality-control measures for EBS materials and EBS installation, particularly in a regulatory environment.

The participants of the EBS project include representatives from a wide range of organisations that have responsibility in their own countries for ensuring safe radioactive waste management and disposal. The benefits of the EBS workshops were endorsed by all participants, and there was consensus that it would be valuable to maintain an international forum under NEA auspices for further collaborative work on the EBS.

Acknowledgements

On behalf of all participants, the NEA wishes to express its gratitude to the Nuclear Waste Management Organisation of Japan (NUMO) and to the Japanese Atomic Energy Authority (JAEA), who co-hosted the workshop, and to the EC for its co-operation in this joint workshop. Special thanks are also due to:

- The members of the Workshop Programme Committee who structured and facilitated the workshop. [1]
- The speakers for their interesting and stimulating presentations, and all participants for their active and constructive contributions.
- The working group chairpersons and rapporteurs who led and summarized the debates that took place in the two working groups.

The workshop synthesis was written by David G. Bennett (Galson Sciences Ltd., UK).

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1. The Workshop Programme Committee consisted of Jesus Alonso (ENRESA, Spain), Betsy Forinash (OECD/NEA), Alan Hooper (UK Nirex Ltd), Katsuhiko Ishiguro (NUMO, Japan), Lawrence Johnson (Nagra, Switzerland), Claudio Pescatore (OECD/NEA), Frédéric Plas (Andra, France), Michel Raynal (EC), Patrick Sellin (SKB, Sweden), Öivind Toverud (SKI, Sweden), Hiroyuki Umeki (JAEA, Japan), Abe Van Luik (US DOE, USA), Sylvie Voinis (Andra, France) and Juergen Wollrath (BfS, Germany).

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INTRODUCTION

Radioactive waste disposal systems typically include a system of barriers that acts to isolate and contain the wastes and, thereby, protect the environment and human health. The presence of several barriers with complementary safety functions is designed to enhance confidence in the protection that will be provided. The barriers include the natural geological barrier and the engineered barrier system (EBS). The EBS may itself comprise a variety of sub-systems or components, such as the waste form, container, buffer, backfill, and tunnel seals and plugs.

The purpose of the EBS is to prevent or delay the release of radionuclides from the waste to the repository host rock. Each sub-system or component of the EBS has its own functions to fulfil. For example, the container may be designed to ensure initial isolation of the waste.

The engineered barriers must also function as an integrated system and, thus, there are requirements such as the need for one barrier to ensure favourable physico-chemical conditions so that a neighbouring barrier can fulfil its intended function. For example, in some disposal systems the buffer or backfill materials that surround the waste container have a role in minimising container corrosion.

There are many interrelated steps in the process of designing, constructing, testing, modelling and assessing the performance of engineered barrier systems, and it is important that these steps are conducted, managed and integrated in such a way that they provide a firm basis for the disposal facility safety case.

The NEA EBS Project

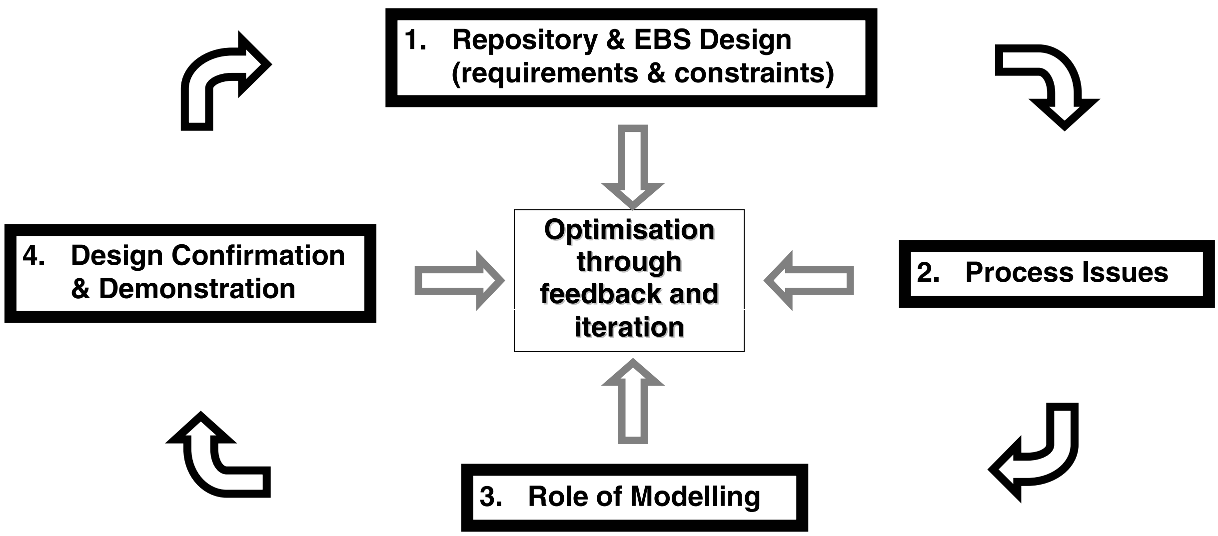
The Integration Group for the Safety Case (IGSC) of the Nuclear Energy Agency (NEA) Radioactive Waste Management Committee (RWMC) is co-sponsoring a project with the European Commission (EC) to develop a greater understanding of how best to design, construct, test, model and assess the performance of engineered barrier systems, and how to integrate these aspects within the safety case for disposal.

The first phase of the EBS project is nearing completion and has been conducted via a series of workshops:

- Launch Workshop: Engineered Barrier Systems in the Context of the Entire Safety Case, Oxford, United Kingdom, 2002 (NEA, 2003; NEA and EC, 2003).
- Workshop 1: Design Requirements and Constraints, Turku, Finland, 2003 – (NEA, 2004).
- Workshop 2: Process Issues, Las Vegas, USA, 2004 – (NEA, 2005).
- Workshop 3: Role of Modelling, La Coruña, Spain, 2005 (NEA, 2007).
- Workshop 4: Design Confirmation and Demonstration, Tokyo, Japan, 2006 (this report).

Workshops 1 to 4 have followed a repository design optimisation cycle (Figure 1). This report presents a synthesis of information and findings from the workshop on design confirmation and demonstration.

Figure 1. **The EBS Project Optimisation Cycle**



Background to the Workshop on Design Confirmation and Demonstration

In 2002, the EBS project participants noted that engineered barrier systems have to operate over long time scales and will experience a considerable range of conditions during manufacture, emplacement, operation, monitoring, and the transient and long-term post-closure phases. Establishing the reliability of the EBS under these conditions, or "qualifying" its performance (which has a legal meaning in some national programmes) is a challenging task. Such qualification requires identifying and understanding the main processes and parameters that affect disposal system performance and, since this requires knowledge of the behaviour of the host rock, qualification is a site-specific issue. It was, therefore, proposed to initiate a project on the topic of the qualification or reliability of the EBS.

Report Structure

This report is structured as follows:

- Workshop objectives and structure.
- Summary of presentations and technical discussions on the opening day of the workshop.
- Summary of results from working group sessions and discussions held during the second day of the workshop.
- Summary of discussions on the final day of the workshop, including the workshop conclusions.
- References.
- Appendix A: Workshop agenda.
- Appendix B: Papers presented to the workshop.
- Appendix C: Membership of the working groups.
- Appendix D: List of participants.

WORKSHOP OBJECTIVES AND STRUCTURE

The workshop began with welcoming comments from Katsuhiko Ishiguro (NUMO, Japan), Hiroyuki Umeki (JAEA, Japan) and Claudio Pescatore (OECD/NEA). It was noted that the Japanese programme is making progress towards identifying a disposal site and that there is keen interest in the role of the EBS, because the EBS is a central component of the safety case in many disposal systems, particularly for those in fractured host rocks, such as those in Japan.

Claudio Pescatore (OECD/NEA) described the background to the NEA EBS Project and its relationship to the NEA's broader programme of initiatives, including the IGSC, the Radioactive Waste Management Committee (RWMC), the Forum on Stakeholder Confidence (FSC), and the Working Party on Decommissioning and Dismantling (WPDD), as well as related NEA outreach programmes and information platforms (see www.nea.fr/html/rwm/).

The general objectives of the EBS workshops were described as follows:

- Promoting interaction and collaboration among experts responsible for engineering design, characterisation, modelling, and assessment of engineered barrier systems.
- Developing a greater understanding of how to achieve the integration needed for successful design, construction, testing, modelling, and assessment of engineered barrier systems, and to clarify the role that an EBS can play in the overall safety case for a repository.
- Sharing knowledge and experience about the integration of EBS functions, engineering design, characterisation, modelling and performance evaluation in order to understand and document the state of the art, and to identify the key areas of uncertainty that need to be addressed.

Throughout its work, the EBS project is considering the engineered barrier system from four perspectives:

- Engineering design (how can a component be (re-)engineered to improve performance or ease of modelling?)
- Characterisation (how can the properties of the EBS and the conditions under which it must function be measured or otherwise characterised?)
- Modelling (how can the relevant processes be modelled?)
- Performance Assessment (PA) (how can the performance of the EBS and/or its components be evaluated under a wide range of conditions?)

The specific objective of the workshop on design confirmation and demonstration was to consider strategies, approaches and methods for confirming and demonstrating that EBS designs will fulfil the relevant requirements for long-term safety, engineering practicality, and quality assurance (QA). An important additional objective of the workshop was to

discuss plans for final reporting of the first phase of the EBS project and for subsequent future work.

In more detail the workshop was expected to address, for example:

- Confirming the industrial-scale feasibility of EBS component emplacement.
- Methods for demonstrating that design requirements have been met in a regulatory environment.
- Confidence-building methods and tools.
- The adequacy and quality of EBS process models.
- The identification of remaining key issues and uncertainties to be addressed in subsequent design-optimisation cycles, given the scope of the envisaged safety case.
- Optimisation at different levels – at the process level, at the individual barrier level and at the total system or safety assessment (SA) level.
- The presentation of design alternatives in the safety case along with information on associated factors (cost estimates).
- The need for (re)assessment of repository and EBS design at later stages of development.
- The opportunities for, and implications of, monitoring and testing.

Following the opening remarks, the workshop continued in plenary session with a series of invited presentations on national and international achievements and ongoing work on design confirmation and demonstration for engineered barrier systems. Papers expanding on the workshop presentations are presented in Appendix B. The plenary session ended with a general discussion. The next section of this report summarises key points from the presentations and discussions in the plenary session.

The second day of the workshop was devoted to working group sessions. Two working groups were convened to consider the following topics:

Working Group A	Decision Making and Design Factors in the EBS Design Process.
Working Group B	Confirmation and Demonstration of the EBS in the Context of Confidence Building.

The results from the working groups are summarised later in the report. The final section of these proceedings presents a summary of the discussions on the last day of the workshop, including conclusions from the workshop and recommendations for future work.

NATIONAL AND INTERNATIONAL ACHIEVEMENTS AND ONGOING WORK ON DESIGN CONFIRMATION AND DEMONSTRATION FOR ENGINEERED BARRIER SYSTEMS: SUMMARY OF PRESENTATIONS AND TECHNICAL DISCUSSIONS

A series of eight invited presentations were made on national and international achievements and ongoing work on design confirmation and demonstration for engineered barrier systems, as follows:

- Approaches and Methods for Demonstration and Confirmation of the Geological Repository Design Concept in the Japanese Programme, H. Ueda, K. Ishiguro, Y. Sakabe and K. Kitayama (NUMO, Japan), H. Umeki, M. Naito and M. Yui (JAEA, Japan) and H. Asano (RWMC, Japan).
- Planning, Assessment and Construction of a Drift Seal in a Salt Repository – Overview of Investigations in the German Programme, N. Müller-Hoeppe (DBE, Germany) and R. Mauke and J. Wollrath (BfS, Germany).
- Performance Assessments for Design Reviews: Lessons from the US Programme, S. Mohanty (CNWRA, US).
- Practical Lessons Learned on the Role of the Engineered Barrier System in a Total System Performance Assessment, D. Sevougian and A. Van Luik (US DOE).
- Design Confirmation and Demonstration for EBS: Current Developments in Several European National Programmes as part of the FP6 Euratom ESDRED Project, C. De Bock and J. Bel (Ondraf/Niras, Belgium), L. Londe (Andra, France) and H. Weber (Nagra, Switzerland).
- The KBS-3 EBS Workshops: An Example of Regulator-implementer Pre-licensing Interaction in the Swedish Programme, Ö. Toverud (SKI, Sweden).
- The EBS Demonstration Programme at SKB: Some Examples, D. Gunnarsson (SKB, Sweden).
- The French Methodology for EBS Confirmation and Demonstration, F. Plas (Andra, France).

Approaches and Methods for Demonstration and Confirmation of the Geological Repository Design Concept in the Japanese Programme

Hiroyoshi Ueda (NUMO, Japan) presented an overview of approaches and methods for demonstration and confirmation of the geological repository design concept in the Japanese programme.

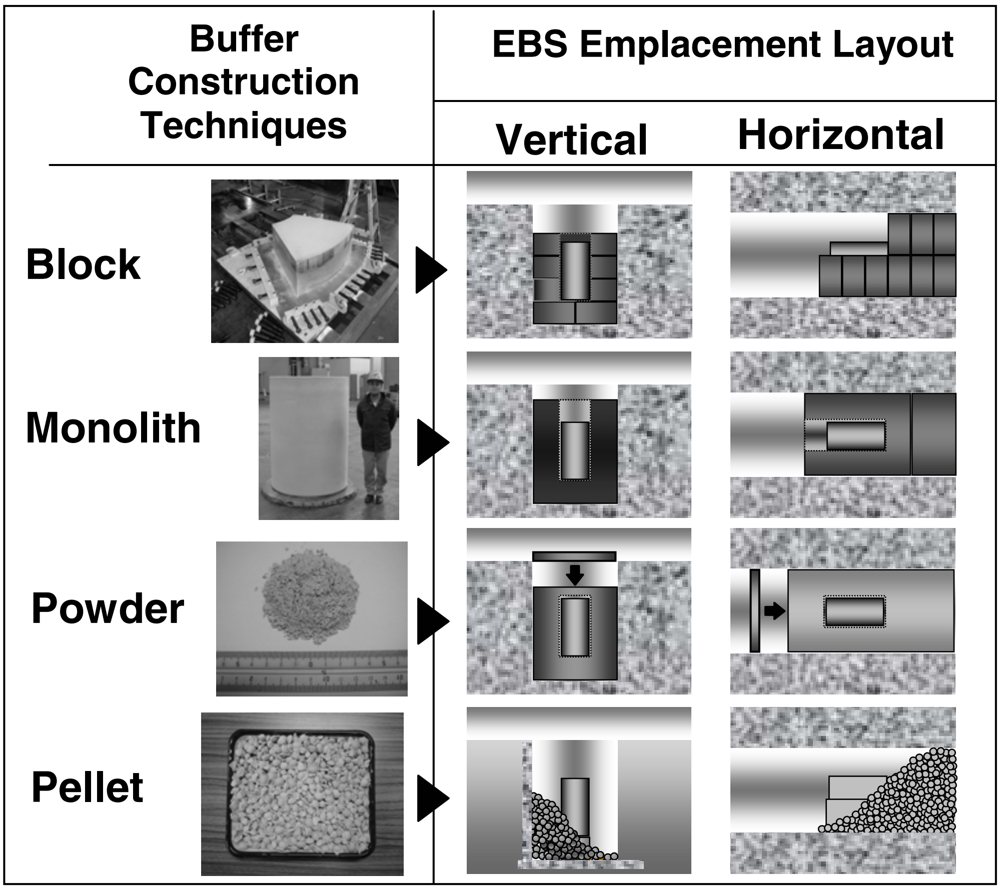
NUMO is following an open solicitation procedure for repository site selection, involving a call for volunteer host municipalities. The emphasis of NUMO's programme is very much on gaining public acceptance for the repository. Currently NUMO is developing one or more repository concepts that are tailored to potential siting environments and, in doing so, is using structured processes for decision making and for requirements management (see NEA, 2004).

Factors being considered during design include:

- Long-term safety.
- Operational safety.
- Engineering feasibility and QA.
- Engineering reliability.
- Site characterisation and monitoring requirements.
- Retrievability.
- Environmental impact.
- Socio-economic aspects.

Various design and construction activities are being progressed to support repository concept development. For example, in the area of engineering feasibility NUMO is investigating alternative concepts and methods for buffer construction and waste emplacements in the repository (Figure 2).

Figure 2. **Alternative buffer construction techniques and emplacement concepts currently being assessed in the Japanese programme**



In addition to the concepts shown in Figure 2, NUMO is also considering use of a pre-fabricated EBS concept in which the waste, overpack and bentonite buffer would be placed within a 20 mm-thick carbon steel handling shell at the surface, before being transferred to the underground repository. Advantages of the pre-fabricated EBS concept include easier and more efficient EBS construction, QA testing, handling and emplacement. These advantages may prove decisive in the Japanese programme because there is a requirement for a high waste emplacement rate (~1 000 waste packages/ year, ~5/day), which places significant constraints on underground logistics. NUMO estimates that waste emplacement using the pre-fabricated EBS concept may be twice as fast as either vertical or horizontal waste emplacement with buffer construction performed underground.

In the area of long-term safety, NUMO is investigating the processes of bentonite alteration by highly alkaline fluids deriving from the cementitious tunnel supports and is considering possible ways to optimise the repository design to minimise these effects (using low-pH cements, including additional bentonite). The approach being taken includes mass-balance calculations to estimate the potential for montmorillonite dissolution given different cement barrier thicknesses and compositions (ordinary Portland cement, low-pH cement). Initial calculations results indicate that the amount of bentonite alteration that may occur is likely to be quite limited, and suggest that by using a more realistic (less conservative) model, possibly in combination with a refined design that includes a slightly thicker bentonite barrier, it may be possible to demonstrate that the use of ordinary Portland cement will be acceptable. This experience provides a good example of the use of modelling in EBS design optimisation. More generally, NUMO has found that optimisation of the EBS design may be achieved by working systematically through the iterative process of design and assessment followed by model and design refinement depicted in Figure 1.

Discussion around the presentation focused on the following points:

- **NUMO's Design Factors Filter.** As part of the process leading to decisions on EBS design, NUMO has been developing and testing the application of a Design Factors Filter (DFF), and there was interest in how this filter was applied in practice. Hiroyoshi Ueda (NUMO, Japan) indicated that the DFF is really a qualitative tool for assessing different EBS designs (or repository concepts) against a wide range of factors. The DFF is a preliminary assessment tool that can be used to help in decision-making and in some senses can be seen as a pre-cursor to a formal Requirements Management System (RMS), which NUMO is beginning to develop.
- **Weighting of Factors.** There was interest as to which (if any) of the factors being considered in decision making on EBS design or repository concept selection were considered most important. Hiroyoshi Ueda (NUMO, Japan) indicated that the weighting given to each factor depends on the issue in question, and that the weightings may also vary over time according to circumstances. For example, the weighting given to retrievability in the Japanese regulations may be relatively small, but NUMO will consider what weighting should be applied in light of all available information; it might be that some local communities would like to see a relatively greater weighting on retrievability. It was agreed that it will be very important to record and document the decision-making process over time and that this record should then provide a strong basis with which to show an appropriate design has been achieved giving due weight to the range of relevant factors.

Planning, Assessment and Construction of a Drift Seal in a Salt Repository: Overview of Investigations in the German Programme

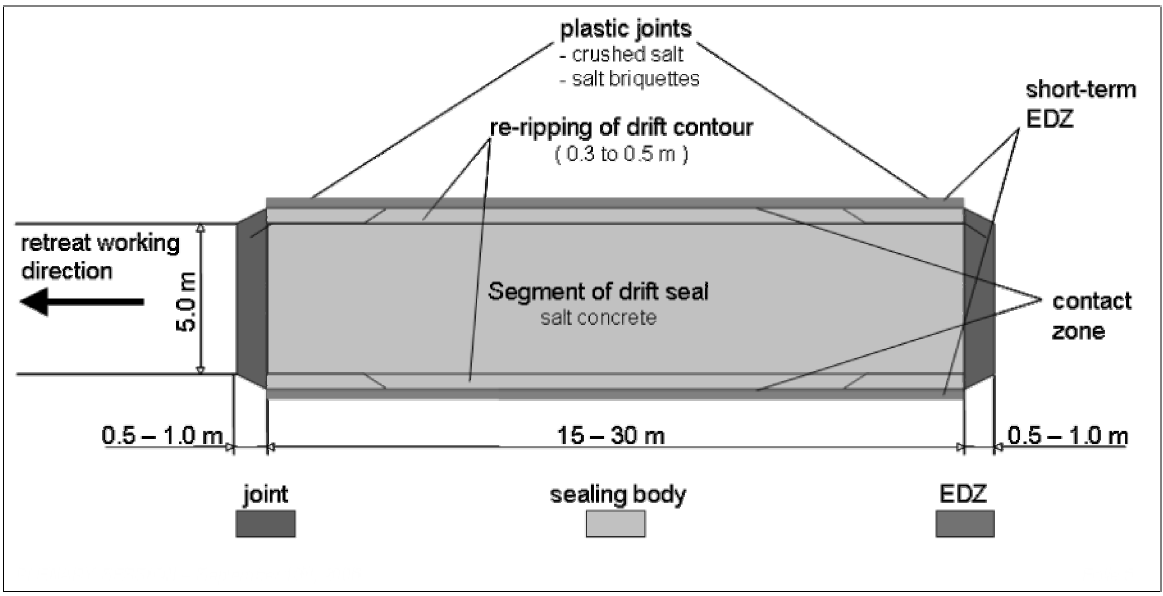
N. Müller-Hoeppe (DBE, Germany) presented an overview of planning, assessment and construction activities undertaken by DBE on behalf of BfS in association with the sealing of the Morsleben repository. The Morsleben repository is hosted in salt, and current plans are to use seals comprised principally of salt-concrete. BfS/DBE is following the optimisation approach depicted in Figure 1, including the following components:

- **Requirements, Constraints and Design.** A key requirement for the drift seals at Morsleben is that they should be constructed to have an initial hydraulic conductivity of 10^{-18} m^2/s or less.

Site-specific constraints on the drift seals include (i) the need to be able to construct the seals in locations with difficult access, (ii) that the seal materials need to be chemically compatible with the host rocks, and (iii) that the seals need to be emplaced where the rates of host rock convergence are not too great. A schematic design for a drift seal is shown in Figure 3.

- **Process Issues.** BfS/DBE has considered various processes and combinations of processes that might influence seal performance, and has established relevant criteria that will need to be met in order for the EBS to provide the required long-term seal performance and repository safety. For example, the need to limit crack evolution within the body of the drift seal calls for consideration of the heat from concrete hydration, and rock and brine pressures. To take account of these processes, safety criteria have been defined for the maximum temperature gradient, for short-term seal strength, and for long-term seal dilatancy.
- **Modelling.** BfS/DBE has conducted various thermo-mechanical modelling studies to assess seal performance and this has resulted in improved understanding of potential seal behaviour and led to the identification of a formerly unidentified process, autogenous shrinking of salt-concrete. DBE is currently considering options for incorporating this new process into its PA models.
- **Design Confirmation and Demonstration.** A programme of *in situ* testing of a seal is underway at the Asse mine. Results from some of these tests are described in Appendix B. Although promising seal permeability and pressure measurements have been obtained in the tests at Asse, it is not straightforward to extrapolate the results from Asse to the Morsleben repository. BfS is planning further studies to test the equipment for seal construction and emplacement.

Figure 3. **Schematic design of a drift seal at the Morsleben repository in Germany**



Discussion around the presentation focused on the following points:

- **The Seal Hydraulic Conductivity Requirement.** The origin of the initial seal hydraulic conductivity requirement (10^{-18} m^2/s or less) was explored, and DBE was also asked what steps would be available if it proved too difficult or impossible to meet this requirement. DBE indicated that the requirement had been derived by BfS from previous PA calculations. BfS has also established a requirement on the "lifetime" for the seals – the period over which the seals should continue to provide adequate performance. This lifetime is specified as 5 000 to 30 000 years, and was derived from consideration of the sequential failure of a series of drift seals along a tunnel. DBE is confident from its work to date that these requirements can be met but, in the unlikely event that this ultimately proves not to be the case, would consider design modifications. For example, it may be possible to use additives in the salt-concrete to prevent shrinkage effects.

- **Location-Specific Seal Designs.** It was noted that the current plan is to install 21 drift seals in the Morsleben repository and participants asked whether these would need to be individually tailored to the existing stress conditions. DBE indicated that results from the studies at the Asse mine suggest that conditions can be significantly variable spatially and that location-specific factors may, therefore, need to be measured and assessed at each seal location. However, the actual extent to which location-specifc seal designs will be necessary at Morsleben is yet to be determined and the costs and benefits for this are still under consideration.

Performance Assessments for Design Reviews – Lessons from the US Programme

Sitakanta Mohanty (CNWRA, US) made a presentation on the regulatory context for the design and assessment of the proposed repository at Yucca Mountain, focussing on the evolution of the design and the relationships between design and PA activities.

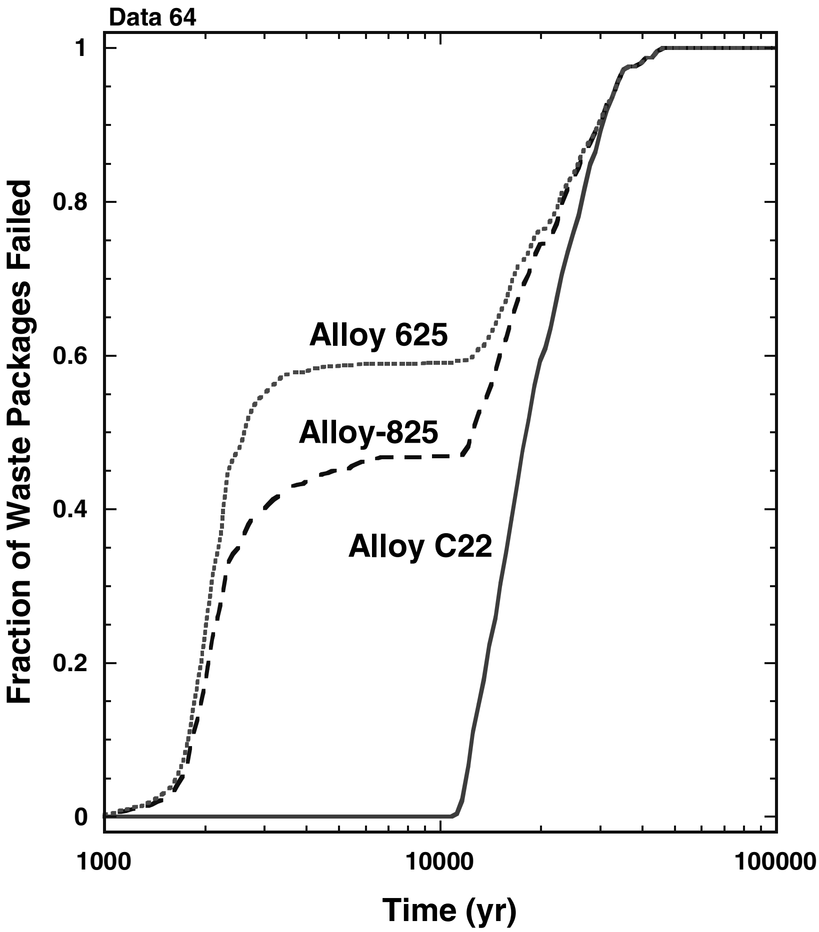
The Yucca Mountain Project has been in progress for over two decades and, during that time, the applicable regulations have evolved. The current regulation for Yucca Mountain, Nuclear Regulatory Commission (NRC) Regulatory Requirement 10 CFR Part 63, is a performance-based regulation that focuses on overall disposal system performance. It requires the US DOE to propose a design for the repository that provides defence-in-depth, that at least two barriers (a natural barrier and an EBS) must be present to isolate the waste. The regulations also require a performance confirmation programme during repository operations to confirm the assumptions, data, and analyses that support findings permitting construction of repository and subsequent emplacement of waste. This performance confirmation programme must also indicate that subsurface conditions are within the limits assumed in the licensing reviews and that the natural and engineered barriers are functioning as intended.

During the Yucca Mountain Project there has been a fairly continuous process of design modification and PA, including four major design changes:

- The late 1980s design included the emplacement of ~50 000 waste packages within vertical and horizontal boreholes drilled from the main drift.
- In 1992, the emplacement concept changed from boreholes to horizontal drifts, and larger but fewer (~10 000) waste packages.
- The 1998 Viability Assessment evaluated several different waste package materials and led to selection of a waste package comprising a 20 mm-thick Alloy 22 inner shell for corrosion resistance and a 100 mm-thick carbon steel outer shell for structural strength and corrosion allowance (Figure 4).
- The 2002 Site Recommendation was based on a design including a waste package comprising a 25 mm-thick Alloy 22 *outer* shell for corrosion resistance and a 50 mm-thick nuclear grade 316 stainless steel inner shell, with an extra Alloy 22 lid to provide an additional barrier against corrosion. The waste package was protected by a titanium drip shield.

- During 2006, the US DOE has been considering a new canister for transport, aging, and disposal, known as the TAD canister, which would help to minimise handling and packaging of fuel at the repository.

Figure 4. **Results from calculations of waste package failure as a result of corrosion for three different corrosion-resistant alloys (Mohanty 1999)**



It was suggested that PA can be an effective aid in design review because it can help to identify individual components of the system that are not significant (even if the EBS as a whole makes significant contribution to safety), components that could be detrimental to performance of other components, and components that are significant to pre-closure operational safety or to calculated post-closure doses or risks.

The importance of PAs in guiding design reviews is a function of the estimated system performance (dose) and uncertainties in relation to the regulatory criteria, and the sensitivity of assessed performance to design parameters.

Discussion around the presentation focused on the following points:

- **EBS Design Changes at Yucca Mountain.** There was discussion of the history of EBS design changes in the Yucca Mountain programme. It was felt that the reasons for this history of change were complex and only partly technically based, but that there had been a considerable process of learning during the dialogue over the proposed facility.

- **Factors other than Calculated Dose or Risk.** There was discussion of the extent to which the risk-informed approach described in the presentation allowed for consideration of other factors that influence design decisions, such as cost. Sitakanta Mohanty (CNWRA, US) indicated that although the US NRC's primary focus is on ensuring safety, it is sensitive to the potential cost implications of design changes and, within the constraint of achieving acceptable safety, would not seek to impose undue additional costs on the operator. It was noted, however, that the operator will often make design changes based on factors other than assessed dose or risk, such as cost.

Practical Lessons Learnt on the Role of the Engineered Barrier System in a Total System Performance Assessment

A. Van Luik (US DOE) gave a presentation based on experience of reviews of the US DOE's representation of the EBS in PA.

It was suggested that one issue in modelling a system with both engineered and natural barriers is that different amounts of information may be available at any given point in time regarding the two barrier systems.

It was also suggested that it may be relatively more difficult to characterise the geological barrier system than the EBS because of the large scale over which site characterisation investigations are required and because of natural spatial heterogeneities and anisotropies. By contrast, the EBS may be easier to characterise and represent satisfactorily in PA because it is manufactured using materials selected for having relatively well-known, desirable properties.

However, prior to repository construction the EBS does not exist, and modelling the disposal system assuming that it meets all design specifications was found in the Yucca Mountain Project not to be sufficient. Laboratory studies, data derived from analogue and other information is, therefore, being used to estimate the potential effects on system performance of potential early failures and emplacement/manufacturing defects. Also, further information is to be obtained through making and testing mock-ups of EBS components and by testing EBS component emplacement technologies.

Discussion around the presentation focused on the following points:

- **The Value of Programme Reviews.** It was noted that programme reviews are generally very beneficial and should be initiated early and remain active throughout the disposal programme. Reviews need to be well-managed and should be structured to focus on the key issues.
- **Use of Analogues and Early Testing of EBS Components.** There was discussion of the potential use that can be made of data from natural and anthropogenic analogues when representing and assessing the performance of EBS components. It was felt that analogue systems can provide useful data regarding the properties of EBS materials and their long-term behaviour. For example, data from naturally occurring clays might be considered and used, particularly early in a disposal programme, for assessing the performance of a clay barrier. However, it was also expressed that analogue information needs to be complemented with data from laboratory experiments, and larger scale tests and trials (mock-ups) of the actual materials to be used in the EBS. The meeting noted that it can be helpful to begin such tests and trials of EBS materials and of EBS construction feasibility early on in the development of a disposal programme. However, there is a balance to be achieved in the relative timing of

selecting an EBS design and conducting feasibility assessments. On the one hand, before going too far down the route of assessing the performance of a conceptual design, it is desirable to confirm that it will be practical to construct – otherwise considerable effort may be spent assessing a design that must later be changed to ensure engineering feasibility. On the other hand, such large-scale trials are very expensive, which provides an incentive to delay them until the EBS design has essentially been confirmed and is unlikely to be significantly changed – otherwise, if the design then changes, it may be perceived that the investment in the trials was wasted. There is no perfect solution; each path carries some pitfalls and each programme must decide the balance. Several programmes have undergone significant EBS design changes (Belgium, US), which would tend to reinforce the view that feasibility tests are best performed only after the design is final, or nearly so. Conversely, it was also noted that some EBS test and trials (FEBEX) have pointed to essential design changes that would not have been identified through PA, which reinforces the importance of such tests. In addition, it should be considered that delaying such long-term and large-scale tests may mean that the programme misses the opportunity to conduct long-term tests and trials prior to licensing. An open question identified at the workshop was the extent to which early disposed wastes can serve as trials of the disposal system and guide later decisions on the disposal of subsequent wastes

Design Confirmation and Demonstration for EBS: Current Developments in Several European National Programmes as Part of the FP6 Euratom ESDRED Project

Johan Bel (Ondraf/Niras, Belgium) presented three examples of demonstration experiments being conducted or planned by different national waste disposal programmes in association with the European Commission (EC) Project entitled Engineering Studies and Demonstration of Repository Designs (ESDRED):

- Fabrication and emplacement of the French buffer system (Figure 5).
- Backfilling the void space in the tunnels surrounding the Belgian waste supercontainer (Figure 6).
- Emplacement of the Swiss buffer.

