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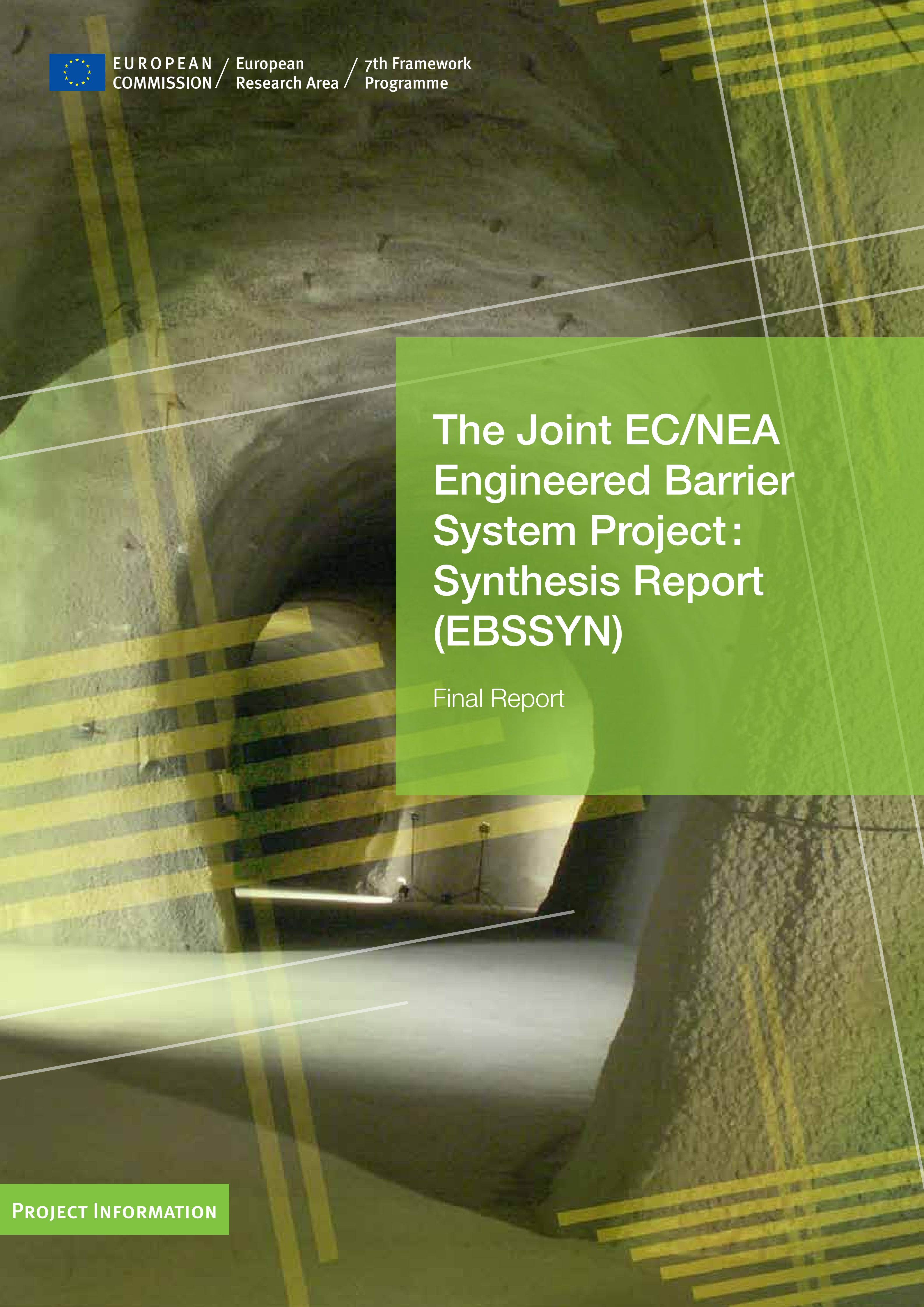

# The Joint EC/NEA Engineered Barrier System Project: Synthesis Report (EBSSYN)

Final Report

PROJECT INFORMATION

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Directorate J – Energy (Euratom)
Unit J.2 – Fission

Contact: Christophe DAVIES

*European Commission*
Office CDMA 01/61
B-1049 Bruxelles

Tel. (32-2) 29 61670
Fax (32-2) 29 54991
E-mail: christophe.davies@ec.europa.eu

EUROPEAN COMMISSION

# nuclear science and technology

# The Joint EC/NEA Engineered Barrier System Project: Synthesis Report (EBSSYN)

## Final Report

Work performed as part of the European Community’s research, technological
development and demonstration (RTD) programme for the period 2007 to 2013
Coordination and support action
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Area: Nuclear Fission and Radiation Protection

**Author:**
David G Bennett (UK)

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## Executive Summary

The European Commission (EC) and the OECD Nuclear Energy Agency (NEA) have, over the past several years, sponsored a project on the engineered barrier system (EBS) used in geological disposal of long-lived radioactive wastes. The EC/NEA EBS Project has examined how to design, characterise, model and assess the performance of engineered barrier systems, and how to integrate these aspects within the safety case for geological disposal of long-lived radioactive wastes. This report provides a synthesis of the EBS Project, and summarises its main results and findings.

After an initial survey of the state of the art and a project start–up workshop in 2002, the rest of the EBS Project was designed to address each of the stages of EBS design, development, assessment and testing through a series of four annual workshops. Through these workshops the EBS Project considered a large body of wide-ranging information from radioactive waste disposal programmes in OECD countries and from related EC-sponsored research and development work on engineered barrier systems and radioactive waste disposal.

The EBS Project has provided a valuable forum, particularly for senior waste disposal programme managers and safety assessors, to discuss EBS design and assessment issues. Key messages from the Project include:

*The development and optimisation of repository and EBS design requires a continual process of iteration between detailed research and process modelling studies, performance and safety assessment studies, and engineering design studies.* This process involves the simultaneous transfer downwards of high-level system requirements, and upwards of detailed materials and process understanding and performance assessment results, coupled with the periodic conduct of safety assessments, which integrate the various different types of information. The process is necessarily multi-disciplinary and involves communication between different teams of staff and wider stakeholder groups over considerable periods of time. The development and maintenance of expertise in safety and performance assessment is, therefore, key to establishing detailed designs for a repository and an EBS that meet the various requirements.

*The EBS is best regarded as a system of components* that functions in conjunction with the surrounding rock and thus provides acceptable levels of safety. The EBS should be tailored to the wastes that need to be disposed of, and to the host rock in which it is required to function. Each component of the EBS will have its own functions, but it is the functioning of the system as a whole that is most important. The importance of regarding the EBS as a *system* can be readily understood from examples in which the function of one EBS component is to protect a neighbouring component.

*The EBS has a central role in the safety case for disposal.* Even where the host rock offers the potential of significant performance, a well-designed EBS that will fulfil multiple safety functions is essential. First, operational issues dictate that reliable engineering solutions must be found for waste transport, handling and disposal, and these solutions must ensure adequate worker protection and radiological shielding. Second, the safety case for disposal cannot rely on a single barrier; confidence in the safety of disposal derives from the provision and fulfilment of multiple safety functions and defence in depth. Third, the EBS plays an important role in other key safety case arguments, such as those relating to feasibility, to monitoring, to the reversibility of waste disposal operations, and to waste retrievability. A well designed EBS is even more important in cases where, on its own, the host rock offers relatively less performance in terms of long-term containment and retardation (e.g., in fractured rock systems).

Recent trends in EBS design and safety case development include the increasing emphasis being given to:

- Spent fuel and high-level waste disposal concepts involving supercontainers. This trend can be seen as part of an overall drive for optimising disposal methods and may bring increased ease, efficiency and quality assurance of waste handling, buffer assembly and waste emplacement. The adoption of supercontainer designs also very much emphasises the need to regard the engineered barriers as a *system* rather than as a set of independent barriers.

- The use of Requirements Management Systems for managing and recording decisions on repository and EBS design. The justification for the current design will often lie partly in the records of previous comparisons and decisions made regarding possible design alternatives.

- The use within safety assessments and safety cases of safety function indicators and criteria. Safety functions are beginning to be used as the basis for the structure of safety assessments (e.g., as a means to scenario development and analysis), with the analysis of features, events and processes (FEPs) being used more as a means of comprehensiveness check, rather than as a main driver for scenario development.

- Structured, inclusive decision-aiding processes and options appraisals. These processes provide more transparent recognition of the wide range of factors that influence repository and EBS design choices, including technical assessments, stakeholder needs, feasibility and cost.

- Operational issues and feasibility assessments and demonstrations. These assessments and demonstrations are increasingly regarded as essential complements to performance and safety assessments, and the associated research and development work. Significant progress has been made over the last few years (within related projects) in large scale trials and demonstrations of EBS component manufacture and installation.

It is suggested that it would be valuable to maintain an international forum under the auspices of the NEA for collaborative work on the EBS and the safety case.

