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THE EC/NEA ENGINEERED BARRIER SYSTEMS PROJECT

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Abstract

The OECD Nuclear Energy Agency and the European Commission have, over the last five years, sponsored a project on Engineered Barrier Systems (EBS) which has examined 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 paper discusses examples from various disposal programmes and identifies lessons that may be drawn relating to disposal system design, EBS testing and the safety case.

1 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 provide 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.

2 The EC/NEA Engineered Barrier Systems Project

The Integration Group for the Safety Case (IGSC) of the Nuclear Energy Agency (NEA) Radioactive Waste Management Committee (RWMC) has co-sponsored 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.

2.1 Objectives

The general objectives of the project were as follows:

- promoting interaction and collaboration internationally 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.

The project has considered the engineered barrier system from several perspectives, e.g.:

- engineering design (e.g. how can a component be engineered or re-engineered to improve performance or ease of modelling?);
- characterisation (e.g. how can the properties of the EBS and the conditions under which it must function be measured or otherwise characterised?);
- modelling (e.g. how can the relevant processes be modelled?);
- performance assessment (PA) (e.g. how can the performance of the EBS and/or its components be evaluated under a wide range of conditions?).

2.2 Project Structure and Timeline

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.

The steps in the repository design optimisation cycle are depicted in Error! Reference source not found.:

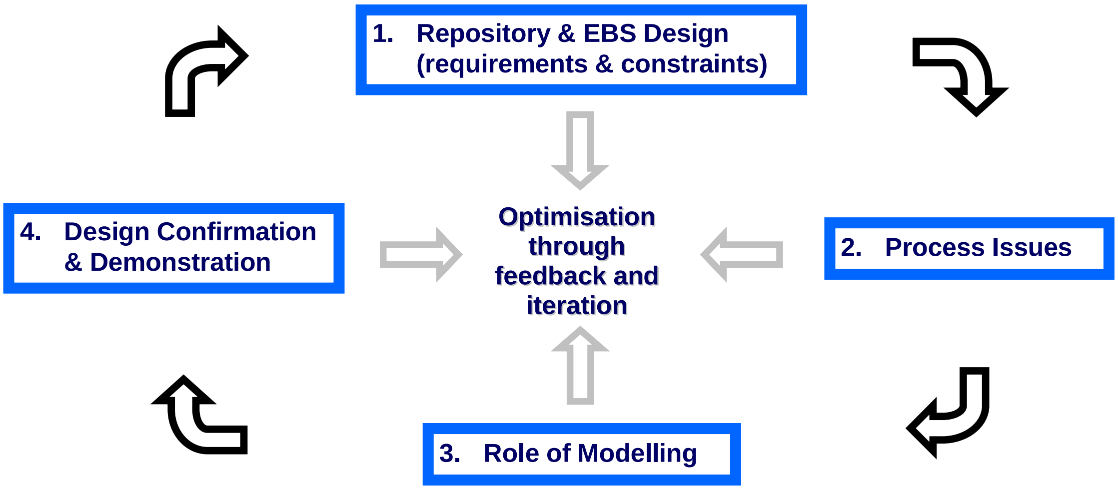

Figure 1: The EBS Optimisation Cycle

The EBS project was designed to address each of the stages of EBS development and their interactions through a series of workshops:

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

This paper draws principally on the outcomes and lessons learned from the Tokyo workshop, which addressed design confirmation and demonstration, but it also attempts to integrate these with some additional considerations (e.g., of pre-closure processes) from the other workshops.

3 Workshop on Design Confirmation and Demonstration

3.1 Workshop Objectives

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). The workshop followed on from a previous workshop that had considered a wide range of pre-closure process issues (NEA, 2005).

3.2 Workshop Structure and Contents

Plenary sessions at the Tokyo workshop described the experience of a range of national disposal programmes (and collaborative international undertakings) from EC and NEA countries in terms of testing and demonstrating EBS and its components. Presentations addressed plans and results for design demonstration programmes in, for example: Belgium, France, Germany, Sweden, Switzerland, and the United States.