Figure 5. **A cartoon of a planned large-scale test of buffer emplacement using an air cushion technique that may be undertaken as part of the EC ESDRED Project**

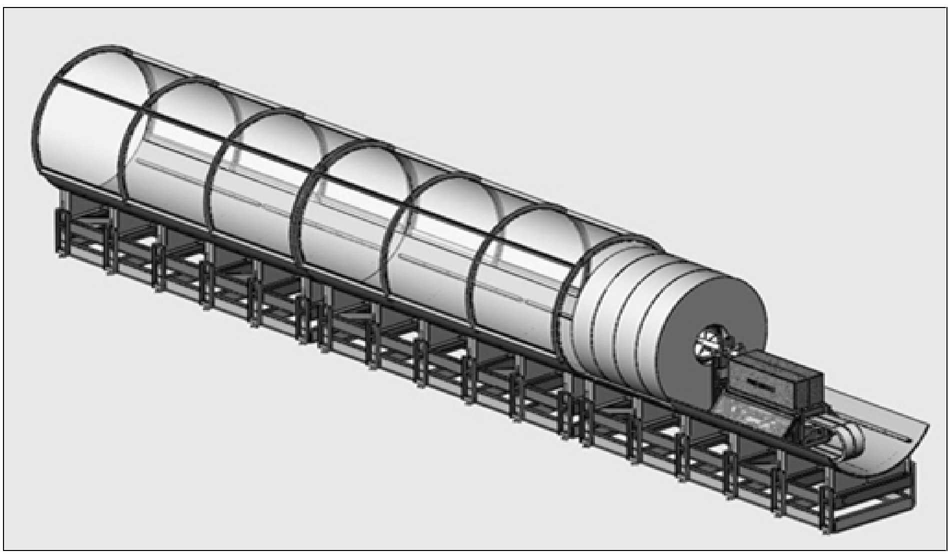
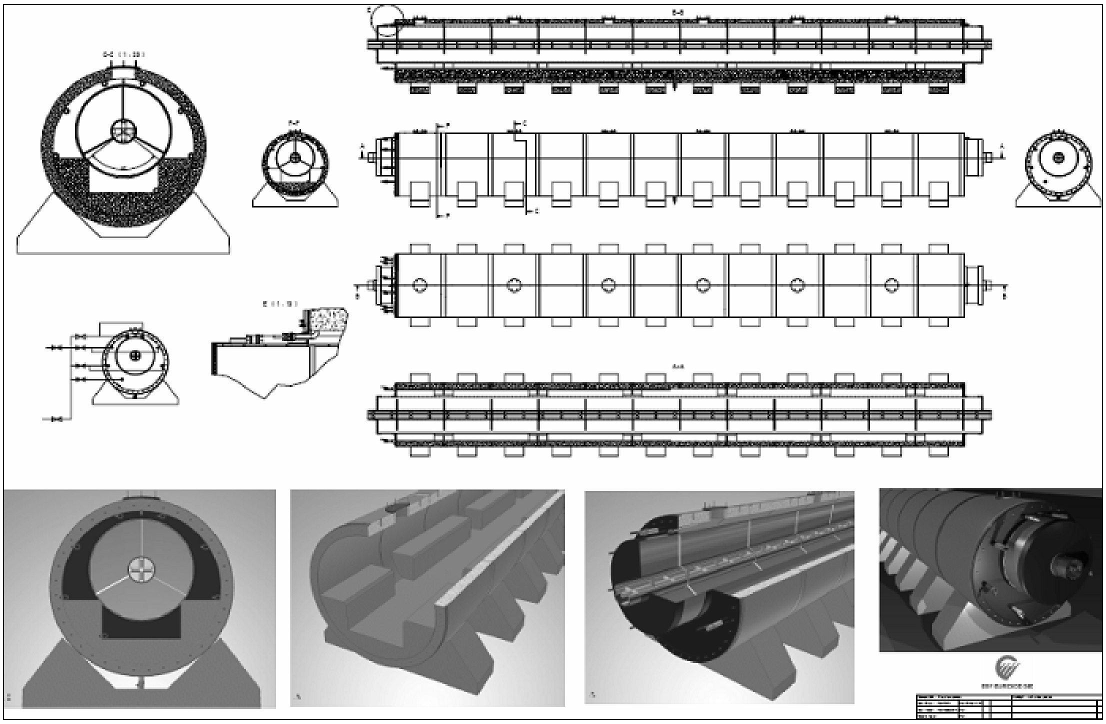


Figure 6. **A 30 m-long, full-scale mock-up of a disposal gallery from the Belgian repository design, that will be constructed as part of the EC ESDRED Project to test the industrial feasibility of the cement grout backfilling technique**



Details of the experiments are described and discussed in Appendix B. Air cushion techniques for waste emplacement are under consideration in several programmes including France, Finland, Japan and Sweden.

Preliminary conclusions from the work include:

- The buffer configuration work being conducted as part of the ESDRED Project by Andra, Ondraf/Niras and NAGRA has reached a very important stage; after two years of computer modelling and small-scale laboratory testing, the partners are now ready to undertake large-scale demonstration tests on mock-ups that they have been preparing.
- The shift from computer modelling and small-scale laboratory testing to large-scale testing will automatically put a greater focus on operational aspects. The existing sets of requirements related to the buffer/backfill components are expected to be complemented with further requirements specific to aspects of construction and operational safety.

Discussion around the presentation focused on the following points:

- **Variation amongst Different EBS Designs**. It was noted that the EBS designs in the three countries discussed differ significantly, even though all three have a clay host rock. Johan Bel (Ondraf/Niras, Belgium) suggested that the different disposal concepts should be seen as solutions to the same problem but within different contexts. A particular point to note for repositories hosted in clay is that the host-rock itself provides a considerable degree of long-term safety and that, therefore, EBS design may be driven by other factors such as the practicalities of handling and waste emplacement. In detail, there are also differences between the wastes and the host rocks being considered in the three countries.

- **Role of Tunnel Seals.** The degree of reliance placed on tunnel seals was discussed. It was noted that in most programmes no reliance is placed on tunnel seals for ensuring long-term safety under normal or expected evolution scenarios, but that the seals may take on increased importance in some less likely scenarios.

- **Effect of High pH on Steel Corrosion.** It was noted that the Japanese programme makes allowance for the possible but unlikely occurrence of relatively rapid localised corrosion of the steel overpack under high-pH conditions (see Appendix B) but that this is not the case in the Belgian programme. Allowance for localised corrosion of the overpack is not made in the Belgian design because, particularly at the elevated temperatures expected during the thermal phase, magnetite (or magnetite and $Fe(OH)_2$) will form a protective layer on the steel and corrosion rates are expected to be low (typically <0.1 µm/y). Experimental studies also indicate lower steel corrosion rates under strongly alkaline conditions than at near-neutral to mildly alkaline conditions. Both carbon steel and stainless steel will re-passivate under anaerobic, high-pH conditions if the protective layer of corrosion products on the steel is damaged, and the corrosion rate remains low (see Bennett 2006).

The KBS-3 EBS Workshops: An Example of Regulator-implementer Pre-licensing Interaction in the Swedish Programme

Öivind Toverud (SKI, Sweden) described a process of pre-licensing dialogue that has been running in Sweden on EBS issues since 2002. This dialogue has been conducted through a series of seven workshops:

- SKI Workshop 1 in 2002: Long-term Integrity of the KBS-3 Engineered Barrier System (SKI, 2003).
- SKI Workshop 2 in 2003: Manufacturing, Testing and Quality Assurance for the KBS-3 Engineered Barrier System (SKI, 2004a).
- SKI Workshop 3: Performance Confirmation for the KBS-3 Engineered Barrier System (SKI, 2004b).
- SKI Workshop 4: Long-term Stability of the Buffer and Backfill of the KBS-3 Engineered Barrier System (SKI, 2005a).
- SKI Workshop 5: Engineered Barrier System – Assessment of the Corrosion Properties of Copper Canisters (SKI, 2006).
- SKI Workshop 6: Mechanical Integrity of the Canister within the KBS-3 Concept (SKI, 2007a).
- SKI Workshop 7: EBS workshop on Spent Fuel Dissolution and Source Term Modelling in Safety Assessment (SKI, 2007b).

These workshops have involved the regulator, SKI, and its expert consultants meeting with the operator, SKB, and its experts, and have led to a better understanding of the KBS-3 concept and design and the data that may be used to support the safety case for such a repository. The workshops have also allowed a series of questions, or key technical issues, to be identified which will be examined in further detail during SKI's review of SKB's safety assessments and applications. In particular, issueshave been identified in the areas of:

- The initial state of repository components.
- Acceptance criteria for EBS materials and construction.
- Design confirmation through long-term large-scale demonstration experiments.

- The timescales for detrimental processes.
- Features, events and processes (FEPs) leading to possible loss of waste isolation.

Discussion around the presentation focused on the following points:

- **Prioritisation of Review Areas**. SKI was asked if it used a risk-based approach to prioritise its reviews of SKB's safety assessments. SKI indicated that the assessment of risk needs to be part of the review because SKB's safety assessment will include a demonstration of compliance with SSI's risk criterion of 10^{-6} per year. However, the review also needs to consider other aspects, the assessments of whether or not the barrier system will withstand potentially detrimental FEPs.

- **Identification of Resolved Issues.** SKI was asked if the pre-licensing dialogue held during the workshops had led to the identification of issues that were considered already to have been resolved. It was explained that this was not really the purpose of the workshops but that SKI reviews SKB's RD&D (Research, Development and Demonstration) Programme every three years and, thereby, gives an indication of where it feels the emphasis of the programme should be going forwards.

- **Regulatory Expectations for QA.** SKI was asked what expectations it has in terms of SKB's quality assurance. SKI indicated that acceptable QA must be applied to all areas of the safety case.

- **Use of International Peer Reviews.** SKI was asked if it uses or plans to use the international peer review service that is coordinated through the NEA. Öivind Toverud (SKI, Sweden) explained that an international review team had been commissioned to review the Interim SR-Can safety assessment in late 2004 (SKI, 2005b) and that currently SKI is beginning to review the completed version of SKB's SR-Can assessment. However, the current review will not be the final chance for review of SKB's plans before licensing of the repository, and an NEA peer review might be requested at a later stage.

The EBS Demonstration Programme at SKB: Some Examples

D. Gunnarsson (SKB, Sweden) presented some examples from SKB's EBS demonstration programme, with the aim of highlighting SKB's work associated with the following workshop topics:

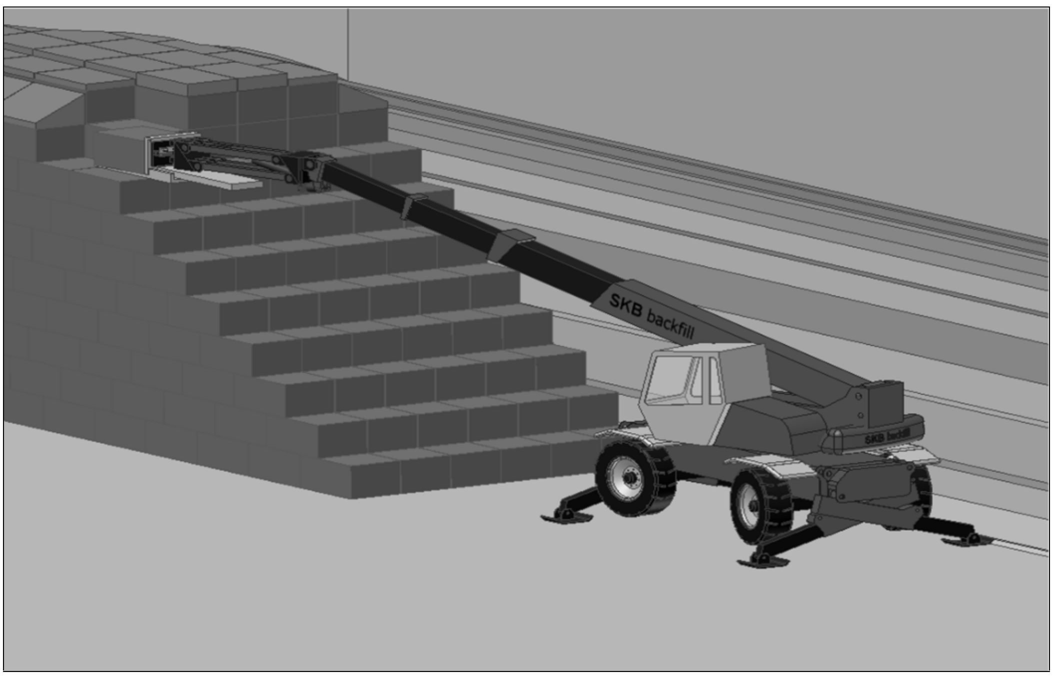
- Confirmation of industrial-scale feasibility of emplacement of EBS components.
- Demonstration of compliance with specifications for emplaced EBS components.
- Demonstrations/examples of the EBS optimisation process.
- The need for (re)assessment of repository and EBS design at later stages of development.

The presentation included a step-by-step guide to the EBS installation sequence for the KBS-3 concept, and a description of a waste canister removal demonstration test (see Appendix B).

A further example relevant to the optimisation cycle presented in Figure 1 is that SKB has recently had to re-assess its concept for the backfilling method to be used in the tunnels above the waste deposition holes. The former backfilling concept and method principally involved the placement and subsequent *in situ* compaction of a granular mixture of bentonite and crushed rock (Figure 7). Factors that made the re-design necessary included new knowledge on the influence of ground-water salinity on bentonite performance, predictions of ground water salinity at the potential repository sites and results from SKB's technology development and demonstration programme. In combination, these factors indicated that there was little or no margin between the expected performance of the previous backfill concept and the relevant safety function indicator criteria.

Figure 7. **Test of granular backfill emplacement by the previous concept in the Swedish underground laboratory at Aspo**

Figure 8. **Revised Swedish backfill emplacement concept involving the placement of pre-formed blocks made from a mixture of bentonite clay and crushed rock**



Backfill safety function indicator criteria had been established for hydraulic conductivity ($<10^{-10}$ m/s), swelling pressure (>100 kPa) and compressibility, which should be low enough to keep the buffer density within specification. Average measurements of hydraulic conductivity from SKB's large scale backfill test at Aspo were, however, found to lie in the range 1.4 x 10^{-9} to 1.4 x 10^{-8} m/s, well above the safety function indicator criterion for hydraulic conductivity.

SKB has, therefore, assessed several revised backfilling concepts for their potential to meet the safety criteria, as well as for engineering feasibility, robustness and cost. The currently favoured concept involves the emplacement of blocks pre-formed from a mixture of bentonite and crushed rock (Figure 8). SKB is planning further experiments on the refined backfilling concept, and suggests that, in general, optimisation of the EBS will involve a stepwise development of component design and emplacement methods.

Discussion around the presentation focused on the following points:

- **KBS-3 Water Protection System.** The EBS installation sequence envisaged by SKB for the Swedish KBS-3 repository currently includes use of a "water protection system", which is designed to limit and control water inflow to the waste deposition holes during EBS installation. SKB was asked if the envisaged scheme would be practical for spent fuel disposal where it might not be possible to have manual intervention close to the waste container. SKB noted that the uppermost blocks of the buffer should provide radiological shielding but acknowledged that the water protection system needs further testing and consideration. SKB noted that another part of the EBS system that may ultimately prove unnecessary is the bentonite "O-ring" in the current tunnel seal design, give that the seal is not required to perform a long-term safety function.
- **Canister Retrieval.** SKB was asked if waste canister retrieval was possible after the bentonite buffer had fully re-saturated and whether the retrieval demonstration test had involved a fully hydrated buffer. SKB indicated that retrieval was possible even after complete buffer saturation.
- **Evaluation and Assessment of Costs.** SKB was asked how it had evaluated and assessed the potential costs of the different backfill concepts and methods considered, and whether the KBS-3H design variant had been considered. SKB indicated that KBS3-H had not been included in this particular assessment of alternative backfill concepts. SKB also noted the difficulty of estimating the future costs of bentonite and, because of this, had placed most emphasis on criteria relating to long-term safety when comparing the different backfilling concepts. While the KBS-3H design variant has not been ruled out, the reference design is still the KBS-3V variant with vertical waste deposition holes.

The French Methodology for EBS Confirmation and Demonstration

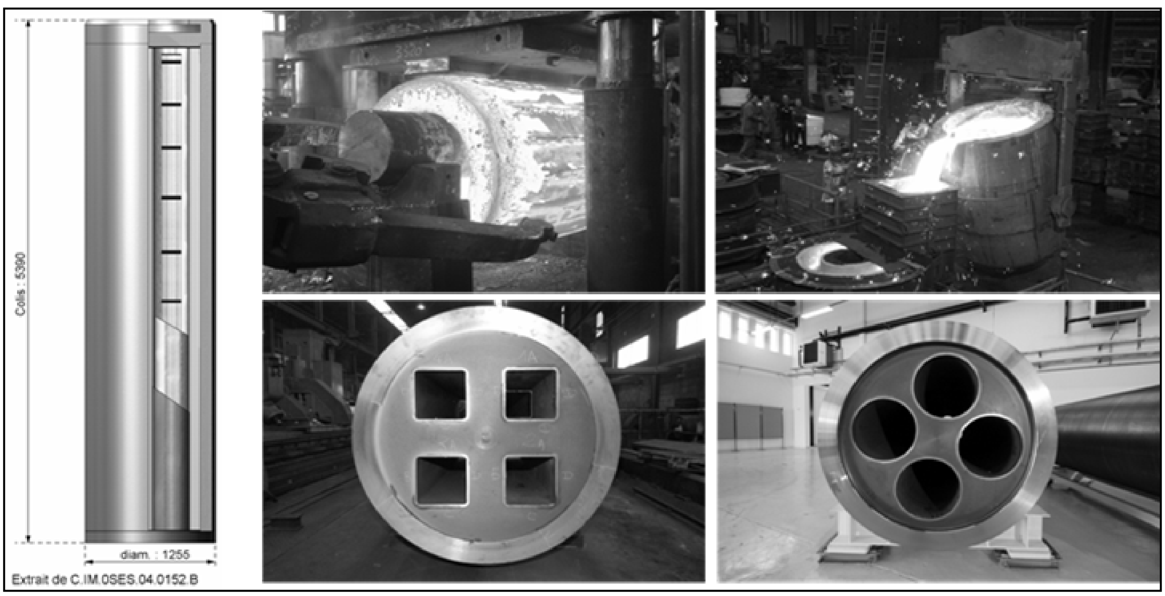
F. Plas (Andra, France) discussed recent developments in the French programme and the approach being followed by Andra for EBS design, assessment, confirmation and demonstration.

The Nuclear Materials and Waste Management Program Act passed into French Law on 28 June 2006. This new Act formally declares reversible deep geological disposal as the reference solution for high-level and long-lived radioactive wastes, and sets 2015 as the target date for licensing a repository and 2025 for repository opening and operation.

Andra's approach to EBS design, assessment, confirmation and demonstration involves iterating through the following activities:

- **Functional Analysis (FA/AF)**. This involves identifying and defining EBS safety requirements and design constraints, and the use of safety functions and safety functions indicators.
- **Phenomenological Analysis of Repository Situations (PARS/APSS)**. This involves developing a simple description of the expected ("most probable" or "normal") thermo-hydro-mechanical-chemical (THMC) evolution of the repository and its geological environment, and describing the associated uncertainties.
- **Qualitative Safety Analysis (QSA/AQS).** This involves:
  - Describing the normal evolution of the repository and considering the effects of uncertainties and key events on the evolution of the repository and the safety functions.
  - Identifying uncertainties and events that can cause the repository to diverge from the normal evolution scenario and ensuring that these are covered by altered evolution scenarios.
  - Completing the list of scenarios and calculation cases to be assessed by making comparisons with international FEP lists and databases (the OECD/NEA FEP 2000 and FEPCAT databases).
- **Quantitative Safety Analysis.** This involves undertaking modelling simulations for normal and altered evolution scenarios, and evaluating safety function indicators and potential doses. The most recent assessment was documented in the Dossier 2005 (Andra 2005).
- **Demonstrations and Experiments.** Andra is conducting a wide range of demonstrations and experiments, particularly in its underground laboratory (Figure 9). These include various feasibility studies, full-scale mock-ups, and demonstrations in the underground laboratory. Further details of the work are described in Appendix B.

Figure 9. **Manufacturing of carbon steel-based disposal containers for French spent fuel**



Discussion around the presentation focused on the following points:

- **French Nuclear Materials and Waste Management Programme Act**. There was much discussion of the implications of the new French Act. It was noted that the timetable for regulatory interactions was not specified in detail in the Act but that Andra was in discussion with the relevant regulatory authorities (ASN and IRSN) over the timetable. Repository site selection will be made in ~ 2009 and the decision will take account of a national debate and local consultation processes. The period specified during which disposed waste should be retrievable is "at least 100 years". It was noted that this could be interpreted as being similar to the duration of the repository operational phase.

WORKING GROUP FINDINGS

This section summarises the discussions of the two working groups. The membership of the working groups is detailed in Appendix C.

Working Group A: Decision Making and Design Factors in the EBS Design Process

Group A focused on questions in two main topic areas:

- Optimisation and Balancing Multiple Design Factors.
- The Iterative Design Process and its Relationship to PA and SA.

Optimisation and Balancing Multiple Design Factors

Questions addressed by the working group under this topic included:

i) What factors are considered in EBS design and how are they balanced? In particular, how are engineering feasibility, practicality and cost balanced with respect to operational and long-term safety and other requirements?

ii) How are possible alternative designs identified, assessed and selected?

Factors in EBS Design

The group noted that there is no international or unique prescription for the EBS design and optimisation process, and that the decisions taken will depend on the programme in question and its status at any given point in time. However, the group suggested that it is necessary to define the basis for disposal system safety (the safety strategy) at the start of the optimisation process.

The group noted that optimisation is an iterative process, and that optimisation can be considered at different levels of detail (system-wide or for an individual component of the EBS). Optimisation is also greatly assisted by undertaking assessments that are as realistic as possible, as this helps the disposal programme to strike an appropriate balance between the various factors that may influence design.

The provision of safety is of paramount importance and must be maintained. As long as an acceptable degree of safety can be achieved, the emphasis given to other factors that influence design decisions can be set accordingly (a desire to increase waste retrievability or to reduce disposal costs). In this regard it may be helpful to distinguish between disposal system requirements that are essential (safety), and those that may be considered “nice to have” (retrievability).

The group considered it important for a disposal programme to put in place a clear and well-defined process for making and recording decisions on EBS design. This process should be put in place as early in the programme as is practical. Design decisions should be recorded in a traceable way and this may be facilitated by establishing a requirements management system. However, although there is a clear need for a record of decisions, and while tools such as requirements management systems can be very useful, they do not replace the need for the design decisions themselves to be based on the consideration of a range of factors, including good science and engineering.

There should also be a process allowing for periodic or even continuous review of the disposal system design. These reviews should check that all relevant requirements of the EBS have been considered.

Design Alternatives

Design alternatives may be established to allow for different types of uncertainties (uncertainty in the host rock, in site conditions, in the effects of process that will occur). The requirements of the EBS may, therefore, change as the programme evolves (as the host rock and site conditions become better known). As noted above, requirements management systems have the potential to help track changes in the requirements and the design as the programme develops.

Even as programmatic uncertainties are reduced or eliminated, it may well be the case that different EBS designs are available that have the potential to fulfil the requirements of the disposal system. An example is provided by the vertical and horizontal design variants of the KBS-3 concept (SKI, 2005c). The group suggested that it is good practice to re-assess the remaining design alternatives after each phase of the safety assessment. Various methods exist for helping to select between design alternatives (multi-attribute decisions analysis) but the group emphasised that ultimately the choice will involve judgement.

The Iterative Design Process and its Relationship to PA and SA

Questions addressed by the working group under this topic included:

i) What are the roles of uncertainty analysis and sensitivity analysis in decision-making on repository and EBS design, and in establishing priorities for confirmation of the performance of the design?

ii) Is the concept of 'margin of safety' (an amount by which the assessed safety of the disposal system is better than that required by regulatory targets or compliance limits) applied and if so, how?

iii) Is the concept of "best available technique" applied and if so, how? By what criteria is "best" defined? How could the concept be interpreted over the timeframes for geologic disposal? For example, is it the best technology that exists at the beginning of the operational period, or at the end?

iv) What reasons and procedures are used to justify design modifications, or even to change to a different design concept? What lessons have been learnt by organisations involved in iterative repository design and optimisation studies?

v) How are design changes incorporated in PA and SA?

Role of Uncertainty and Sensitivity Analyses in EBS Design

An uncertainty analysis is an analysis to estimate the uncertainties and error bounds of the quantities involved in, and the results from, the solution of a problem, whereas a sensitivity analysis is a quantitative examination of how the behaviour of a system varies with change, usually in the values of the governing parameters (IAEA, 2000). The group considered that uncertainties should, as far as possible, be captured within the safety assessment, and that sensitivity analyses could then be used to identify which parameters relating to the design of the EBS are important. Identifying the most important design parameters and the associated uncertainties allows priorities to be set for work in the forward programme of research and development.

Margin of Safety and Best Available Techniques

The group noted that margins of safety are not set or prescribed in existing regulations or guidance governing radioactive waste disposal, and that the margin of safety concept is not usually applied. Further, the group considered that because the regulations already require a thorough treatment of uncertainty, it is not necessary or desirable to establish quantitative margins of safety over and above those already provided for by demonstrating compliance with existing regulations.

For example, some regulations require a determination of the expectation value of risk (EVR) associated with a disposal facility; this requires a thorough evaluation of the uncertainties associated with disposal system performance, and because the mean value is strongly influenced by the highest calculated risks, demonstrating compliance with the EVR may implicitly provide sufficient assurance that the uncertainties have been taken into account. This latter judgement is, of course, site- and case-specific and will formally be made by the regulator.

The group noted, however, that if appropriately defined, the concept of a margin of safety might be considered by the implementer at a subsystem level. For example, the implementer will have to decide issues of repository design such as what thickness of waste overpack to use. In making design decisions of this type, the group suggested that the implementer should consider what the relevant Best Available Technology (BAT) is as well as "project risk". Thus, at a sub-system level, and in a less regulatory sense, a margin of safety (or a "reserve feature of the EBS" or tolerance) might be defined by the implementer as the additional amount of metal overpack thickness beyond that strictly necessary for the expected rates of overpack corrosion.

Design Changes and Safety Assessment

Possible reasons for repository or EBS design modifications or changes include:

- Results from testing and characterisation.
- Changes in programme boundary conditions (changes in the waste inventory).
- Scenario analysis and modelling.
- Reviews and comments from the regulator or other stakeholders.
- New regulations.
- Change of candidate-sites and changes in Government policy.

The group considered that there was a clear need for the use of programme-wide procedures for decision-making on repository design and for recording the decisions and their basis. The justification for the current project design may be strengthened by keeping records of comparisons made between alternative designs.

The group noted that, at any particular stage of a repository development programme, the design of the repository and the EBS should be only as detailed as necessary. The level of design detail required for PA or SA is typically less than that required from an engineering design perspective. Experience suggests that if too detailed a design is established early on in a programme then this can lead to inertia and inflexibility (in responding to stakeholder views). This suggests that, at an initial stage, the repository development programme should establish a rather conceptual design, sufficient for preliminary assessment. The practicalities associated with implementing the conceptual repository design and the details of the EBS should be assessed through trials at this early stage, but the design details should probably not be part of the formal project position at this stage. Only later, as licensing and construction are approached, should detail be incorporated into the formal project position on design. This approach should help the programme to remain flexible and responsive to the various factors identified above.

Indeed, experience shows that over the course of a repository development programme, changes in regulations and programme strategy that lead to design modifications are to be expected. Similarly, more information will become available on the characteristics of the repository site as the programme proceeds, and the layout of the repository and details of the EBS may need to be finalised in response to the real site conditions encountered.

Throughout the design and assessment process, it is helpful to apply formal methods of safety and performance assessment to integrate the various different types of information to be considered (scientific understanding, site characterisation data, engineering and materials knowledge, stakeholder perceptions). Over time, the perceived importance of particular FEPs may evolve, and PA and SA provide a means for evaluating the effects of such changes.

Design changes may be incorporated into PA and SA by revising scenarios, modifying FEP screening decisions, updating models, and revising parameters. The extent to which it is necessary to revise and re-run the assessment models etc. will depend on the nature of the particular design change being considered. The nature of the design change may also be the cause for additional research and development work.

Working Group B: Confirmation and Demonstration of the EBS in the Context of Confidence Building

Group B focused on questions in three topic areas:

- Demonstration Experiments.
- Monitoring.
- Additional Lines of Evidence.

Demonstration Experiments

Questions addressed by the working group under this topic included:

i) What lessons have been learnt from demonstration experiments on the EBS? What can we do well and what are the practical problems associated with fabricating, constructing, and emplacing engineered barriers?

ii) What level of practical experience in engineered barrier fabrication, construction, and emplacement have we gained from conducting demonstration experiments and large-scale tests on the EBS or its components?

iii) What further experiments and modelling programmes are planned, and with what objectives?

The group considered that many useful large-scale experiments have been conducted (in underground laboratories) that have allowed an assessment of the feasibility of methods for waste package construction, tunnel construction, waste emplacement, buffer and backfill emplacement, tunnel seal construction etc (see in particular the Andra, ESDRED, NUMO/JAEA/RWMC and SKB papers in Appendix B). In general, these demonstrations have been successful and have shown that the necessary methods (waste container welding, buffer block formation and emplacement) for manufacturing and installing EBS components are feasible and available. However, further trials of some methods (backfill emplacement, supercontainer construction and emplacement) are still required, particularly at the repository or industrial scale.

The group noted that while tests and trials of engineering feasibility are essential (for demonstrating operational safety), there is also a need to develop a good understanding of the processes and effects that may occur after EBS construction and emplacement. The group, therefore, distinguished between tests and trials principally aimed at assessing engineering feasibility, and experiments aimed principally at the development of process understanding and assessing the likely long-term behaviour and performance of EBS components. The group noted that the development of process understanding is best approached through the conduct of an iterative process of experiments and modelling and that these experiments may be conducted at a range of scales (from tests in conventional surface-based laboratories to full scale tests in underground facilities). The group suggested that it may be appropriate to begin with small-scale experiments to investigate processes and only progress to larger tests if needed.

The group suggested that further experiments are likely to be required to increase understanding of the long-term behaviour of the EBS and noted that the national radioactive waste disposal programmes are currently conducting and planning a wide range of experiments and modelling programmes, from tests and demonstrations of manufacturing and emplacement techniques to scientific experiments aimed at improving understanding and model capabilities. The group noted that this is an active area which might be reviewed and discussed in an updated EBS state-of-the-art report in due course (see Section 5.2).

Monitoring

Questions addressed by the working group under this topic included:

i) What are the role and limitations of monitoring in performance confirmation and demonstration?

ii) How are monitoring parameters established?

The group noted that it is currently possible to monitor a number of parameters within an underground laboratory or within a repository during operations, and that it may be possible to extend some monitoring of a repository into the post-closure period. Given the current status of available monitoring technologies, the group suggested that post-closure monitoring of parameters such as temperature, rock displacement, and humidity might be possible for up to a few hundred to a thousand years. The group considered, however, that post-closure monitoring of many chemical parameters is unlikely to be achievable with current technologies.

Indeed, from a technical perspective, the group questioned the need for post-closure monitoring, but accepted that such monitoring might bring some wider benefits, for example, in terms of stakeholder reassurance and confidence-building.

The group noted, however, that if post-closure monitoring was to be carried out, then a strategy would need to be developed that defined how to respond to any changes in monitoring information collected. In particular, the group was concerned by the difficulties of dealing with sensor deterioration/failure and the possibility of gathering 'false positive' monitoring information.

In conclusion, the group considered that possibly the best use of monitoring for performance confirmation and demonstration purposes lies in monitoring long-term experiments in underground laboratories or possibly within a portion of a repository set aside for demonstration purposes. It was noted that some programmes (Switzerland, United States) are considering whether it may be possible to monitor a part of a repository into which perhaps 10% of the waste would be emplaced before a decision is taken on whether to proceed with disposing of the remainder of the waste.

Additional Lines of Evidence

Questions addressed by the working group under this topic included:

i) What approaches and arguments can be used (in addition to modelling and experiments) to support a demonstration of satisfactory EBS performance in the context of the safety case?

ii) Can natural and anthropogenic analogues be used to support confirmation of performance and confidence building?

iii) What factors have been identified as contributing to confidence in EBS decisions by the general public, by local communities, by regulators? Are these factors the same across all groups? Do these factors differ from those considered important in a technical sense to demonstrations or confirmations of performance?

The group focused on the need for sound management practices and the application of suitable quality assurance throughout the waste disposal programme as being necessary components of the safety case. The group also noted the potentially valuable aspect of involving local communities when making decisions and choosing between viable technological choices. Arguments that the operator is using the BAT may also help, but the application of the BAT concept has to be made in a realistic and practically achievable way that recognises that technologies will continue to change and improve with time.

The group recognised that anthropogenic and natural analogues can potentially provide useful information on materials similar to those of the EBS and, particularly, on the processes that may operate in the longer-term. However, the group suggested that some caution may be needed in the use of analogue information in safety cases. Ideally, the conditions leading to the preservation of the analogue materials need to be understood, and preference should be given to analogues that are as relevant as possible to the conditions expected in the disposal system. Given the positive potential of analogues to help in developing and demonstrating knowledge of long-term processes, the group suggested that the availability of analogues should be a factor taken into account when selecting materials for EBS components.

The group identified the following examples of aspects of the EBS that were felt to have improved the general public's confidence in proposals for radioactive waste disposal:

- An appearance that inspires confidence (it helps if the EBS is easy to interpret visually and its function is readily apparent, it helps if waste containers are shiny rather than rusty, it helps if barriers appear to be substantial).
- Demonstrating that relevant regulatory requirements for waste package inspection and acceptance have been met.
- Involving representatives from local communities in decisions on waste management.
- Using materials and technologies that are well known and well-tested.

WORKSHOP CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Several, if not the majority, of the waste management organisations are actively following the approach to EBS design and optimisation that has been used to structure the NEA EBS Project. The approach is considered to be useful and not only enables EBS design, but may also play a central role in safety case development. Sound management practices and the application of suitable quality assurance throughout the waste disposal programme are also necessary components of the safety case.

EBS design and optimisation is necessarily an iterative process that follows from an initial step of defining the basis for disposal system safety (the safety strategy). The optimisation process involves a range of studies to:

- Define the requirements of the disposal system and of the EBS and its components, and to take account of waste-specific and site-specific constraints that will influence the design.
- Understand the materials of the EBS components and the processes that may affect them as the disposal system evolves.
- Model the behaviour, and assess the performance, of the EBS components and of the disposal system as a whole under the range of conditions that may occur.
- Confirm and demonstrate that the EBS can be manufactured, constructed and installed satisfactorily.
- Provide reasonable assurance that the disposal system will provide an acceptable level of safety during repository operations and for a long period after repository closure.

It is important for a disposal programme to put in place clear and well-defined processes and procedures for making decisions on EBS design, and for recording the rationale for those decisions. These processes and procedures should be established as early in the disposal programme as is practical. Design decisions should be recorded in a traceable way, and this may be facilitated by establishing a requirements management system. The justification for the current repository design may be strengthened by maintaining records of assessments of alternative designs.

Design decisions need to be based on consideration of a wide range of factors, such as:

- Long-term safety.
- Operational safety.
- Environmental impact.
- Engineering feasibility.
- Cost.

The relative weighting given to the factors considered should take account of the uncertainties involved and the views of the stakeholders, as appropriate.

There is a need to develop a good understanding of the processes and effects that may occur in the disposal system after EBS construction and emplacement. The development of process understanding is best approached through the conduct of an iterative process of experiments and modelling. The experiments may be conducted at a range of scales (from tests in conventional surface-based laboratories to full-scale tests in underground facilities), and it may be appropriate to begin with small-scale experiments to investigate processes and only progress to larger tests if needed.

The use of formal methods of safety and performance assessment helps in integrating the various different types of information to be considered (scientific understanding, site characterisation data, engineering and materials knowledge, stakeholder perceptions). Assessments of safety and design work should be undertaken by suitably qualified personnel. Over time, the perceived importance of particular FEPs may evolve, and PA and SA provide a means for evaluating the effects of such changes.

Optimisation is greatly assisted by undertaking assessments that are as realistic as possible, as this helps in striking an appropriate balance between the factors that influence the design decisions. Sensitivity analyses can be used to identify which assessment parameters relating to the design of the EBS are the most important. Identifying the most important design parameters and the associated uncertainties allows priorities to be set for work in the forward programme of research and development.

Experience shows that over the course of a repository development programme, changes in repository and EBS design are to be expected for many reasons. There should, therefore, be a process allowing for periodic review of the design, and it is probably good practice to re-assess design alternatives after each significant phase of safety assessment. At any particular stage of a repository development programme, the design of the repository and the EBS should only be as detailed as necessary; this preserves programmatic flexibility in terms of being able to respond to programmatic changes. Design reviews should check that all relevant requirements of the EBS (safety functions etc) have been considered. Ultimately, the layout of the repository and details of the EBS may only be finalised as the repository is constructed and real site conditions are encountered.

Many useful large-scale experiments have been conducted (in underground laboratories) that have allowed an assessment of the feasibility of methods for waste package construction, tunnel construction, waste emplacement, buffer and backfill emplacement, tunnel seal construction etc. In general, these demonstrations have been successful and have shown that the necessary techniques for manufacturing and installing EBS components are feasible and available. However, further trials of some methods (backfill emplacement, supercontainer construction and emplacement) are still required, particularly at the repository or industrial scale. Further experiments are also likely to be undertaken to increase understanding of the long-term behaviour of the EBS after installation.