# Contents

## Abbreviations

| | |
|---|---|
| EBS | Engineered Barrier System |
| EC | European Commission |
| EDZ | Excavation Disturbed Zone |
| ESDRED | EC Project on Engineering Studies and Demonstrations of Repository Designs |
| FEBEX | Full-scale Engineered Barriers Experiment |
| FEPs | Features, Events and Processes |
| HLW | High-Level Waste |
| IGSC | NEA Integration Group for the Safety Case |
| ILW | Intermediate-Level Waste |
| LLW | Low-Level Waste |
| NEA | OECD Nuclear Energy Agency |
| NF-PRO | EC Project on Near-Field Processes |
| OECD | Organisation for Economic Co-operation and Development |
| SAFIR-2 | Safety Assessment and Feasibility Interim Report 2 |
| THMC | Thermo-Hydro-Mechanical-Chemical |
| UKAEA | United Kingdom Atomic Energy Authority |
| URL | Underground Research Laboratory |
| US DOE | US Department of Energy |
| US NRC | US Nuclear Regulatory Commission |

# The Joint EC/NEA Engineered Barrier System Project: Synthesis Report

## 1 Introduction

### 1.1 Background

The European Commission (EC) and the OECD Nuclear Energy Agency (NEA) have, over the past several years, sponsored a collaborative international project on the role of the engineered barrier system (EBS) in the context of the safety case for geological disposal of long-lived radioactive waste.

The fundamental objective of disposing of radioactive wastes is to protect people and the environment from harmful effects of ionizing radiation (IAEA 2006). The ability of a disposal system to achieve this objective is demonstrated through the development of a safety case. The NEA defines the safety case as '*an integration of arguments and evidence that describe, quantify and substantiate the safety, and the level of confidence in the safety, of the radioactive waste disposal facility'* (e.g., NEA 2004a).

The role of the safety case may include:

- Integrating relevant scientific, technical and other information in a structured, traceable and transparent way and, thereby, developing and demonstrating an understanding of the feasibility and potential behaviour and performance of the disposal system.

- Identifying uncertainties in the behaviour and performance of the disposal system, describing the possible significance of the uncertainties, and identifying approaches for the management, or further treatment, of significant uncertainties.

- Demonstrating long-term safety and providing reasonable assurance that the disposal facility will perform in a manner that adequately protects human health and the environment.

- Facilitating communication amongst stakeholders on issues relating to the disposal facility and explaining why the audience should have confidence in the acceptability of the disposal facility.

- Aiding decision-making on the authorisation / licensing of radioactive waste disposal and related issues.

The safety case should put the findings of quantitative performance assessments and safety assessments into a broader context by taking account of other factors and considerations that are relevant to decision-making.

The preferred strategy for safe geological disposal of long-lived radioactive wastes is one of isolation and containment. Isolation and containment represent the principle safety functions of the disposal system and these may be provided in different ways, depending on the particular wastes and disposal site in question, through appropriate repository design and operation, and by using an appropriate EBS.

The EBS may be defined as the man-made components of a disposal system including, as appropriate, the waste form, the waste containers, the buffer, the backfill, the repository seals and other engineered features.

The purpose of the EBS is, generally, to provide the required level of waste containment. The EBS also delays the release of radionuclides from the waste to the repository host rock. Each component of the EBS has its own requirements to fulfil. For example, the waste containers are typically required to provide initial containment of the waste. In some disposal concepts the period of initial containment can last for thousands of years.

The engineered barriers function as an integrated system and, thus, requirements may be defined relating to the need for one barrier to provide favourable conditions so that a neighbouring barrier can fulfil its intended functions. For example, in some disposal systems, one role of the buffer is to protect the canister from mechanical damage and corrosion.

The specific role that an EBS is designed to play in a particular waste disposal system is dependent on the conditions that may occur over the period of interest, on regulatory requirements, and on the nature of the host rock.

To be effective, an EBS must be tailored to the specific environment in which it is to function. Consideration must be given to factors such as the heat that will be produced by the waste, interactions between different materials in the waste and the EBS, the groundwater chemistry and flux, the mechanical behaviour of the host rock, and the evolution of conditions over time.

Designing an EBS to fulfil all of the requirements requires integration of data from site- and waste-characterisation studies, from research on the engineering and physico-chemical properties of the barriers and their materials, and from experience gained during demonstration trials and repository operation. This data may be gathered from a range of sources, including laboratory tests and tests performed in underground facilities, and can be interpreted by modelling and integrated within the safety case.

The EC/NEA EBS Project has examined how best to design, characterise, model and assess the performance of engineered barrier systems, and how to integrate EBS related activities within programmes developing safety cases for geological disposal of long-lived radioactive wastes.

## 1.2 The EC/NEA EBS Project 2002 – 2006

### 1.2.1 Objectives

The objectives of the EBS Project have been to:

- Promote interaction and collaboration internationally among experts responsible for design, characterisation, modelling, and assessment of engineered barrier systems, as well as those involved more broadly in the development of safety cases and the licensing of radioactive waste disposal.
- Develop a greater understanding of how to achieve the integration needed for successful design, characterisation, modelling, and assessment of engineered barrier systems, and to clarify the role that the EBS plays in the safety case for a repository.
- Share knowledge and experience about the integration of EBS design, characterisation, modelling and assessment in order to understand and document the state of the art, and to identify key areas of uncertainty.

### 1.2.2 Scope

The EBS Project has focussed on geological disposal of long-lived radioactive wastes. During the project most attention has been given to the disposal of spent fuel and high-level wastes (HLW), but long-lived intermediate-level wastes (ILW) have also been considered.

The disposal of spent fuel, HLW and ILW within a single repository is a feature of several waste disposal concepts considered during the EBS Project. Where this is the case it is envisaged that the different waste types would be disposed of in different parts of the repositories envisaged, so as to avoid any significant interactions between the wastes. The EBS Project did not, therefore, focus on such interactions.

Given its broad objectives relating to integration, the EBS Project has involved considering repository development, operation and near-field[1] processes from the wide perspective of the safety case, rather than focusing on highly detailed discussions of specific scientific issues (e.g., details of particular corrosion processes). However, where appropriate, detailed information has been drawn into the EBS Project from research studies conducted under other projects and programmes.

Notable examples of programmes that have provided information to the EBS Project include the EC research and development project on Near-Field Processes (NF-PRO – e.g., Huertas *et al.* 2008) and the EC research and

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[1] The near-field includes the EBS and the host–rock that has been affected by the presence of the repository (NEA and EC 2003)

development project entitled Engineering Studies and Demonstrations of Repository Designs (ESDRED – e.g., Seidler 2009).

### 1.2.3 Organisation

The EBS Project was organised under the auspices of the NEA Integration Group for the Safety Case (IGSC), with support from the EC for specific activities and workshops. A Project Steering Committee assembled by the NEA was led by Dr H. Umeki (now of the Japan Atomic Energy Agency). In addition, each project workshop (see below) was designed and overseen by the NEA and a dedicated Workshop Programme Committee, comprising senior managers from waste management organisations in OECD countries.

### 1.2.4 Approach

The EBS Project considered the engineered barrier system from several perspectives:

- 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?)
- Assessment (e.g. how can the performance of the EBS and its components be evaluated under a wide range of conditions?)

At the start of the project a 'state of the art' report on engineered barrier systems (NEA and EC 2003) was developed, based on results from a questionnaire survey of waste management organisations and regulatory authorities, and their technical support organisations. This provided a snap-shot of the status of the various disposal programmes at the start of the project, reviewed the role of the EBS in the different disposal concepts, identified the components of the engineered barrier systems, and documented their primary roles and functions. The report also discussed approaches to the characterisation and modelling of EBS components, the assessment of EBS performance within safety assessment, and addressed various other topics relevant to the safety case, including monitoring, retrievability and optimisation[2].

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[2] Optimisation is a key part of the system of protection established by the International Commission on Radiological Protection (e.g., ICRP 2007). Optimisation is also one of the International Atomic Energy Agency's safety principles (IAEA 2006). Optimisation is a continuing, iterative process aimed at maximising the margin of benefit over harm. Optimisation takes into account both technical and socio-economic factors, and requires qualitative as well as quantitative judgements. Optimisation involves continually questioning whether everything reasonable has been done to reduce risks.

The findings from the state of the art report survey were presented at a project start-up workshop, which was held in Oxford, UK, and hosted by UK Nirex Limited (NEA 2003a). One of the objectives of the project start-up workshop was to discuss and design the structure, content and working methods to be adopted during the rest of the project.

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 – see NEA 2004a). The optimisation process then involves a range of studies to:

- Define the requirements of the disposal system and the EBS and its components, and take account of waste-specific and site-specific constraints influencing 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 after repository closure.

The stages in the optimisation cycle are depicted in Figure 1.1.