Working group sessions allowed in-depth discussions on:

- Decision-Making and Design Factors in the EBS Design Process, including the use of safety functions, the optimisation cycle and the iterative nature of developing a safety case and its implication for design and for ongoing evaluation and demonstration of the EBS.

- Confirmation and Demonstration of the EBS in the Context of Confidence Building, including 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 for disposal.

3.3 Examples from Selected ‘non-ESDRED’ Programmes

3.3.1 The US Yucca Mountain Project

The Yucca Mountain Project has been in progress for over two decades, during which there has been a fairly continuous process of repository and EBS design, and performance assessment. In addition, the applicable regulations have evolved significantly. The current regulation, NRC Regulatory Requirement 10 CFR Part 63, is a performance-based regulation that focuses on overall disposal system performance, and requires the US DOE to propose a design for the repository that provides defence-in-depth, i.e., that at least two barriers (a natural barrier and an EBS) must be present to isolate the waste.

EBS design evolution during the Yucca Mountain Project can be illustrated as follows:

- The late 1980’s 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.

- 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.

- Since 2005, the US DOE has been considering use of a new canister for Transport, Aging, and Disposal, the TAD canister. Waste spent fuel would be placed in the TAD canister at the power plant. This would then be placed inside a disposal package with a stainless steel inner barrier to provide additional strength and an outer barrier consisting of a high-nickel alloy (Alloy 22), which is highly resistant to corrosion. Aims of using the TAD canister approach include eliminating repetitive waste handling activities and simplifying facility design and operations.

Key lessons learned during the project have included the importance of using PA to guide design reviews. However, modelling alone is not sufficient, and the regulations therefore also require a *performance confirmation* programme to confirm the assumptions, data, and analyses that led to findings permitting construction of repository and subsequent emplacement of waste.

Briefly, the performance confirmation programme seeks to:

- Confirm that subsurface conditions, geotechnical and design parameters are as anticipated and that changes to these parameters are within limits assumed in the License Application
- Confirm that the waste retrieval option is preserved
- Evaluate information used to assess whether natural and engineered barriers function as intended
- Evaluate effectiveness of design features intended to perform a post-closure function during repository operation and development
- Monitor waste package condition.

Table 1 identifies the various performance confirmation activities related to the EBS and links these to relevant PA models (US DOE 2004).

Table 1: EBS Performance Confirmation Activities and Related PA Models (US DOE, 2004)

EBS Performance Confirmation Activities	**EBS Model**
Drift inspection, construction effects monitoring, and thermally accelerated drift thermal-mechanical monitoring	Drift degradation and rockfall
Thermally accelerated drift near-field environment monitoring	Thermal-hydrologic-chemical
Thermally accelerated drift near-field environment monitoring	Thermal-hydrologic
Thermally accelerated drift in-drift environment monitoring	In-drift physical and chemical environment
Corrosion testing and corrosion testing of thermally accelerated drift samples	Drip shield degradation
Corrosion testing, dust build-up monitoring, corrosion testing of thermally accelerated drift samples, and waste package monitoring	Waste package degradation
Waste form testing	In-package water chemistry
Waste form testing	Cladding degradation
Waste form testing	Commercial spent nuclear fuel degradation
Waste form testing	Defense spent nuclear fuel degradation
Waste form testing	High-level radioactive waste glass degradation
Waste form testing	Dissolved concentration limits
Waste form testing and unsaturated zone testing	Colloid transport
Waste form testing, dust build-up monitoring, thermally accelerated drift in-drift environment monitoring	Engineered Barrier System flow and transport
Seal testing	N/A

3.3.2 The Japanese Programme

The Japanese implementing organisation for geological disposal, 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 a repository.

To support this NUMO is developing several repository concepts that are tailored to potential siting environments and, in doing so, is using structured processes for decision-making and for requirements management (e.g. see NEA 2004, NUMO 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 emplacing the waste in the repository (**Figure 2**).