The national radioactive wastes disposal programmes are currently conducting and planning a wide range of experiments and modelling programmes, from tests and demonstrations of manufacturing and emplacement techniques, to scientific experiments aimed at improving understanding and model capabilities. As the disposal programmes mature further and repository implementation is approached, work will also be required related to the process of demonstrating the application of quality assessment and quality control measures over EBS materials and EBS installation, particularly in a regulatory environment.

Recommendations for Future Work

A decision was taken to produce a synthesis report for the full EBS Project, covering the results of all workshops. The report will describe the progress regarding EBS studies over the course of the project, key messages from all four NEA EBS workshops, with specific examples from national disposal programmes, and open issues where further challenges have been identified. There was consensus that further information beyond the outcomes of the EBS workshop series would be required for development of an updated state-of-the-art report on the EBS. The need for an updated report, as well as the mechanisms and resources, will be brought forward for discussion by the IGSC.

The benefits of the EBS workshops were endorsed by all participants, and there was consensus that it would be valuable to maintain an international forum under the auspices of the NEA for further collaborative work on the EBS. Suggestions regarding areas where further work is likely to be required include:

- Progress in performance confirmation activities and large-scale demonstrations and experiments.
- Studies related to operational safety and the EBS.
- Studies of integrated waste packages and containers (supercontainers, pre-fabricated EBS systems, TAD canisters), where even greater emphasis is placed on the functioning of the EBS as a *system.*
- Retrievability considerations in EBS design.
- Specific technical issues such as gas migration and effects of cementitious materials in repository environments.
- Demonstrating the application of quality assessment and quality control measures over EBS materials and EBS installation in a regulatory environment.

It was agreed that the suggestion for continued NEA activities related to EBS will be brought forward for discussion by the IGSC.

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Appendix A

WORKSHOP AGENDA

12 September 2006

Visit to JAEA Tokai R&D Centre

NUMO/JAEA will host a technical visit, the day before the workshop begins, to JAEA's Tokai R&D Centre. The Centre is located in Tokai-mura, Ibaraki Prefecture, about 100 km northeast of Tokyo. Visits to the R&D facilities for the geological disposal (http://www.jaea.go.jp/english/04/tokai-cycle/04.htm) are planned, including: ENTRY (Engineering Scale Test and Research Facility) and QUALITY (Quantitative Assessment Radionuclide Migration Experiment Facility). The visit will begin and end in Tokyo, leaving at approximately 09:00 and returning around 18:30. Transportation will be provided between the hotels and the Tokai R&D Centre.

13 September 2006

PLENARY SESSION

Co-Chairs: *K. Ishiguro (NUMO, Japan) and H. Umeki (JAEA, Japan)*
Rapporteur: *D. Bennett (Galson Sciences Ltd., United Kingdom)*

09:00 1. Welcome

09:10 2. Context: History of the EBS Initiative, Results and Conclusions of the Previous Workshops

09:30 3. Design Confirmation and Demonstration for EBS: National and International Achievements and Ongoing Work

3.1 Approaches and Methods for Demonstration and Confirmation of the Geological Repository Design Concept in the Japanese Programme
H. Ueda et al. (NUMO/JAEA/RWMC, Japan)

10:15 3.2 Planning, Assessment and Construction of a Drift Seal in a Salt Repository – Overview of Investigations.
N. Müller-Hoeppe (DBE, Germany), R. Mauke and J. Wollrath (BfS, Germany)

11:15 3.3 Independent Performance Assessments with Evolving Repository Design
S. Mohanty (CNWRA, United States)

13:30 3.4 Practical Lessons Learned on the Role of the Engineered Barrier System in a Total System Performance Assessment
D. Sevougian and A. Van Luik (US DOE)

14:15	3.5	Design Confirmation and Demonstration for EBS: Current developments in several European National Programmes as part of the FP6 Euratom ESDRED project *C. De Bock, J. Bel (Ondraf/Niras, Belgium); L. Londe (Andra, France); H. Weber (Nagra, Switzerland)*
15:00	3.6	The KBS-3 EBS Workshops: An Example of Regulator-Implementer Pre-Licensing Interaction in the Swedish Programme *Ö. Toverud (SKI, Sweden)*
16:00	3.6	The EBS Demonstration Programme at SKB: Some Examples *D. Gunnarsson (SKB, Sweden)*
16:45	3.7	The French Methodology for EBS Confirmation and Demonstration *F. Plas (Andra, France)*
17:30		Meeting Adjourn

14 September 2006

WORKING GROUP SESSIONS

4. The second day will be devoted to working group (WG) sessions. Two working groups will be convened:

- Working Group 1, "Decision Making and Design Factors in the EBS Design Process," will explore the use of safety functions, the optimisation cycle and the iterative nature of developing a safety case and its implications for design and for ongoing evaluation and demonstration of the EBS.
- Working Group 2, "Confirmation and Demonstration of the EBS in the Context of Confidence Building," will focus on process understanding, demonstration experiments, monitoring, analogues, and additional lines of evidence to build confidence in EBS (and its components) and in the overall safety case.

09:00	4.	Welcome
09:15	4.1	Introduction of Topic, Summary of Relevant Work form Earlier EBS Workshops
10:00	4.2	Workgroup Discussions (including *Coffee Break*)
13:30	4.2	Workgroup Discussions – continue (including *Coffee Break*)
16:00	4.3	Wrap-up/Main Points/Conclusion
17:00		Meeting Adjourn

15 September 2006

A ROUND-UP PLENARY SESSION

Chair: *F. Plas (Andra, France)*
Rapporteur: *D. Sevougian (SNL, USA)*

5. The morning of the third day will comprise a round-up plenary session at which the working groups will report back to the full workshop on general lessons that can be drawn regarding the key questions. The day will continue with a plenary discussion on the findings from both of the previous days. It will include agreement of logistical steps for publication of the 4th workshop proceedings.

09:00	5.	Welcome
09:10	5.1	Working Group 1 Report
09:35	5.2	Working Group 2 Report
10:00	5.3	Path Forward on Proceedings

PLENARY DISCUSSION ON THE SYNTHESIS OF THE EBS PROJECT

Chair: *C. Pescatore (NEA)*
Rapporteur: *B. Forinash (NEA)*

6. This plenary discussion will focus on the lessons learnt from the project and identify the added value as well as future directions. As a result, the outcome from the discussion will provide a key input for the synthesis of the project to be reported to IGSC 8th in October 2006.

10:30	6.1	1. Key Points/Lessons Learned from EBS 1-3
	6.2	2. Findings from EBS Survey
11:30	6.3	3. Proposed framework/Structure
12:00	6.4	4. Discussion/Conclusions
12:50	7.	Final Remarks

13:00 MEETING CLOSED

Appendix B

PAPERS PRESENTED TO THE WORKSHOP

Note that at the time of publication a paper from the US DOE Yucca Mountain Project was not available; the reader is, therefore, referred to the summary of the US DOE presentation provided in the main body of this report.

APPROACHES AND METHODS FOR DEVELOPING AND DEMONSTRATING GEOLOGICAL REPOSITORY DESIGNS IN THE JAPANESE HLW PROGRAMME

H. Ueda[1], K. Ishiguro[1], Y. Sakabe[1], K. Kitayama[1], H. Umeki[2], M. Naito[2], M. Yui[2], H. Asano[3]
[1] Nuclear Waste Management Organization of Japan (NUMO), [2] Japan Atomic Energy Agency (JAEA), [3] Radioactive Waste Management Funding and Research Center (RWMC), Japan

Abstract

Repository site selection in the Japanese HLW disposal programme is based on a volunteering approach, which places special constraints on the process of developing repository designs. In particular, a high degree of flexibility is needed in order to respond to conditions in the specific geological environments in the communities that may come forward. In order to meet this challenge, NUMO has developed a structured process for tailoring repository concepts to siting environments, which considers many options for each design components and assesses them with regard to a number of design goals, long-term safety, operational safety, engineering feasibility, etc.

Various associated design demonstration activities have been carried out by R&D organisations, such as JAEA and RWMC, to support the NUMO structured approach. Such activities are presently focused on engineering feasibility and the long-term safety of a range of repository design options. The preliminary results from such demonstration tests have useful feedback for further design improvements. This suggests that optimisation of repository design can be achieved by working systematically through an iterative process of design and assessment followed by re-evaluation and design refinement.

Introduction

In Japan, the technical foundation for geological disposal of high-level radioactive waste (HLW) was documented by the H3 [1] and H12 [2] projects. Based largely on the platform provided by H12, the implementation phase for HLW disposal was initiated in the year 2000; the law regulating implementation ("the Final Disposal Act") was passed and the HLW implementer, NUMO (Nuclear Waste Management Organization of Japan), was established. In accordance with the R&D framework specified by the Atomic Energy Commission of Japan in 2000 for the implementing phase of HLW disposal, relevant R&D organisations, such as Japan Atomic Energy Agency (JAEA, previously Japan Nuclear Cycle Development Institute (JNC)) and the Radioactive Waste Management Funding and Research Center (RWMC), have been actively promoting technical R&D with the aim of supporting this programme.

The H12 generic safety assessment illustrated the fundamental feasibility of siting a safe repository in the Japanese archipelago. Based on this, NUMO decided to adopt a novel "volunteering" approach to siting, which acknowledged the great importance of acceptance – particularly by local communities [3]. A three-stage siting process for a HLW repository is specified in the Final Disposal Act. Volunteer sites must first be characterised on the basis of existing literature and then Preliminary

Investigation Areas (PIAs) selected for field investigation, including deep boreholes. Thereafter, Detailed Investigation Area(s) (DIAs) will be chosen for further investigation, including construction of underground testing facilities. This would lead, around 2025, to selection of a site for Japan's first deep geological repository.

This volunteering process presents a unique challenge for those responsible for developing repository concepts. Although the key initial step involves solicitation of volunteers, NUMO's subsequent plans for stepwise site selection, involving increasing characterisation of the sites carried through to later phase, are fundamentally similar to those in other national programmes. However, the comparison and ranking of potentially very different sites is a critical activity that is initiated soon after volunteers come forward, which requires appropriate repository concepts (including associated safety cases) to be developed in a clear and transparent manner. This is quite different to other programmes where the repository concept may be defined in advance of – or in parallel with – initiation of the site selection process.

In order to respond to such challenge, NUMO has developed a structured approach to the entire stepwise repository development process [5]. This approach provides supporting R&D organisations with guidelines for their R&D activities to provide input for repository design development, in particular for work to demonstrate the function of key components. These activities involve refining the H12 concept, together with variants and/or advanced alternatives, and thus will support pragmatic, focused optimisation and tailoring of the designs.

A structured approach for repository concept development

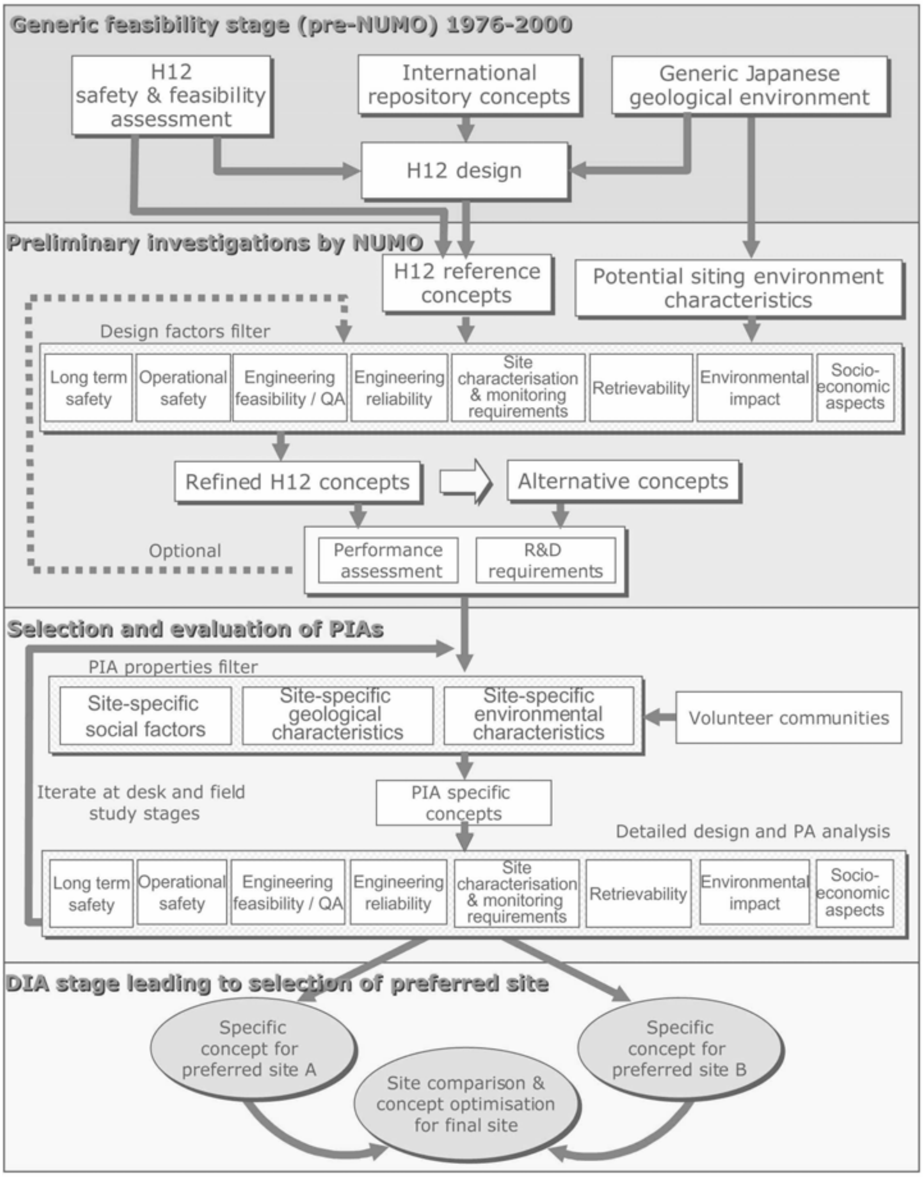
NUMO uses the general term "Repository Concept" (RC) to include a repository design for a specific site environment, along with an associated description of construction, operation and closure, an assessment of operational and post-closure safety and an evaluation of socio-economic and environmental impacts [5]. At early stages, Repository Design Options (RDOs) provide input for RC tailoring to volunteer site conditions. All RDOs are based on the robust Engineered Barrier System (EBS), established in H12, which assures long-term, post-closure safety. The structured tailoring process to select and evaluate such RDOs, which is termed the "NUMO Structured Approach" (NSA), has been discussed in previous papers [4]. Critically, RCs set at early stage need to evolve, being tailored at later stages in response to increasing site understanding.

The strategy for this iterative development of RCs, as the process of site selection and characterisation progresses, is illustrated in Figure 1. The starting point is provided by over two decades of Japanese R&D on HLW disposal, which has been carried out by a range of organisations, led by JNC (presently JAEA) before NUMO was established. This work, which is summarised in the H12 report [2], involved a generic evaluation of the requirements for a safe repository in the types of rocks and siting environments expected to be found in Japan.

Designs of repositories in Japan for HLW have focused very much on demonstration of post-closure safety. For the EBS considered, safety can be assured using very simple assessment techniques, which cover uncertainties by many conservative simplifications. The generic H12 designs (see Figure 2) that form the basis for initial RDOs are very robust – but may lead to extremely over-conservative with regard to long-term safety in particular settings.

Such a situation is reasonable for the early stages of generic concept demonstration, but becomes less appropriate as NUMO moves towards siting, where a number of issues involved with construction and operation of a repository need more consideration. Aspects of practicality and operational safety need to be assessed carefully, in particular, when different design requirements are contradictory. For example, although safety has clear priority, the requirement to develop the repository project efficiently and in an economic manner is established within the framework for Japanese nuclear energy policy [6].

Figure 1. **Repository concept development during the staged site selection and characterisation process [5]**

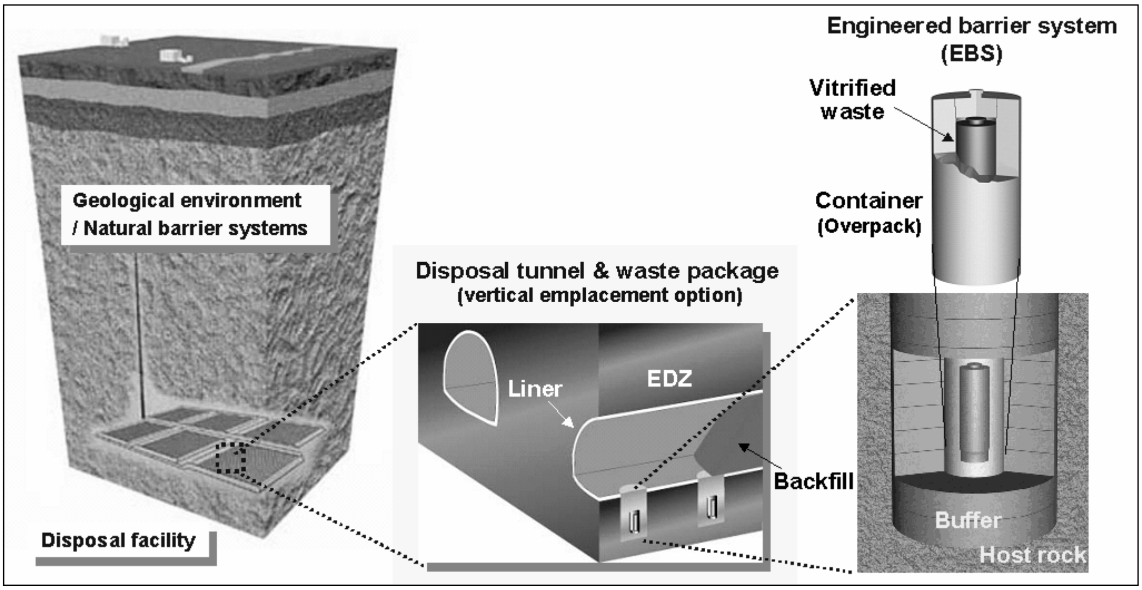


At each stage of the site selection process, the RC is assessed and requirements evaluated to allow it to be better tailored to available sites. Here again, although long-term safety is an essential performance requirement, a much wider set of "Design Factors" are considered in this assessment [5]:

- **Long-term safety**: the robustness of the post-closure safety case.
- **Operational safety**: conventional and radiological safety of construction, operation and decommissioning.

- **Engineering feasibility/quality assurance (QA)**: fundamental feasibility of construction and operation to defined quality levels;
- **Engineering reliability**: practicality of implementation in view of boundary conditions (emplacement rate) and robustness with regard to operational perturbations.
- **Site characterisation/monitoring**: effort required to satisfy technical requirements for site characterisation and monitoring data.
- **Retrievability**: ease of waste package retrieval after emplacement.
- **Environmental impact**: extent of all environmental impacts associated with repository implementation.
- **Socio-economic aspects**: factors contributing to costs and acceptance by all key stakeholders.

Figure 2. **H12 Repository Concept [2]**

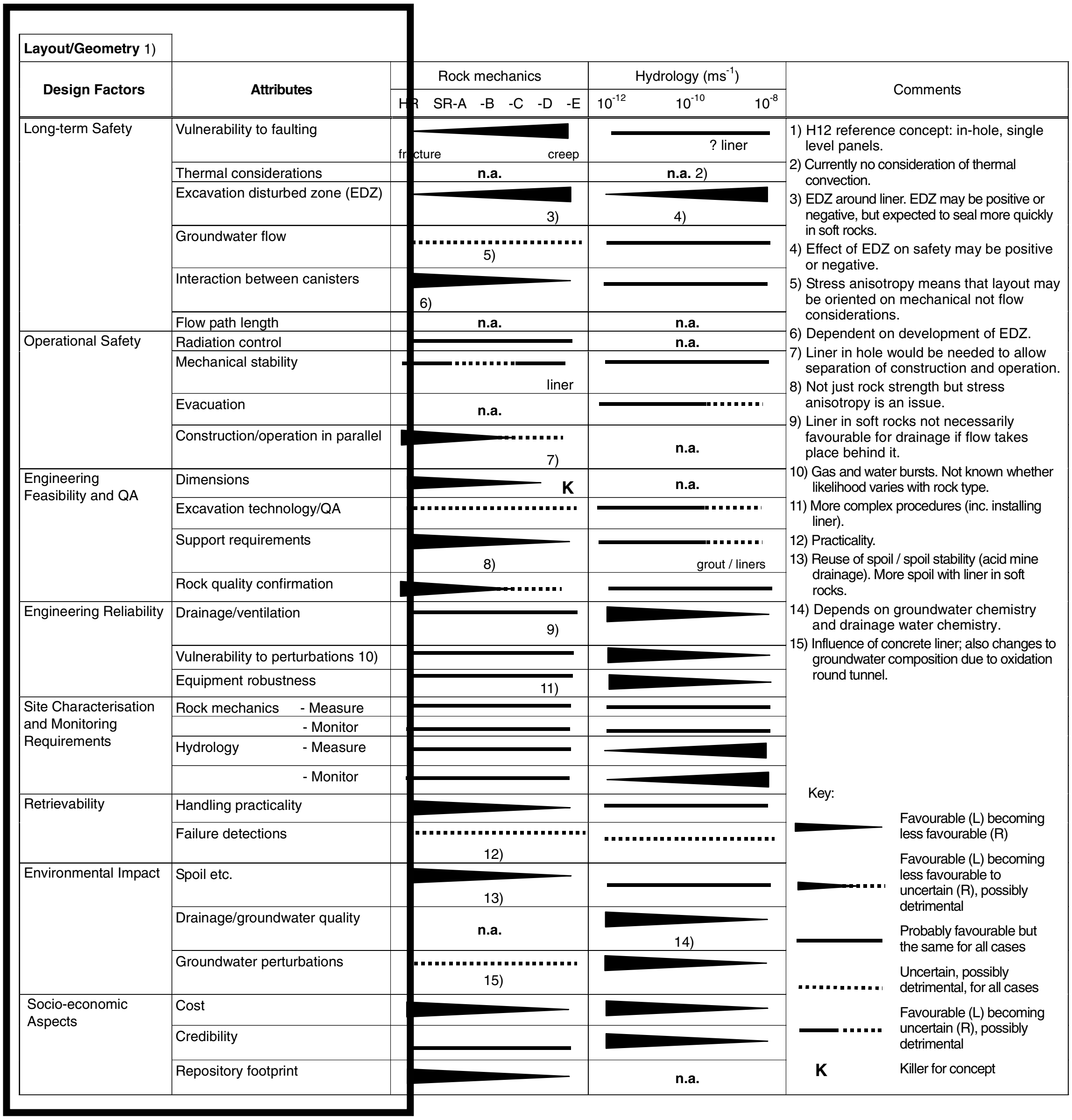


Studies carried out over the last couple of decades in Japan and abroad have shown that, under the constraints set by national programmes, many different combinations of engineered structures and geological settings can provide high levels of safety for HLW disposal. These design options for Japanese boundary conditions are summarised in the "Repository Component Catalogue" (RCC), which aims to maximise system design flexibility [5].

For each option of a repository component or a geometrical layout identified in the RCC, impacts of site characteristics on the Design Factors are evaluated in terms of how the performance of that RDO in isolation would be affected by changes in these characteristics. Each of these identified sub-factors (attributes) can then be evaluated by a multi-disciplinary expert team. An abbreviated version of one of the filtering matrices is shown in Figure 3, where the H12 concept of vertical in-hole emplacement of single waste packages is examined for a range of possible rock strengths (using a Japanese classification scheme) and hydrogeological conditions (represented here by the average hydraulic conductivity) [7].

The filtering matrix has been applied initially to the key components of the H12 design and other components of alternative designs in reduced form, focusing on the Design Factors "long-term safety" and "engineering feasibility". These two factors are of particular importance at the early stages in RC development process. The identified requirements resulting from this analysis help focus R&D activities to demonstrate engineering technology and assess performance of key safety barrier components. In the following sections, examples of such R&D activities currently being carried out by NUMO and supporting organisations will be described.

Figure 3. **Abbreviated version of a matrix of the Design Factors Filter [7]**



Hierarchical system of the Design Factors and their sub-factors (attributes)

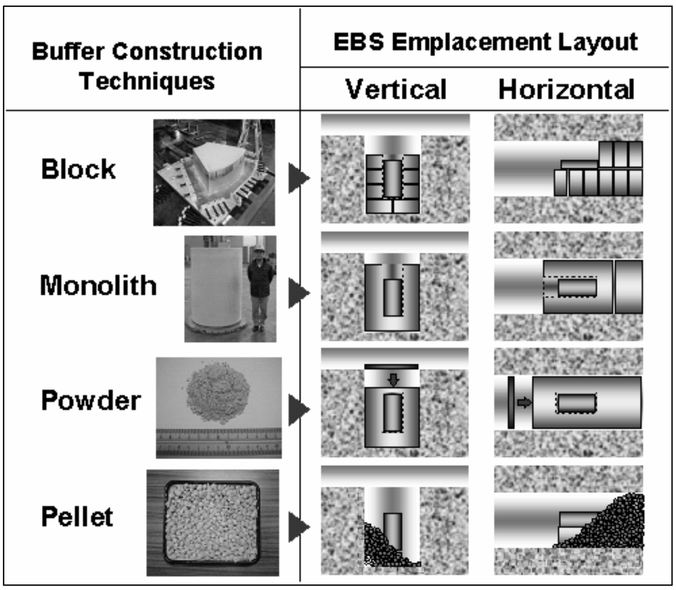
Design development and demonstration

Demonstration of engineering feasibility

According to the Final Disposal Plan [8], it is required that the repository should operate with annual emplacement of 1 000 canisters of vitrified HLW. Due to this hard requirement in terms of engineering feasibility, NUMO has investigated operational components of the repository system – particularly associated with EBS emplacement – focusing on H12 safety barriers, but also taking a range of RDOs into account.

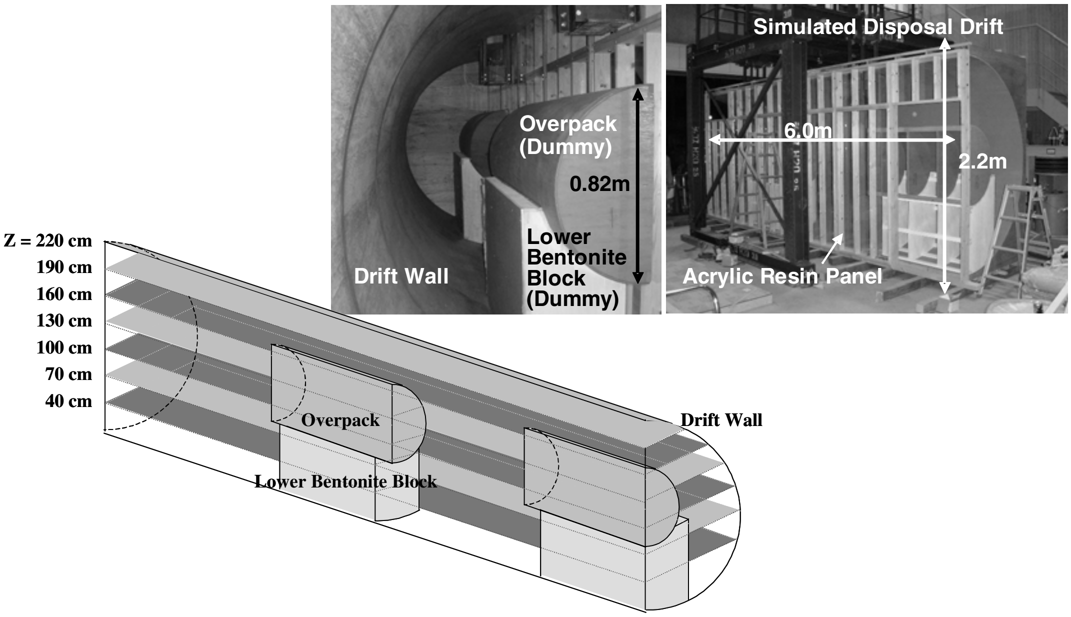
To support this study, construction techniques for the bentonite buffer, which plays a critical role in the H12 safety case, have been investigated by RWMC in its series of R&D projects on EBS tele-emplacement methodology, expanding considerably on earlier H12 engineering studies. As shown in Figure 4 [9], both the conventional bentonite block concept and variants, monolith, powder and pellet, were investigated for vertical pit and horizontal drift emplacements. Key technical elements of each option were identified and their engineering feasibility was examined and demonstrated by component-level and system-level tests.

Figure 4. **Buffer construction options for the EBS tele-emplacement study [9]**

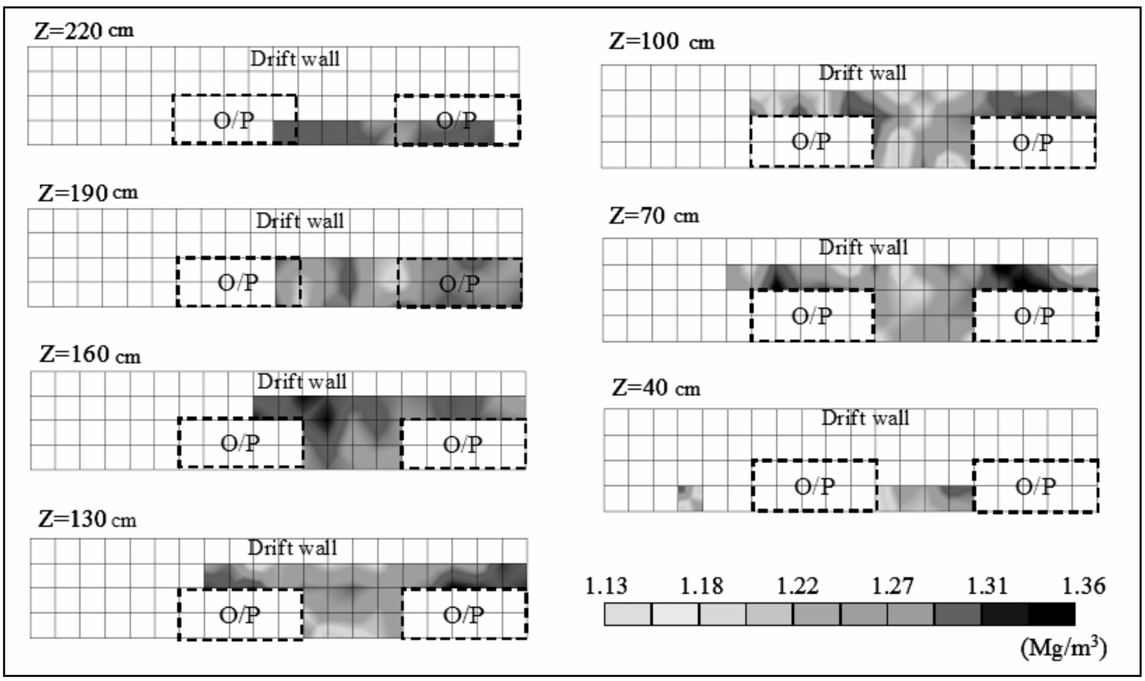


As an example of a system-level demonstration test, Figure 5 [10] shows the configuration of a full-scale bentonite pellet filling test for the H12 horizontal emplacement option and the resulting dry density distribution of the buffer, measured by the RI densimeter. As seen in the photos, the test facility simulates disposal in a half-drift model, represented as a semi-cylindrical section with an inside diameter of 2.2 m. The cut plane is made of transparent acrylic resin to allow inspection of the bentonite emplacement process. Two units, consisting of simulated waste packages (overpacked waste bodies) and lower bentonite blocks, were placed in the 6 m-long test drift. It was observed, as feedback to improve design, that the dry density varies considerably across the model – although the average dry density of 1.29 Mg/m^3, which can realise the buffer permeability equivalently low as in the H12 buffer design, was achieved. With respect to the occurrence of lower density regions, a mechanism due to material segregation was discussed. A moveable delivery head for better mixing was proposed for future development [10].

Figure 5. **Full-scale bentonite pellet filling test [10]**



Dry density distribution of the buffer

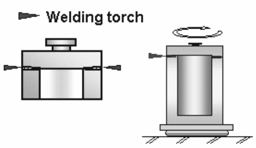
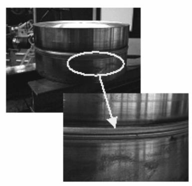
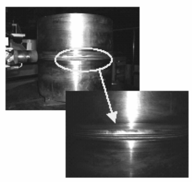
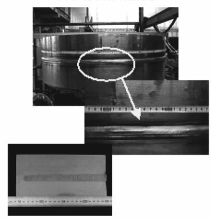
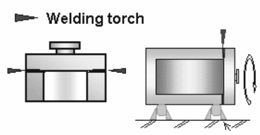
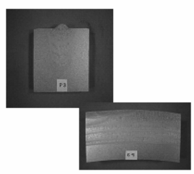
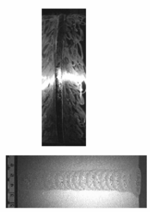
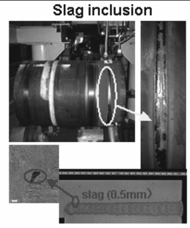
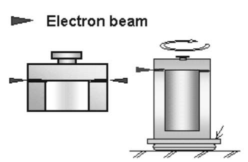
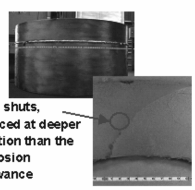
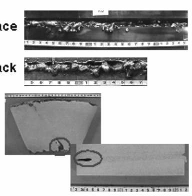


From work to date under laboratory conditions, it seems evident that demonstration of buffer emplacement at defined quality levels (density, homogeneity), especially when implemented with appropriate remotely-operated procedures, could be particularly challenging in the geological environment, which is likely to be rather wet. Handling of highly compacted bentonite is known to be difficult under high humidity conditions and its entire practicality/QA becomes questionable if significant liquid water is present. Nevertheless, there are certainly ways to engineer around this problem, such as the use of pre-fabricated EBS modules – a concept which was mentioned in H12 based on desk studies but, in the interim, is being increasingly studied utilising experience gained in full-scale tests (discussed further later and illustrated in Figure 8).

RWMC has also been carrying out component-level testing on encapsulation techniques for the H12 carbon steel overpack, focusing on welding methods, non-destructive examination (NDE) technologies and corrosion properties of lid welds.

Several welding techniques have been tested to identify their advantages and disadvantages. Figure 6 shows the overall test results for lid welding, where Gas Tungsten Arc Welding (GTAW, or TIG, Tungsten Inert Gas), Gas Metal Arc Welding (GMAW, or MAG, Metal Active Gas) as typical arc welding methods and Electron Beam Welding (EBW) as a high energy beam welding method were applied to test pieces up to 190 mm thick, equivalent to the H12 reference steel overpack thickness. Three ultrasonic testing (UT) methods and an Alternating Current Field Magnetic (ACFM) method were investigated as NDE options to quantitatively detect artificial flaws within the 190 mm thick specimens.