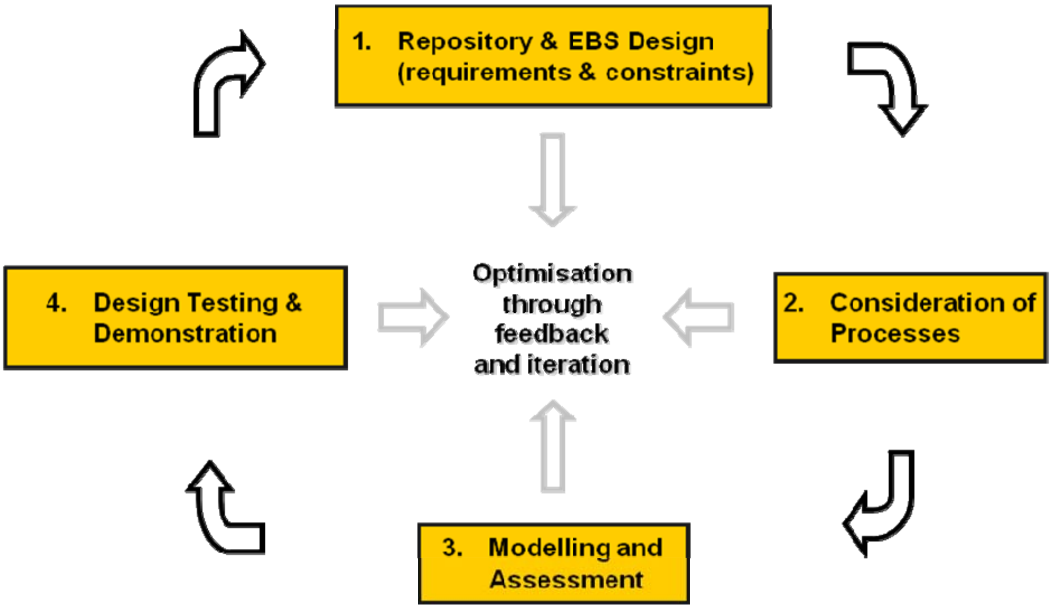

**Figure 1.1 The EBS Project Optimisation Cycle**

The rest of the EBS Project was, therefore, designed to address each of the stages of EBS design, development, assessment and testing through a series of annual workshops:

- Design Requirements and Constraints, Turku, Finland, 2003 (NEA, 2004b).
- Process Issues, Las Vegas, USA, 2004 (NEA, 2005).
- Role of Modelling, La Coruña, Spain, 2005 (NEA, 2007a).
- Design Confirmation and Demonstration, Tokyo, Japan, 2006 (NEA, 2007b).

The workshops each involved between 40 and 50 participants. The participants included programme managers from waste management organisations, regulators, safety and performance assessors, engineers and other technical specialists in relevant disciplines.

Reports were developed and published by the NEA after each workshop and, in addition, papers publicising the project were presented at selected international conferences (Bennett *et al.* 2005, 2006; Umeki *et al*. 2008).

## 1.3 This Report

This report:

- Provides a synthesis of the EC/NEA EBS Project as a whole, and summarises its main results and findings. The report does not, however, attempt to reproduce the great wealth of detailed information considered within the EBS Project - this is contained in the individual workshop reports, papers and presentations, many of which have been published previously.
- Documents a series of examples that illustrate the process of EBS design and optimisation through development and maintenance of the safety case[3].
- Identifies trends in studies supporting the geological disposal of long-lived radioactive wastes.

The report is structured as follows:

- Section 2 discusses topics covered in the EBS Project workshops and summarises key findings.

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[3] Safety case maintenance refers to the updating, development and evolution of the safety case as information is gathered during the development, operation and closure of the repository.

- Section 3 provides examples of EBS design and optimisation through development of the safety case.
- Section 4 draws conclusions for a range of topics relevant to the EBS, its role, design, characterisation, modelling and assessment.
- Section 5 contains a list of references.
- Appendix A lists the wide range of organisations from around the world that contributed to the EBS Project.

# 2 EBS Project Workshops and Findings

This section summarises key findings from the EBS Project workshops.

## 2.1 Project Initiation

At the start of the EBS Project, the information gathered within the state of the art report (EC and NEA 2003) was presented and discussed at the project start-up workshop (NEA 2003a). This provided a baseline of understanding regarding the EBS.

There was good agreement on the definition of the EBS and on its primary role: the containment and long-term minimisation / retardation of radionuclide releases.

There was generally good consistency amongst national EBS designs for spent fuel and HLW disposal, but less for ILW:

- For spent fuel, the main components of the EBS were $UO_2$, mixed uranium and plutonium oxides, and other waste matrices, steel or copper and iron waste containers, copper, steel or nickel alloy overpacks, and (except for repositories in salt host rocks) bentonite or bentonite-based buffers.

- For HLW, the main components of the EBS were a borosilicate glass matrix, steel containers and overpacks, and (except for repositories in salt host rocks) bentonite or bentonite-based buffers.

- For ILW, the main components of the EBS included a wide variety of waste matrices (e.g., concrete conditioned wastes, bitumenised wastes), steel or concrete containers, and a wide variety of backfill materials (e.g., cementitious materials, bentonite-based materials and salt-based materials, including crushed salt and salt-concrete).

The greater variation in the ILW disposal concepts reflected the greater range of ILW waste streams, as well as the range of disposal sites considered by the different disposal programmes.

Many waste disposal programmes were actively involved in conducting underground research laboratory (URL) experiments, and this was an area of extensive international collaboration. There were clear links between URL experiments, laboratory experiments, process modelling and data gathering, and some of the disposal programmes were linking URL experiments into an iterative process of performance assessment and design refinement.

Key issues identified at that time (NEA 2003a) included:

- How to demonstrate technical feasibility.

- How to link EBS design and emplacement, to disposal system performance.

- How to determine and represent the complex thermo-hydro-mechanical-chemical (THMC) behaviour of buffer and backfill materials and their evolution in safety assessment.

- The effects of gas generation.

- The mechanisms of release and uptake of key radionuclides, such as $^{14}C$.

- The balance between the roles of the EBS and the natural barriers.

- The treatment of uncertainty.

Lessons identified from performance and safety assessments included:

- Adopt a methodical, systematic and fully documented approach to repository design and optimisation.

- Simple designs and models are easier to implement and verify.

- Integrate EBS design and performance assessment activities within iterative optimisation cycles.

- Ensure and demonstrate design feasibility.

- Continue to build confidence in performance assessments.

- Focus on the most important issues (e.g., through the use of risk-informed approaches).

## 2.2 EBS Design

The process of repository and EBS design was the main topic of the 2003 EBS Project workshop held in Turku, Finland. The following sections summarise key aspects from the workshop.

### 2.2.1 EBS Design Requirements and Constraints

When developing a disposal facility, EBS design proceeds from stakeholder needs to system requirements. In this context, the term stakeholder should be interpreted broadly to include, government and regulatory authorities, waste producers and waste management organisations, potential host communities, local governmental structures, interest groups, and the public, etc. However when it comes to implementation, it may be that the waste management organisations and regulatory authorities have the most detailed influence on EBS Design.

The stakeholder needs define what the stakeholders wish to accomplish with the disposal system. System requirements provide the solution to the waste management problem and are, thus, defined to satisfy the needs of stakeholders. In developing details of the design for an EBS, various constraints will also have to be considered. Such constraints may relate to disposal site characteristics, the nature of existing waste packages, the waste inventory, available technologies, understanding of processes and uncertainties, and the need for operational safety and programmatic flexibility.

In more detail, different levels of design requirements will exist, and these will need to be managed in a structured fashion so that they are met using a technically feasible design.

High-level regulatory requirements, such as the potential need for retrievability and long-term repository monitoring, are often expressed by stakeholders or may be included within legislation or other statutory documents. Other high-level requirements may derive from the owners of the waste.

Lower-level requirements and constraints may derive from the characteristics of the site, the waste or the materials of the EBS, or stem from a desire to simplify the assessment of disposal system performance. For example a ‘requirement’ that the temperature of a repository is kept below the boiling point of water may simplify the assessment of disposal system performance, but not be a primary stakeholder desire or objective of disposal. The management of repository temperature is discussed further in Section 2.3.2.

Workshop discussions (NEA 2004b) indicated the view that safety and performance assessment are the primary means of linking different levels of design requirements. This is because safety and performance assessment are necessarily based on fundamental scientific understanding of the behaviour of the wastes and the materials of the EBS, and can therefore link these with the higher-level objectives of the disposal system and measures of performance and safety. The importance of understanding the various physico-chemical processes that can occur during repository evolution is discussed in Section 2.3.

As a first step in the safety case development process, the safety strategy (or safety concept) has to be developed, and this should be communicated and developed taking due account of the views of the various stakeholders. The safety strategy enables the translation of high-level requirements into system requirements, from which more detailed design requirements can then be established.

The safety strategy needs to satisfy all of the high-level requirements to an appropriate degree; otherwise the proposed waste management solution would not be acceptable. The selected option also has to be technically feasible, and this may bring various lower-level requirements and constraints.

Having established the safety strategy, safety and performance assessment studies can be conducted and used in an iterative fashion, together with engineering design studies and tests and trials of feasibility to gradually develop and refine a design that meets the different levels of requirements and provides acceptable safety. Examples of such linkages are discussed in Section 3.

In addition to technical assessments and modelling results, a range of other factors may influence EBS design decisions, including:

- Engineering feasibility (e.g., of wasteform manufacture, of repository and EBS construction and installation, of waste emplacement, of repository closure).
- Operational safety (radiological protection and conventional safety).
- Experimental 'demonstrability'; that is the ability to carry out relevant tests and trials over relevant spatial scales and time periods.
- Cost.
- Quality assurance.
- The availability of relevant data (possibly from natural and other analogues) and the ability to gather necessary data.
- Stakeholder views.
- Others (retrievability, monitoring, policy issues).

The full range of factors influencing design decisions is increasingly being considered using carefully designed decision-making, or 'optioneering', processes (such as discussed in Section 2.2.3) that aim to be both traceable and inclusive of a range of relevant stakeholders. This is consistent with the 'step-wise' processes being taken towards repository licensing and implementation in many countries.