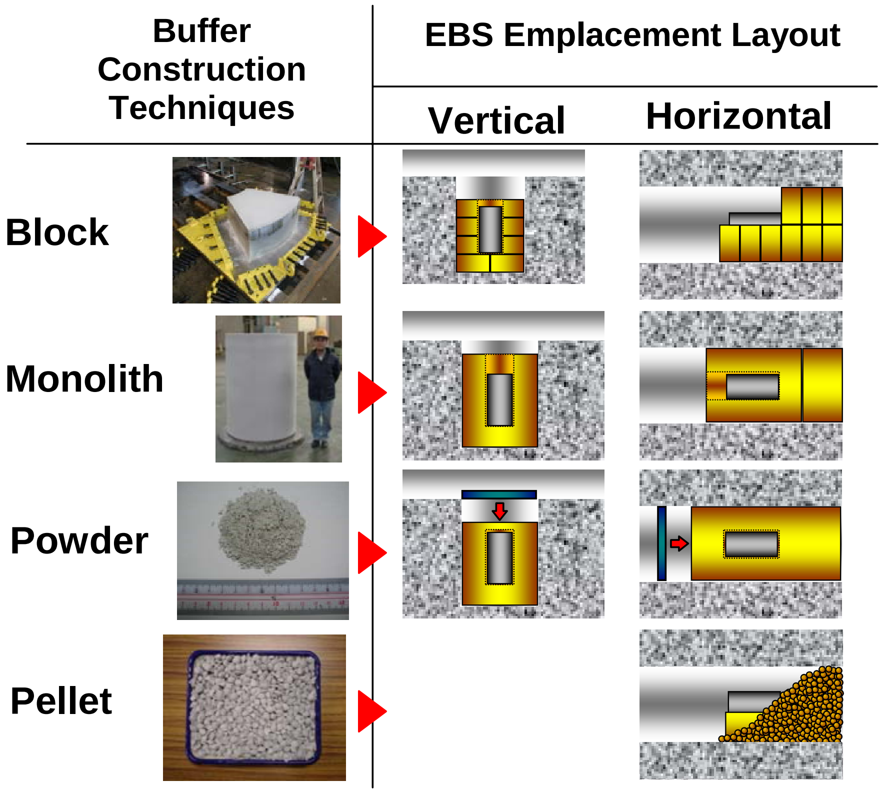

Figure 2: Alternative buffer construction techniques and emplacement concepts being assessed in the Japanese programme.

In addition to the concepts shown in **Figure 2**, NUMO (like other disposal organisations in Belgium, Finland, and Sweden) 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 such pre-fabricated EBS (supercontainer) concepts 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, i.e., ~5/day), which places significant constraints on underground logistics. NUMO estimates that waste emplacement using the pre-fabricated EBS concept may be twice a fast as either vertical or horizontal waste emplacement with buffer construction performed underground.

In the area of long-term safety assessment, NUMO has been 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 (e.g. 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 (e.g. 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**.

3.4 Working Group Sessions

3.4.1 Decision-Making and the EBS Design Process

3.4.1.1 Optimisation and Balancing Multiple Design Factors

There is no unique prescription for the process of EBS design and optimisation, but it is clear that the safety strategy—the disposal concept and the basis for safety—must be defined at the start of the process. It is also important early in the 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.

The requirements of the EBS system may change as the programme evolves and more information becomes available. Design alternatives may be established to allow for various types of uncertainties. Design decisions should be recorded in a traceable way, and this may be facilitated by establishing a requirements management system. The justification for repository designs may be strengthened by maintaining records of assessments of alternative designs.

Optimisation may be performed at various scales and levels of detail, e.g. system-wide or for an individual component – and is an iterative process. Optimisation is greatly assisted by undertaking performance and safety assessments that are as realistic as possible, as this helps in striking an appropriate balance between the different factors that influence the design decisions.

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 (e.g., see Section 3.3) can be set accordingly.