Figure 6. **Results of lid welding tests for a carbon steel overpack (flat lid option)**

Welding Techniques	Test Results	Penetration depth (mm)		
		50 ~ 100 mm	100 ~ 150 mm	190 mm
GTAW (TIG)		100 mm	150 mm	190 mm
Welding: horizontal position Overpack: vertical position Welding torch 	Appearance & Macrostructure	No weld flaws 	No weld flaws 	No weld flaws 
	Welding time	11.9 h (26 layers / 26 passes)	20.0 h (31 layers / 45 passes)	24.5 h (38 layers / 54 passes)
	Residual Stress	—	—	406 MPa
GMAW (MAG)		50 mm	100 mm	190 mm
Welding: flat position Overpack: horizontal position Welding torch 	Appearance & Macrostructure	No weld flaws 	No weld flaws 	Slag inclusion  slag (0.5mm)
	Welding time	0.9 h (6 layers / 12 passes)	1.7 h (11 layers / 22 passes)	2.4 h (20 layers / 40 passes)
	Residual Stress	—	—	380 MPa
EBW			100 mm	190 mm
Welding: horizontal position Overpack: vertical position High-vaccum condition Electron beam 	Appearance & Macrostructure	—	Cold shuts* at the start-end overlapped zone  Cold shuts, induced at deeper position than the corrosion allowance	Void at the start-end overlappned zone Surface Back 
	Welding time	—	10 min (Single pass)	26 min (Single pass)
	Residual Stress	—	—	281 MPa

* Cold shut: weld flaw as a type of lack of fusion

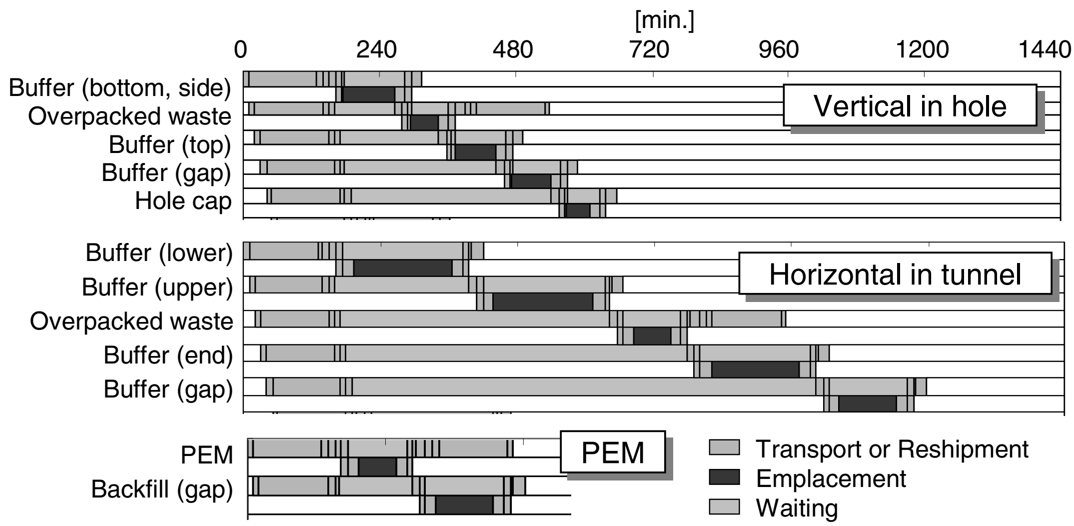
These tests and subsequent evaluations resulted in the following findings:

- TIG was applicable to weld the test pieces to 190mm thickness with no weld flaws while some flaws such as slag inclusions and cold shuts were observed in MAG and EBW pieces [11,12].
- TIG was the most time-consuming of the three methods. The estimated TIG welding time for one overpack lid of 190 mm thickness is 24.5 hours [11].
- With respect to NDE, at least 7 repeats of individual scanning by a combination of three UT methods and ACFM were needed for fully quantitative flaw detection through the entire 190 mm thickness [13].
- Preferential corrosion was observed at a part of weld metal resulting from TIG and MAG, for tests in synthetic sea water under oxidising conditions. The relevance of this observation is still under discussion, but optimisation of the weld metal composition could improve the corrosion resistance [14].
- Evaluation of the maximum size of tolerable initial flaw and improvement of the corrosion properties of the welds were identified as issues for future R&D activities.

These demonstration tests have provided first confirmation of the engineering feasibility of specific RDOs and identified issues requiring further to be investigated. The results have also been incorporated into NUMO studies on the repository operations, to determine if particular RDOs can meet the requirement of annual emplacement of 1 000 canisters.

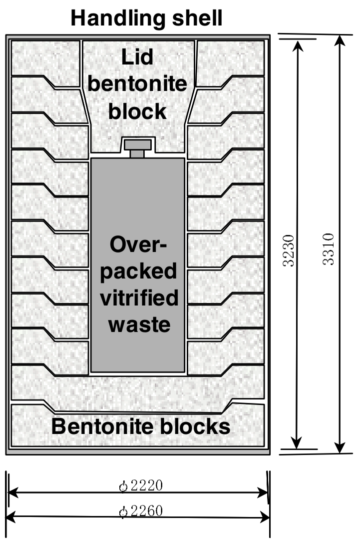
In the operational analysis, processes such as material transport from the surface to the underground and the EBS emplacement sequence were investigated through simulation studies, which incorporated realistic logistics and time scheduling. An example of a Gantt chart to illustrate the sequence of underground transport and emplacement operations for one waste package is shown in Figure 7 for H12 variants of "vertical in hole" and "horizontal in tunnel" options utilising bentonite blocks. The longest time is needed for the horizontal-in-tunnel option, because of long emplacement time of the bentonite buffer.

Figure 7. **Simulation of underground transport and emplacement (Gantt chart for one waste package)**



In Figure 7, an analysis for a Prefabricated EBS Module (PEM, see Figure 8 for a typical example design) variant concept is also shown. It is indicated that this option could reduce the overall time to less than half of that for the horizontal-in-tunnel option, owing to simpler sequence of operations involved.

Figure 8. **An example of a prefabricated EBS module (PEM) design**



Vitrified waste	**0.5 ton**	**H12 reference**
Overpack	**5.6 ton**	**H12 RC, Carbon steel**
Bentonite buffer	**24.0 ton**	**H12 RC + Handling gaps**
Handling shell	**6.1 ton**	**Carbon steel, 20 mm thick**
Total	**36.1 ton**	

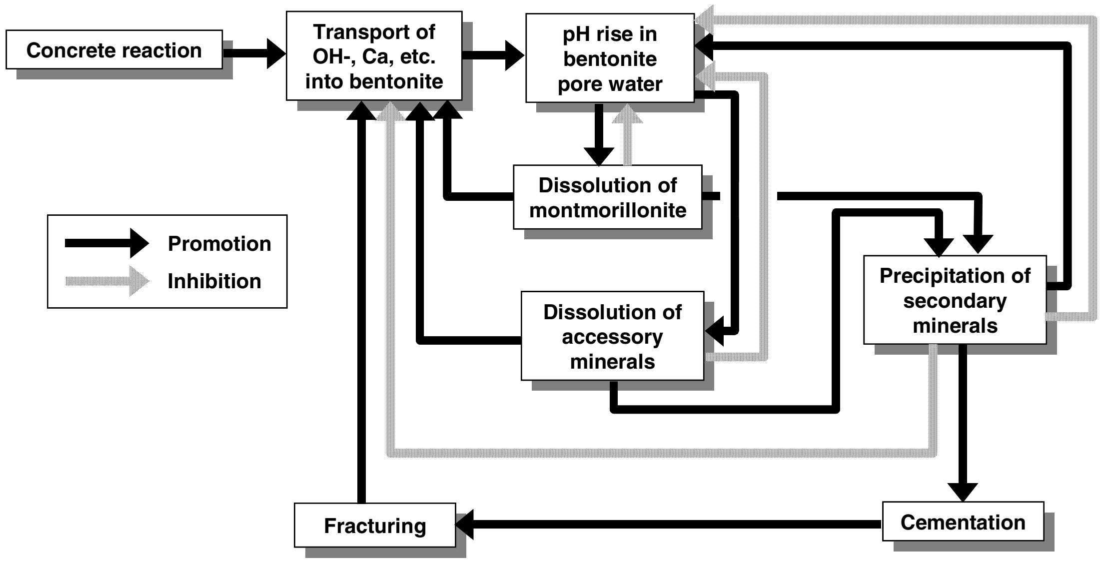
Assessing long-term safety performance to confirm repository design

The process of demonstration of the engineering feasibility of RDOs is coordinated with an assessment of long-term safety. A particular challenge may arise when the requirements for engineering feasibility and operational safety give rise to a conflict with post-closure safety requirements. A typical example could involve use of cement/concrete for grouting, tunnel lining, etc. [15]. Construction engineers may prefer extensive use of this well-known material to minimise difficulties (and hence risks) of construction activities. The long-term performance assessors, on the other hand, may want to avoid or minimise the chemical complexities associated with hyperalkaline leachates from cementitious materials.

From the engineering viewpoints, possible approaches to solving this issue are to develop low-pH cement as alternative material ([16, 17]) for critical cement components and/or to design the repository to minimise any such effects. In any case, it is important to demonstrate that any detrimental effects due to the hyperalkaline plume from the conventional cement such as the ordinary Portland cement (OPC) are either small or negligible in terms of long-term safety. For this purpose, models and databases are being developed in order to more rigorously and realistically evaluate effects of the hyperalkaline plume [18, 19].

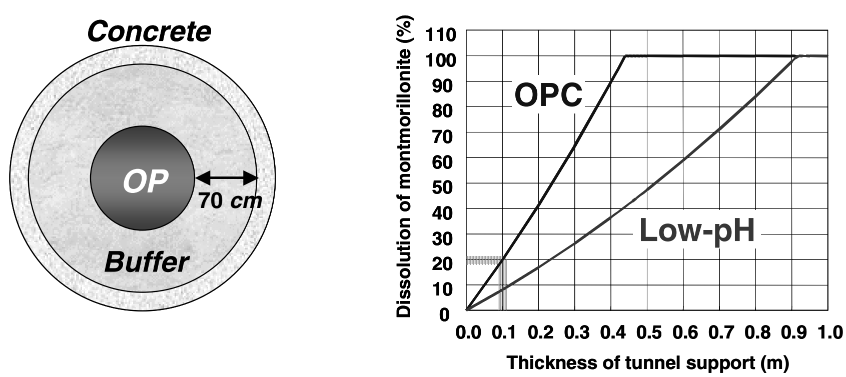
Some of the important mechanisms controlling the bentonite alteration by the hyperalkaline leachate were identified and represented schematically as shown in Figure 9 [15]. These discussions have been expanded and summarised into the form of a process-influence diagram, where influences to the safety functions of the bentonite buffer from key processes, such as calcium ion-exchange, dissolution of the smectite, precipitation of the secondary minerals and cementation, are systematically shown [19].

Figure 9. **Cement/Bentonite interaction as a coupled non-linear dynamical system [15]**



The approach being taken for modelling such perturbations includes scoping mass balance calculations to estimate the potential for montmorillonite dissolution – for example, given different cement barrier thicknesses and compositions (OPC and low-pH cement). Preliminary calculations indicate that leaching of a 10 cm thick concrete liner could dissolve 20% of the bentonite, as shown in Figure 10. This suggests that the amount of bentonite alteration that may occur is likely to be quite limited if this occurs homogeneously and that, by using a more realistic model in combination with a refined design that includes a slightly thicker bentonite barrier, it may be possible to demonstrate that use of OPC could be acceptable in this case. Nevertheless, such simple calculations should not be overinterpreted; in the case that bentonite cementation is the critical factor, localised loss of the buffer barrier as a result of cracking may occur well before significant mineral alteration has occurred. In any case, feedback from such results could lead to changes in the design requirements/specifications to avoid the problem completely or setting R&D priority on better understanding of bentonite alteration, leading to development of more realistic models.

Figure 10. **Results of mass balance calculations for bentonite dissolution by hyperalkaline leachate**



Extended demonstration programme in the JAEA URLs

To support site-specific tailoring of the rather simple concepts used originally for feasibility demonstration in order to improve operational practicality, robustness and safety, there seems to be much that could be gained from large-scale, long-term demonstration projects in underground test facilities. These, in the past, have clearly illustrated the difference between a design that it is *possible* to implement and one that is truly *practical* under the boundary conditions in a working repository. Such optimisation is needed to ensure operational safety, practicality and ease of quality assurance – but has also to be assessed in terms of potential impact on long-term performance. This will probably require long-duration experiments (in conventional laboratories and underground, complemented by analogues, if possible).

These projects can also play a valuable role in communicating design concepts to non-technical audiences. In this context, a further international trend is the increasing general acceptance of the idea that enhanced retrievability/reversibility may need to be built into repository designs, to increase acceptance but also allow flexibility by keeping options open for future societies to make use of possible technical advances in waste management and materials technologies [20]. As yet, however, there has been little research on the extent to which such enhanced retrieval provisions – such as delaying the placement of backfills and seals – could have negative impacts on safety. Again here, long-term *in situ* demonstration experiments could be useful.

Moving forward towards development of practical designs appropriate to Japanese repository conditions will inevitably require concepts to be tested underground at large (or full) scale. Generic URLs can make an important contribution to the development of geological repository projects in this regard – particularly as they allow the inevitable problems to be ironed out before sensitive confirmation studies are initiated at URLs in potential repository locations. The expected roles of the JAEA URL projects have been defined widely in terms of contributions to NUMO and to the regulatory organisations, with respect to site characterisation, repository engineering, safety assessment methodology and gaining the acceptance of key stakeholders [21].

In order to develop optimised designs for specific sites, it is important to have not only an integrated database of the required information from site characterisation and supporting R&D, but also a formal mechanism for supporting and documenting decisions. JAEA has been promoting R&D aimed at increasing confidence in the technical basis provided in H12 by making maximum use of its infrastructure. Through development of a quality-assured knowledge base, JAEA, as an independent third party, can provide as a valuable resource for both the implementer and the regulator [22, 23].

Conclusions

The Japanese HLW disposal programme involves a step-wise approach with an iterative process of site characterisation, repository design and safety assessment, which is consistent with that internationally accepted and implemented in other national programmes. Through this approach, RCs will be tailored to siting environments, taking account of not only long-term and operational safety, but also engineering practicality, retrievability, monitoring, environmental impact and socio-economic aspects. The selected volunteering approach to siting does, however, create rather unique boundary conditions for this process. NUMO has developed a structured approach for RC development, taking these special boundary conditions into account.

Key R&D challenges are associated with ensuring a clear and transparent process of repository development for volunteer sites, which includes continuously tailoring the design to site conditions, in order to support the decisions leading to final site selection. Additional issues are associated with increasing reliability and robustness of the repository concept and extending assessment of operational practicality – both of which may benefit from in-situ engineering demonstration at large or full scale. A series of demonstration tests have been carried out by Japanese R&D organisations and these will be complemented by large projects planned in URLs that will play important roles in the future.

Finally, it should be noted that, in order to develop an optimised design and safety assessment basis for specific sites, a formal "requirements management system" is being investigated, which could be integrated with the development of "knowledge management" and "quality management" systems. Development of a quality-assured knowledge base and a structured approach to managing technical knowledge on geological disposal will be critical in this regard, preserving a legacy of crucial intellectual property that will be needed for successful implementation of the Japanese HLW disposal programme.

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PLANNING ASSESSMENT, AND CONSTRUCTION OF A DRIFT SEAL IN A SALT REPOSITORY – OVERVIEW OF INVESTIGATIONS

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Introduction

In the former German Democratic Republic the abandoned salt mine of Bartensleben was selected to serve as a repository for low and intermediate level (LLW, ILW) radioactive waste. Located near the village of Morsleben in the Federal State of Saxony-Anhalt, this mine was named "Repository for Radioactive Waste Morsleben (ERAM)". The decision to establish the repository was based on safety and technical-economic studies performed in the 1960s. It was designed, constructed and commissioned between 1972 and 1978. Following several studies and the successful demonstration of the disposal technologies used, a first operational licence was granted in 1981. The licence did not cover repository closure.

After the German reunification (October 3, 1990) the Federal Government of Germany took over the responsibility for the repository. The Federal Office for Radiation Protection (Bundesamt für Strahlenschutz, BfS) acts on behalf of the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU), which represents the German Federal Government. DBE then became operator of the repository on behalf of the BfS. The final disposal of waste was stopped in 1998. In accordance with the German Atomic Energy Act (AtG [1]) a licence application for repository closure is being prepared by the BfS. In this context, BfS concluded contracts concerning the backfilling and closure of the Morsleben repository, which is presently being planned [2,3].

According to the closure concept 21 drift seals have to be constructed. Situated in the access drifts to the disposal areas these drift seals are important components of the multi barrier system. To guarantee compatibility of all closure measures planned [4], salt-concrete is the preferred construction material for the seals.

The conceptual design of the ERAM drift seals was presented at the Oxford workshop [5], the optimisation process of drift seal design within a rock salt environment was described at the Turku workshop [6]. The alteration of salt concrete and the related process model applied to the ERAM drift seals were presented in the Las Vegas [7], and the treatment of the drift seal performance within the safety assessment was described in the La Coruña [8] workshops, respectively.

This paper focuses on the proof of structural reliability, the confirmation of producibility, demonstration of compliance with specifications for emplaced drift seals, and methods for demonstrating that design requirements have been met in a regulatory environment. The relevant design criteria used to prove structural reliability determine the type and general set-up of the experiments.

Fundamental requirements on ERAM drift seals

In the context of long-term safety assessment only one parameter is of interest, the flow resistance of the drift seal over time. Mostly for practical reasons the flow resistance is described as a function of the drift seal's length, its cross-sectional area including the excavation damaged zone (EDZ), and its permeability. In order to avoid radionuclide release from the disposal areas for several thousand years and to achieve a low alteration rate of drift seals, an initial average permeability of $k \leq 10^{-18}$ m^2 is required leading to a design working life of 5 000-30 000 years [6,7,8] provided that the drift seals´ mechanical integrity is assured.

To guarantee compatibility with backfilling measures already being performed [4], salt concrete is favoured as material to build the drift seals.

In the technical context the following circumstances must be considered. To serve geological, mining and technical issues, the drift seal's length assumed in long-term safety assessment is divided into segments of 15-30 m in length. In some cases a drift seal consists of one segment only due to restricted space. For this reason, the drift seal is designed in such a way that it serves not only as a seal but as an abutment as well. Evidently, the construction process follows a retreat working direction, and difficult and limited access to the drift seals´ locations must be taken into account. In the ERAM, some drift seals´ locations have very low convergence rates.

Drift seal consisting of one segment

Next, a one-segment drift seal is regarded. The conceptual design of a segment is given in [5]. The design takes into account that in reality the drift seal consists of the sealing body, the contact zone to the EDZ, and the EDZ itself, which is considered to belong to the drift seal within the long-term safety assessment. To preclude that the contact zone and the EDZ may act as primary migration paths, grouting is intended. Due to the low convergence rates at some drift seal positions in the ERAM, creep-induced high pressure tightening the contact zone and the EDZ in the short term is negligible so that injection is of major importance. More details on drift seal design and the relevant properties of the selected material for the ERAM drift seals are given in [5,6].

Proof of structural reliability

In Germany state-of-the-art technology for the proof of function of conventional barriers consists of the following set of proofs [9,10,11]:

- proof of tightness or of adequate flow resistance;
- proof of mechanical resistivity (mechanical stability and integrity);
- proof of durability or long-term stability respectively;
- proof of producibility.

In the case of the ERAM seals a first set of quantitative design criteria was published to prove mechanical resistivity and adequate flow resistance [5]. The average permeability limit of 10^{-18} m^2 may be exceeded because of two reasons:

- mechanical failure and crack evolution;
- insufficient flow resistance of the sealing body, the contact zone, or the EDZ.

Mechanical stability and integrity (limited crack evolution) have to be proved during the construction phase as well as under dry and wet repository conditions in the long term. The interaction between sealing body, contact zone, and EDZ must be considered because they form a firm unit. Flow resistance, however, is of importance only under wet repository conditions. If flow resistance proves to be sufficient the sealing body, the contact zone, and the EDZ may be treated separately.

The proof of durability or long-term stability respectively is coupled with the proof of adequate flow resistance [7,8]. As low alteration rates are a direct consequence of high flow resistance this paper focuses on the proof of adequate flow resistance.

Mechanical integrity is the first item to be regarded because it is a necessary condition of adequate flow resistance. In the next paragraphs results of a first approach [12,13] to prove mechanical resistivity by numerical calculations are shown using quantitative design criteria [5].

Proof of mechanical resistivity

With respect to the conceptual design of the ERAM drift seals the proof of mechanical resistivity is reduced to the proof of mechanical integrity because this proof meets the most restrictive design criteria. Thus, the proof of mechanical stability is covered as well.

For calculation purposes, the drift seal situated in the northern ventilation drift [5] was selected as example. The calculation model included the geological structure of this location, the drift seal itself, the construction process, and several representative load cases.

The material models applied are the classical secondary creep salt models [14] and the elasto-plastic Drucker-Prager salt concrete model [15] with tension cut-off using parameter values of salt concrete determined experimentally [6]. The hydration-induced heat production of salt concrete was also taken into account [16].

Kinematic stability of rigid body (sealing body)

The proof of kinematic stability [5] is not considered in this context because the proof of integrity is more restrictive (see paragraphs below).

Integrity of sealing body

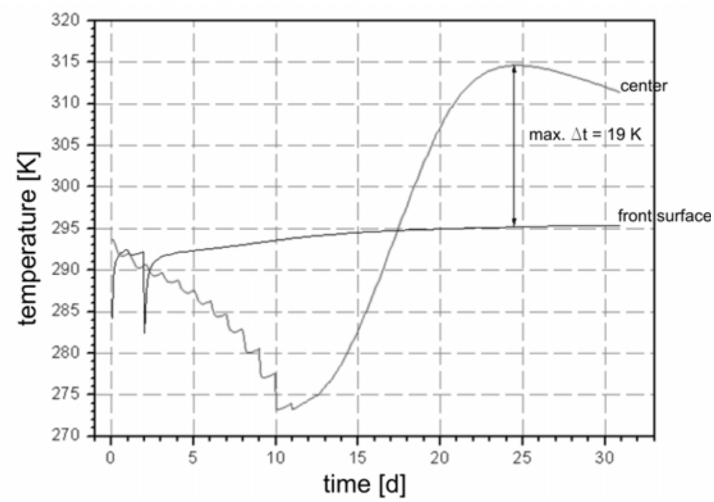
With regard to the integrity of the sealing body, limiting crack evolution inside the sealing body, different load cases have to be considered. During the construction phase temperature-induced stresses arise due to hydration heat inside the sealing body. Thus, the temperature gradient between the interior of the sealing body and the boundary has to be limited. A maximum temperature gradient of 20 K is used as design criterion [5,12]. Under dry repository conditions the relevant load case arises under maximum rock pressure. Integrity is proved by evaluating the stress state inside the sealing body and fulfilling the Drucker-Prager strength criterion according to technical standards in the short term for the first 100 years after building of the seal [12] and by fulfilling the dilatancy criterion of the salt concrete in the long term [5]. A further load case to be considered is the combination of maximum fluid pressure at one side of the drift seal and the related rock pressure over time leading to the most unfavourable deviatoric stress state inside the sealing body. Again, the local stress state resulting from this load case is compared to the dilatancy criterion of the salt concrete.

Concerning the integrity of the sealing body the calculation results may be summarised as follows:

The temperature gradient criterion is met provided that the fresh salt concrete is cooled down to about 2°C before concreting. See Figure 1 for the maximum temperature gradient versus time.

The Drucker-Prager strength criterion is met inside the sealing body for the first 100 years while subsequently the dilatancy criterion is fulfilled for up to 30 000 years.

Figure 1. **Maximum temperature gradient inside the sealing body versus time**



Integrity of contact zone

Due to crack evolution in the contact zone the most unfavourable load case is the combination of maximum fluid pressure at one side of the drift seal and the related rock pressure at the contact zone. The stresses induced by this load case were evaluated and the maximum and minimum principal stresses rated against the permissible uniaxial tensile and compression strength, the weaker material, rock salt, being decisive.

Concerning the integrity of the contact zone the calculation results may be summarised as follows:

The tensile stress criterion of rock salt is met for the first 100 years after building of the drift seal. Later on, tensile stresses do not occur in the contact zone anymore and the resulting pressure is far below the compression strength limit.

Integrity of EDZ

To avoid damage inside the EDZ and increased permeability as a consequence the fluid criterion must be met, $\sigma_1 > p_{fluid}$ is applied to prove safety, with p_{fluid} being the local pore pressure, σ_1 the minimum component of total stresses. Alternatively, the effective dilatancy criterion, the dilatancy criterion of rock salt reduced by the pore pressure, may be applied as a less conservative approach.

Concerning the integrity of the EDZ the calculation results may be summarised as follows:

First, evaluation of the calculation results showed that in the EDZ both the fluid criterion and the effective dilatancy criterion are exceeded when applying the conservative assumption of instantaneous flooding [8], Figure 2. Both criteria hold (Figures 2, 3) if a brine pressure build-up over time according to site specific conditions is assumed. Second, it turned out that due to local stress concentrations the drift seal is not in its whole length effective, Figure 3.

Figure 2. **Hydrostatic pressure against fluid criterion versus time with respect to the whole length of the drift seal**

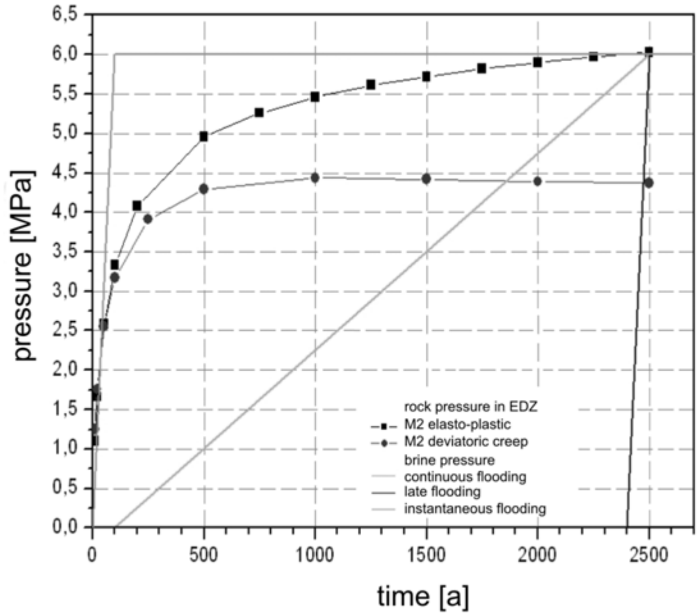
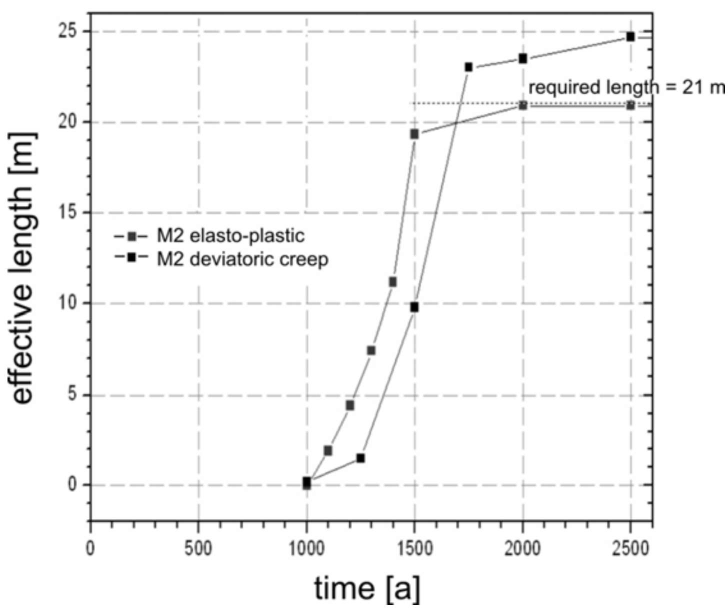


Figure 3. **Effective length of drift seal versus time when using the effective dilatancy criterion for design**



Third, the calculation results demonstrate that the material model of the sealing body significantly influences the stress development in the EDZ. The black dotted line in Figure 3 shows the evolution of the effective length versus time if the elasto-plastic Drucker-Prager model for salt concrete is used [15]. The red dotted line shows the effective length if it is assumed that the salt concrete shows a material behaviour comparable to rock salt, deviatoric creep is taken into account. In this case, the stress increase period until fulfilling the fluid criterion or the effective dilatancy criterion respectively at the obligatory minimum length is longer.

Technical consequences of calculation results and modifications

Technical consequences of first approach

Based on the above mentioned calculations it has to be concluded in the first instance that the salt concrete has to be cooled down to about 2°C before concreting. Although cooling of concrete has a long tradition, neither large-scale cooling of salt concrete nor cooling of concrete deeply underground have ever been performed. Before spending resources on cooling BfS decided to check whether a less conservative approach could be used. For this reason BfS decided to add a so-called alternative proof evaluating the crack evolution of the salt concrete body during the hydration phase using a more sophisticated material model [17]. This designated alternative approach replaces the temperature gradient criterion used for standard concrete, the applicability of which is under discussion because it is an empirical criterion based on temperature alone whereas in reality crack evolution is caused by temperature induced stresses.

Modification: Alternative approach

Additional experiments were performed to determine the parameters of the more sophisticated material model [17]. The material model includes heat production during hydration, evolution of short-term compression strength, tensile strength, Young's modulus, and viscoelastic behaviour of the salt concrete as a function of the degree of hydration. Shrinking is also included in the model because a relatively large amount of autogenous shrinking was detected when performing the laboratory tests to determine the parameters which describe the viscoelastic behaviour of the green salt concrete.

In case of the alternative proof the crack index γ_{cr} is used as design criterion. Quantitatively, $\gamma_{cr} = 2.0$ is used for dimensioning,

$$\gamma_{cr} = 0.75\ f_{cte}/\sigma_{max}\ ,$$

f_{cte}: uniaxial tensile strength depending on the actual degree of hydration

σ_{max}: maximum principal stress

0.75: factor to reduce laboratory values to *in situ* values

Table 1 shows the preliminary results of the crack index calculations within the cross sectional area for different fresh concrete temperatures and different amounts of shrinking strain after 2 000 hours.

Table 1. **Crack index within the cross sectional area depending on fresh concrete temperature and amount of shrinking**

Crack index γ_{cr} [-]		Fresh concrete temperature [°C]				
		20	15	10	5	2.4
Shrinking strain after 2 000 hours [mm/m]	1.40	0.33	-	-	0.35	0.35
	1.00	0.40	0.41	0.42	0.44	0.44
	0.50	0.50	-	-	0.64	-
	0.25	0.25	-	0.75	0.80	-
	0.00	0.00	0.92	1.00	1.09	1.14

Applying the more sophisticated material model, the calculation results can be summarised as follows: Safety against cracking is only shown when shrinking is negligible and the salt concrete is cooled down to a temperature of 2-5°C before concreting. When assuming the hypothetical case of negligible shrinking the results of the first approach are confirmed. The empirical temperature gradient criterion captures the ultimate limit state correctly even when salt concrete is used. However, the safety margin against the ultimate limit state seems to be very small and the crack index of 2.0 is still not reached. In reality, though, shrinking is not to be neglected. Additionally, when regarding the cross section the EDZ shows a lower tensile strength and thus is the primary location of crack localization. Increased damage inside the EDZ will be the consequence. Calculated in lengthwise direction the cracks inside the sealing body are in cross sectional direction, thus not reducing the effective length of the drift seal.

Technical consequences of the alternative approach and further modifications

The alternative approach has shown that further modifications are necessary to prove structural reliability by complying with the crack index and the safety margins assigned. Presently, two options are being discussed.

One option is to prevent shrinking or even to generate a small swelling by applying additives to the salt concrete. First results show that shrinking can be suppressed successfully, but, it still has to be confirmed whether the excellent properties of the salt concrete, its extremely low permeability, will be maintained when the material modification process is finished. Investigations are going on.

At the same time, a further modified approach is being discussed by BfS as a second option. The main idea of this approach is to permit cracking at selected positions, a controlled localization of cracking. This option is highly favourable because the cooling of salt concrete is not necessary and the autogenous shrinking of the material does not play a decisive role.

In lengthwise direction, vertical predetermined breaking points will be integrated into the structure, thus reducing residual stresses from the hydration process on the one hand but not reducing the hydraulic effective length on the other hand. In cross sectional direction, the EDZ or rather the contact zone is assumed to be a natural predetermined breaking point. As cracks and fissures in the EDZ increase the permeability of the drift seal the EDZ must be improved either by natural processes, sealing or healing due to convergence of rock salt respectively [18], or technical measures, grouting which was already considered in the basic concept for drift seals at locations of insufficient convergence rates [5]. Natural time-dependent sealing processes of the EDZ were investigated within the framework of the ALOHA2 research project [19].

Adequate flow resistance

As a next step adequate flow resistance has to be proved. Assuming mechanical resistivity of the drift seal is confirmed the proof of adequate flow resistance is carried out separately for the sealing body, the contact zone, and the EDZ. Due to corrosion processes in the sealing body and the contact zone continually increasing permeability must be taken into account. In the EDZ corrosion will not occur. As an average permeability of 10^{-18} m^2 is required, a higher permeability of the EDZ may be compensated by a lower permeability of the sealing body summing up the volumetric flow rate of the whole system. In a first approach, however, the permeability of the three elements of the drift seal were considered separately in order to reduce complexity.

According to German technical regulations in civil engineering [10] it is permitted to prove adequate flow resistance of the sealing body based on laboratory tests and calculations [5], see Chapter 4.1. The flow resistance of contact zones, however, has to be quantified by investigating comparable structures. This means it has to be shown that no defects and faults exist in the contact zone which would result in an intolerable degree of permeability of the seal.

In order to gain a reliable data basis, in-situ tests were performed in the Asse salt mine investigating the contact zone of a 10-year old salt concrete seal by means of permeability tests, hydraulic fracturing and ultrasonic fault analysis [20]. Additionally, mechanical and hydraulic properties of core samples from the Asse seal and the contact zone were examined in laboratory tests to get a better knowledge of the quality of salt concrete obtained in situ and of its adhesion to the salt rock contour. In this paper, the results of the Asse seal project [20] are used only to demonstrate the proof of structural reliability.

To rate the permeability of the EDZ, measurements available from different research projects [18,19] are summarised.

Limitation of flow rate through sealing body

This load case assumes maximum brine pressure at one side of the drift seal and normal air pressure at the opposite side resulting in the maximum hydraulic gradient possible. An initial permeability of $k \leq 10^{-18}$ m² fulfils the requirements resulting from long-term safety assessment [8]. In addition to this, long-term stability has been proven as corrosion due to NaCl or $MgCl_2$ brines migrating through the seals proceeds sufficiently slowly during the required time period [7]. Since laboratory tests have indicated that the permeability of the salt concrete meets the requirement that $k \leq 10^{-18}$ m² [5, 6], the required limited flow rate through the sealing body and thus sufficient long-term stability can be proved [7, 8].

The laboratory results have been confirmed by in-situ measurements within the framework of the Asse seal project, although it has to be taken into account, that the Asse seal´s sealing body concrete mixture [20] differs from mixture intented to be used at ERAM [5]. In both cases the results of the permeability of the salt concrete from laboratory tests [5] and from in-situ tests [20] showed a consistent permeability of $k \leq 10^{-18}$ m². Thus, the permeability of the salt concrete sealing body is sufficiently small, both in laboratory tests and in the real construction.

In detail, the salt-concrete body of the Asse seal showed a permeability to gas in the range between $6.0 \cdot 10^{-19}$ m² and $4.4 \cdot 10^{-24}$ m² and a permeability to brine between $4.1 \cdot 10^{-20}$ m² and $9.0 \cdot 10^{-21}$ m². The gas permeability measured at the brine measuring points, however, showed values between $6 \cdot 10^{-19}$ m² and $7 \cdot 10^{-23}$ m².

Limitation of flow rate through the EDZ

The relevant load case for the EDZ assumes maximum brine pressure at one side of the drift seal and normal air pressure at the opposite side resulting in the maximum hydraulic gradient. Due to the positions of the drift seals, the brine is assumed to be saturated, thus long-term stability of the EDZ is automatically given. Hence, as regards the EDZ the permeability needs to be limited to $k \leq 10^{-18}$ m². In the ERAM, permeability measurements at the walls of trimmed drifts showed values of $5 \cdot 10^{-17}$ m² – $1 \cdot 10^{-20}$ m². The EDZ of the drifts, which are up to 70 years old, will be removed before building the drift seals.