### 2.2.2 Requirements Management

As noted above, a radioactive waste disposal programme will typically have many detailed design requirements and constraints to consider, and it may be beneficial to develop or use available requirements management systems and software tools (e.g., the DOORS software, see Moren 2003) for this purpose. Advantages of requirements management systems are that they formalise the repository design process, ensure that the design takes adequate account of the various requirements and constraints on the disposal system, and help to achieve the goals of clear communication and traceable, justified decision-making.

Figure 2.1 illustrates a systematic process of working from stakeholder requirements by decomposing the design problem into system, sub-system and lower-level design requirements. Successful testing at each level of requirements ensures that each sub-system fulfils its requirements, and that when brought together, the whole disposal system should, therefore, be acceptable.

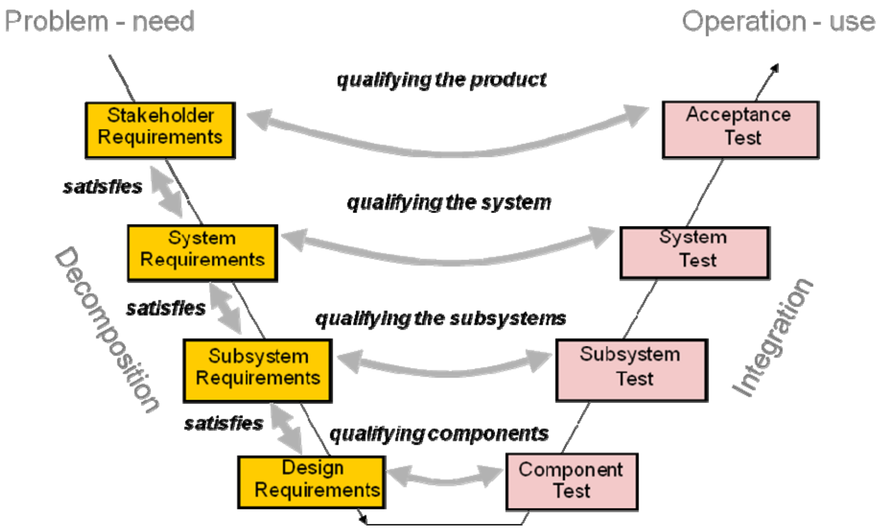


**Figure 2.1 The 'V-model' design and testing process.**

Requirements management systems and the associated software tools are complementary to safety and performance assessment techniques and tools. Requirements management and performance assessment share some common inputs (e.g., site characterisation information, regulations), methods (e.g., iteration, change control), goals (e.g., transparency), and needs (quality assurance, traceability, successful integration of project teams, stakeholder dialogue), but each provides important and distinct outputs. For example, outputs from safety and performance assessments typically include estimates of potential dose and/or risk, as well as radionuclide fluxes through certain parts of the disposal system. Results from the use of a requirements management system would be detailed specifications enabling the construction of the repository and engineered barrier system.

Thus, while the perspectives of requirements management systems and performance assessment are slightly different, both have a logical place in the development of a disposal facility.

### 2.2.3 Considering Alternative Design Options

Making choices between possible alternative designs for an EBS or repository is a necessary and important part of the decision-making process that will eventually lead to a final repository design and waste disposal.

Considering a range of possible design alternatives increases flexibility and allows the management or further treatment of uncertainties. However, it is not feasible to continue carrying out detailed studies in parallel for a large number of alternative design options - at different stages choices have to be made (Bel *et al*. 2003).

The use of structured, inclusive processes for the comparison of alternatives has the potential to build confidence in the choices being made, not only amongst those directly involved, but also because the wider community should be able to see that a reasonable and open process of design development has been followed.

The impact of different stakeholders (waste producers, waste management organisations, regulators, research centres, etc) in making such design choices will differ according to the context (e.g., from one country to another) but, in general, the choices should be based on sound, objective, clear and unambiguous reasoning.

To this end, increasing use is being made of multi-criteria options appraisal techniques for informing key choices on repository concepts and EBS designs. Such multi-criteria options appraisals often involve some or all of the steps shown in Figure 2.2. Key steps in the process include the generation and description of the options, the identification of a set of attributes (e.g., feasibility, post-closure radiological safety, operational exposures, conventional environmental impacts, costs) against which each option can be assessed, the inclusion of relevant stakeholders, particularly at the stage of scoring the options against the attributes, and the consideration of results. Experience shows that it may be necessary to consider strategies based on the combination of several options.

The use of multi-criteria techniques is most appropriate at some of the more strategic or key decision points that a disposal programme will face; it would not be sensible to open up all of the more minor or very detailed design decisions to such collective decision making. It may be understood, therefore, that the use of such multi-criteria techniques would probably be used to inform just some of the many decisions that could be tracked using an overarching requirements management system of the type mentioned above (Section 2.2.2).

During the EBS Project, examples of the use of multi-criteria options appraisals were discussed from the Belgian, Japanese, Swedish and UK radioactive waste disposal programmes.

The Belgian programme used multi-criteria options appraisal in reviewing the design for HLW disposal (see Bel *et al*. 2003; Ondraf-Niras 2004) and this was one of the inputs that led to the decision to change from the SAFIR-2 design to the BSC-1 Supercontainer design (see Section 3.4).

The Swedish programme used multi-criteria options appraisal when re-considering the design for the backfill in its spent fuel disposal concept (see Section 3.3). In the UK, multi-criteria options appraisal techniques are widely used within the radioactive waste management sector - a notable example was the choice of depth and design for a new low-level waste (LLW) repository at Dounreay in Scotland (UKAEA 2004).

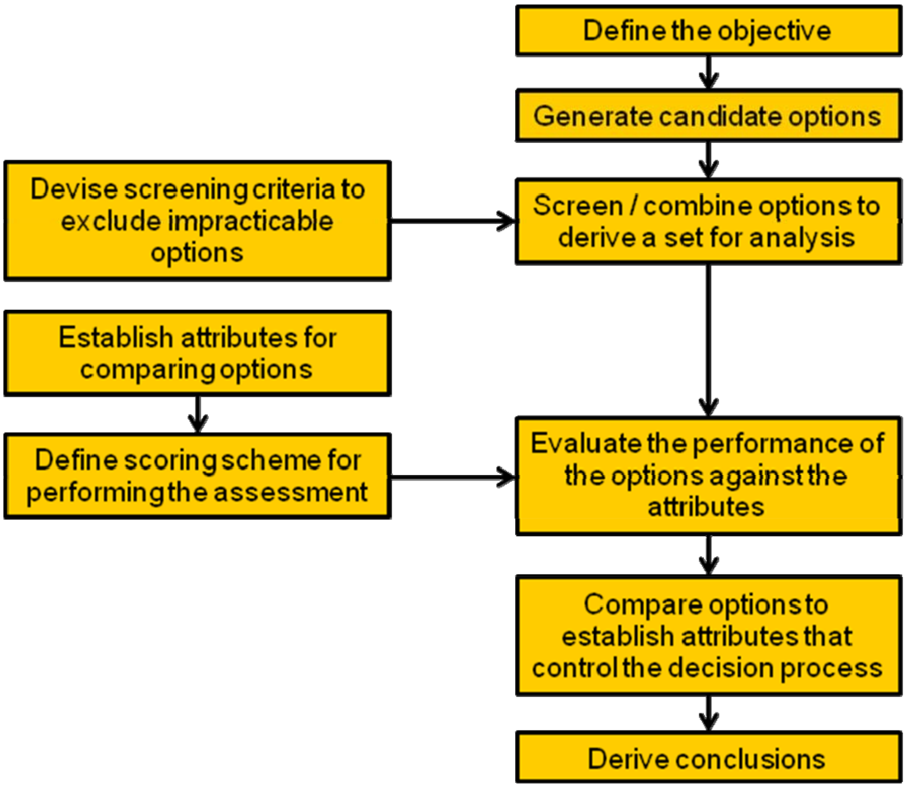


**Figure 2.2 Steps in a typical multi-criteria options appraisal.**

An important point to note is that although multi-criteria options appraisals can help to guide decision-making, they should not be seen as providing a deterministic answer or substituting for the use of reasoned judgement in actually settling on a particular decision.

### 2.2.4 Design Re-assessment and Modification

Experience, particularly from the development and operation of LLW waste repositories, shows that changes that require new safety assessments (or re-assessments) and that may lead to design modifications are to be expected.

Possible reasons for repository or EBS design modifications include:

- Changes in programme boundary conditions (e.g. changes in the waste inventory, new regulations, changes in policy, developments associated with repository siting).
- Results from experiments and site characterisation studies.
- Results from scenario analysis and safety assessment.
- Reviews and comments from the regulator or other stakeholders.

There is, therefore, a need to establish and apply programme-wide procedures for recording decision-making on repository and EBS design. These procedures and the associated records also need to be maintained throughout the disposal programme. Indeed, the justification for the current design will often lie partly in the records of previous comparisons and decisions made regarding possible design alternatives.

At any particular stage of a repository development programme, the design of the repository and the EBS should only be as detailed as necessary. Although some performance assessment modelling might incorporate a great deal of design detail (e.g., to assess the stress state of canister materials), the level of detail incorporated within safety assessment is typically less than that required from an engineering design perspective.

In its initial stages, therefore, a repository development programme should establish a conceptual design, sufficient for preliminary safety assessment. The feasibility of implementing this conceptual design should be assessed at an early stage, but details of the design may only be confirmed and formally adopted later on, as licensing and construction are approached. This gradual approach of assessment and design development should help the disposal programme to remain flexible and responsive to the various possible causes of change identified above.