3.4.1.2 The Iterative Design Process and Its Relationship to Performance and Safety Assessment

There are important links between the EBS design process and the process and results of performance and safety assessment (PA/SA). Obviously, the EBS design and the functions it is required to fulfil have a significant impact on the scope and processes to be addressed in PA/SA. On the other hand, results from PA/SA should be used to help direct subsequent stages of the optimisation process – for example, sensitivity analysis can be used to identify which parameters are most important related to the EBS design in order to set priorities for future research and performance confirmation activities. SA, in particular, provides a means of integrating a wide range of information on EBS and disposal system performance, and for assessing the associated uncertainties.

At any stage of repository development, the design of the repository and the EBS should be only as detailed as necessary. Experience indicates that if too detailed a design is established early in a programme, this can lead to inertia and inflexibility. This suggests that, at an initial stage, the repository development programme should establish a rather conceptual design. Later, as licensing and construction are approached, and when the knowledge base has expanded, detail can be incorporated into the design.

In fact, experience shows that over the course of a repository development programme, changes in regulations and programme strategy that lead to EBS design modifications are to be expected. Similarly, more information will be become available on the repository site, and the layout of the repository and details of the EBS may need to be finalised (or modified, if they have already been set) in response to the actual site conditions. Possible reasons for repository or EBS design modifications or changes include:

- changes in policy;
- change of candidate sites;
- changes in programme boundary conditions (e.g. changes in the waste inventory);
- results from testing and characterisation;
- scenario analysis and assessment modelling;
- reviews and comments from the regulator or other stakeholders;
- new, additional or revised regulations.

Design changes should be considered and may be incorporated into PA/SA by revising scenarios; revisiting screening decisions for features, events, and processes (FEPs); updating models; and revising parameters. The extent to which it is necessary to revise and re-run assessment models depends on the nature and degree of the design change. Design changes may also highlight the need for additional research and development work.

3.4.2 Confirmation and Demonstration of the EBS in the Context of Confidence Building

3.4.2.1 Demonstration Experiments

Many useful large-scale experiments have been conducted (particularly in underground laboratories) that have allowed an assessment of the feasibility of methods for waste package construction, tunnel construction, waste emplacement, buffer and backfill emplacements, tunnel seal construction, etc. In general, these demonstrations have shown that the necessary methods for manufacturing and installing EBS components are feasible and available. In addition, some EBS test and trials have pointed to essential design changes that would not have been identified through PA modelling alone. However, further trials of some methods (e.g. backfill emplacement, overpack construction and emplacement) are still required, particularly at the repository or industrial scale.

Tests and trials of engineering feasibility are essential, especially for demonstrating operational safety, but there is also a need to develop a good understanding of the processes and effects that may occur after EBS manufacture and emplacement, and which can be crucial to the likely long-term behaviour and performance of EBS components. The development of process understanding is best approached through an iterative process of experiments and modelling on a range of scales.

National radioactive waste disposal programmes are currently conducting and planning a wide range of experiments and modelling programmes. One general lesson is that it can be helpful to begin such tests and trials (e.g., of EBS materials and of EBS construction feasibility) early on in the development of a disposal programme as there is a balance to be achieved between going too far down the route of assessing a conceptual design without confirmation that it will be practical to construct, and taking the view that it may be too soon to begin expensive large-scale trials before the EBS design has essentially been confirmed and is unlikely to be significantly changed.

3.4.2.2 Monitoring

It is currently possible to monitor a number of parameters within an underground laboratory or within an operating repository, which can give insights and confirm that emplacement assumptions are valid. Given current monitoring technologies, it may also be possible to monitor some parameters after closure, possibly for up to several thousand years. The aims of such long-term monitoring may include increasing stakeholder confidence. However, there are some concerns regarding sensor deterioration and failure, and strategies would need to be developed for dealing with possible “false positive” readings that could result.

A more promising use for monitoring is related to performance confirmation and demonstration, where monitoring equipment may be deployed as part of long-term experiments in underground laboratories or in pilot zones of within a repository. This approach is being considered in several countries.