In the rock salt contour (former EDZ) of the Asse seal a permeability to gas in the range between $6.5 \cdot 10^{-21}$ m^2 and $2.0 \cdot 10^{-24}$ m^2 was measured. The highest permeability of $6.5 \cdot 10^{-21}$ m^2 was measured in the former EDZ of the roof. This low permeability of the former EDZ is interpreted to be a result of creep and stress redistribution that has already taken place. These results verify the results obtained within the ALOHA2 project showing that the permeability of the EDZ around a bulkhead after 90 years is reduced to values of $k < 10^{-18}$ m^2.

Thus, in the case of the EDZ an average permeability of 10^{-18} m^2 is highly probable to adjust. If the EDZ permeability exceeds the limit value slightly it can be compensated by a lower permeability of the sealing body as there is no danger of increasing corrosion rates inside the EDZ.

Limitation of flow rate through the contact zone

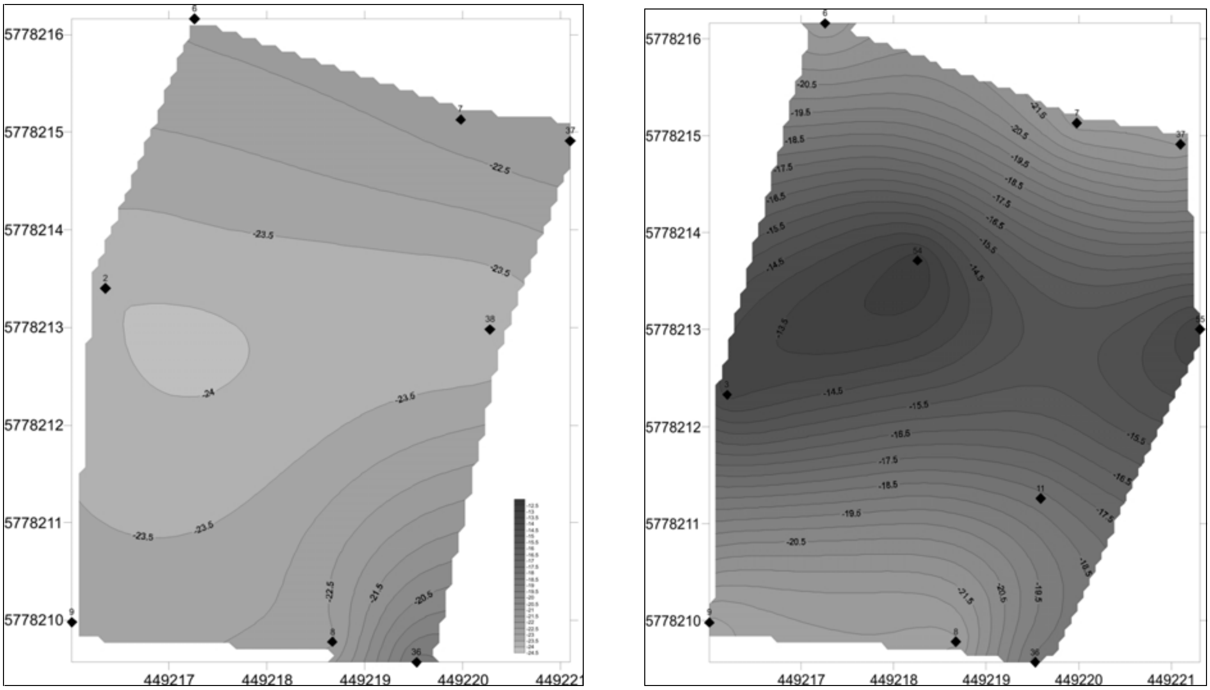
The relevant load case for the contact zone is identical to that of the sealing body. Evidently, the same requirement of $k \leq 10^{-18}$ m^2 is the safety proof criterion for the contact zone. It has to be verified on comparable structures.

In-situ measurements at the Asse seal show the following: The contact zone to the walls and the floor showed a permeability to gas in the range between $6 \cdot 10^{-23}$ m^2 and $1.0 \cdot 10^{-24}$ m^2 and a permeability to brine in the range between $8.0 \cdot 10^{-21}$ m^2 and $1.4 \cdot 10^{-21}$ m^2. These results indicate a good adhesion of the salt-concrete body to the rock salt contour. In the contact zone to the roof a permeability to gas in the range between $2.1 \cdot 10^{-13}$ m^2 and $6.5 \cdot 10^{-19}$ m^2 was measured.

Figure 4 gives an overview of the permeability distribution based on interpolated results of the in-situ permeability measurements [21]. In general, in-situ measurements show that the contact zone is not weaker than the EDZ or the salt concrete sealing body, except for the roof. In the roof, the permeability requirements are not met. The interpolated results correlate well with the results of ultrasonic reflection measurements [20].

The high permeability in this area is caused by the insufficient quality of the salt concrete which was used to fill the 10 cm gap at the roof (Figure 5). This conclusion is drawn from permeability measurements that were performed in the former EDZ with a minimum distance of about 1.5 cm to the contact zone by fixing a packer in the former gap area with its inner border aligned with the contact zone. These measurements proved that the high permeability was not caused by the contact zone itself but by defects and large pores of the salt concrete in the gap, see Figure 5. Subsequent tightening of the roof by injection was evidently not successful.

Figure 4. **Interpolated permeability of the contact zone: floor and walls (left), roof and walls (right), exponents of permeability [-]**



Supplementary permeability measurements were performed using core samples from the contact zone of the Asse seal consisting of half a shell of rock salt and half a shell of salt concrete, the contact zone situated in the centre. The results of the in-situ measurements would be verified if the RQD index of the core samples was higher than 85% and the fracture intensity lower than 7.5%. 2 core samples from the floor with RQD indices below 85% and fracture intensities above 7.5% respectively showed a permeability to brine of $2{\cdot}10^{-17}$ m^2 at a confining pressure of 2.7 MPa [22]. But the increase of the confining pressure (1st level of 5 MPa to the uppermost level of 14 MPa) leads to a lower permeability (10^{-18} to 10^{-19} m^2). These results were confirmed by uniaxial tensile tests. Very few test specimens (2 of 28 specimens) showed damages [23], the defects being located inside the former drift contour and oriented parallel to it (Figure 6), thus showing a uniaxial tensile strength of 0.41 and 0.71 MPa. The values of "intact" specimens showed 0.88 and 1.55 MPa, these values being typical for intact rock salt. When repeating the in-situ hydraulic fracturing tests [20], the tensile fracture failure strength showed a range of 4.4 to 9.6 MPa at the walls, values typical of intact rock salt. In contrary to this, the floor showed values between 0.9 and 2.5 MPa indicating damaged rock salt [24]. Thus, in the floor region sealing occurred within 10 years but it could be possible that healing did not take place despite high shut-in pressures and low permeability measured at these locations. The results of the ALOHA2 project were confirmed in an impressive way.

Figure 5. **Construction phase of the salt concrete Asse seal showing casting segments, the partly filled gap, and injection pipes**

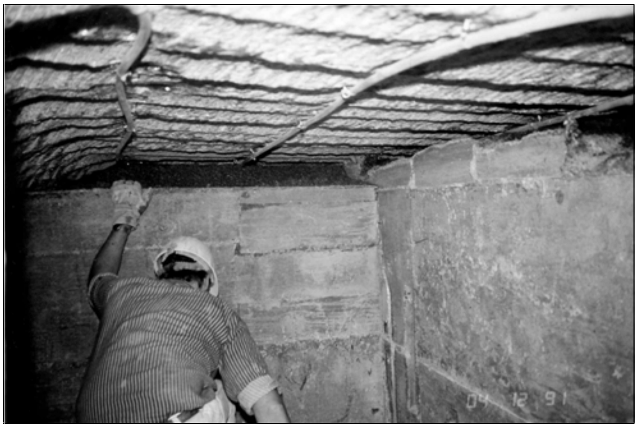


Figure 6. **Test specimens showing defects located in the former drift contour**

When analysing all results we have to conclude that the contact zone is not weaker than the EDZ with respect to its mechanical properties. Neither is it weaker as regards permeability provided that quality is assured during the construction process.

Application of Asse seal results to ERAM conditions

In order to transfer the site specific conditions from the Asse seal to the site specific conditions of the ERAM seal positions, the state of the Asse seal position and its history is modelled numerically taking into account the measuring results. By modelling comparable seals at the ERAM seals' positions the point of time is estimated when comparable tightness can be expected at these positions in the ERAM.

Preliminary notes on the Asse seal site

The Asse seal was built within the framework of an abandoned research dam project [25]. Due to the intended research activities the Asse seal is situated in a test field which has been explored intensely, and knowledge of its state is above average due to geotechnical instrumentation recording geotechnical data for more than ten years. However, it has to be taken into account that the original

Asse research dam was of larger size and thus the geotechnical instrumentation was designed for this project and not for the Asse seal investigations actually performed [20].

For the test field, additional measuring results are available from a pilot study testing the concreting procedure. Before concreting, the drift contour was instrumented with cauls, and their data was recorded from 1991-2001. This pilot study is of special interest because it is located in the same test field close to the Asse seal. It is also used for comparing calculation results because its structure is similar to that of the Asse seal.

First step: Validation of the calculation model

Before transferring the Asse results to ERAM by numerical modelling, the calculation model had to be validated by reproducing the measuring results. First, the initial stress state of the test field was identified by means of deformation measurements. Selected stress measurements far from the excavations were used for assessing the order of magnitude of the initial stresses. A first result showed that the initial stress state in the test field exhibits a moderate anisotropy. This is of importance because the design criterion is the stress in the relevant EDZ, and capturing the stress state correctly is essential to prove safety. As a result of parameter studies, a reduced number of initial stress states best approximating the measuring results were investigated further as the optimal initial stress state was not unique. However, it could be concluded that the highest principal stress component is mainly oriented in vertical direction with a value of about 19.6-20 MPa. The mean principal stress component is mainly oriented from East to West showing a range between 17.5 and 20 MPa, and the lowest principal stress component runs North to South and is about 17-18 MPa.

Except for the initial stress state no calibration of the calculation results to the measured data was performed. Thus, the calculation results may be considered to be a blind prediction. The calculation results demonstrate that the conditions for sealing the contact zone and the EDZ of the Asse seal were obtained two years after building the seal with the exception of an area influenced by a wide borehole in the roof. These results correlate with the low permeability measured. With respect to stress the calculated pressures were consistently higher than the measurements, whereas the calculation and measuring results of the pilot study correlated better than the results of the Asse seal. This holds for the pressure magnitude as well as for its variation over time. At the Asse seal itself only the highest values measured are of the same magnitude as the calculated values. With regard to stress the following must be stated:

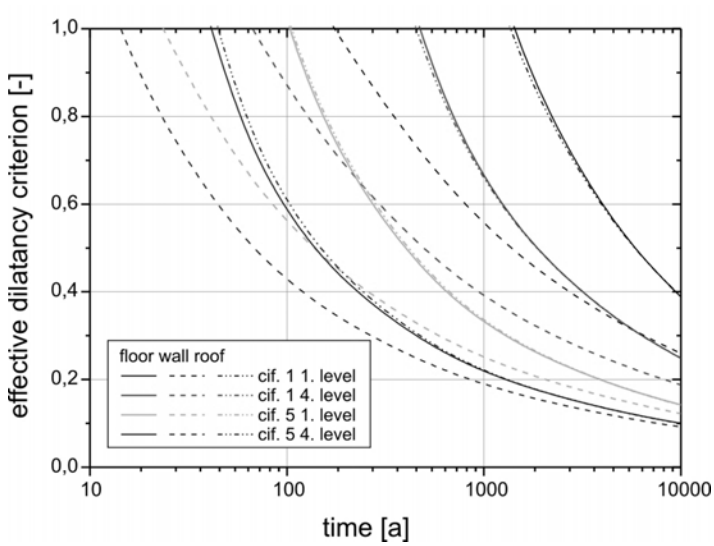
- In all cases the measured pressure values are lower than the calculated ones.
- The range of the measured values is significantly higher than the range of the calculated values.
- The measured values of the Asse seal and the pilot study show different results although both experiments were conducted close to each other in the same test field.

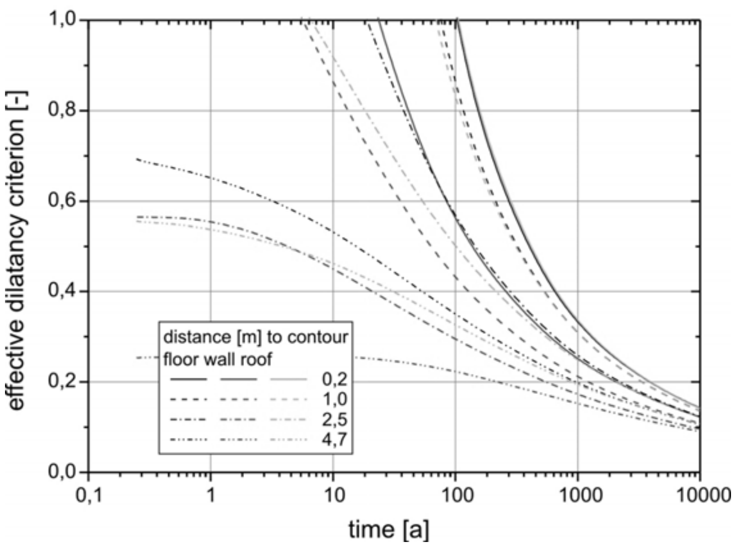
When assessing the results we have to conclude that the calculations overestimate the stresses. The measured values themselves differ from location to location. As both design criteria – fluid criterion and effective dilatancy criterion – rely on stresses these results must be analysed and evaluated carefully with respect to safety. The uncertainty does not exist exclusively within the calculation model and its validation and/or calibration as the pilot study measurements agree to a high degree with the calculation results. Evidently, every drift seal should be roughly evaluated individually, taking into account the local geotechnical conditions, although the general interrelationships are well known as is shown by the blind prediction.

Results of application to ERAM conditions

Based on the global interrelationships the results of the Asse seal were applied to ERAM conditions. As the geotechnical knowledge of the locations where the ERAM seals are to be built is still poor the application is performed relying on depth, geothermal temperature, and creep intensity of the adjacent rock salt. The depth of the first level is about 387 m and the respective rock temperature is 20.6°C, the depth of the fourth level is about 506 m and the rock temperature is 22°C. The creep intensity varies between values of 1 and 5. The results of 2D-calculations are given in Figure 7. As 2D-calculations show creep rates higher than or equivalent to the creep rates of 3-D-calculations the results constitute lower bounds demonstrating the minimum time needed until conditions comparable to the Asse seal prevail at the ERAM seal positions. The time span varies between about 50 years at the fourth level and creep intensity 5 and 1 500 years at the first level and creep intensity 1.

Figure 7. **Evolution of the effective dilatancy criterion at the ERAM drift seals´ positions depending on depth and creep intensity (left) and on distance from drift contour using first level location and creep intensity 5 as an example**





Proof of producibility and prototype testing

For the ERAM seals the proof of producibility is still pending. Producibility will be proved in the framework of a pilot study taking into account the lessons learned from the Asse seal regarding the properties of the contact zone at the roof and the floor. This pilot study will be initiated by BfS in the near future.

Decisions on prototype testing are still pending as the preferred way to prove structural reliability has not finally been determined yet, see Chapter 4. As an appropriate investigation programme focuses on safety-relevant properties it does not make sense to decide on prototype testing before the options on proving structural reliability have been discussed conclusively.

Summary

This paper focuses on the proof of structural reliability of the drift seals of the "Repository for Radioactive Waste Morsleben, ERAM". When regarding conventional barrier tightness, mechanical resisitivity, durability, and producibility must be shown to guarantee state-of-the-art tightness. Thus, the proof of structural reliability is a necessary condition for licensing a geotechnical barrier in general. The methodology applied to the ERAM seals is simple. Taking into account the additional requirements from long-term design working life and following technical standards and guidelines it was checked step by step whether all design criteria and/or requirements arising from the regulatory environment are met. This procedure is at an advanced state, the basic approach is clear. Several new questions, however, came up during this process and some are still being investigated, how to handle autogenous shrinking and how to avoid cooling of the salt concrete.

Relevant progress was made by investigating the Asse seal, which is similar to the ERAM seals. So far, the proof of sufficient flow resistance in the contact zone to the roof has failed, the quality of the construction process needs to be improved, but there are no doubts that man is capable of achieving this objective. As far as the proof of structural reliability as a whole is concerned the EDZ has the highest uncertainty factor at present.

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PERFORMANCE ASSESSMENTS FOR DESIGN REVIEWS

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Abstract

This paper discusses the evolution of the design of the potential repository at Yucca Mountain, Nevada, USA, in light of the various postclosure performance assessments conducted to prepare for regulatory reviews of a potential license application. The regulations require that any proposed repository design must meet both long-term performance and operational safety requirements. This paper surveys the evolution of the design of the potential Yucca Mountain repository, especially the engineered barrier system, and discusses the related performance assessments conducted by DOE in support of repository development and NRC in support of developing its capability to review a license application. The survey indicates that DOE design changes correlate well with release or dose-based performance criteria during the earlier part of design evolution. During the latter part, DOE design changes focused more on waste isolation and uncertainty reduction (strengthening the technical bases). NRC regulations recognise that the design may continue to evolve and performance confirmation information will continue to be collected until repository closure.

Introduction

The U.S. Department of Energy (DOE) has studied Yucca Mountain for more than two decades as a potential site for the disposal of high-level radioactive waste. The studies have included site characterization, engineered barrier system design, and performance assessment of the repository system and associated subsystems. Using the outcome of these studies, DOE is expected to submit a license application to construct a repository at the Yucca Mountain site. The U.S. Nuclear Regulatory Commission (NRC) will review any such application. Consistent with the Nuclear Waste Policy Act, NRC has been interacting with DOE during the pre-licensing period to resolve outstanding issues so that DOE will be able to submit a high-quality license application, reducing the need for requests for additional information during the licensing review.

Since the initiation of the study of Yucca Mountain as a potential high-level waste disposal site, DOE has revised the proposed repository design several times. The repository design encompasses geotechnical modifications to the natural system (excavation of tunnels and shafts), emplacement strategies (layout of and spacing between drifts to not exceed a specified temperature), and engineered structures such as the drip shield, invert, and waste package.

DOE has conducted performance assessments to support repository design development by (i) estimating the long-term performance of a given design; (ii) comparing the results with the regulatory performance criteria; (iii) estimating performance contributions of design features; (iv) identifying specific proposed design constraints and possible alternative designs; and (v) identifying risk significant design parameters, model development and data needs, and testing needs. Independent assessments by NRC support (i) development of regulations for high-level radioactive waste disposal and (ii) pre-licensing interactions with DOE to better understand the DOE approach (e.g., development of risk insights to focus interactions and reviews).

The objectives of this paper are to (i) provide a regulatory context for repository design and performance assessment in the United States, (ii) summarise the evolution of the design of the potential Yucca Mountain repository, and (iii) discuss performance assessments and design evolution. This paper emphasises the engineered barrier system, especially the waste package. Moreover, it focuses on NRC independent performance assessments and the evolution of the DOE design of the engineered system.

Importantly, the potential licensee (DOE for Yucca Mountain) is responsible for proposing these designs for the repository and conducting performance analyses to assess the design and demonstrate regulatory compliance. The role of NRC is to independently evaluate the adequacy of the design and compliance demonstration in the context of its regulations.

Regulatory context for repository design and performance assessment

In 2002, NRC promulgated site-specific regulations in 10 CFR Part 63 for a repository at Yucca Mountain. These regulations reflect NRC emphasis on a risk-informed, performance-based approach to regulation. In this approach, the regulatory decision-making process uses risk insights together with other factors such as physical security to establish requirements that better focus licensee and regulatory attention on design and operational issues commensurate with their importance to public health and safety (NRC, 1999).

The regulations require DOE to propose a repository design and conduct a post-closure performance assessment as part of the compliance demonstration of repository safety. Requirements focus on overall system performance. As stated in the regulations, DOE must demonstrate, using performance assessment, that there is a reasonable expectation that, for 10 000 years following disposal, the reasonably maximally exposed individual receives no more than an annual dose of 15 mrem [0.15 mSv] from release of radionuclides from the Yucca Mountain disposal system.[1]

The regulations also require defense-in-depth through at least two barriers to isolate high-level waste – a natural and an engineered barrier. The engineered barrier system must be designed so that it will work with the natural barriers to meet the regulatory limits. Demonstration of compliance requires identifying design features of the engineered barrier system (in addition to natural barrier features) important to waste isolation, taking into account uncertainties in characterising and modelling the behaviour of the barriers. NRC recognises that there are uncertainties in the isolation capability and performance of engineered barriers. Although the composition and configuration of engineered barrier structures can be characterized more precisely than the natural barriers, NRC recognises that the

1. The State of Nevada and other petitioners challenged both the U.S. Environmental Protection Agency (EPA) standards and the NRC regulations in court. On July 9, 2004, the United States Court of Appeals upheld both EPA standards and NRC regulations on all but one of the issues raised by the petitioners. The court disagreed with the EPA decision to adopt a 10 000-year period for compliance with the individual protection standard and the NRC adoption of that 10 000-year compliance period in the regulations. Thus, the court vacated the EPA rule at 40 CFR Part 197 to the extent that it specified a 10 000-year compliance period and remanded the matter to EPA. In response to the remand, EPA proposed a revised standard, which would provide for a separate dose limit {350 mrem/yr [3.5 mSv/yr]} to be applied beyond 10 000 years up to 1 million years. In response to this change, NRC proposed revisions to 10 CFR Part 63. The proposed rule would implement the EPA proposed standards (EPA, 2005) for doses that could occur after 10 000 years up to 1 million years.

experience with complex, engineered structures is limited to only a few hundreds of years. The uncertainties are expected to be accounted for in barrier performance by using ranges of parameter values and/or alternative models in performance assessments.

The regulations also require further evaluations of the design through the performance confirmation program. Should NRC make an affirmative licensing decision, performance confirmation will evaluate the adequacy of assumptions, data, and analyses that led to findings that permitted construction of the repository and subsequent emplacement of high-level waste. Performance confirmation requirements include monitoring key design parameters. NRC regulations recognise that the design may continue to evolve and performance confirmation information will continue to be collected until repository closure.

The evolution of the potential Yucca Mountain repository design

In the late 1980s design, possible emplacement configurations included vertical and horizontal boreholes, short and long boreholes, and filler materials such as chemical buffers or a shielding material. Waste packages (more than 50 000) were thin-walled containers made of metals, ceramics, or composites with a 300-year design life. DOE identified a number of shortcomings, including structural instabilities associated with larger boreholes and the confined space required for maintaining optimum temperature that posed handling difficulties (MacKinnon, 2003; Benton and Connell, 2004).

The 1992 conceptual design focused on easier waste package handling, more stable rock framework by changing to the waste package emplacement configuration from vertical to horizontal, better decay-heat dissipation, longer waste package life (~1 000 years), better access for performance confirmation, and more straightforward performance assessment (Benton and Connell, 2004). The design changes resulted in a larger waste package (21 PWR and 44 BWR) but fewer waste packages (~10 000) being considered for emplacement in horizontal drifts.

The Viability Assessment design of 1998 (DOE, 1998) emphasized prolonged radionuclide containment. The waste package included a 2-cm [~ 0.8-in]-thick inner shell of Ni-based Alloy 22 for corrosion resistance. The design for the inner overpack of the waste package was revised several times: from Alloy 625 to Alloy 825 to Alloy 22. The outer overpack of the waste package was 10.2-cm [4-in]-thick carbon steel (Alloy 516) for structural strength and corrosion allowance. Drip shields were included to protect against dripping water or rock falling on the waste package. Titanium grade 7 plates were proposed for water-diverting surfaces and grade 24 for structural members. DOE justified the use of titanium by stating that a class of alloys different from that of the waste package would protect against systemic failure (MacKinnon, 2003; Benton and Connell, 2004).

The DOE targeted the Site Recommendation design of 2001 (CRWMS M&O, 1999 and 2000; DOE, 2001) to increase corrosion resistance of the waste package, limit groundwater contacting high-level waste, and increase structural strength against rockfall and seismicity. An important design change was to use the corrosion resistant material (Alloy 22) for the outer shell and use nuclear grade 316 stainless steel as the inner shell for structural strength. An extra Alloy 22 lid was incorporated in the design to provide an additional barrier against closure weld corrosion. This design, reversing the location of the Alloy 22, had the benefit of a more corrosion resistant waste package with the structural material mechanically supporting the thinning corrosion-resistant material. The site recommendation design also considered alternative thermal options for repository flexibility: High-Temperature Operating Mode (HTOM) allowing waste package temperature above the boiling point of groundwater and Low-Temperature Operating Mode (LTOM) limiting waste package temperature below the boiling point of groundwater. The same drip shield design as in the viability assessment was to be emplaced just before the repository is closed.

Performance assessments for various repository designs

Independent performance assessments were conducted by the NRC with assistance from the Center for Nuclear Waste Regulatory Analyses using each of the DOE designs chronologically up to the site recommendation design described in the previous section. These analyses were done to support pre-licensing interactions between NRC and DOE. Results are consistent with the performance measures in the regulations applicable at the time each design was proposed.

The first two performance assessments conducted by the NRC, referred to here as Iterative Performance Assessment (IPA) Phase 1 (NRC, 1992) and Phase 2 (NRC, 1995), used designs of the late 1980s and 1992, respectively. The performance assessment results from Phase 1 and Phase 2 were expressed as a complementary cumulative distribution function (CCDF) of normalized radionuclide releases, consistent with the release-limit based regulations in 10 CFR Part 60, defined for a generic high-level waste repository. IPA Phase 2 results were significantly different from IPA Phase 1 in scope and approach. Major improvements in IPA Phase 2 over Phase 1 indicate the amount and relative significance of factors that may be influencing the difference. The difference between the CCDF of releases in IPA Phase 1 and Phase 2 analyses primarily resulted from the new consequences and probabilities of processes in the natural system (pluvial-climate scenario and the addition of the gas pathway for carbon-14 migration in Phase 2). These early performance assessments were conducted by the NRC primarily to demonstrate staff capability to conduct performance assessment analyses.

NRC independent analyses showed a substantial drop in the fraction of the waste package undergoing localised corrosion by transitioning from Alloy 625 to 825, and the transition from Alloy 825 to Alloy 22 showed no localised corrosion failure during the first 10 000 years after repository closure (Dunn, *et al.* 1999). Performance assessment results for the viability assessment (and later designs) were presented in the form of expected dose, consistent with the NRC regulations in 10 CFR Part 63. Potential concerns with the viability assessment design were identified as fast carbon steel corrosion degrading waste package structural strength, potential stress build-up as a result of the corrosion product accumulating between the shells, and difficulties in achieving long-term cathodic protection by carbon steel.

Independent calculations by NRC using the DOE design for site recommendation showed no corrosion failure during the first 10 000 years after repository closure, under various repository thermal loading strategies. However, the technical bases for supporting the long-term integrity of the waste package and other components of the engineered barrier system are complicated. Examples include the stability of long-term passive film, localised corrosion, microbially influenced corrosion, structural strength, and thermal effects on waste form cladding. Performance assessments continue to play a significant role in evaluating the relevant importance of such factors and their consideration in design.

After Site Recommendation, concerns were raised that the drift may not be stable over long periods, and the drip shield may not be capable of withstanding the load from accumulating rock rubble. DOE then discussed a modified design, increasing the clearance between the drip shield and waste package to minimise waste package-drip shield interaction and reinforcing the bulkhead by adding a flange. Analyses are continuing in this area.

Discussions

Consistent with the design optimisation theme of this workshop, an attempt was made to discuss DOE's design evolution and performance assessments. The latter part of the design evolution showed improved waste isolation capability (through, for example, increasing the life of the engineered system) and decreased uncertainty in overall repository performance. In particular, the Viability Assessment design changes to the waste package outer overpack material (from Alloy 625 to Alloy 825 to Alloy 22) increased the estimated life of the waste package. Switching the inner and outer overpacks of the waste package in the Site Recommendation design resulted in better performance estimates for the waste package. The post Site Recommendation change to the drip shield design (increasing the clearance between the waste package and the drip shield crown, and reinforcement of the bulkhead) was intended to prevent waste package failure from the drip shield-waste package interaction.

Although design optimisation is not a regulatory requirement, the repository developer may optimise design for reasons such as controlling cost, building stakeholder confidence, and providing operational efficiency. If the performance assessment results are used in design optimisation, it appears that both the overall system performance measure (peak expected dose) and the waste isolation capabilities of the engineered and natural systems could be used to maximize the benefits from various iterations of performance assessments as optimization goals.

NRC review does not focus on design optimisation but on regulatory compliance. The NRC design review is geared toward identifying engineered components that (i) are significant to repository performance, (ii) could be detrimental to performance of other components, and (iii) are significant to preclosure operational safety.

Conclusions

From a regulatory standpoint, any proposed design must meet both long-term performance and operational safety requirements. The survey identified and discussed early design changes and performance assessment results. The design evolution during the latter part of the repository program appears to have increased the waste isolation capability of engineered barrier systems and reduced overall uncertainty. Performance and assessment can be an effective review tool to both evaluate the current design and optimise the design as long as both overall system performance criteria and the waste capabilities of the barriers and uncertainties are considered together. NRC regulations recognise that the design may continue to evolve and performance confirmation information will continue to be collected until repository closure.

Acknowledgments

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DESIGN CONFIRMATION AND DEMONSTRATION FOR EBS: CURRENT DEVELOPMENTS IN SEVERAL EUROPEAN NATIONAL PROGRAMMES AS PART OF THE FP6 EURATOM ESDRED PROJECT

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Abstract

In the context of the technological project ESDRED: "Engineering Studies and Demonstration of Repository Designs", the national waste management agencies ANDRA, ONDRAF/NIRAS and NAGRA are currently in the process of demonstration testing the construction of the buffer/backfill component inside the disposal drifts for high level waste (HLW). ESDRED is co-funded by the European Commission (EC) as part of the sixth Euratom research and training Framework Programme (FP6) on nuclear energy (2002-2006).

The work aims to demonstrate the technical feasibility at an industrial scale of the construction of the buffer around the disposal package and/or the associated activity of backfilling the remaining voids within the disposal drift. The tests described in this paper are performed in a workshop on the surface, which will enable a better control over the test conditions and facilitate the evaluation of the test results.

The following configurations are being tested:

- a prefabricated buffer in a horizontal disposal cell (representative of the ANDRA design);
- granular and grout backfills in a horizontal disposal drift (representative of the ONDRAF/NIRAS design);
- a combination of a prefabricated and a granular buffer in a horizontal disposal drift (representative of the NAGRA design).

After the preceding stages of defining the functional requirements of the buffer/backfill component, computer simulation, laboratory testing and designing the buffer prototypes or disposal drift mockups, the work is currently focused on the execution phase of the demonstration testing.

The work, although conducted by the agencies in parallel, is characterised by frequent mutual status reporting and exchange of "lessons-learned" within the context of ESDRED. The work on the in-workshop demonstrators is scheduled to be finalized by the end of 2006.

ESDRED as the context of the performed demonstration tests

The technological project ESDRED: "Engineering Studies and Demonstration of Repository Designs" is co-funded by the European Commission (EC) as part of the sixth Euratom research and training Framework Programme (FP6) on nuclear energy (2002-2006). The project aims to demonstrate the technical feasibility at an industrial scale of a number of specific technologies related to the construction, operation and closure of a deep geological repository for spent fuel and long-lived radioactive waste. ESDRED comprises four technical modules each addressing one or more specific technologies which will be tested. Module 1 aims to demonstrate the technical feasibility at an industrial scale of the construction of the buffer around the disposal package and/or the associated activity of backfilling the remaining voids.

In its turn, Module 1 is subdivided in a number of work packages. The work described in this paper basically relates to Work Package 3, which is the in-workshop demonstration of the construction of the buffer/backfill component. Work Package 3 has been prepared in the preceding Work Packages 1 (definition of functional requirements) and 2 (computer simulations, lab testing).

The tests in Work Package 3 are performed in a workshop on the surface, which will enable a better control over the test conditions and facilitate the evaluation of the test results.

The following configurations are being tested by the concerned agencies:

- a prefabricated buffer in a horizontal disposal cell (representative of the ANDRA design);
- granular and grout backfills in a horizontal disposal drift (representative of the ONDRAF/NIRAS design);
- a combination of a prefabricated and a granular buffer in a horizontal disposal drift (representative of the NAGRA design).

The work, although conducted by the agencies in parallel, is characterized by frequent mutual status reporting and exchange of "lessons-learned" within the context of ESDRED. The work on the in-workshop demonstrators is scheduled to be finalized by the end of 2006.

Note that Module 1 also contains a work package on *in situ* testing of sealing material and a work package on *in situ* experimental development of non-intrusive monitoring technology. The ESDRED project is scheduled to be finalised by the end of 2008.

Buffer with prefabricated rings (by ANDRA)

Brief presentation of the reference disposal design

The reference host rock is the Callovo-Oxfordian argillite formation, located at the eastern rim of the Paris Basin. The Callovo-Oxfordian argillites are made of clay minerals amounting to up to 60% by mass, the remaining minerals being fine-grained quartz and carbonates. The formation lies at a depth of approximately 500 m. Its thickness exceeds 100 m. Owing to its textural properties, hydraulic conductivity of the Callovo-Oxfordian is low through its entire depth (from 5×10^{-14} m/s to 5×10^{-13} m/s). The strength is relatively high for an argillaceous rock. Deformability is limited.

The repository concept consists of disposal cells (underground rooms), excavated in the argillite formation, containing waste disposal packages. The waste packages consist of primary waste packages supplemented by an overpack. The architecture studied contains disposal cells for various categories of waste within specific repository zones. The repository zones for B waste (ILLW-LL), C waste (HLW) and, if applicable, spent fuel are therefore physically separated from each other. For C waste and spent fuel, the overpack aims at encapsulating the primary package during the thermal phase.

Prefabricated buffer rings can be placed around two types of packages: C waste and spent fuel. ANDRA have studied various concepts, with or without buffer rings. The description that follows focuses on concepts with buffer rings. Type C packages and spent fuel packages are emplaced in horizontal drifts, approximately 40 m long (see Figure 2-1) according to the current design. Considering the rather short length of these drifts, they will be referred to as "disposal cells" in what follows. Horizontal cells are of the same type for both C and spent fuel packages. Cell diameters vary with package diameters, but remain around 2.5 – 3 m.

Each disposal cell is composed of (from the exterior to the interior, see Figure 2-2):

- a steel liner, approximately 30 mm thick, perforated with holes in order to allow swelling clay resaturation with water coming from the host rock,
- an annular layer of swelling clay mixed with sand, 800 mm thick (in radius),
- an inner steel sleeve, made of carbon steel, 25 to 40 mm thick, which holds 3 to 22 disposal packages.

Figure 2-1. Disposal cell for spent fuel (after closure)

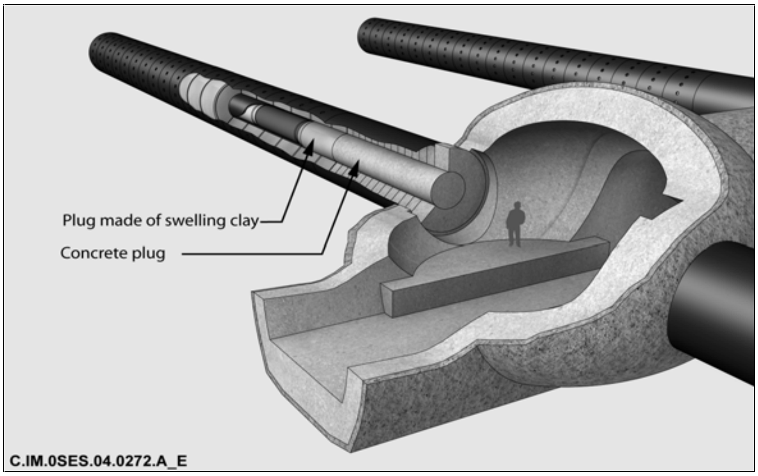
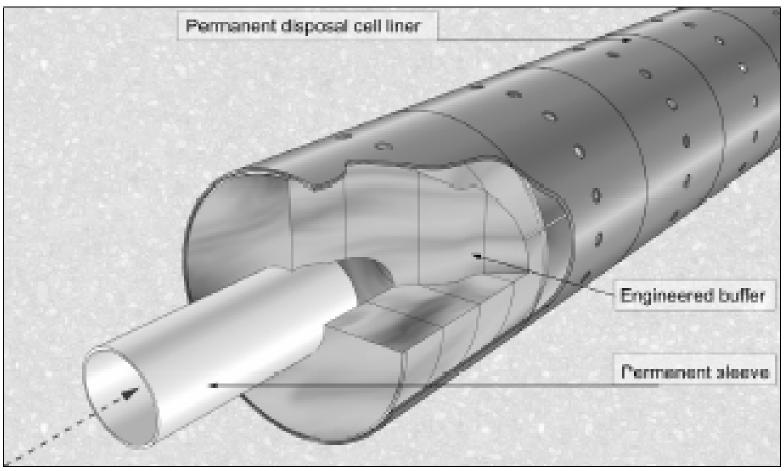


Figure 2-2. **General view of the cell concept with prefabricated buffer rings**



List of requirements for the prefabricated buffer rings

The swelling clay buffer goes through different phases during its life in the disposal cell.