Design changes may be incorporated into performance and safety assessment by revising scenarios, modifying decisions on the screening of FEPs (Features, Events and Processes), updating models, and revising parameter values. The extent to which it is necessary to revise and re-run assessment models at each stage 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.

## 2.3 Process Understanding

Various physico-chemical processes will occur within the repository system from the time of its excavation, during waste emplacement and afterwards.

Over the last two decades or more, the various national radioactive waste disposal programmes have conducted many detailed research studies into the processes that may occur within underground repositories. The range of processes is well known, and international lists of FEPs have been developed.

Several waste disposal programmes have also developed detailed concept-specific and/or site-specific descriptions of repository evolution based on the understanding of the processes expected to occur (e.g., Andra 2005; Ondraf-Niras 2008; Posiva 2006; Van Luik 2004).

The importance of understanding such processes was the main driver for the 2004 EBS Project workshop held in Las Vegas, US. The following sub-sections discuss processes that may occur during the pre-closure phase, during the thermal phase and subsequently, including various chemical processes that may affect the performance of the engineered barriers.

### 2.3.1 Pre-Closure Processes

Owing to the fact that radioactive waste repositories may need to remain operational and receive radioactive waste for a period on the order of several decades or possibly a hundred years or more, increased attention is being given to assessing the potential effects of the processes that could occur during this long pre-closure period. These pre-closure processes will influence the state of the repository at the time of repository closure.

The range of materials proposed for use in the EBS is fairly limited and typically comprises cement-based and bentonite-based materials for buffers, backfills, seals and plugs, and copper, steels, and other alloys for waste canisters. Given this range of EBS materials, the 2004 EBS Project workshop identified the following as key pre-closure processes:

- The creation of an excavation disturbed zone (EDZ) in the host rock around the excavations. Rock spalling may also occur in some host rocks.

- The effects of ventilation on the host rock and the EBS materials.

- Hydrological drawdown and re-saturation.

- Water inflows to repository tunnels, and piping of bentonite-based materials.

- The effects of grouting and high-pH solutions resulting from interaction of groundwater with cementitious materials on other EBS materials (particularly clays) and the host rock.

- The effects of stray materials left in the excavations (e.g., oils).

- Microbiological activity.

The effects of such pre-closure processes are usually accounted for in post-closure safety assessments implicitly, via the establishment of suitable initial boundary conditions. However, in order to justify this approach it may be necessary to conduct more detailed process-based modelling studies of the individual processes. Most pre-closure effects are transient and operate on similar time and length scales to those which can be investigated directly in URL experiments. Shaft sinking and repository construction operations may also provide opportunities to study such processes.

In conclusion, there is good understanding of the range of possible pre-closure processes that need to be considered, and reasonable approaches and sources of information exist with which to assess their effects. Assessments of repository safety need to take due account of the effects of pre-closure processes and this can be done explicitly (e.g., by defining the ‘time-zero’ initial condition as being the time of waste deposition rather than closure, and using FEPs analysis), but is more often done by defining suitable initial conditions at the start of post-closure safety assessment (NEA 2005).

### 2.3.2 Thermal Phase Processes

Particularly in repositories for spent fuel and high-level waste, heat from the waste will cause temperatures in and around the repository to rise significantly for a period after waste disposal (e.g., Figure 2.3). Repository temperature is, therefore, an important constraint on repository layout and EBS design.

Key factors affecting the magnitude and duration of the thermal phase in a repository include the heat output from each waste package, the spacing between the waste packages, the spacings between waste emplacement tunnels, galleries and drifts, the duration and efficiency of any storage, cooling and ventilation periods, the properties (e.g., thermal conductivities) of the EBS materials and the host rock, and any movement of heat that occurs by advection or evaporation and condensation of water (NEA 2005).

The heat output from the waste packages depends on a range of factors, including fuel burn-up levels and pre-disposal cooling periods, but these are usually regarded as parameters that determine the initial conditions for waste disposal, rather than being parameters that are set by the disposal programme.

Peak temperatures are likely to be attained in some tens of years following disposal and may remain significantly above ambient rock temperatures for several hundreds of years. Water may play an important role in the thermal history of the repository. For example, water flow into the EBS can increase thermal conductivity, thus reducing temperatures. Water flow is likely to be most significant for repositories in fractured hard host rocks. Less flow may be expected in mudstones or evaporites.

Other factors to be considered when assessing the thermal history and performance of a repository include the magnitudes of temperature and chemical gradients and the reactions that will occur in different places and at different times.

Figure 2.4 provides an example from the US waste disposal programme at Yucca Mountain that illustrates various thermo-chemical processes expected to occur in that disposal system.

In addition to couplings between temperature, water movement and chemistry, various mechanical effects will need to be considered. For example particularly in fractured host rocks, spalling may be sufficiently important to require the implementation of measures to minimise its impacts. The importance of the couplings between THMC processes are likely to be strongly dependent on the particular repository, host rock and design of the

EBS. The importance of rock creep, for example, will differ considerably between clay, granite and salt host rocks.

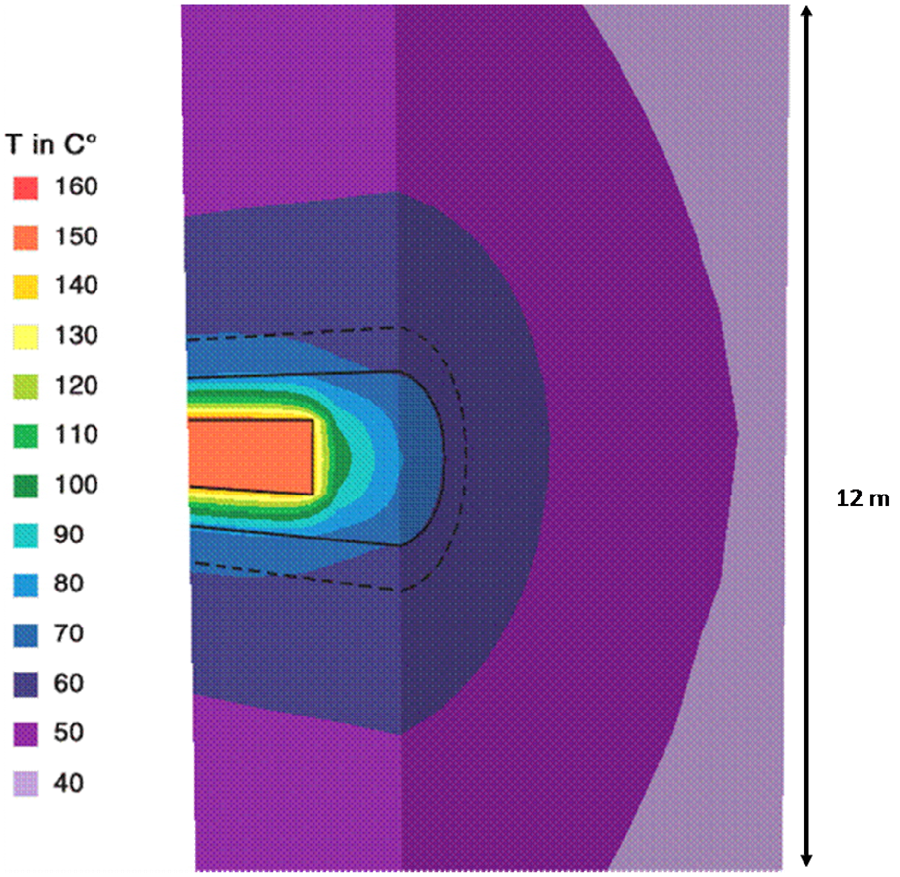


**Figure 2.3 Illustration of modelling results for the temperature field surrounding a UO2 spent fuel container ten years after disposal in a clay host rock (Johnson *et al*. 2004)**

### 2.3.3 Chemical Processes

This section looks briefly at key processes that can affect the corrosion of metallic engineered barriers (e.g., waste containers) and cause alteration of other, non-metallic, components of the EBS.

#### 2.3.3.1 Corrosion of Metallic Barriers

As noted above, copper, iron and steel are the main materials that have been proposed for spent fuel and HLW disposal container materials, although further alternatives (e.g., titanium) have also been considered. Iron and steels are also used routinely for the packaging of long-lived ILW. This section discusses the corrosion processes that may affect such materials under the environmental conditions that may be expected, given likely repository host rocks and groundwaters.