3.4.2.3 Additional Lines of Evidence to Build Confidence

Confidence in the safety case may be enhanced if amongst other things it can be shown that:

- appropriate management systems and procedures have been applied;
- there has been sufficient stakeholder involvement throughout the safety case development process;
- the safety case includes or refers to a clear and unbiased discussion of the various options for managing the wastes in question, and presents convincing reasons for the proposed / adopted waste management option;
- the facility has been designed in accordance with the defence in depth concept;
- the safety case and safety assessment are based on sound scientific and technical / engineering principles, and traceable evidence, and have been compiled and conducted in a systematic manner;
- multiple lines of reasoning have been used to show that waste disposal is appropriate and will remain safe;
- suitable plans and commitments have been put in place for addressing any significant unresolved issues.

Arguments that the operator has applied the concept of Best Available Technology (BAT) may also foster confidence, but there is no universally agreed method or criterion for determining what represents BAT. In any case, consideration of BAT must be made in a realistic and practically achievable way that recognises that technologies will continue to change and improve with time.

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, caution must be exercised in applying analogue information to safety cases. The conditions leading to the preservation of 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.

Finally, examples identified from national programmes of measures that were felt to have improved the general public's confidence in proposals for radioactive waste disposal, include:

- a design that inspires confidence (e.g. 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.

4 Conclusions

4.1 Workshop Outcomes

Key lessons learned during the EBS project have included the importance of using PA/SA to guide EBS design as part of an iterative process of optimisation. Performance assessment and safety assessment modelling alone are not sufficient, rather, a wider range of factors need to be taken into account, including engineering feasibility, socio-economic factors and possible alternative waste management options.

The Tokyo workshop highlighted numerous useful large-scale experiments that have been conducted (e.g. 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 (e.g. backfill emplacement, overpack 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 assessment 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.

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.

4.2 Next Steps

Proceedings have been issued for each of the EBS workshops. A synthesis report will be produced for the full EBS project, covering the results of all workshops. The synthesis report will describe the progress regarding EBS studies over the course of the project, key messages from all four EBS workshops, with specific examples from national disposal programmes, and open issues where further challenges have been identified.

Areas that might benefit from further collaborative international work and discussion 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 (e.g. overpacks, 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.

Many of these issues are expected to be addressed in a series of NEA workshops beginning in 2009 regarding “cross-cutting issues” that affect, and are affected by, both the geosphere and the EBS.

References:

NEA and EC, 2003. Engineered Barrier Systems and the Safety of Deep Geological Repositories, State-of-the-art Report, EUR 19964 EN. ISBN 92-64-18498-8. European Commission. Luxembourg. OECD. Paris.

NEA, 2003. Engineered Barrier Systems (EBS) in the Context of the Entire Safety Case: Workshop Proceedings Oxford, United Kingdom 25-27 September 2002. ISBN 92-64-10354-6. OECD. Paris.

NEA, 2004. Engineered Barrier Systems (EBS) in the Context of the Entire Safety Case: Design Requirements and Constraints, Workshop Proceedings Turku, Finland. 26-29 August 2003. ISBN 92-64-02068-3. OECD. Paris.

NEA, 2005. Engineered Barrier Systems (EBS) in the Context of the Entire Safety Case: Process Issues, Workshop Proceedings, Las Vegas, United States, 14-17 September 2004. ISBN 92-64-01313-X. OECD. Paris.

NEA, 2007. Engineered Barrier Systems (EBS) in the Context of the Entire Safety Case: The Role of Modelling, Workshop Proceedings, La Coruña, Spain. OECD. Paris.

NEA, 2007. Engineered Barrier Systems (EBS) in the Safety Case: Design Confirmation and Demonstration, Workshop Proceedings, Tokyo, Japan, 12-15 September 2006. OECD. Paris.

NUMO, 2004. Development of Repository Concepts for Volunteer Siting Environments. NUMO-TR-04-03. Nuclear Waste Management Organisation (NUMO) of Japan. Tokyo.

US DOE, 2004. Performance Confirmation Plan, TDR-PCS-SE-000001 REV 05.