During the initial phase (approximately 50 years), the unsaturated buffer does not play any role as a hydraulic barrier (the overpack of the package fulfils this function). During this phase, the clay buffer must ensure the transfer of heat coming from the disposal packages, which is still quite high: the thermal conductivity of the clay buffer must therefore be at its highest and the annular voids as small as possible. This requirement is dealt with by adding sand to the clay.

During the second phase (approximately from 50 to 1 000 years), the clay buffer still does not act as a confining barrier (the overpack still ensures this function). However, as it saturates, the clay buffer progressively plays a role as a hydraulic barrier by limiting the renewal of water around the overpack (which slows down the overpack corrosion). Besides, it is starting to play an ever increasing role providing mechanical support, as the perforated steel liner is corroding and losing its structural integrity. This mechanical function is not as much required to protect the primary packages (the overpack still provides that) as it is to limit damage to the surrounding rock. The clay buffer is acting as a thermal conductor between the disposal packages and the geological formation, but its importance with this respect decreases in proportion to the decrease in thermal power of the disposal packages.

During the third phase (approximately from 1 000 years onward), the main function of the clay buffer is to act as a confining barrier insuring diffusion to be the dominant transport mechanism for radionuclides; since the overpack will have lost its structural integrity and the primary package (glass or spent fuel) is now fully exposed. Saturation will allow the clay buffer to fill any voids that may be created in order to give the system a hydraulic conductivity of less than 1 x 10-11 m/s. The mechanical role of the engineered buffer comes from the swelling pressure that results from its saturation. The clay buffer continues to play a small and continuously decreasing thermal role.

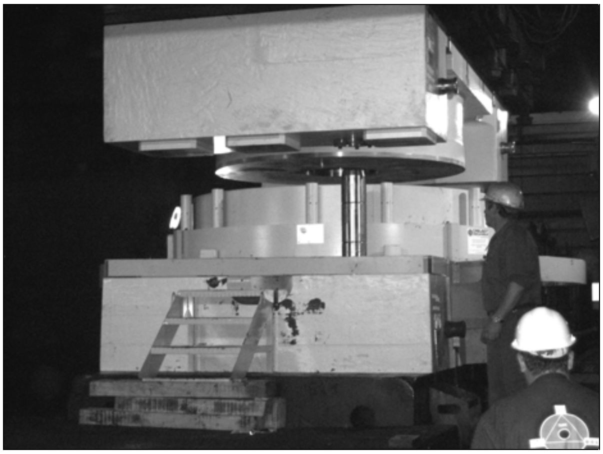
The main functions and the corresponding requirements are presented in the Table 2-1.

Description of testing within ESDRED (mould construction and buffer rings compaction)

Laboratory tests have been performed in order to define buffer ring composition and compaction requirements. Sand content was set at 30% (in mass). Compaction pressure was set at 80 MPa.

A mould has been designed and built in order to sustain such high compaction pressures (see Figure 2-3). Mould design has been carried out by the GME, a consortium between MPC, CEA, and Segula. Mould pieces have been cast by Ferry Capitain, and then machined and assembled by Creusot Mécanique.

Figure 2-3. The mould before pressing the first ring



The first compaction test took place in Issoire (France), using Interforge's 65 000 tonnes press (see Figures 2-3, 2-4, 2-5), in June 2006. The press capacity exceeds the 30 000 tonnes required for pressing a ring with an external diameter of 2.3 m, at 80 MPa. Additional rings and solid end pieces will be compacted in July 2006.

Figure 2-4. Interior of the mould before (left) and after (right) pouring the clay/sand powder

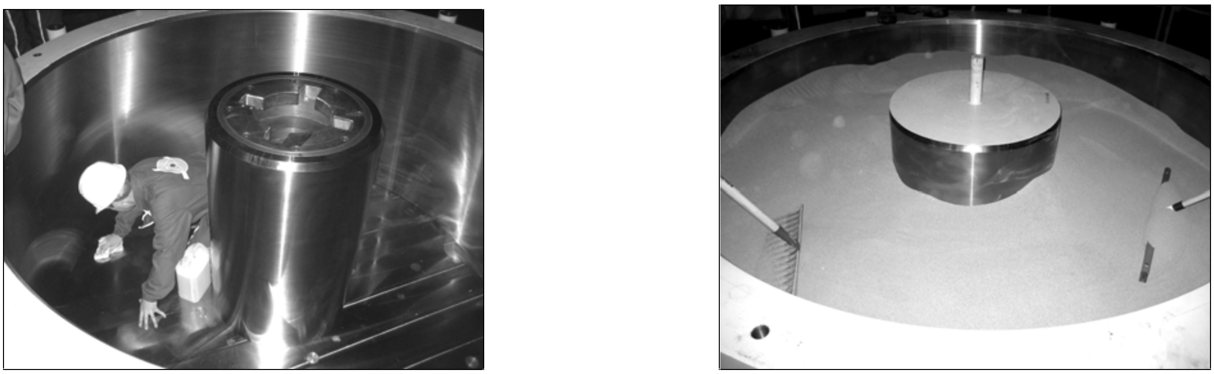
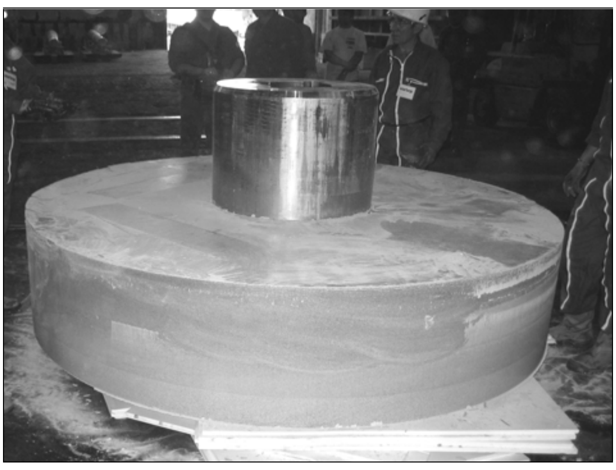


Figure 2-5. The first clay buffer ring during stripping



Verification of the buffer requirements with the performed tests

The first objective of the test has been achieved: the equipment was used with success to fabricate a first buffer ring in real scale.

When other rings are available, additional tests will be carried out to check the strength, the homogeneity, and the dimensions of the rings. Dimensional measurements will be performed after post-swelling has taken place. Indeed, the mould dimensions take into account the post-swelling of buffer rings so that the final dimensions of the rings meet the requirements. Post-swelling is a mechanical expansion of the clay observed after stripping. Post-swelling is measured in the laboratory on small samples a few minutes after stripping. This immediate post-swelling accounts for about 80% of the total post-swelling. It is then possible to compute the mould dimensions.

The final test will consist of assembling the rings in a mockup of a disposal cell (Figure 2-6). This emplacement test procedure is as follows: rings are assembled in sets of four units and installed on an air cushion pallet. After the air cushions are inflated, a cart that rolls along guide rails takes them to the required position in the disposal cell. The air cushions are then deflated. The rings then sit on the rails, liberating the transport cradle which is returned to the head of the disposal cell by the cart to pick up the next series of rings. This emplacement test will be performed by Mécachimie, the design and fabrication contractor during the second semester of 2006.

Figure 2-6. **Foreseen emplacement test using air cushion technique**

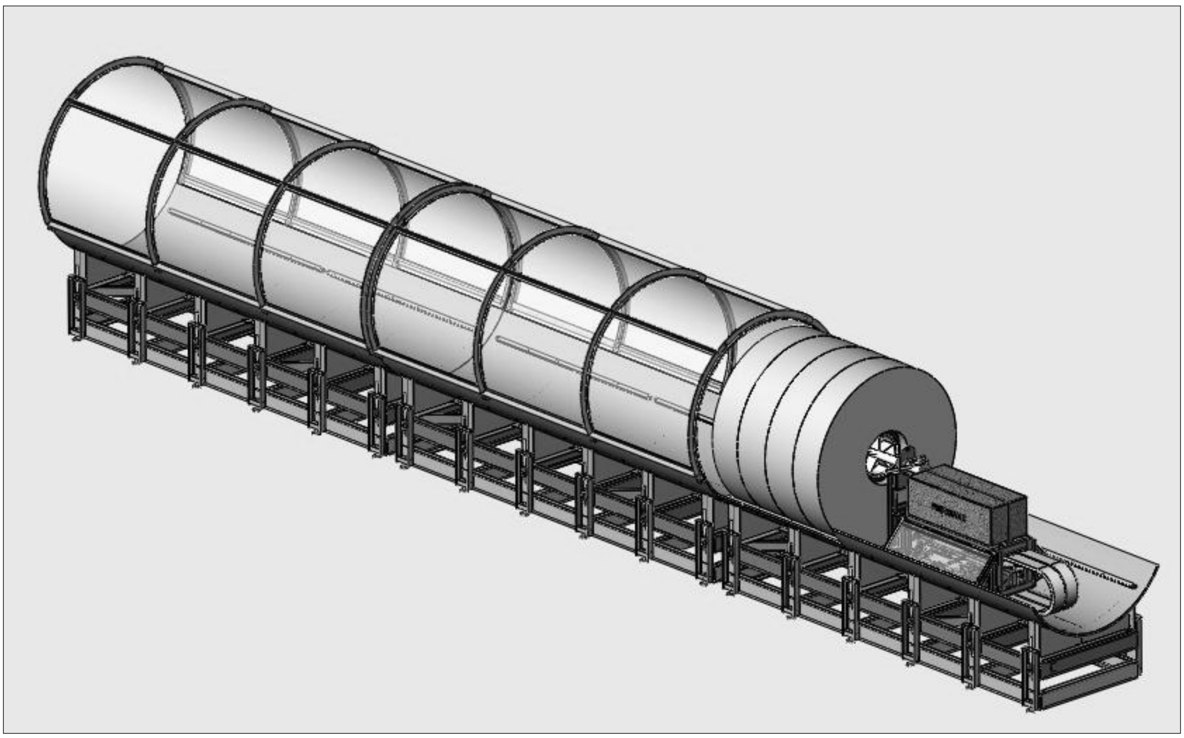


Table 2-1: Requirements for the buffer component in ANDRA's HLW disposal concept

Objective				Associated Parameters and Criteria		
#	**Type**	**Description**	**Time Frame**	**Parameter**	**Criterion**	**Basis for Criterion**
1	function	To isolate the canister from the rock and to support and protect it against **rock displacements**.	**before** canister loss of integrity, i.e. < a few thousand years	Plasticity	As high as possible	(most swelling clays on the market are satisfactory)
2	function	To isolate the canister from **groundwater** flow and transport processes taking place in the surrounding rock; achieved by providing a low-permeability medium for water flow around the waste packages.	**before** canister loss of integrity, i.e. < a few thousand years	Hydraulic conductivity K	$K < 10^{-12}$ m/s	Radiological performance assessment basis
				Swelling pressure P	P > 1 MPa after sliding of the concrete plug P < 7 MPa at any time	To make sure the buffer remains in close contact with the rock (min. pressure) and in order not to damage the rock (max. value)
3	function	To create a geochemical environment that will protect against **corrosion**	**before** canister loss of integrity, i.e. < a few thousand years	Compatibility with steel (pH)	pH not too low	High pH tends to reduce corrosion of carbon steel
				Hydraulic conductivity	$K < 10^{-12}$ m/s	High flow rate accelerate corrosion
4	function	To create a geochemical environment that will promote the stability of the **matrix** glass and U/Pu oxides	**after** canister loss of integrity, i.e. > a few thousand years	Compatibility with glass		
				Hydraulic conductivity	$K < 10^{-12}$ m/s	High flow rate accelerate glass dissolution
				Swelling capacity	P > 1 MPa after sliding of the concrete plug P < 7 MPa at any time	Same as function 2
5	function	To **delay radionuclides** release by retarding the transport of radionuclides	**after** canister loss of integrity, i .e. > a few thousand years	Hydraulic conductivity	$K < 10^{-12}$ m/s	Radiological performance assessment basis
				Swelling pressure P	P > 1 MPa after sliding of the concrete plug P < 7 MPa at any time	Same as function 2
				Sorption		

6	constr aint	Buffer should allow **gas** to escape (as long as steel parts are present)	many thousands of years	Gas permeability	As high as possible	To minimize gas pressure and avoid fracturation of the rock
7	constr aint	Buffer should be a good **thermal conductor** (as compared to rock mass) i.e. should not act as an insulator	thermal phase	Thermal conductivity λ (which depends on dry density, nature of additives, water content)	$\lambda > 1.2$ W m^{-1} K^{-1} (before saturation and swelling- loss of conductivity due to gaps to be added)	In accordance with lay out optimisation based on thermal calculation (to satisfy the thermal criterion of 100°C inside the cell) – calculation before saturation
					$\lambda > 1.5$ W m^{-1} K^{-1} (after saturation and swelling- no more gaps)	To minimise the duration of the canister "thermal phase", which defines the overpack thickness

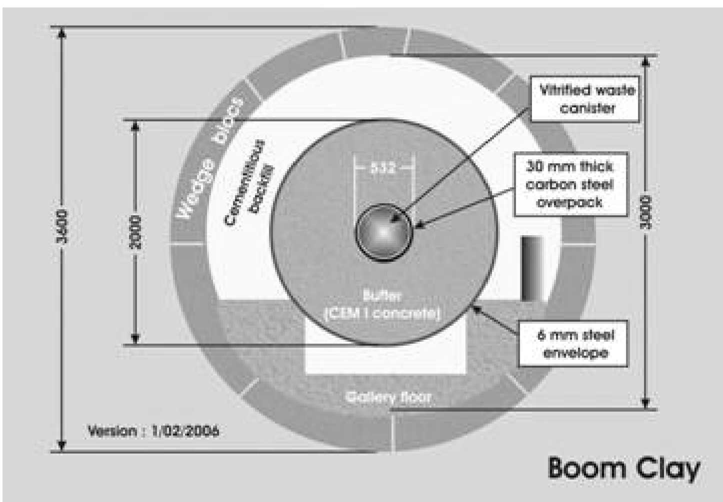
Annular gap configuration (by ONDRAF/NIRAS)

Brief presentation of the reference disposal design

The reference host rock is the Boom Clay formation. This layer of "poorly-indurated" plastic clay is located in the north-eastern part of Belgium. At the location of the research site of the SCK•CEN, the layer lies at a depth of about 240 m, is 100 m thick and has a slope of 1% in the north-northeast direction. Over the course of the last 30 years, the SCK•CEN has built up an extensive knowledge basis on the Boom Clay formation. Nevertheless, the characterisation of the clay under high temperature transient conditions, such as would be the case during first centuries after disposal of the HLW, will remain difficult. Therefore, in its disposal strategy, the Belgian waste management organisation ONDRAF/NIRAS (O/N) has chosen to maintain the HLW in watertight encapsulated conditions during this thermal phase.

In the Supercontainer design, this is realized by placing the HLW within a carbon steel overpack, which is surrounded by a high pH concrete buffer. The thickness of the concrete layer is designed to provide sufficient radiological protection to eliminate the need for a shielding cask during transportation and handling. A high pH concrete was chosen with the aim to create a corrosion-protective environment for the overpack, in analogy with the situation of reinforcement bars in concrete. Between the sometimes conflicting interests of the long-term safety functions, O/N decided to give preference to the integrity of the overpack during the thermal phase rather than to other considerations, such as the lixiviation of the waste matrix, or the perturbation of the host rock adjacent to the EBS. The latter considerations were judged to have only a limited effect from a performance assessment perspective. Next to radiation protection, the objective of the Supercontainer design is to ensure a watertight integrity of the overpack for a time period of 500 years for vitrified HLW and 2 000 years for spent fuel. A radial cross-section of the design, also indicating the reference materials, is given in Figure 3-1.

Figure 3-1. **Radial cross-section of disposal gallery for vitrified HWL (ONDRAF/NIRAS concept)**



Role of the backfill component and list of requirements

The remaining empty space in the HLW disposal gallery after emplacement of the disposal package (Supercontainer) needs to be filled up with an incompressible solid material in order to ensure the long-term mechanical stability of the disposal gallery. This is one of the main functions of the backfill component. The concern is that, without a backfill, in case the gallery lining loses its integrity after a time of several decades or centuries, the Supercontainer would somehow be damaged, leading to the disturbance of the configuration designed to provide watertight encapsulation of the waste for the duration of the thermal phase.

The other function of the backfill is that it should preserve and stabilize the corrosion-protective characteristics of the Supercontainer buffer, more specifically, that it should provide protection against the intrusion by corrosive species coming out of the Boom Clay and the activity of SRBs (sulfate-reducing bacteria) residing in the near field.

Hence, in brief, the backfill is there to protect the Supercontainer, both mechanically and chemically. The list of requirements for the backfill component, derived from these functions and a number of constraints, is given in Table 3-1. It should be emphasised that this list is based on a current state of affairs and that the definition of the requirements and the associated criteria is prone to change in the course of the ESDRED project, as more insights are gained.

Description of testing of a range of backfill materials within ESDRED

O/N will perform a number of backfill demonstration tests on the site of EURIDICE, which is one of the ESDRED partners. For this purpose, three mockups will be built.

A first mockup, 5 m long and 2/3rd scale diameter, will be used to test a grout material that has been specially formulated to comply with the backfill requirements given in Table 3-1. It is essentially composed of CEM I cement, fine-grained quartz sand and a very limited addition of the superplasticizer Glenium®. The mockup includes a heating element, to simulate the heat generated by the HLW, which plays an important role in the hardening of the grout backfill material. A photograph of this mockup, taken in March 2006 during the filling of the tubular steel element with sand to represent the thermal inertia of the Supercontainer, is shown in Figure 3-2.

A second mockup, 5 m long and 2/3rd scale diameter, will be used to test a range of dry granular materials. Candidates are sand, bentonite and cement/sand and some possible mixtures of these. These materials are tested as alternative materials to the grout option. The material will be emplaced by use of a dry-gun. Pre-testing will determine the adequate granule size and mixing ratios of the candidate materials for the mockup. A photograph of this mockup, taken in June 2006 just before the testing of the projection of sand, is shown in Figure 3-3.

The third mockup is a full scale, 30 m long representation of a disposal gallery. It will be used to test the industrial feasibility of the backfill technique using grout. Grout is perceived as agreeing the most with the given backfill requirements. The test will essentially be a repetition of the test on the 2/3rd scale mockup, but this time on full scale and taking account of the lessons learned from the preceding test.

Figure 3-2. **2/3rd scale mockup for the testing of grout backfill (situation in March 2006)**

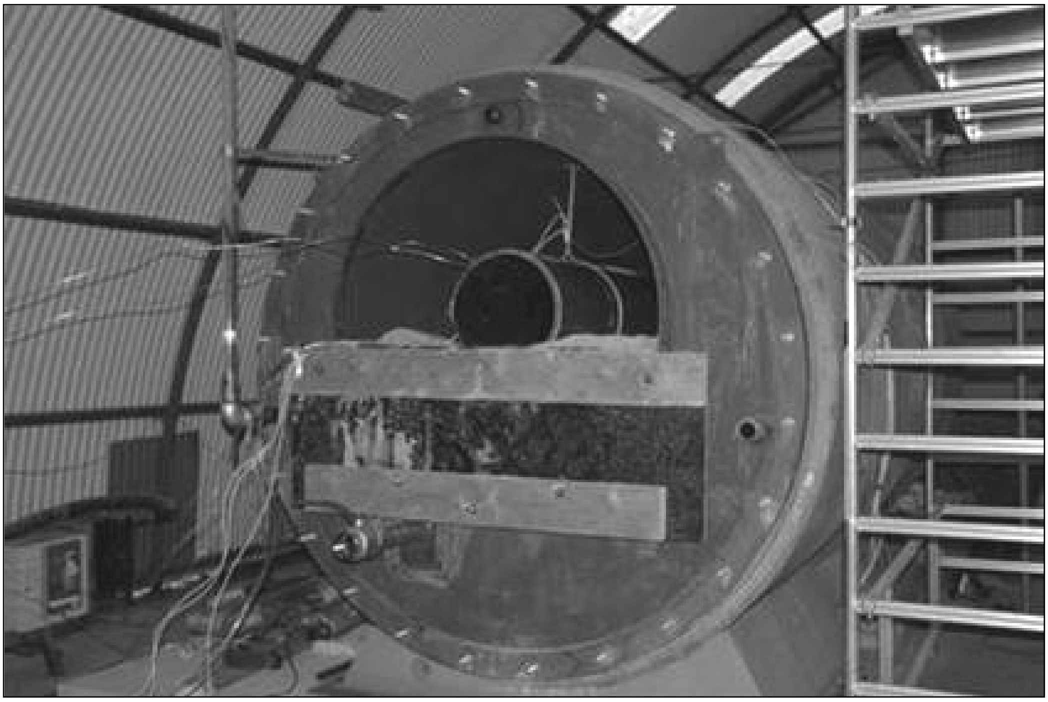


Figure 3-3. **2/3rd scale mockup for the testing of dry granular backfill (situation in June 2006)**

Verification of the backfill requirements with the performed tests

In the first place, the demonstration tests will be used to gain experience and to further develop the technology of backfilling. The tests will not verify the chemical requirements, since these are basically already determined by the composition of the material and can thus be seen as boundary conditions for the tests. The high pH grout has been formulated without the use of pozzolanas, with a very low content of chlorides or organic materials and no sulfur species. The compressive strength of the backfill material has been engineered beforehand, to remain below the criterion limit.

The tests will concentrate on verifying the achievement of the following backfill objectives:

1. Level of filling of the gap

   In the case of the grout, several months after the test the mockup will be sawn in a number of slices and the filling level of the cross-sectional areas will be visually assessed. In addition, some radial and axial core bore samples will be investigated.

   In the case of a dry material, it will be assessed during course of the test how well the gap can be filled at the top and around the line of contact between the Supercontainer and its mechanical support.

2. Thermal characteristics (for grout test)

   The mockup will be heated up until the Supercontainer reaches a temperature in the range of 40 to 50°C, the expected temperature at the moment of backfill in the repository. Then the power of the heater will be decreased down to a level where only the heat losses are compensated, in order to stabilise the temperature. Sensors will capture the evolution of the temperature of the Supercontainer during the injection and several days after that, to see the immediate effect of the addition of grout material, the effect of the hydration several hours later and the effect of the hardening of the material. Sensors will also capture the temperature of the grout.

3. Industrial feasibility

   In the case of a grout, the final aim will be to test the feasibility of filling up a 30 m long section of gallery of real-life dimensions with the specific grout material. For this, the diameters and the location of the injection tube(s) are important factors, together with the type and capacity of the grout pump used. Sensors will capture the hardening of the grout after injection. The casing will be removed a given number of days after the start of the injection. Upstream of the industrial process, important factors are the grout preparation capacity in cubic meters per hour and the control over the homogeneity of the composition of the material.

   In the case of a dry material, the pace at which the gap can be filled is an important parameter to verify. At the same time, the level of dust development and water spilling from the mockup will be assessed. An important factor here is capacity and the quality of the dry-gun machine. Upstream of the industrial process, important factors are the preparation capacity in cubic meters per hour and the control over the homogeneity of the material and the water addition.

Table 3-1: requirements for the backfill component in ONDRAF/NIRAS' HLW disposal concept

Objective				Associated Parameters and Criteria		
#	**Type**	**Description**	**Time Frame**	**parameter**	**criterion**	**Basis for criterion**
1	function	The remaining empty space in the HLW disposal gallery after emplacement of the disposal package (Supercontainer) needs to be filled up with an incompressible solid material in order to ensure the **long-term mechanical stability** of the disposal gallery.	thermal phase	**level of filling** of a cross-sectional area after emplacement	~ 100% (e.g. > 98%)	postulated working value, covering aspects of emplacement technique and material data (viscosity, shrinkage)
2	function	The backfill must act as a **chemical shield** for the Supercontainer concrete buffer, thus stabilizing and preserving its corrosion-protective characteristics.	thermal phase	**pH** of backfill	> 12.5	A high alkalinity will make the backfill act as a chemical filter for corrosive species coming out of the Boom Clay and annihilate the activity of SRBs.
				concentration of **pozzolanas** in backfill	very low	Pozzolanas shorten the duration of the high alkalinity. Pozzolanas combine with lime in the presence of water to form stable insoluble compounds with cementing properties.
3	function (spent fuel)	This function is only applicable in case of spent fuel surrounded by a granular filler material. The backfill must **block any potential escape path for the filler material around the spent fuel** when the integrity of the overpack is lost. The concern is that the escaped filler material be replaced by ingressing water. The presence of water around enriched uranium material is an undesirable situation.	thermal phase	level of filling of a cross-sectional area	~ 100% (e.g. > 98%)	currently no fundamental reason to choose other than for objective # 1

4	constraint	The backfill may not disturb the retention characteristics of the host rock formation by introducing organic materials that can give rise to the formation of migration-enhancing **complexes** between radionuclides and soluble organic compounds.	system containment phase	concentration of **organic materials** in backfill	very low	
				concentration of: •**polymelamine sulfonates,** •**polynaphtalene sulfonates,** •**cellulose-based additives,** •**gluconic acid based compounds** in backfill	zero	
5	constraint	The backfill may not disturb the designed **corrosion**-protective characteristics of the environment around the overpack, created by the Supercontainer.	thermal phase	concentration of **chlorides** in backfill	very low	A zero value cannot be specified. The water used for preparing the grout or projecting the dry material will inevitably contain traces of Cl^-
				concentration of **reduced sulfur species** (polysulfides, thiosulfates) in backfill	zero	
				concentration of **organic materials incorporating sulfur** (S) in backfill	zero	
6	constraint	The backfill may not act as a **thermal isolator** for the Supercontainer.	thermal phase	thermal conductivity of the backfill	> 1 $W\ m^{-1}\ K^{-1}$	conservatively high value, based on current thermal models and the current 100°C max. temperature criterion for the overpack
7	constraint	The backfill may not jeopardize the mechanical stability of the disposal gallery by **overstressing the surrounding components** (Supercontainer, gallery wall and floor) due to thermal expansion and/or swelling.	thermal phase	thermal expansion coefficient of the backfill	7 to 12. $10^{-6}\ °C^{-1}$	The backfill thermal conductivity should be in the same order of magnitude or slightly higher than the one of the Supercontainer. The given criterion values are only indicative working values.
				swelling	very low	

8	constraint	The backfill may not jeopardize the mechanical stability of the disposal gallery by acting as an **impenetrable barrier to the gasses** generated inside its enclosed volume, hereby leading to the build-up of a relatively high pressure.	all phases	no specific criterion		Because this is currently not assumed to impose permeability limitations on the backfill material, even though the processes are not yet well-studied, no specific criterion has been defined.
9	constraint	The backfill component should be **constructible at an industrial level**.	operational phase	length of section that can be backfilled in one operation (if with grout)	> 30 m	indicative working value, based on current operational models
				time after which casing can be removed (if with grout)	< 4 days	indicative working value, based on current operational models
				pace of backfilling (if with dry granular material)	1.25 m/h	indicative working value, based on current operational models
				Knowledge of composition of emplaced backfill	good	
				Homogeneity of emplaced backfill	high	
				Dust development during emplacement	relatively low	
				Water spilling during emplacement	relatively low	
				Market availability of backfill material	good	
				Robustness of emplacement equipment	high	high reliability of equipment is a must for underground operation
10	constraint	A constraint which is associated with the option of **retrievability** is that the backfill should not be too difficult to remove. Retrievability is not a legal requirement in Belgium, but O/N takes it into account as a possible option in so far as it does not negatively impact the operational or long-term safety of the repository.	operational phase	**compressive fracture strength** of the backfill	< 10 MPa	indicative working value, which should allow the use of high pressure beam technology to remove the material again

Buffer with prefabricated blocks and granular material (by NAGRA)

Brief presentation of the reference disposal design

NAGRA's reference concept for radioactive waste disposal is based on several fundamental requirements and basic ideas. The most fundamental (high-level) requirements for a repository are the multi-barrier system with built-in redundant barriers and the principle of robustness. Therefore, the proposed repository consists of a system of engineered and natural barriers designed to provide safety through isolation of the wastes in a stable geological environment. The depth of the planned repository is 400 – 900 m in the case of the overconsolidated claystone (Opalinus Clay).

The repository is required to provide a set of engineered barriers that act in a complementary manner with the natural geological barrier to contribute to the safety functions of "confinement" and "attenuation". The principles of predictability, avoidance of detrimental phenomena and insensitivity to detrimental phenomena apply to the engineered barriers as well as to the geological setting. In brief, the repository design and implementation should conform to the following principles (NAGRA, 2002c):

- *Confinement and attenuation;* the engineered barriers have to contribute through their physical and geochemical properties to the key safety functions of the repository system;
- *Initial complete containment for spent fuel (SF) and vitrified high-level waste (HLW)*; the design should ensure substantially complete containment of the radionuclides associated with spent fuel and vitrified HLW for a period of a thousand years or more;
- *Redundancy*; a cautious approach should be adopted in the choice of barriers and the dimensioning of particular components of the EBS. There may be barriers or processes that only make a significant contribution to safety if some parts of the system do not perform according to expectations;
- *Avoidance of and insensitivity to detrimental phenomena*; through an adequate choice of materials and a careful design;
- *Reliability of implementation*; the site and design should be selected such that the properties that favour safety can be relied upon to exist when the repository is implemented, without placing excessive demands on novel engineering technology and allowing for reliable quality assurance;
- *Reliability of closure of the repository*; the repository must be designed in such a way that it can be sealed within a few years;
- *Predictability*; in order to favour the predictability of their evolution, the engineered structures of the repository should preferably employ simple, well-understood materials.

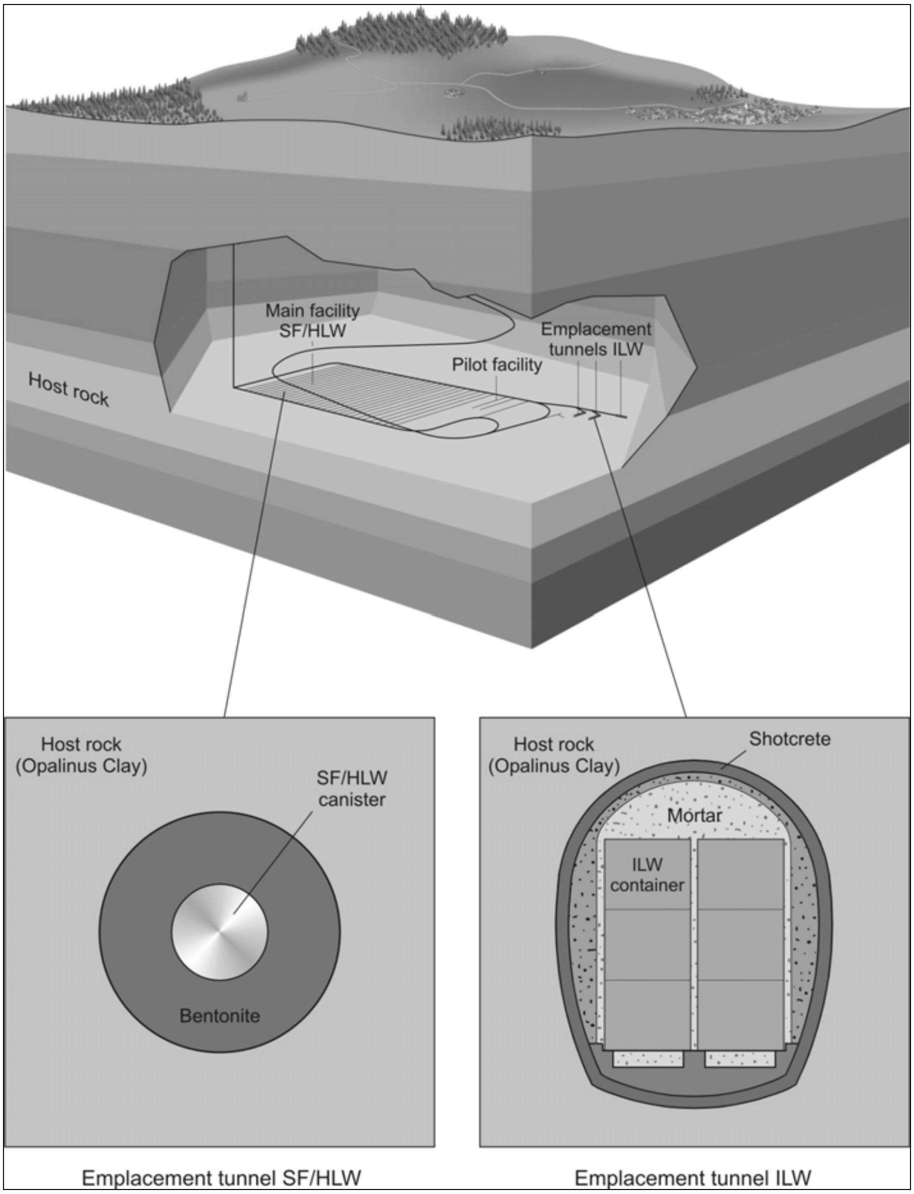
For SF and vitrified HLW, the engineered barrier system comprises:

- dissolution-resistant waste matrices, incl. SF (MOX, UO_2 and Zircaloy clad) and HLW glass,
- corrosion-resistant canisters (steel),
- a layer of low permeability bentonite buffer surrounding the canisters, that slows groundwater movement around the canisters to negligible levels, and sorbs radionuclides and retards radionuclide transport when the canisters eventually fail.

In addition to the engineered barriers mentioned above, several seals or plugs will be constructed at strategic positions to limit the flow of water through the repository.

Figure 4-1 (NAGRA, 2002c) gives on overview on a possible, general repository layout indicating that the canisters containing SF/vitrified HLW are disposed of in long emplacement tunnels (800 m long) with a diameter of about 2.5 m, whereas ILW will be placed in shorter but larger size tunnels (about 100 m long; diameter about 6 m).