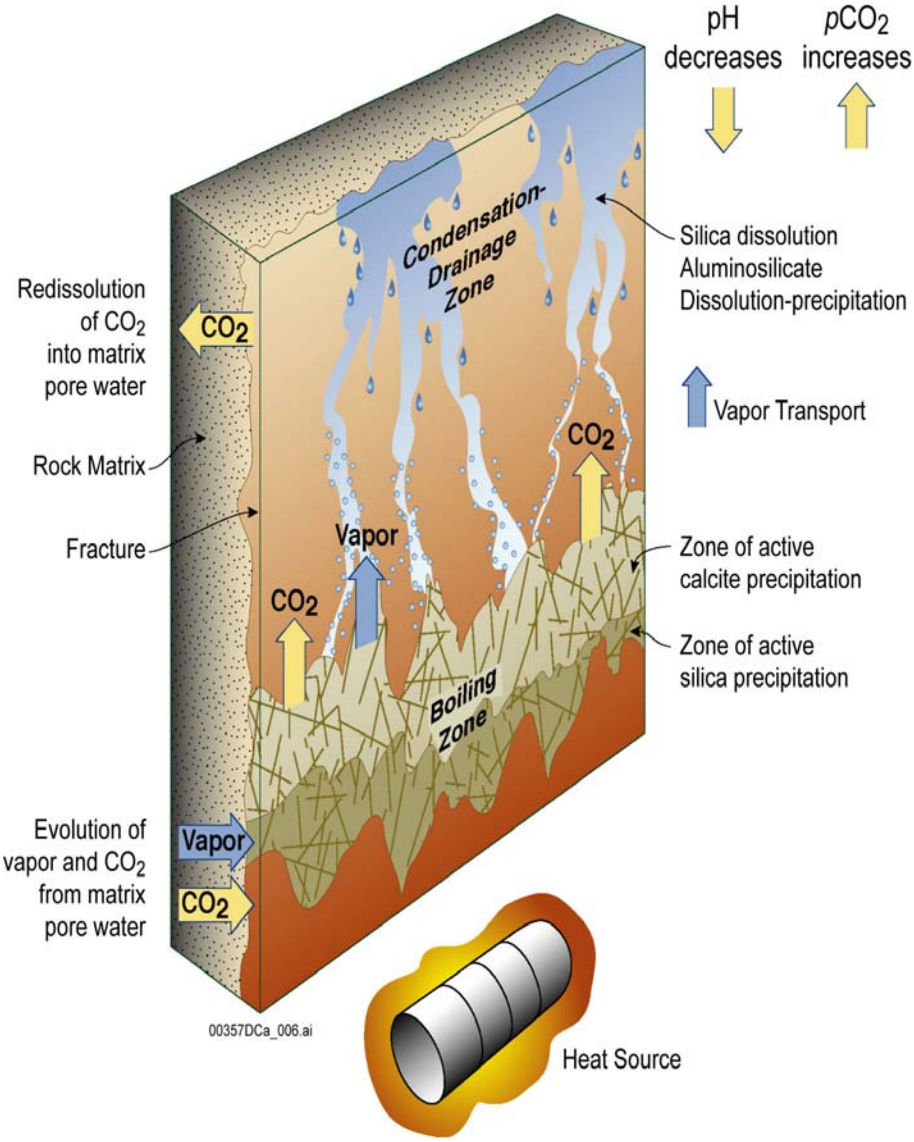


**Figure 2.4 Illustration of processes expected to affect the thermo-chemical evolution of the repository at Yucca Mountain (Van Luik 2004).**

Spent fuel and HLW disposal programmes are pursuing disposal options in which the primary waste container is designed, in conjunction with the surrounding EBS materials, to provide complete containment of the waste for at least the period when temperatures in the disposal system are significantly increased by radioactive decay. Such containers include the Swedish/Finnish KBS-3 copper canister (e.g., SKB 2006), the Belgian carbon steel overpack (Ondraf-Niras 2008), and the French steel overpack (Andra 2005).

Various types of corrosion have been addressed in safety assessments and related research and development studies (Table 2.1). The types of corrosion that occur will depend on the prevailing conditions and the materials in question:

- Materials including carbon steel, low-alloy steels, cast irons and copper in oxidising and sulphide containing environments corrode under the conditions expected during geological disposal, but do so at relatively predictable general corrosion rates. Such materials are sometimes described as corrosion-allowance materials.

- Materials including austenitic stainless steels, Ni-Cr-Mo alloys and titanium alloys passivate due to the formation of protective oxide films. These films considerably reduce the rate of general corrosion. Such materials are sometimes described as corrosion-resistant materials. For such materials, the risk of localised corrosion has to be considered because the protective films may break down locally (e.g., as a result of corrosive species dissolved in porewaters), and localised corrosion processes (such as pitting and crevice corrosion) may occur that can be much more rapid than general corrosion.

Where significant container lifetimes are required, it is necessary to allow for the effects of relevant corrosion (and other degradation) processes and to specify a sufficient thickness of material. Performance assessments can help to inform the selection of container material and the specification of container thickness. Such assessments can also be used to take account of the various couplings and feedbacks that may occur between processes in the disposal system. For example, hydrogen gas production from steel container corrosion may significantly reduce rates of spent fuel dissolution.

Based on a review of corrosion research findings and recent safety assessments (Bennett and Gens 2008), it is possible to identify some corrosion-related topics that represent remaining uncertainties. For example, in concepts that use longer-lived waste package / overpack combinations and corrosion-resistant materials (e.g. the copper canisters in the KBS-3 concept), it may be important to consider the potential for localised corrosion and stress-corrosion cracking.

Research and assessment of waste canister corrosion (e.g., Figure 2.5) may be an important part of the safety case, but it is also important to consider the complementary roles of the surrounding engineered barriers (e.g., the bentonite or concrete buffer) in protecting the canister and providing chemical conditions that will control corrosion processes. Some of the processes that can affect such barriers are discussed in the following section.

## Table 2.1 Corrosion processes

| Process | Description | Key factors |
|---|---|---|
| Atmospheric corrosion | Corrosion in air | Relative humidity, concentration of atmospheric pollutants, air flow rates |
| General (uniform) corrosion | Corrosion proceeding at almost the same rate over the entire surface of the metal when exposed to an aggressive aqueous environment | Presence or absence of oxygen, redox conditions and presence of other aggressive species |
| Crevice corrosion | Localised attack of a metal surface associated with, and taking place in, or immediately around, a narrow aperture or clearance formed between the metal surface and another surface | Geometry of crevice, size of cathodic area |
| Pitting corrosion | Localised attack of a metal surface resulting in pits, i.e. cavities extending from the surface into the metal | Geometry of pit, size of cathodic area |
| Stress corrosion cracking | Cracking of a metal caused by the simultaneous action of corrosion and sustained straining of the metal (due to applied or residual stress) | Residual stresses, applied load, size of surface defects, presence of stress concentrators, mechanical properties of the material, chemical environment |
| Intergranular corrosion – grain boundary attack | Localised corrosion (dissolution) in or adjacent to the grain boundaries of a metal which otherwise exhibits corrosion resistance | Material properties |
| Galvanic corrosion | An electrochemical process in which one metal corrodes preferentially when it is in contact with a different type of metal and both metals are in an electrolyte | Material combinations, relative areas, differential aeration cells |
| Microbially influenced corrosion (MIC) | Corrosion caused or promoted by microorganisms, usually chemoautotrophs. Can occur under aerobic or anaerobic conditions | Viability of microbial population under prevailing conditions, the presence of water and availability of nutrients |
| Hydrogen embrittlement | A process by which various metals, most importantly high-strength steel, become brittle and crack following exposure to hydrogen | Size of surface defects, presence of stress concentrators, mechanical properties of the material, sub-surface defects |
| Radiation influenced corrosion | Corrosion caused or promoted by radiation | Strength of gamma radiation field |
| Stray current corrosion | Corrosion caused by an external source of direct current – effects are similar to, but in some case more severe than, those of galvanic corrosion | Presence and strength of electrical currents |
| Corrosion due to magnetic fields | Corrosion caused or promoted by electrical currents induced by magnetic fields | Strength of electrical currents induced by magnetic fields |

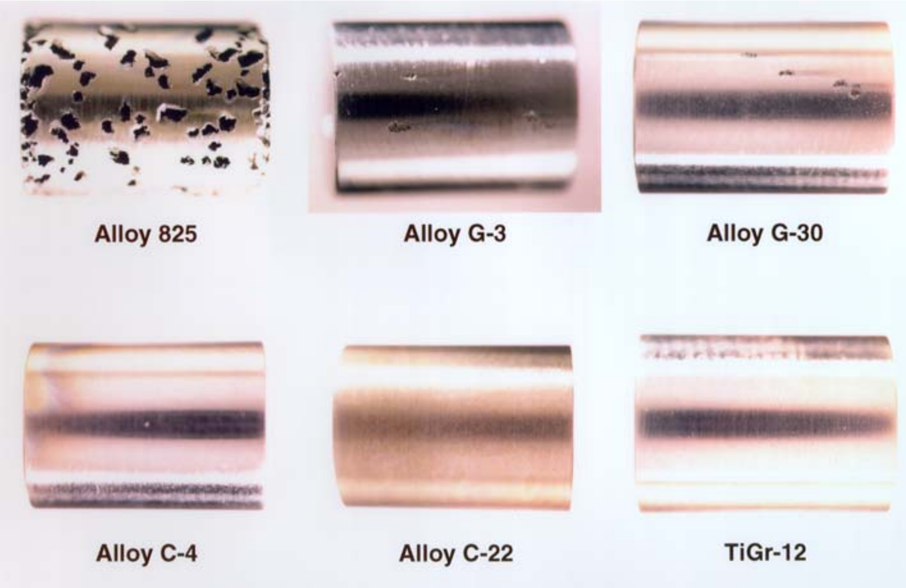


**Figure 2.5 The susceptibility to localised corrosion of different Ni-Cr-Mo alloys during tests of alternative the waste container materials in the US Yucca Mountain Project (Sevougian *et al*. 2006).**

#### 2.3.3.2 Geochemical Evolution and Alteration of Non-metallic Barriers

The expected geochemical evolution of the EBS will be affected by several factors; most notably temperature, reactions between EBS materials, and the chemistry of groundwaters flowing from the host rock.

Chemical processes are often strongly influenced by temperature. For example, different chemical reactions and chemical species occur at different temperatures. Reaction rates are also typically faster at elevated temperatures. Thermal gradients may also act as drivers for chemical transport. Thermal gradients may lead to the:

- Redistribution of water within the EBS and, in some cases, (e.g., at Yucca Mountain) boiling and condensation of water in the unsaturated zone, and in others (e.g., salt hosted repositories) the migration of brines.
- Mineralogical alteration (e.g., illitisation of clays) and other solid phase changes in EBS materials (e.g., development of more crystalline phases in cementitious materials).
- Redistribution of trace elements in clays.
- Precipitation of minerals at reaction fronts.

The importance of these thermo-hydro-chemical effects depends on the temperatures attained, the duration of the thermal phase, and the magnitudes of the thermal gradients.

An example of the type of mineralogical alteration processes considered during the EBS Project (NEA 2005) is the potential illitisation of the bentonite buffer in spent fuel and HLW disposal systems of the types being considered in Finland, Japan, Sweden and Switzerland. Illitisation of bentonite is a complex coupled effect that requires both elevated temperatures and a supply of potassium ions from groundwaters. The process also involves the transport of silica. Uncertainties relate to the details of the alteration processes and their kinetics, the availability and quality of thermodynamic and kinetic data, and the likely mass transfer rates. Typical approaches for assessing the potential extent and consequences of illitisation seek to bound mass-transfer rates by using simplified models and assumed kinetic rate laws. However, in addition to these uncertainties, it is important to assess how much barrier alteration can be tolerated in the disposal system of interest, given the defined functional requirements of the buffer.

Generally, unless fluid flow rates are high, the presence of even a moderately reactive solid phase will tend to buffer the chemistry of the associated pore fluids. For this reason heterogeneous fluid-solid reactions tend to lead to the formation of only limited narrow zones of alteration. This means that fluid-solid reactions may be taken into account during the repository design process by specifying that engineered barriers are sufficiently thick, as appropriate to the conditions and waters likely to be encountered in the repository environment.

Examples of changes that may occur between different EBS materials, include iron – bentonite interactions, and cement – bentonite interactions.

Iron – bentonite interactions may result from the corrosion of iron or steel which, under anaerobic repository conditions, releases Fe(II) species to the pore water. The subsequent interactions of Fe(II) species with bentonite, could potentially include:

- Saturation of ion exchange/sorption sites with $Fe^{2+}$ ions.
- Transformation of smectite to non-swelling sheet silicates.
- Perturbation of buffer physical properties, such as decreased swelling and/or increased hydraulic conductivity.

An essential feature of these interactions is that they are strongly coupled in a non-linear fashion, and a number of remaining uncertainties are undergoing investigation (Arcos *et al.* 2009; Johnson *et al.* 2009).

Cement – bentonite interactions involve various mineral dissolution, precipitation and alteration reactions that may cause temporal changes in the porosity, permeability and mechanical properties of the bentonite. The effects of cement on bentonite are mainly governed by the concentration of hydroxyl ions and the rate at which they enter the bentonite. There is a risk of bentonite alteration in regions of the buffer that are affected by a plume of high pH. The physical properties of the buffer may also be modified by cations (e.g. $Ca^{2+}$) entering the buffer. Over timescales relevant to post-closure safety, propagation of a high-pH plume into the buffer seems to be possible, but the extent of this and the potential consequences will depend on the disposal concept and the EBS design. The potential consequences of such interactions can be reduced through design, for example, by selecting appropriate masses or thicknesses of bentonite and concrete (NUMO 2004).

Further information on these and related topics may be found in the literature (e.g., Huertas *et al*. 2008).

## 2.4 The Role of Modelling

Assessing the performance of the EBS typically involves a variety of modelling studies. Modelling may be conducted for a range of purposes (e.g., to understand processes, to evaluate uncertainties in barrier degradation rates, to assess disposal system performance) and may be approached in various ways (e.g., by developing detailed or simplified models, by making realistic or conservative assumptions, by using deterministic or probabilistic models).

The role of modelling was the topic of the 2005 EBS Project workshop held in La Coruna, Spain. The workshop distinguished between process models, performance assessment models and safety assessment models.

### 2.4.1 Process Models

As the term implies, a process model provides a detailed representation of one or more physico-chemical processes. Such models may be used as part of, or to support, performance assessment and safety assessment, and to inform repository and EBS design studies.

Process models may be described as *empirical*, if they are based only on observations or data from experiments, without regard to mechanism or theory, or as *mechanistic*, if they are derived from accepted fundamental laws governing the behaviour of matter and energy. In practice, however, this distinction is often not clear cut because the development of mechanistic understanding involves experimentation, which may yield both fundamental laws and empirical data such as reaction rates.

Process models are commonly used to evaluate the performance of engineered barriers and engineered barrier systems. Examples of process models with a mechanistic character include thermodynamic chemical speciation and solubility models. These models can be used, for example, to assess the pH and chemical composition of pore waters in engineered barrier materials. They can also be used to calculate the solubility of radionuclides released from the waste.

Examples of process models that might be regarded as having a more empirical nature include the simple rate law models sometimes used in performance assessment codes for quantifying the corrosion of iron and steel waste containers. However, these models still sit within the context of a large body of research and knowledge on corrosion mechanisms, and it is this that justifies the simplification involved in using an empirically-based rate parameter, instead of a detailed modelling representation of the corrosion reactions themselves.

It is a necessity that basic aspects of the relevant mechanisms are known, but the level of detail to which the process must be broken down is something that needs to be carefully considered in terms of the relevant uncertainties. The level of detail of mechanistic understanding needed should be consistent with the overall importance of the process and sufficient that the uncertainties can be adequately assessed.

Factors affecting the choice of model include the availability of data and the ease of model justification. Mechanistic models may be more costly to develop in the short term, but are generally more widely applicable than empirical models, and may require less revision in the long term.

Process models can be used to increase and demonstrate understanding and thereby build confidence in the safety case. They can also be used to assess the significance of processes and thus may be used to provide support for the screening of FEPs within safety assessment.

Process modelling may also contribute by:

- Helping to understand features and processes observed in nature and at sites affected by anthropogenic activities.

- Allowing evaluation of alternative conceptualisations of FEPs.

- Allowing the development of relevant technical expertise, and demonstrating the competence of staff involved in work aimed at developing and reviewing safety cases.

- Supporting regulatory assessments of the safety case and demonstrating an appropriate level of regulatory competence and scrutiny.

- Proving a means of investigating the effects of process couplings.

Process couplings (e.g., hydro-thermal effects, bio-chemical effects) can lead to significant complexity when assessing EBS behaviour, particularly in disposal systems for heat-generating wastes, and there may be associated difficulties in explaining and communicating the results of such assessments. The strength and potential significance of each coupling varies over repository evolution, for example as radioactive decay and temperatures decrease.

In considering some aspects of disposal systems for spent fuel and HLW it has been found necessary to develop models that include all of the principal couplings between THMC processes because, for example, bentonite hydration leads to changes in pore water chemistry that in turn affect the mechanical and hydraulic properties of the buffer, and influence heat transfer. In other cases, for example when assessing a particular issue such as salt creep, it can be helpful to focus on individual couplings, in this case between thermal and mechanical processes. In yet other cases it may be possible to decouple the thermal processes because the prevailing thermal gradients are shallow at the point of interest. The general lesson, therefore, is that process couplings should be considered and need to be treated appropriately, according to the problem of interest.

Workshop discussions during the EBS Project suggest that capable two and three-dimensional modelling codes are available to simulate THMC processes in repository systems and the couplings amongst them. However, uncertainties inevitably remain, for example, in the availability of data with which to parameterise fully coupled THMC models, particularly at elevated temperatures. There are also issues associated with the application and testing of coupled process models over time and distance scales relevant to disposal system safety. As a result, the degree to which it is appropriate to incorporate such detailed process-based models directly within safety assessment codes has to be considered carefully, and it is sometimes appropriate to use the more detailed models separately for providing insights into, and demonstrating understanding of, disposal system behaviour.

### 2.4.2 Safety Assessment and Performance Assessment Models

Safety assessment is the process of assessing the performance of a disposal system as a whole, where the performance measure is radiological impact (e.g., potential dose or risk) or some other holistic measure of impact or safety. Although the terms are sometimes used interchangeably, it is generally accepted that performance assessment differs from safety assessment in that performance assessment can consider just parts of a disposal system, and does not necessarily involve the assessment of radiological impacts. For example, an assessment of the performance of a hydrological barrier might calculate water flux as a function of time and barrier evolution.

Performance assessment and safety assessment models are more than just tools for calculating assessment end-points such as potential dose or risk. Such models provide a means for integrating knowledge and information on the wide range of FEPs that may influence the behaviour of the disposal system and can, therefore, be used to illustrate and assess:

- Possible disposal system futures.

- The behaviour, evolution and performance of the wastes, the engineered barriers and other disposal system components.

- Routes that may lead to radionuclide release and exposure.

- Uncertainties and variability within the disposal system.

An important beneficial characteristic of performance and safety assessment models is that they can provide this *integrated* evaluation of a wide range of FEPs without being overly complicated. Performance and safety assessment models can, therefore, help to communicate understanding of potential disposal system behaviour, as long as adequate support can be demonstrated for the simplifications made in their development.