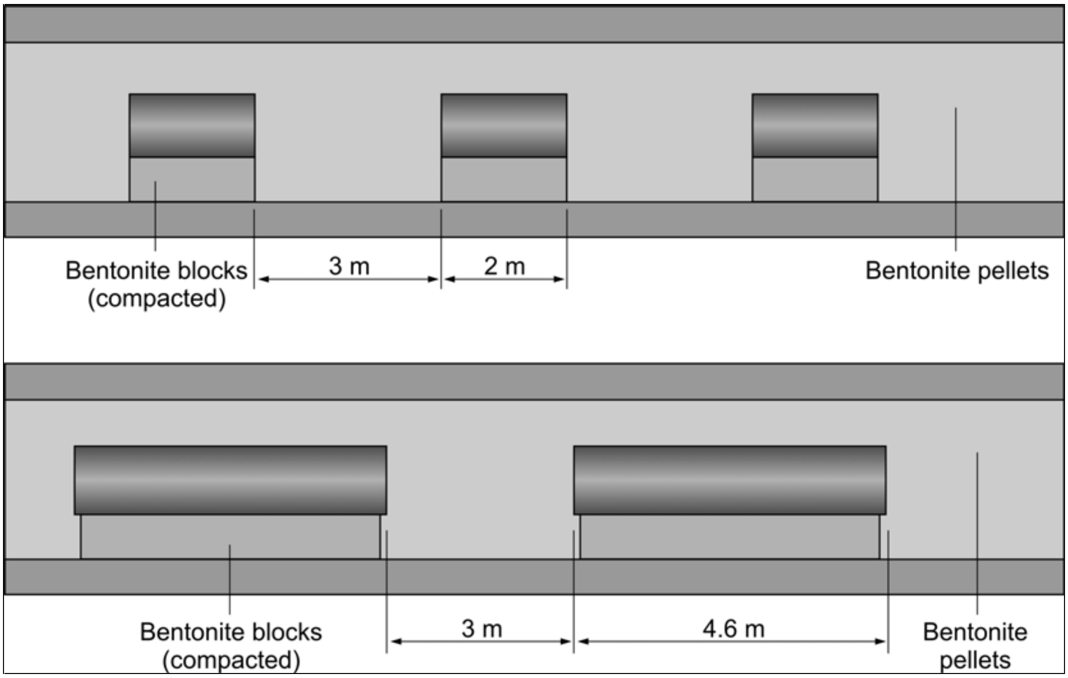
Figure 4-1: Possible layout of a deep repository for SF, vitrified HLW and ILW in Opalinus Clay



The design of the repository has been outlined in the different technical reports (NAGRA, 2002a,b,c), which have been submitted to the authorities. A detailed international peer review of NAGRA's post-closure radiological safety assessment of the disposal concept in Opalinus Clay of the Zürcher Weinland reported by (NEA, 2005) attested that "the waste emplacement strategy and the use of multiple seals to compartmentalise and isolate the waste packages are feasible and prudent".

Based on technological (ease of remote handling) and geotechnical constraints (non-cylindrical shape of tunnels due to potential local instabilities), a buffer system (Figure 4-2, NAGRA, 2002a) has been designed consisting of the combined use of bentonite blocks as support for the waste canisters and highly-compacted granular bentonite material (Naundorf & Wollenberg, 1992).

Figure 4-2: **Longitudinal section through emplacement tunnels for SF and vitrified HLW**



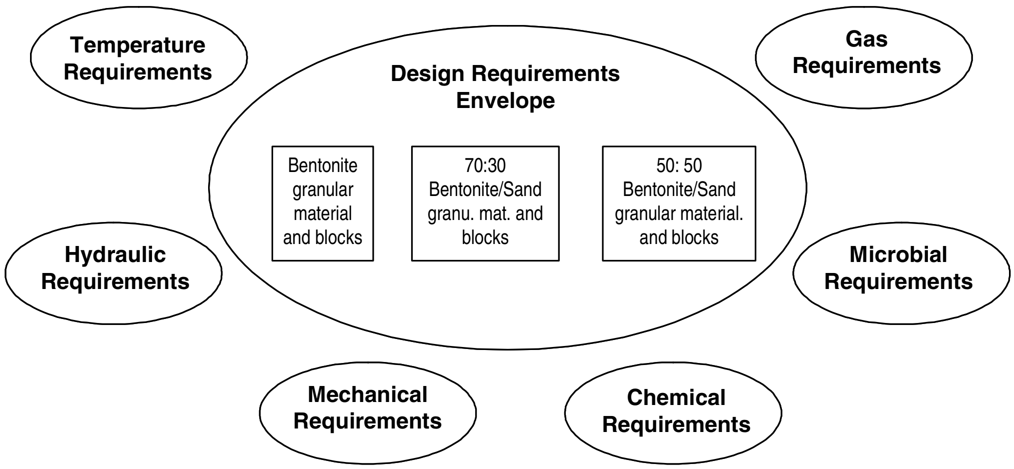
Requirements for the granular buffer

The engineered barriers, which employ large quantities of material with favourable and well-known properties and predictable performance, provide the primary containment of the waste. After canister failure, the bentonite will be a very effective barrier and therefore, it is expected that most radionuclides will decay to insignificant levels within the engineered barriers. In the case of vitrified HLW and SF, the canisters are placed in tunnels surrounded by a bentonite buffer which has the following functions:

- to keep the canisters in place and protect them by homogenising the stress field;
- to mechanically stabilise the rooms;
- to act as a transport barrier for radionuclides and a barrier for colloids;
- to provide a suitable geochemical environment;
- to ensure low corrosion rates of both canister and waste form;
- to limit microbial activity;
- to prevent human intrusion.

In order to provide these functions, it is necessary that at least a significant part of the bentonite is not altered in an unacceptable way by temperature or chemical interaction with the formation water, rock or corrosion products of the canister. To achieve these functions in a desired way, a number of predefined requirements have to be fulfilled (Figure 4-3)

Figure 4-3: **Concept for buffer design requirements for different buffer materials**



According to the current disposal concept the following main requirements have been defined:

- thermal conductivity of the unsaturated buffer: λBuffer ≥ 0.4 W m-1 K-1;
- hydraulic conductivity: k ≤ 10-12 m/s;
- swelling pressure: minimum 2 MPa and maximum lower than the minimum principal in-situ stress component.

All these requirements can be met for pure bentonite buffers if the average dry density of the buffer material ranges between 1 300 and 1 600 kg/m3. It should be noted that most of these requirements need to be verified during the on-going research activities.

Description of testing of the granular buffer within ESDRED (the steel model)

The first basic tests to demonstrate the feasibility of the proposed design of the combined use of bentonite blocks and granular material were performed within the EB "Engineered Barrier" project at Mont Terri (Mayor *et al.* 2005), [http://cordis.europa.eu/fp5-euratom/src/lib_finalreports.htm], which was co-funded by the EC within the 5th EURATOM Framework Programme (1998-2002). The results clearly outlined the potential of the proposed method leading to the decision to further evaluate potential advancements of the concept and optimisations of the proposed technology.

Within the actual project it is envisaged:

1. to improve the production of the granular material concentrating on developing particles with more appropriate shape and better defined particle size distributions;
2. to conduct theoretical and numerical studies to optimise the granular material;
3. to carry out large scale emplacement tests to verify the proposed improvements and to optimise the remote-handled backfilling technology.

The model representing part of the tunnel situation with a dummy canister and the bentonite blocks was constructed from steel. The left photo of Figure 4-4 shows the outside view of the model, the right photo provides a look inside the model where canister, bentonite blocks and the slope of granular material in the already backfilled section of the tunnel are represented by steel elements. The steel model will be backfilled with the granular material using a twin-auger system (Figure 4-5). Key objective of this test is to demonstrate that the backfill material can be emplaced at a proposed dry density of 1 400 – 1 500 kg/m^3. Beside the overall bulk density, the achievable homogeneity of the buffer will be investigated by minimizing segregation effects.

Figure 4-4: **Photos of the steel model for the planned emplacement tests for buffer**

Figure 4-5: **Twin-auger system during the inspection in the workshop**

Verification of the granular buffer requirements with the performed test

A comprehensive laboratory testing program is foreseen to investigate the performance of the system. After every backfill operation of the model, the following parameters will be investigated:

- global bulk density (net weight of buffer material over total volume of the test section);
- local densities at predefined points;
- water content of the bentonite before and after emplacement;
- particle size distribution at selected points of the model;
- physical properties of the granular material (thermal conductivity).

The results will be evaluated and compared to the predicted and required buffer parameters.

Summary and conclusions

The buffer configuration work being conducted by the three partners whose designs form the basis of this report ANDRA, ONDRAF/NIRAS and NAGRA, has reached a very important stage in the evolution of the ESDRED project. After 2 years of computer modeling and laboratory testing, the partners are now ready to undertake the demonstration testing on mockups that they have been preparing. Some of the early results obtained so far look promising suggesting that the designs described herein appear to be feasible.

The shift from the computer and laboratory work to the workshop environment will automatically bring along a greater attention to the operational aspects. The expectations are that, as a result of these demonstration tests, the set of requirements related to the buffer/backfill component will be complemented with prescriptions specific to the aspects of construction feasibility and operational safety.

Even though the disposal concepts appear to be quite different and in some aspects may even seem contradictory, it should be well understood that these differences are essentially driven by local boundary conditions such as host rock geology and the nature and magnitude of the waste inventory. The basic target remains nevertheless the same, the safe disposal of HLW and spent nuclear fuel. As such, the different disposal concepts should be seen as solutions to the same problem but within different contexts. Because of these differences, the partners had to conduct their work within Module 1 of ESDRED independently. In spite of this situation, work has progressed in an integrated manner to the maximum extent possible, by maintaining a frequent exchange of information on the status of each other's work.

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THE KBS-3 EBS WORKSHOPS: AN EXAMPLE OF REGULATOR – IMPLEMENTER PRE-LICENSING INTERACTION IN THE SWEDISH PROGRAMME

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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 an encapsulation plant in late 2006 and for construction of an underground waste repository for spent nuclear fuel in 2009. The latter will be based on results from currently ongoing site investigations at two sites in Sweden (Forsmark and Laxemar).

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.

Background for workshops

The current SKB safety strategy involves considerable emphasis on the long-term performance of the engineered barrier system (EBS). However, this does not lessen the importance of the natural bedrock barrier, which provides the environmental conditions for the man-made barriers. The SKI EBS workshops were intended to complement SKI's ongoing review of the SKB site investigations.

Over the last couple of decades, much of the focus in the KBS-3 safety assessment has shifted from the radionuclide retardation safety function (provided by slow groundwater flow, dispersion, sorption, matrix diffusion) to the isolation safety function provided by complete containment of radionuclides in the canisters. More detailed evaluation of isolation safety function will thus be needed in future safety assessments and most of the outstanding issues are connected to isolation of fuel rather than retardation of radionuclides after the isolation is broken. For the assessment of the retardation safety function there are many uncertainties connected to measuring and deriving input data for calculations, but the basic processes are rather well known. For the assessment of the isolation function, there are also uncertainties regarding the processes that must be explicitly included and those that can be ruled out from further consideration in PA. These distinctions and the judgements needed for determining how processes and features are dealt with in safety assessment were discussed throughout the workshop series.

Purpose of workshops

The main objective of the now completed workshops series 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.

The purpose of the workshops was not necessarily to provide the answers to all conceivable questions related to the safety functions of the EBS components, which is rather an expected outcome of SKB's safety assessments. However, there is a need for SKI to have a sufficient insight before reviewing such safety assessment work, such that the right questions can be asked and such that there is a focus around the most safety relevant aspects during the review process.

There has been a gradual development of EBS component design and also in the integration between results from EBS component tests and site investigation results, as well as performance assessment strategy. This means that there has been an evolution of the priority of various key issues. One can not rule out that completely new issues arrive and that old issues get a new significance. For these reasons it is an important part of regulatory review to be constantly well-informed of developments in the proponent's programme.

In this paper, we will present some of the viewpoints and issues brought about from the workshops which have some relevance to the theme of this NEA meeting. In general, discussions explicitly connected to design issues were rather limited, since the fundamental process understanding needed as a basis for justifying a particular design was judged to be the most important aspect during this particular phase of the Swedish programme. However, design issues are likely to be important in an expected gradual evolution and refinement of the KBS-3 concept in later stages of the Swedish programme.

Format of workshops

In the series, seven workshops were held, each covering three days with a format that was gradually developed and refined based on the lessons learned. It was, for instance, found that the best outcome and most fruitful discussions were obtained when SKB received just enough information about the topics of the hearing to be able to have access to the right experts and prepare in a superficial rather than detailed manner.

The standard format of the workshop was approximately the following:

- In the morning session on the first day, the experts independent from SKB were invited to give presentations covering the background for specific issues, including their current understanding of SKB's approach to the actual topic. In the afternoon session the participants were split into working groups. These groups discussed the list of question that had been provided to SKB ahead of the workshop and a list of supplementary questions was prepared.
- On the second day, SKB and their consultants participated in order to give presentations addressing the list of questions provided. This was followed by an informal hearing with SKB, drawing on the supplementary questions that had been prepared.
- In a final session of the third day, the participants (SKB's experts did not attend the final day) discussed the responses that SKB had given, in preparation for the production of the workshop report. The reports have been developed on the basis of the workshop discussions with additional material provided by the participants after the workshop.

Experience from using workshop format

The following general benefits of the workshop series initiative have been identified:

- The workshops have provided SKI with a good knowledge basis of the KBS-3 engineered barrier system for upcoming regulatory reviews.
- All concerns brought up by the various external reviewers, who participated during the workshops, may not necessarily be critical or even relevant. However, because they have been brought up in a previous regulatory context, knowledge of their existence should make it possible to explain and justify them in a more transparent way.
- The workshops have provided some guidance for SKI's own research programme, and several recently initiated projects have been directed towards issues brought up at the workshops (creep phenomena in copper, influence of saline groundwater, thermal buffer alteration, sulphate reducing bacteria, processes relevant for montmorillonite alteration)
- The workshops may have increased SKB's awareness of some weak areas in their safety assessment reasoning, or research programme.

SKI plan to continue the review of the KBS-3 EBS with a dedicated group of external consultants (an EBS expert group).

Table 1. **Summary of workshop schedule**

Period	Activity
Morning and afternoon of the first day	Introduction and workshop objectives
	Presentations to participants by invited experts
	Summary of conclusions from previous SKI workshops on the engineered barrier system
	Working group sessions to identify further questions to be put to SKB
Evening of the first day	Working group leaders and rapporteurs collate and finalise new questions to be put to SKB
Morning of the second day	Presentations 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

Overview of workshop series

General themes for each of the workshops were identified early on, with an emphasis of overview themes at the onset and more detailed themes for the last few workshops. This section includes a description of the workshops with some examples of the issues that were raised.

Workshop 1 in 2002: ***Long-term integrity of the KBS-3 Engineered Barrier System, SKI report 2003:29***

This first workshop discussed a number of fundamental issues of relevance for the KBS-3 design and especially the safety function of complete containment of the spent fuel. This was the first time canister as well as bentonite experts met in SKI workshops. The following issues were discussed:

- Have all FEPs been identified which must be considered in the design of the engineered barriers and in the safety assessment?
- Are all the interactions between canister and buffer as well as buffer and near-field rock fully understood?
- Are all scenarios that could lead to loss of the spent fuel isolation identified and considered?

Workshop 2 in 2003: ***Manufacturing, Testing and Quality Assurance for the KBS-3 Engineered Barrier System, SKI report 2004:26***

The most essential aspect discussed during this workshop was; can a repository really be build as good as is specified in the safety assessment? Evaluation of material selection and manufacturing of all repository components, their testing and quality assurance is needed to answer this.

Workshop 3 in 2004: ***Performance Confirmation for the KBS-3 Engineered Barrier System, SKI report 2004:49***

This workshop addressed the need for longer term testing as a complement to laboratory tests and short term testing during manufacturing and installation. This is related to monitoring and to the requirement of some degree of performance confirmation (used in the US spent fuel programme). The following issues were discussed:

- What long-term performance confirmation experiments are needed to provide sufficient level of reassurance that design is functioning as intended?
- How would the result of such experiments feed into the continued repository development?
- How would data be gathered under the repository development phase and early operation to further optimise the disposal design concept?

Workshop 4 in 2004: ***Long-term stability of the Buffer and Backfill of the KBS-3 Engineered Barrier System, SKI report 2005:48***

This workshop mainly addressed functions and so called function indicators for the buffer and backfill. SKB also presented their current thinking regarding the handling of a range of physical and chemical processes. Specific issues addressed at the workshop included:

- What are the required results of THMC-modelling, and in particular is the KBS-3 design compatible with very long resaturation times?

- How will changes during the course of a glacial cycle affect buffer and backfill performance (changes in groundwater salinity, pH and Eh, permafrost)?

Workshop 5 in 2005: Engineered Barrier System – Assessment of the Corrosion Properties of Copper Canisters, SKI report 2006:11

This workshop dealt with the relevant canister corrosion mechanisms. There is a limited connection to the repository design and confirmation, but understanding of fundamental processes is of critical importance for SKB's safety case. Specific issues addressed at the workshop included:

- Is there a sufficient basis for providing an upper limit of the corrosion during the early oxidising phase of the repository evolution?
- Is there a sufficient knowledge about how much sulphide that can be available near the canister (as the most significant corroding agent in the typical long-term repository environment)?
- Is there a sufficient basis for being able to completely rule out all forms of localised corrosion?

Workshop 6 in 2006: Mechanical Integrity of the Canister within the KBS-3 concept SKI report 2006

This workshop addressed the mechanical integrity issues for the copper canister and its cast iron insert. Specific issues addressed at the workshop included:

- If real cast iron inserts have sufficiently good properties for the isostatic loads in connection with a peak glaciation (addressed in was SKB's recently completed demonstration and probabilistic modelling projects)?
- If the canister can preserve its isolation function after shear displacements of 10 cm (design criterion associated with major earthquakes)?
- If creep failure of the copper shell due to ductile failure or intergranular creep fractures has been considered to a sufficient extent (the roles of S contaminants and P additives were discussed)?

Workshop 7 in 2006: EBS workshop on Spent Fuel Dissolution and Source Term Modelling in Safety Assessment SKI report 2006

This workshop addressed alteration mechanism in spent fuel as well as radionuclide chemistry. For these topics, there is no obvious connection with design confirmation and demonstration.

Components of the KBS-3 EBS

An efficient analysis of the EBS performance needs to be based on a suitable division of component and subject-areas. Nevertheless, it should be recognised that the integrated performance can for some issues not be evaluated if experts and review tasks are distributed in a strict component wise way. The following components are considered to be the most important ones:

A. Fuel
B. Canister
C. Buffer

D. Backfill
E. Other components (access tunnels including the layout in the repository, shafts, plugs)

The fuel itself (A) was addressed in workshop No. 7. The fuel can be regarded as a barrier since it has barrier functions (slow long-term release of radionuclides under reducing conditions). However, since it is not connected to repository design confirmation and demonstration it will not be further dealt with in this paper.

The canister (B) is the key barrier providing the isolation safety function in the KBS-3 concept and was dealt with in all workshops (apart from No. 4 and 7). Workshop No. 5 and 6 was exclusively devoted to this barrier. Design confirmation and demonstration is essential for this barrier.

The buffer (C) is perhaps the most complex barrier. It is expected to sustain several key capabilities to protect the canister over long periods of time, limit supply of corrodants, prevent microbial activity, and prevent damage due to minor rock movement. It is gradually evolving and consists of a complex natural material (in spite of being considered an "engineered barrier") and it is at the interface to the natural bedrock conditions and is thus subjected to the changing environmental conditions. This barrier was dealt with in workshop No. 1-4. Design confirmation and demonstration is essential for this barrier. Long-term experiments are highly relevant for this barrier.

The backfill (D) is needed to limit groundwater flow and protect the buffer. Even if its performance characteristics are less critical than for the buffer, the large amount of materials needed, the difficulty of emplacement and the uncertainty about some long-term performance aspects require that it is more thoroughly addressed in future safety assessment. It was mainly dealt with in workshop No. 4. Little is known of the final design selections for this barrier since SKB have abandoned earlier concepts that have been tested in full scale (*in situ* compaction of a bentonite – crushed rock mixture). Design confirmation and demonstration is essential for this barrier. Long-term experiments are highly relevant for this barrier.

Other components (E) have not been addressed in the context of the workshops. Repository layout is evaluated as part of SKI's review of SKB's site investigations.

An important design issue is whether or not SKB will choose the vertical or horizontal emplacement option for the KBS-3 concept. This will have important implications for especially the design of the buffer and backfill of access tunnels (backfill of deposition tunnels will not be needed). This issue was discussed at the workshops and areas particularly important for the horizontal design alternative were identified.

Timescales relevant for EBS components in the context of safety assessment

A division into several timescales was proposed at the first workshop to simplify the discussion of how the EBS components could gradually evolve in the safety assessment timescale:

- Initial state of repository after excavation and emplacement of the spent fuel canisters and other EBS components.
- Early evolution after sealing repository galleries. This phase mainly coincides with the occurrence of oxidising conditions in the repository and may last for a number of years.
- Evolution during thermal phase with an early rapid increase in temperature followed by a slow decline over a few thousand years.

  - The period of resaturation with return to fully saturated hydraulic conditions within repository volumes are presumably in between the two above mention timescales. However, relatively dry conditions in the bedrock with very limited flow in fractures could possible mean that the resaturation and thermal timescales more or less coincide.

- Evolution after thermal phase up to 1 million years. This timescale involves potential threats to canister integrity mainly due to changed chemical and physical conditions related to glacial events.
  - A subdivision of this timescale may include first an assessment of how a glacial cycle affect the state of the EBS, and secondly an assessment of whether or not repeated cycles of up to 1 million years could change anything in comparison with the assessment of the first glacial cycle.

Based on the first workshop discussion, there appear to be few issues in intermediate timescales in between the ones mentioned above. It is clear that detrimental processes that could seriously affect the isolation function of a KBS-3 repository mainly occur in the very long time scales and are in such cases related to future glaciation. However, workshop participants still felt that the basic understanding of the earlier phases was important to analyse to the extent possible, especially since the spent fuel repository provides the greatest health hazard during this phase.

A main connection to design confirmation and demonstration concern the assessment whether or not the repository and EBS components can be built as good as specified. Design confirmation is also connected to long-term large-scale demonstration experiments discussed during the third workshop:

- Impact of various processes occurring in the normal evolution after sealing of deposition tunnels (in the SKB case addressed with a prototype repository).
- Impact of adverse conditions in terms of saline groundwater, higher temperatures, higher groundwater pressure, gas generation, high mechanical loading etc (addressed with dedicated experiments in various physical scales).

It is clear that only short measurement timescales will be possible in relation to the time scale during which barrier functions are required. For this reason sufficient modelling capability and demonstration of process understanding can not be replaced by performance confirmation experiments. Nevertheless, the experiments are likely to be a key component in the demonstration of confidence for the selected repository concept.

Initial state of repository components

In order to justify a decision to build a KBS-3 repository, there is a need to realistically or conservatively assess the initial state of the repository at the time of sealing galleries. This is a difficult task since there are still so many unknowns about how the repository will be built and operated. During the second workshop, a number of issues related to the repository initial state were discussed:

- Material selection material for the buffer, backfill or canister insert.
- Manufacturing of EBS components canister, buffer blocks. This included advantages and disadvantages with various manufacturing methods.
- Final closing of spent fuel canister (methods for producing the sealing weld).
- Non-destructive testing of EBS components.
- Transportation and storage (storage of rather moisture sensitive bentonite blocks).

- Emplacement of EBS components within the repository.
- Role of quality assurance.
- Mishaps, dropping a canister.
- Extraneous materials.

It is clear that there are many aspects of the repository initial state which has so far not been considered in sufficient detail. Previous SKB safety assessment SR-97 has been based on very simplified assumptions, which after more detailed scrutiny could both turn out to be too good or too conservative.

Features, event and processes that could lead to loss of EBS isolation safety function

A key element of the safety assessment is that all reasonably realistic scenarios that include a loss of the isolation function of the canister are identified and dealt with. During the fourth, fifth and sixth workshop the following mechanisms, potentially leading to loss of containment, were discussed:

- *Elevated hydrostatic pressure* (due to ice loading). Understanding is of critical importance since it could in principle affect all canisters. Appear to be unlikely, but there could be issues connected to creep of insert cast iron and defects.
- *Uneven swelling of buffer.* Probably not likely to impact canister integrity.
- *Initial thoroughgoing defects at the time of canister disposal* (canister isolation lost already from the start). Most probably very unlikely but was the main assumption in Sr-97.
- *General corrosion* leading to penetration of copper canister. Probably not an issue if not accompanied by microbial activity (sulphate reducing bacteria) and loss of buffer safety functions (buffer erosion).
- *Localised corrosion.* Most likely to occur initially when oxygen is still available in the repository environment.
- *Stress corrosion cracking*. In general difficult to assess with a high level of confidence (limited literature data), but appears to be very unlikely given reasonable canister tensile stresses and the repository chemical environment.
- *Rock movements giving shear displacement* (due to earthquakes especially during post-glacial phases). May be hard to rule out. In any case, effects may be limited to relatively few canisters.

The assessment of the above mentioned mechanism should be key elements in the safety assessment. It was felt that some combinations of the above mentioned mechanisms would be difficult to analyse (creep of a copper shell already partially affected by shear movement of the rock mass or mechanical effects of a partially corroded canister). Nevertheless, the significance of combined cases was not clear and some might be possible to address conservatively without detailed analysis. The design of the EBS has to be shown to be based on an assessment of all the detrimental processes, using design basis calculation cases. A more or less definite confirmation that such processes have been appropriately considered may be possible for some processes (elevated hydrostatic pressures through full scale demonstration experiments), but not for others (shear movement of rock mass).

Development of systematic criteria for EBS components

SKB has previously specified basic requirements for the different system components. However, there is a need to translate these basic requirements to acceptance criteria, which can be related to measurable properties. The existence and in some cases lack of explicit criteria was a subject continuously discussed during the workshop series. In the future, there will also be a need for procedures on how to handle deviations from acceptance criteria.

Studies on procedures in connection with documentation and non-destructive testing of barrier properties have been initiated, but these are not at a mature stage yet. These issues were briefly brought up in the context of the second EBS workshop, but SKI had at that time not formulated a consistent strategy on these matters. However, SKI's recommendation related to the manufacturing and testing of the canister is now at a fairly advanced stage, but this has been achieved after the workshop series.

SKB has introduced the idea of using function indicators as a key tool in the context of safety assessment work. This is an important concept partially addressed at the workshops, but this will be reviewed by SKI and SSI in more detail after the safety assessment SR-Can has been published late 2006.

A few critical design issues

Based on the discussions at the workshops it is possible to identify single issues and some basic questions related to repository design confirmation and demonstration. These questions may be used by SKI and SSI as a starting point for future reviews. Below are just a few examples of questions that may be regarded as particularly important?

Are suitable materials used for the various EBS components?

- How are creep properties of the copper shell affected by additives and impurities?
- To what extent are the buffer performance affected by the selection of commercial clay product (MX-80, Milos Clay)?
- What are key performance and cost implications for the wide range of materials proposed for the backfill?
- Are so called low pH cements suitable and sufficiently tested for large scale engineering construction work?

Are the proposed manufacturing and testing methods suitable and reliable?

- Is there a strong basis for the selection of friction stir welding as the main method for sealing of copper canister (variation of material properties in the weld, deposition of contaminants for the welding tool)?
- What are the characteristics of possible weld defects?
- Which non-destructive testing methods will be used and how do they complement each other (digital radiography, ultrasonic testing, and eddy current testing)?
- Why is isostatic compaction SKB's reference method for manufacturing of buffer blocks and how will full-scale demonstration be achieved?

Do the repository components have suitable physical dimensions?

- Is the canister copper shell sufficiently thick to withstand known corrosion processes?
- Is the insert of sufficient dimensions to withstand elevated hydrostatic pressure with some margin?
- Is the current insert sufficient to withstand a typical rock movement associated with a reasonably realistic (not extremely improbable) earthquake?
- Is the density and dimensions of the buffer optimal in relation to the size of each canister, to allow for a margin for buffer degradation, and to inhibit mechanical damage to the canister?
- Are the deposition tunnels of suitable dimension to allow for a safe handling of EBS components, while avoiding unnecessary costs and long-term risk contributions associated with excessive backfilling of tunnels?

Use of vertical or horizontal emplacement of canister and buffer

- What are the critical difference in between SKB's two variants of the KBS-3 concept in terms of a) long-term safety significance b) manufacturing, excavation, emplacement, testing, and operation?
- How will SKB achieve a comparable basis for the horizontal emplacement option which will be needed for a future decision on the selection in between the two variants?

Conclusions

The new completed SKI workshop series about the KBS-3 engineered barriers is an example of regulator implementor pre-licensing interaction used for information exchange and identification of issues that need further scrutiny. During intense periods of activity, it is essential that the regulator keeps up with the rapid developments in the proponent's programme. Well-documented workshops based on hearings with the proponent's experts may be one method to improve the regulator's insight and knowledge base. The key objective with these types of activities is that the regulator should be sufficiently prepared for licensing, but early feedback from independent experts is also expected to improve the proponent's awareness of weak areas in terms of data, demonstration, reasoning and transparency. It should then be possible to more easily focus a licensing process on the most safety relevant issues.

This workshop series in particular improved SKI's insight in possible interactions between canister and buffer and in the combination features, events and processes that must considered in the assessment of the period of complete containment of radionuclides within the spent fuel canisters. Moreover, there is now a better awareness of some detailed aspects related to the initial state of the repository such as material selection, manufacturing, testing, and handling of various components. The workshop series provided SKI with a better basis to evaluate the design requirements and justifications, as well as the design criteria for different system components. All these issues are expected to be of importance in an upcoming licensing process.

THE EBS DEMONSTRATION PROGRAMME AT SKB – SOME EXAMPLES

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Introduction

SKB has been conducting research in the area of nuclear waste disposal in underground environment since the early 1980s. The early tests were conducted in the Stripa mine and in the late 1990ties the first full scale tests of EBS installations were carried out in Äspö HRL that was built for the purpose of performing repository research and EBS development.

This article focuses on lessons learned concerning the practical aspect of the EBS installation procedures. Specific practical issues as well as how the gained knowledge can be used in the continued EBS design and optimisation are addressed.

The article focuses on the workshop topic "Confirmation of industrial scale feasibility of emplacement of EBS components" but also addresses the topics:

- demonstrations of compliance with specifications for emplaced EBS components;
- demonstrations/examples of the EBS optimisation process;
- identification of remaining key issues and uncertainties to be addressed in the next design optimisation cycle in relation to the scope of the envisaged safety case;
- need for (re)assessment of repository and EBS design at later stages of development.

EBS installation process applied in the full scale Äspö tests

In this section the installation sequence for a KBS-3 repository is described using examples from the full scale tests comprising installation of EBS components. The material in the text is taken from the installation of the prototype repository (Börgesson *et al.*, 2002) and (Johannesson *et al.,* 2004), backfill and plug test (Gunnarsson *et al*., 2001) and canister retrieval test (Thorsager *et al*., 2002). The layout of the Prototype Repository is shown in Figure 1, the layout of the Backfill and Plug test is shown in Figure 2 and the layout of the Canister Retrieval test is shown in Figure 3.

The objectives of the SKB EBS demonstration program can be expressed in the following way:

- Test and demonstrate the integrated function of the deep repository components under realistic conditions in full-scale and to compare results with model predictions and assumptions.
- Develop, test and demonstrate appropriate engineering standards and quality assurance methods.
- Simulate appropriate parts of the repository design and construction processes.

The modelling work that is performed as an integrated part of the demonstration tests is not addressed in this article.

Figure 1. **The layout of the prototype repository**

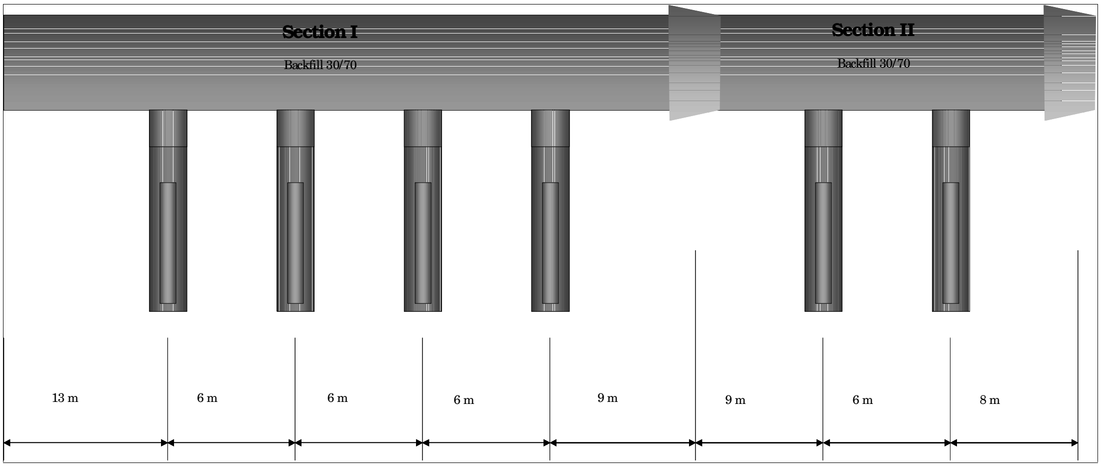
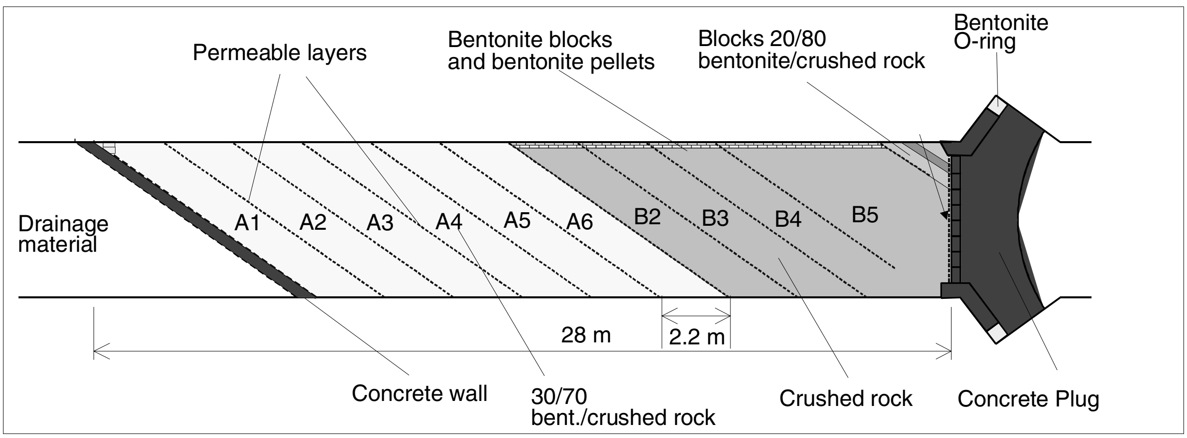


Figure 2. **The layout of the Backfill and Plug Test**



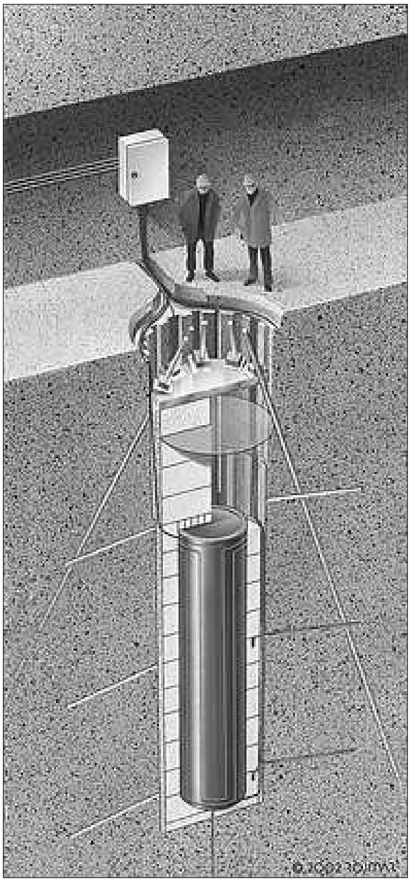
Since the Prototype Repository comprises installation of all EBS components it is used as a base for the description. If nothing else is stated examples referred to are from the prototype repository.

Prior to the installation the backfill material and the buffer blocks were prepared.

The backfill consisted of 70 weight % crushed rock and 30 Weight % Na-converted bentonite from Milos. This was mixed in a large concrete paddle mixer above ground at Äspö and the water ratio was adjusted to 12.5% (Gunnarsson, 2002).

The bentonite for the buffer blocks were adjusted to 17 w% and were compacted into blocks. The top cylindrical blocks were compacted with 40 MPa and the Rings with 100 MPa (Johannesson L-E., 2002). The blocks were given dry density so that the specified average saturated density in the deposition holes was according to specifications.

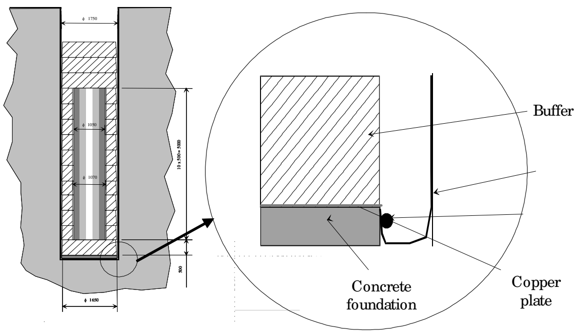
Figure 3. **The layout of the canister retrieval test**



For the installation of the prototype repository the following sequence was used:

1. Preparation of deposition holes, casting bottom plate etc.
2. Preparing the deposition tunnel plug installation.
3. For each deposition hole:
   3.1. Installing water protection in deposition hole, see Figure 4.
   3.2. Placing the buffer bottom block and rings, see Figure 5.
   3.3. Placing the canister, see Figure 5.
   3.4. Placing the top buffer block.
   3.5. Preparing buffer deposition hole awaiting backfilling
4. Backfilling from the inner end of the tunnel to the first deposition hole, see Figure 6.
5. When the backfilling front approaches a deposition hole:
   5.1. the water protection is removed;
   5.2. the upper part of the deposition hole is backfilled.
6. Backfilling to the next deposition hole and 5) was repeated.
7. Backfilling to the position of the plug.
8. The plug is installed, see Figure 6.

Figure 4. **System for water protection. Detail in to the left and photo on the right**



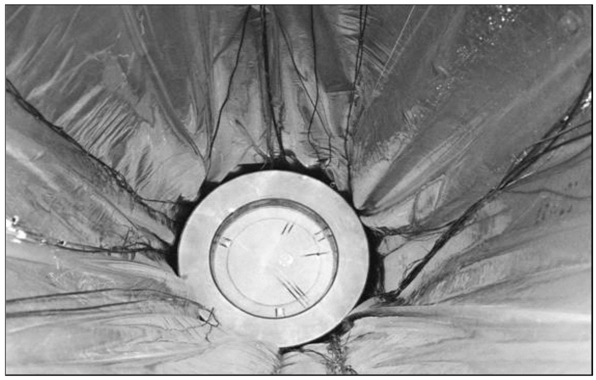
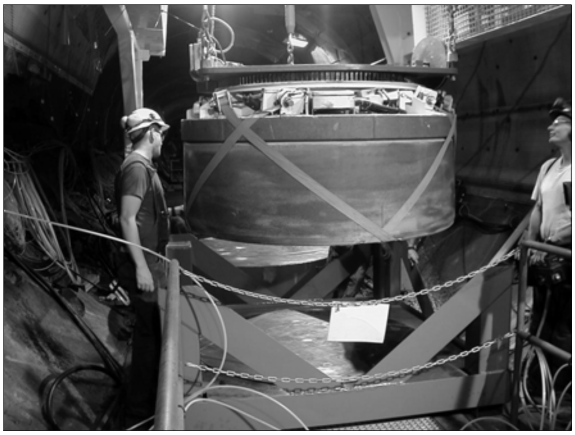


Figure 5. **Installation of buffer blocks (left) and Installation of canister (right)**



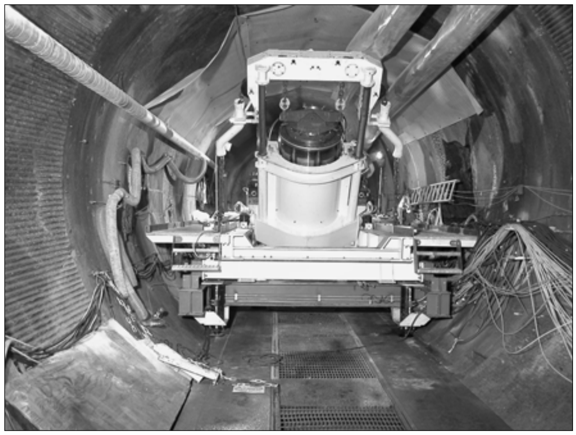
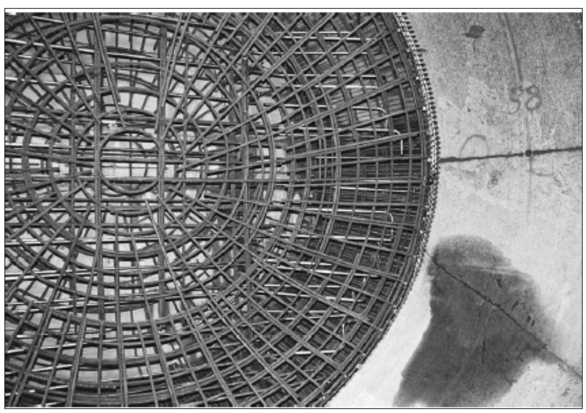


Figure 6. **Backfilling the tunnel (left) and installing the end plug (right)**



Test of canister retrieval

In the canister retrieval test a full scale canister with heaters and buffer was installed in a deposition hole at the -420 level in the Äspö HRL. The buffer was saturated with water from the bedrock using filters in the rock/buffer contact. When the bentonite between the canister and the rock had been saturated the test was dismantled. The upper half of the buffer was sampled and installed instrumentation was recovered for re-calibration. The lower half of the buffer was then removed with the method and equipment developed for the purpose. Saline water was used for dissolving the bentonite. The water was pumped out of the deposition hole, was purified and re-circulated. When the buffer had been removed the canister was lifted out of the deposition hole.

Lessons learned

Buffer installation

Concerning the installation buffer the whole chain of activities from drilling of deposition holes to manufacturing and installation of buffer components could be made so that the intended saturated buffer density was achieved with high accuracy.

The need to protect the buffer from the water flowing into the deposition holes and from the high humidity was identified. The plastic bag water protection system was developed and successfully used for the installation of the buffer in the prototype repository.

It was realised that this type of water protection may be necessary also for the production installation of EBS in the final repository and that it needs to be further developed and tested for the application in the repository. For what conditions the water protection system will be needed was identified as necessary to investigate.

Backfilling of deposition tunnels

Concerning the backfilling of the deposition tunnels it was, as the requirements were quantified, realised that the developed concept did not result in a high enough safety margin. As a result of this a joint SKB-Posiva program to choose and develop a new backfill concept was started.

Also for the backfilling it was realised that the effect of water inflow on the backfilling operation needed to be further investigated.

Plugging of deposition tunnels

For the installation of plugs it was concluded that it was possible to plug deposition tunnels according to the stated specifications. However the quantification of the requirements set on the backfill in turn led to higher swelling pressures and higher mechanical requirements on the plug. To prevent water pressure from building up behind the plug during installation the plug design should allow for water to flow past the plug during the installation. An alternative solution would be to, as for the prototype repository and the backfill and plug test, drain the water to a parallel tunnel through a borehole.

Retrieval technology

The retrieval was successful and the method judged to be feasible. Further development is necessary to adapt the method for live canisters and industrial application.

Lessons learnt concerning the continued development of EBS design

The main purpose of the installation of large scale tests was to demonstrate the installation of the and to show that the EBS behaves as expected in the short term after installation (5-20 years) after installation.

The experiences from the installations have shown that there is more to gain from the large scale test and from the work that was made to make the installation possible:

- The gained knowledge can be used for optimisation of EBS design and installation methods
- A stepwise development of design and method is necessary to achieve optimisation of EBS considering long term safety, feasibility of installation and site acceptance criteria.
- Since different conditions will be encountered in the repository there is a need to develop a set of methods, a toolbox, to handle different conditions, different water inflow.

Summary and conclusions

The KBS-3 installation process has been tested in the Äspö full scale tests Prototype Repository, Backfill and Plug Test and Canister Retrieval Test.

For the installation of buffer and canister it was confirmed that the installation is feasible and that the target density of the buffer can be reached with high accuracy.

It was shown that the developed method for backfilling tunnels was feasible but as the requirements were quantified it was concluded that the safety margin was to low. Based on this a joint SKB-Posiva program for development of backfilling concept was initiated.

The end plugs for the deposition tunnels were installed according to specifications. However the new backfilling concept showed to put new requirements on the plugs. The plug design is being revised based on the new requirements.

For the installation of the large scale test methods of handling water inflow were developed. These methods needs to be further developed for the production installation in the repository.

The knowledge gained for the installation of the large scale tests is a vital component for the continued work with the detailed EBS design and the further development of installation methods.

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THE FRENCH METHODOLOGY FOR EBS CONFIRMATION AND DEMONSTRATION

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Introduction

The December 30, 1991 French Waste Act [1] entrusted Andra, the French national agency for radioactive waste management, with the task of assessing the feasibility of deep geological disposal of high- and medium-level long-lived waste (HLW and ILW, respectively C-waste and B-waste types in French) plus spent fuel (CU in French).

In that context, the "Dossier 2005 Argile" [2,3,4,5] submitted by Andra presents the feasibility assessment – with regard to the technical capacity to accommodate all wastes, to reversibility, and to safety – of a radioactive waste disposal in a clay formation studied at the Meuse/Haute-Marne URL. This report was built upon an iterative approach between site characterisation, design, modelling, phenomenological analysis and safety analysis, in which two principles always guided the elaboration of the safety case: the principle of robustness – repository components must maintain their functionality given reasonable solicitations, taking into account uncertainties on the nature and level of these solicitations; and the principle of demonstrability – safety must be verified without requiring complex demonstrations, and based on multiple lines of evidence/argument (numerical simulation, qualitative arguments such as use of natural analogues, experiments and technological demonstrators). In that respect, the EBS definition, demonstration and confirmation of design is a part of the overall safety case.

The "Dossier 2005 Argile" was submitted to three independent peer reviews [6,7,8]. The aim of this article is to present the methodology that Andra implemented in the context of "Dossier 2005 Argile" for defining, demonstrating and confirming the EBS design as well as the future programme with respect with the new Act of 28 June 2006 [9].

"Dossier 2005 Argile"

EBS design/ methodology

Safety Approach

The safety approach of the "Dossier 2005 argile" [5] differs, for some aspects, from the "classical safety of nuclear industries" as such:

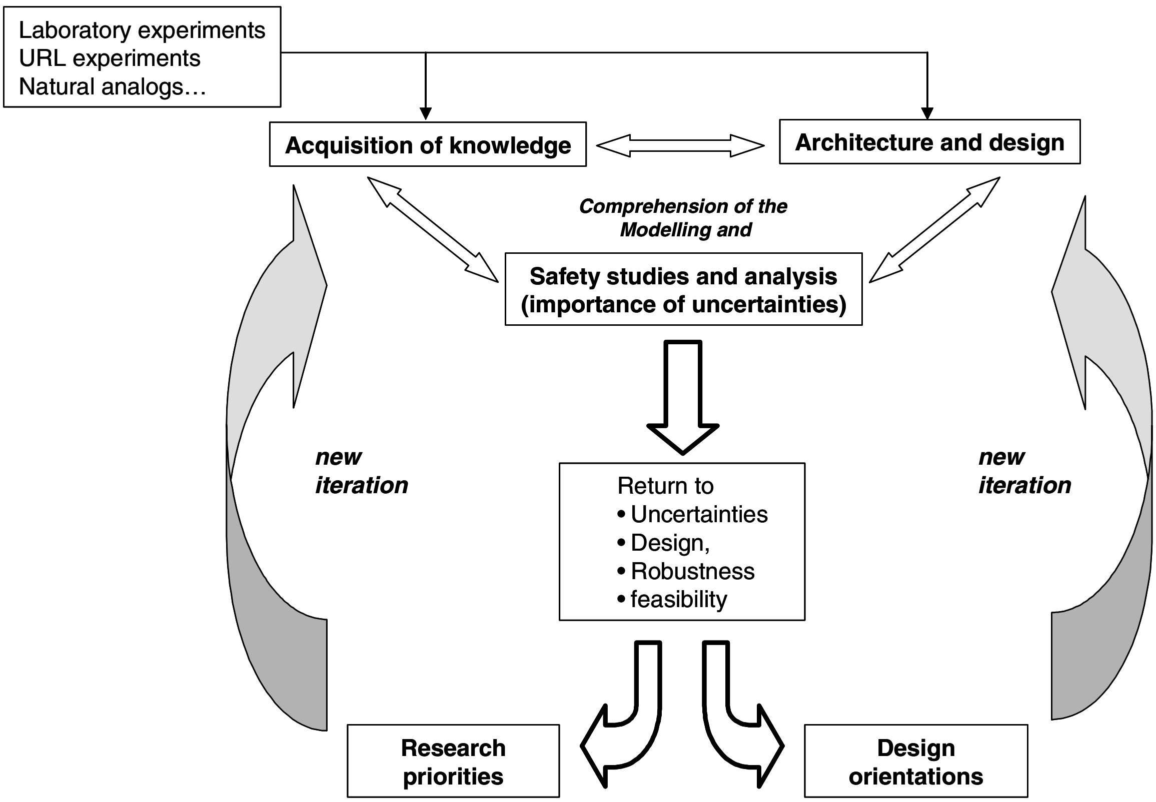
- Necessity of approaching in a co-ordinated way the different life phases of the repository (operation, and post-closure).
- Need to take into account timescales that extend beyond human experience.

- Development of strong relationship between technical design, scientific knowledge acquisition and safety assessments.
- Key importance given to the notion of uncertainties management in particular, for the post-closure phase.

The safety analysis has two-fold specificities: an operational safety analysis globally related to a more "conventional approach"; and a long-term safety analysis emphasising scientific knowledge and uncertainty management. The safety analysis relies on both qualitative and quantitative arguments. Qualitative arguments are based on the analysis of uncertainties and risks; quantitative arguments are based on the quantification of impacts (dose or other safety indicators) for normal evolution and alterated scenarios.

These peculiarities result as much from the specificity of the system under study (the repository in a deep geological formation) as from the question raised about its feasibility. It requires calling on many disciplines (mining and nuclear engineering, earth sciences, material sciences, safety) and implementing specific methods at the interface between those disciplines. These principles and objectives are taken into account at the core of the EBS studies and design. In this context, the integration of the scientific knowledge and the definition of a clear safety approach are key elements in the development of a coherent safety case (see Figure 1).

Figure 1. **Dossier 2005 Argile: three iterations loops since 1991 (1996, 2001, 2005)**



The feasibility assessment for the EBS builds upon a number of key elements:

- Basic inputs such as the models of the waste inventory and the geological site.
- Safety functions and requirement management (operation and post-closure phases).
- Technical solutions based on industrial experience [3].
- Management and monitoring, to allow retrievability.
- Phenomenological Analysis of Repository Situations (PARS) and detailed, coupled process modelling [4].
- Qualitative Safety Assessment (QSA; in French: AQS).
- Numerical simulation platforms, namely "ALLIANCES", and quantitative assessment results.

EBS design concepts – Andra main functions

The fundamental objective of the repository with respect to safety in the basic safety rules RFSIII.2.f [10] consists of "protecting the human being and the environment against hazards associated with the dissemination of radioactive substances" in the short and long term. This objective is formally restated in the functional form 'to protect humans and the environment from the dispersal of radioactive nuclides" and is considered as the main safety function for the post closure phase.

Additionally, with respect to international guidance regarding the main elements of a safety case [1], Andra applied the notion of "multi-safety functions" (a system of controlling the safety of the repository by assigning safety functions) In many ways, the "multi-function" approach is a generalization of the "multi-barrier" concept which relied on the geological layer (host rock), engineered components of the repository and waste containers and packages as sequential barriers.

The approach allows safety to rely on multiple functions performed by various components of the disposal system, characterised by: a performance level, the period during which the function has to be available and the component(s) (one or more) that have to fulfil the function. With respect to this method, the fundamental safety function "protecting the human being and the environment against hazards associated with the dissemination of radioactive substances" can be declined into three high-level safety functions, which are at the core of the long-term safety assessment, (see Figure 2):

1. to prevent water circulation in the repository;
2. to limit the release of radionuclides and immobilise them inside the repository;
3. to delay and to reduce the migration of radionuclides toward the environment.

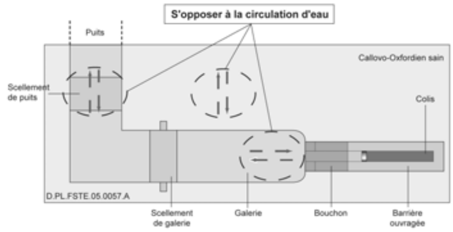
The high level safety functions are systematically broken down into technical functions (see box 1 for examples)

Figure 2. **"Dossier 2005 Argile": High-level safety functions and components**

Safety functions over time

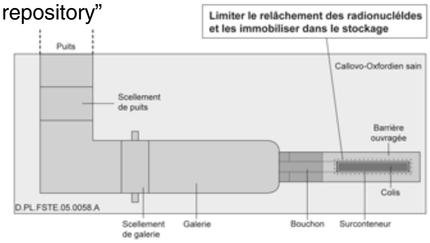
Opposing the circulation of water

- Control the water flow
- Reflects the requirement for sealing resaturation



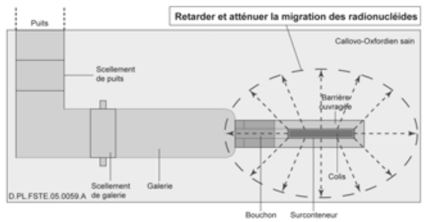
"Limiting the release of radioactive nuclides and immobilising them within the repository"

- Control the thermal flow (C-type waste and SF) During the initial thermal phase
- Reflects the requirement to protect the waste packages from water and place them under favourable physicochemical conditions (pH…).



Delaying and reducing the migration of radioactive nuclides

- Control the radionuclide flow
- Act after radionuclide have been released in the geological medium
- Reflects the transport properties, time for diffusive transport process



Box 1

Systematic breakdown of high level safety functions into technical functions

Example: Limit release of radionuclides and immobilize them within the repository

↘ To prevent water from contacting glass during the thermal period (~ 1 000 yrs for HLW)

Traceable link between safety functions and design

Example:
1. Overpack for extended corrosion resistance
2. Airtight seal at cell head

Link to safety assessment:
1. Uncertainties taken into account
2. Impact on function performance analyzed

… see AQS and SA

EBS design concepts – Andra's constraints and recommendations

The EBS designs follows some guidelines as such (i) simplicity (can be built, safe, ease of operation and closure), (ii) robustness (operation, demonstrate safety case, intrusion scenario, criticality), (iii) performance (cost, adapted to inventory, long-term safety) and retrievability (flexibility, monitoring). Andra EBS design must satisfy the following constraints:

- Variety of waste types and properties:
  - assist repository design (distinct repository areas), HLW/ILW types are characterised and inventoried;
  - minimise disturbance to geologic site;
  - avoid large excavations; unique access shaft; blind cavities.
- Phase specific performance objectives:
  - complete WP containment during operating phase;
  - no release during poorly understood migration conditions (T>80°);
  - monitoring ability before closure.
- Management of uncertainties of near-field transport scenarios:
  - control thermal zone;
  - control geochemical alterations;
  - monitor before closure.

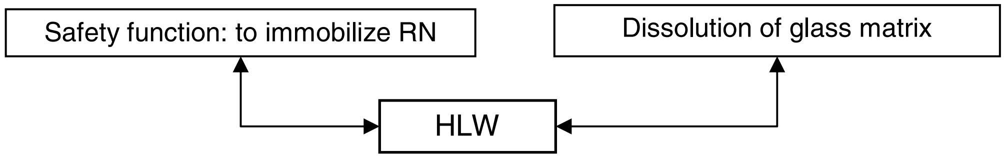
The safety analysis

The operational safety analysis as indicated in Figure 1, is conducted to define EBS measures in order to prevent a risk or limit the consequences. That could also influence the designing of architectures (geometry, arrangements) as such to prevent critically.

As a complement, feedback of the post-closure safety to the EBS design is preformed through the qualitative analysis, which aims to manage uncertainties with relying on the functional analysis and on the PARS without duplicating them (illustration of application into box 2).

Additionally, quantitative evaluation of indicators aims to evaluate the performances of the EBS in respect with the main safety functions for different scenarios including sensitivity analysis (see Figure 3). According to the results, requests for EBS design improvement and/or for a better scientific understanding in order to reduce uncertainties can be provided.

Box 2



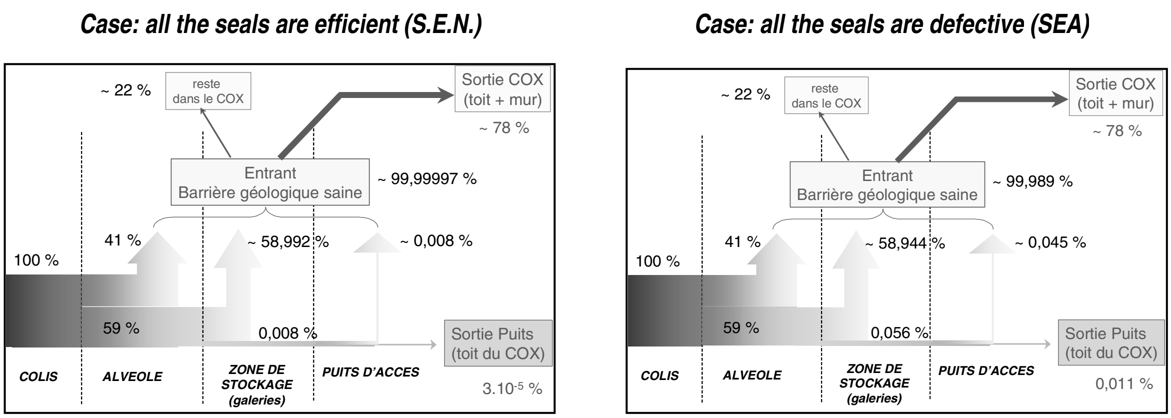
For each model/parameter, the uncertainties are identified from various information sources (PARS, referential notes…)

For each uncertainty identified:

- **How does the concept address the uncertainty? Could the disposal concept fail?**
  - → Ex: uncertainty about the alkaline plume within HLW disposal cells and pH limitation is a characteristic of the functional analysis. The HLW plug of the disposal cell permits to limit the ph plume by isolation the cell from the concrete plug.
- **Is the range of uncertainty covered by sensitivty cases in SEN?**
  - → $V_o \rightarrow V_r$ is a model with a large experimental feedback, but underlying mechanisms are yet to be completely understood (=> sensitivity calculation in SEN)
  - → Surface accessible to water (S) is subject to uncertainties (=> sensitivity calculation in SEN)
- **Which uncertainty may conduct to an alterated evolution?**
  - → By referring to the AQS on HLW cell plugs, one can identify situations that may lead to the loss of the « controlling the pH within the cell » function. These situations are said to be covered by the « sealing failure scenario » (=> in this scenario, one has to take into account a possible modification of the dissolution rate of the glass matrix).

Figure 1. **"Dossier 2005 Argile": Some lessons learn on EBS from Safety Assessment – Cases on seal performances (^{129}I as indicator)**

Example of I^{129} (Spent fuel disposal): Distribution of mass transfer through the different compartments
Performance indicator: accumulated mass of I^{129} at 10^6 years



⇨ **Whatever the situation, the dominating transfer pathway is the host rock**

The phenomenological evolution of repository situations

The objective of PARS is to identify the phenomena acting on the evolution of the disposal facility. This evolution is that considered as the most probable according to the current scientific knowledge. In this evolution, each state of a disposal facility naturally depends on the previous state. For the sake of completeness, it is therefore necessary to analyse the development of the repository from the start of its construction up to times in keeping with the decay of radioactivity in the waste – approximately a million years. The evolution of the geosphere which forms the repository environment is also analysed in conjunction with the facility's size and its effects on this environment.

To analyse such a complex system it is advisable to break it into segments. A repository "situation" is one element in this segmentation. The repository segmentation retained is a time/space breakdown. Each situation corresponds to a phenomenological state of one part of the repository or its environment at a given moment in its life. The disposal and the geological medium are divided in components according to a tree structure. Segmentation is then made possible by the difference between the time characteristics of the different phenomena acting on the repository evolution, and is made easy by the repository's modular design. Thus it is possible to take advantage of some unsynchronised phenomena or the phenomenological independence between repository components to limit the modelling of a given "situation" to only those phenomena influencing repository evolution during this situation.

The repository situation phenomenological analysis input data are the repository designs under consideration and the data used to develop them, together with the body of available phenomenological knowledge. The phenomenological analysis of different repository situations identifies links between design choice and phenomenology – the relationship between disposal solutions studied and the understanding acquired of their "behaviour" as regards waste containment, limiting radionuclides migration and delaying their possible transfer into the biosphere. It therefore acts as a system of reference for safety analyses, particularly in identifying indecisiveness and uncertainties at analysis stage, and contributes to identifying areas for further research. It is also a system of reference in the design process: to clarify design-option choices and adjust or modify the design to facilitate the understanding and modelling of repository behaviour. In particular, by identifying the successive physico-chemical states of a repository, its reversibility levels can be defined as the repository process progresses further.

Input data within the "Dossier 2005 Argile"

Geological media and waste inventory

The working hypotheses include in particular:

- The extent of knowledge acquired on the Meuse/Haute-Marne site. This geological data set includes mechanical, hydraulic, thermal, pore water chemical, solute transfer and retention properties.
- The inventory and knowledge of radioactive waste.
- The disposal vaults and the complete architecture sizing were based on the inventory model, particularly from the repository footprint point of view.

Using this reference, the phenomenological analysis of repository situations clarifies the phenomenological consequences of waste inventory modifications specific to the repository situations being studied. The modifications concern the thermal characteristics of vitrified (type C) waste and spent fuels in particular.

Repository design

The repository refers to disposal vaults for ILW waste, HLW, UOx/MOx Spent Fuels and repository facility architecture.

Disposal vaults

Types of disposal vaults studied are:

- For ILW: large diameter horizontal tunnels with an engineered barrier in concrete.
- For HLW: short horizontal tunnels without engineered barriers (reference) short horizontal tunnels with an engineered barrier in clay. The over-pack of disposal package is in carbon steel.
- For Spent Fuels: horizontal tunnels with clay engineered barrier and steel over-pack.

Disposal architecture

As far as phenomenology is concerned, design choices aim at simplifying phenomena, which could influence the development of a repository and thus their understanding and modelling, in particular:

- For the repository general architecture, disposal areas for ILW, HLW, UOx Spent Fuels and MOx Spent Fuels are separate and arranged on a single level in the middle of the Callovo-Oxfordian clay layer: this facilitates modelling and safety analyses and furthermore makes the repository process itself more flexible.
- From the hydraulic point of view, the general disposal architecture, but also that of the disposal vaults, is a “cul de sac” (dead end) design in an attempt to limit, “a priori”, hydraulic connections inside the repository. Modelling is easier, the earlier the choice is made. In return, the construction and operation of the repository can give rise to constraints requiring re-examination in view of the safety analysis results (operational and long-term safety).

From the thermal point of view, temperature criteria are used as the basis for sizing designs for disposal of vitrified waste and UOx and MOx spent fuels (number of packages per vault, distance between vaults, type of canister, etc.). Thermal criteria imply that temperature should never exceed 90°C in the host rock and that temperature should be lower that 70°C after 1 000 years. Designs are sized so that the leaching of vitrified waste by the Callovo-Oxfordian pore water does not start before the temperature has dropped below 50°C, as the leaching rate increases with the temperature.

Furthermore, current understanding of the chemical behaviour of radionuclides means that modelling their migration is more uncertain for temperatures above 80°C. In the early stages, before safety analyses, preliminary repository designs avoid such configurations, which make the phenomenological analysis and modelling easier. On the other hand, this implies design constraints for spent fuels in terms of disposal volumes or canister specifications.

In view of the separation of disposal areas, underground structures are broken down at a second level into disposal areas for ILW, HLW, UOx and MOx spent fuels, service and connecting drifts between these areas and the shafts, and the shafts themselves as a whole.The underground structures are listed on several levels in the tree diagram. In particular, disposal areas distinguish between disposal modules, then disposal vaults and vaults components (package, engineered barrier, vault plug, etc.), then specific aspects of the vault components (swelling clay of a vault plug, etc.). Not all repository components on the tree diagram lower levels are defined at the preliminary design stage. The analysis identifies definition needs and introduces hypotheses which are clarified. For example, the water, electrical and communication networks required by the repository or monitoring operations are not defined. It is assumed at this stage that they have no influence on the phenomenological evolution of a repository.In this analysis, waste packages are considered as components within the repository. Their behaviour before emplacement in the repository is taken into account as input data, but is not included in this analysis.

The geological environment is divided by geological layers: the "Callovo-Oxfordian clay", the argillite host formation for the repository, the Dogger "water-bearing" carbonate formation beneath the argillite, which is not intersected by any repository structure, the "water-bearing" Oxfordian limestone above the argillite, the Kimmeridgien marl and near the surface the Tithonian limestone, all three being intersected by the repository shafts. This section of the tree diagram concerns the geological environment in its natural state, "undisturbed" by the repository. The geological environment sections disturbed by the repository, in particular the repository vaults walls ("near field"), are attached to the repository area tree diagram ("disturbed geological medium (MG) area").

The Disposal evolution during operating period

The time breakdown is based on a succession of operations carried out in the repository. These operations trigger permanent or temporary changes in the state of the structures: digging of vaults and cavities, fitting them out and ventilation naturally trigger modifications in the mechanical, hydraulic and chemical status of the Callovo-Oxfordian argillite; the emplacement of waste packages modifies the thermal and radiological status of the facility: sealing the structures triggers the start of their resaturation and a temporary chemical status.

For the disposal areas, the evolution of a module determined by these operations can thus be described according to the following situation sequence:

- before the structures are constructed, a Callovo-Oxfordian area is designated to become a module;
- digging and fitting out the module and its vaults;
- waste package emplacement;
- pre-sealing phase before the disposal vaults are sealed;
- sealing the vaults;
- closing handling module and internal drifts;
- pre-closing phase before the connection drifts and shafts are closed;
- closing the connection drifts and shafts.

The duration of each of these phases is specific to each of the ILW, HLW and UOx and MOx spent fuels disposal areas.

The phenomenology linked to excavating a module varies with its situation in the facility architecture. To take account of this, situations describe clearly the phenomenology of any module "j" as distinct from any other module "i". The aim is to assess design flexibility towards modifications in the disposal process.

The disposal evolution after closure

The time breakdown is based on its phenomenological evolution: in fact, there are no further operations likely to modify the facility evolution. As long as the geological and geo-dynamic context remains the same, the evolution of the repository is basically determined by its own phenomenology. The different thermal, hydraulic, mechanical, chemical and radiological phenomena have their own time characteristics (constants), which determine the successive, distinctive states of the facility. It is possible therefore to define a "typical sequence" of situations by distinguishing between:

- a thermal phase for waste disposal areas giving off heat;
- a re-saturation phase for excavated structures, once closed. This re-saturation defines new physical states for the facility: it triggers chemical material exchanges, particularly between the disposal vaults and the surrounding geological environment. It takes into account the hydrogen production phase related to the corrosion of steel packs and overpacks as well as the radiolytic processes;
- a phase during which the mechanical evolution of the structures is determined by progressive damage to their supporting structures and coatings;
- a phase during which the repository is subject to the generalised mechanical load by the geological environment due to damage of supporting structures and coatings and the phenomenological evolution of other components within the modules and drifts (back-filling, sealing, vacuums, etc.);
- at the very long term, when the mechanics have stabilised, only material exchanges survive, particularly between the repository zones and the surrounding geological environment.

How long these different situations last depends greatly on the nature of the structures. In particular, the thermal phases have very different time spans for HLW (a few hundred years) and spent fuels (thousands of years). In the same way, the dimension of the tunnels for HLW results in quicker re-saturation than ILW ventilated large tunnels.

The geological environment determines the context of repository evolution. The initial state of the geological state is modified in the long term by forecast climatic changes on the scale of several tens of thousands of years (ice age). This justifies distinguishing a situation for the most superficial or "water-bearing" formations through possible modifications of the hydro geological flux linked to these climatic changes.In the shorter term, the effects of natural erosion of surface formations must also be analysed. In the very long term, the aim of the geological environment analysis is to identify the elements of a reasonable forecast of its geo-dynamic evolution and the consequences on hydraulic regimes.

Regarding the surface installations, two situations are differentiated before and after the repository closure. The aim is to identify possible links between the surface installations and the evolution of a deep disposal facility, as for example keeping the excavated material (argillite, limestone) for back-filling purposes.

The analysis of the evolution in the surface environment is also based on two situations: before and after closure. In the long term, this evolution analysis is carried out with that of the geological environment.

The phenomenological analysis of radionuclides leakage and transfers in the repository and its environment forms an essential input to the safety analyses by the Phenomenological Analysis of Repository Situations. However, considering the concentrations and masses in question, the presence of dispersed radionuclides after release does not influence the phenomenological evolution of the repository and its environment. Consequently, the time/space breakdown of the facility evolution analysis is not based on the conceptual evolution of a mixture of radionuclides.

The future: The 28 June 2006 Planning Act [9]

In 2005, developments on radioactive waste management in France were marked mostly by the preparation of the 2006 milestone specified in the act of 30 December 1991. A new bill on radioactive waste management was prepared by the Government at the beginning of 2006 and passed to the French Parliament and became Law on 28 June 2006.

The Planning Act of 28 June 2006 concerning the sustainable management of radioactive waste marks a new step in the French legislation. It sets 2015 as the deadline to submit the statutory application in order to commission a deep geological and reversible repository for mid- and high-level, long-lived radioactive waste to be operational by 2025.

This Planning Act defines a number of principles and strategic orientations for implementing the repository and sets guidelines for the procedure leading to a license application. It delegates specific research and development responsibilities to Andra, and ensures adequate funding will be available to Andra to act upon these responsibilities.

Research and studies pertaining to a reversible repository in a deep geologic formation must be conducted so as to allow for selecting a site and for drawing up a license application for construction in 2015. Submission of a license application will be preceded by a public debate. It is likely to be held in 2012-2013 and to especially address the site selection process and potential impacts resulting from future construction and operation activities. This debate will be based on the submission by Andra of a dedicated report, including sufficiently detailed repository design elements and describing the overall safety approach and underlying study results. Only a license application adequately demonstrating reversibility will be accepted. Technical details allowing fulfilling the reversibility requirement are not specified, except pertaining to a minimum duration of at least one century. Further details will be given in a later law, to be established after submission of the license application. The vote of such a law on reversibility conditions as well as positive evaluations, from the nuclear safety authority, is a prerequisite for authorizing construction of the repository. Construction is to be scheduled to start emplacement operations of the waste packages in 2025. In a somewhat distant future (one or several centuries from today…), a dedicated law will be required to authorize closure of the repository.

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Appendix C

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Engineered Barrier Systems (EBS) in the Safety Case: Design Confirmation and Demonstration

The presence of several barriers serving complementary safety functions enhances confidence that radioactive waste placed in deep geological repositories will be adequately isolated and contained to protect human health and the environment. The barriers include the natural geological barrier and the engineered barrier system (EBS). The EBS itself may comprise a variety of sub-systems or components, such as the waste form, container, buffer, backfill, seals and plugs. Given the importance of this subject, the Integration Group for the Safety Case (IGSC) of the OECD Nuclear Energy Agency (NEA) sponsored a series of workshops with the European Commission to develop greater understanding of how to achieve the necessary integration for the successful design, testing, modelling and performance assessment of EBS for deep underground disposal of radioactive waste.

These proceedings present the main findings from, and the papers delivered at, the fourth NEA-EC workshop on EBS, which took place in Tokyo, Japan, in September 2006. This final workshop of the series focused on strategies and methods to demonstrate that EBS designs will fulfil the relevant requirements for long-term safety, engineering feasibility and quality assurance. The workshop highlighted that large-scale experiments have confirmed the feasibility of techniques for manufacturing and installing engineered components in disposal systems and have also provided valuable lessons to improve designs and refine practical aspects to construct and implement EBS.

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