Within a safety assessment a sufficient range of calculations should be conducted to ensure that the effects of possible combinations of assumptions relating to scenarios, models and parameter values have been captured adequately. In doing this an assessment may include deterministic or probabilistic calculations, or a combination of approaches.

Safety assessment also provides a means for identifying and, to the extent possible, quantifying uncertainties in a clear and systematic manner. Sensitivity analyses should be conducted following a reasoned approach in order to identify the parameters that most affect the calculated performance of the disposal system.

Variability is a feature of natural systems, including the host rocks to geological repositories, and can be both potentially significant to disposal system performance and difficult to characterise sufficiently. For example, the task of characterising the spatial heterogeneity of fractured crystalline host rocks is not trivial, and the results of performance assessment and safety assessment for repositories in such host rocks can depend on the location of water bearing fractures and their relationship to the waste. Where variability is difficult to constrain owing to a lack of data, one approach is to account for variability within uncertainty analyses.

An important characteristic of safety assessment is that the assessment is progressively refined as further knowledge becomes available. Successive assessments should, therefore, provide a record of increasing disposal programme maturity, knowledge and understanding.

### 2.4.3 The Role of Modelling in EBS Design and Optimisation

Key to development and optimisation of repository and EBS design is a continual process, throughout the disposal programme, of iteration between detailed research and process modelling studies, performance and safety assessment studies, and engineering design studies. This process involves the simultaneous transfer, or communication, downwards of high-level system requirements, and upwards of detailed materials and process understanding and performance assessment results, coupled with the periodic conduct of safety assessments, which integrate the various different types of information. The process is necessarily multi-disciplinary and, therefore, involves communication between different teams of staff and wider stakeholder groups over considerable periods of time.

The development and maintenance of expertise in safety and performance assessment is key to establishing detailed designs for the repository and the EBS that meet the various requirements. The maintenance of such expertise is particularly important where repository development and waste disposal projects will last for several decades. Good integration is also necessary across the disposal programme covering the work of scientists, safety assessors and engineers contributing to the design.

The role of modelling in this process can be to help guide EBS design work by illustrating barrier evolution and by determining the significance of barrier degradation to overall disposal system performance. Modelling can also assist EBS materials selection, and be used to assess interactions between EBS materials.

It is important to recognise that the degree to which repository design is optimised will depend on the status of the repository development programme. In the early stages of a disposal programme, the aim may be to use existing information and expert judgement to describe a design that is feasible. With successive safety assessments, interspersed with appropriate research and development and process modelling, the design may be refined as the repository development programme progresses, and a closer approach to optimisation should be achieved.

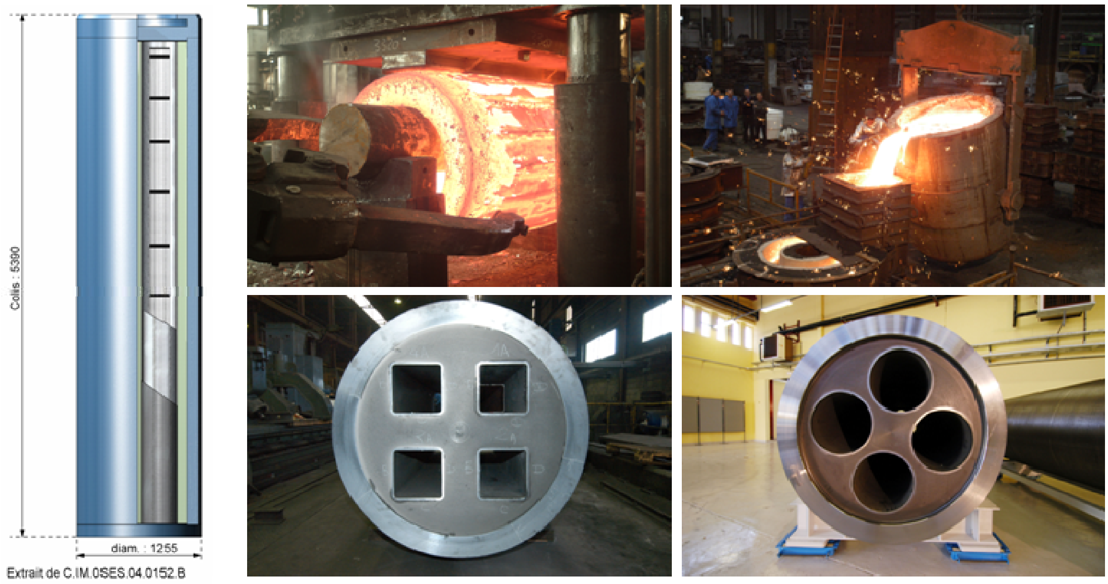
This process of refinement need only be taken so far that an acceptable design is reached. Several alternative designs may provide a sufficient level of safety, and the key is to consider these alternatives together with other relevant factors and come to a wise licensing decision. Thus, performance assessment and safety assessment modelling on their own are unlikely to be the deciding factor in choosing between different, but inherently safe, disposal concepts.

## 2.5 Design Confirmation and Demonstration

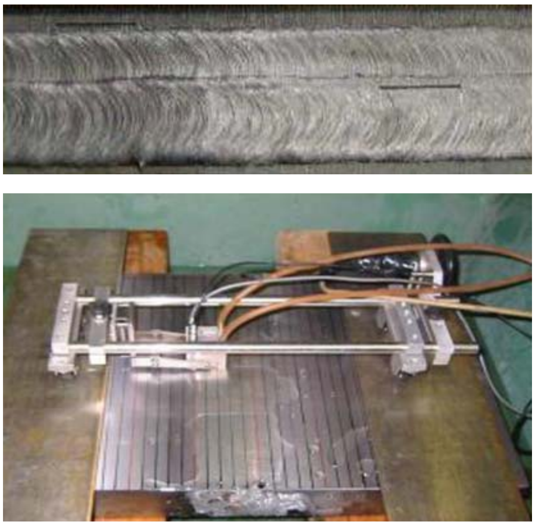
Design confirmation and demonstration was the main topic of the 2006 EBS Project workshop held in Tokyo, Japan. The workshop considered the roles of laboratory and URL experiments, of quality assurance testing and monitoring of EBS components, and the relationships between such design confirmation activities and performance and safety assessment and the rest of the optimisation cycle (Figure 1.1).

### 2.5.1 Feasibility Demonstration Trials

A range of national and international studies has, in broad terms, demonstrated the feasibility of manufacturing and installing/emplacing the various EBS components in the underground (e.g., the EC ESDRED Project, e.g., DeBock *et al.* 2006; Seidler 2009). Figure 2.6 shows tests and trials of the manufacture, testing and installation/emplacement of spent fuel canisters, of bentonite buffer rings and blocks, and of tunnel backfills and plugs. It is recognised that more testing remains to be done to address particular aspects of some disposal systems and concepts, and such work is expected to continue during the period leading up to waste disposal.



Steel canister manufacture (France)



Canister weld inspection (Japan)

Canister emplacement (Germany)

The KBS-3H supercontainer and emplacement machine (Sweden)

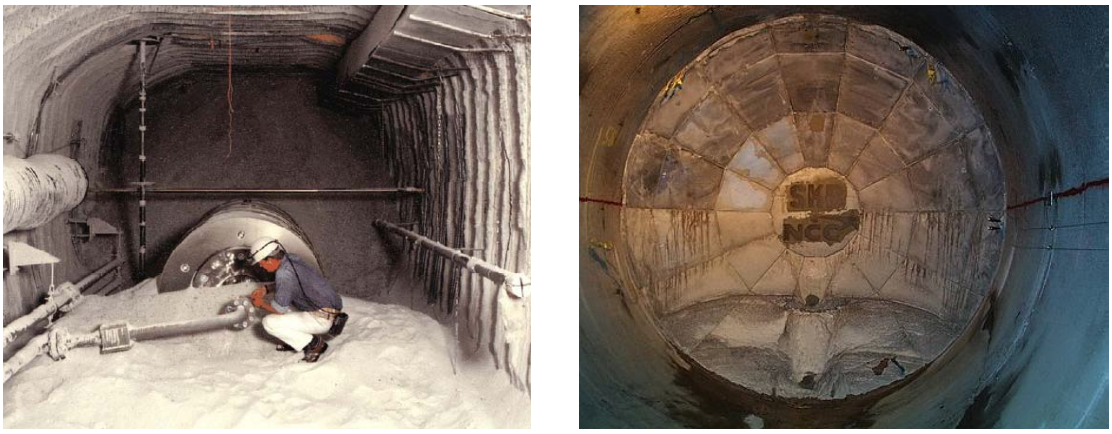
**Figure 2.6 Examples of EBS component manufacture, testing and installation.**

Bentonite buffer ring manufacture (France)

Bentonite buffer ring emplacement (Sweden)

Bentonite buffer blocks (Spain)

Granular backfill emplacement (Switzerland)



Crushed salt backfill (Germany)

Concrete tunnel plug (Sweden)

**Figure 2.6 (cont.)** **Examples of EBS component manufacture, testing and installation.**

One of the most challenging aspects of the work is the large scale and weight of the EBS components and the large volumes of materials required. The large scale of the EBS components, particularly of the waste containers and supercontainers (see Section 3.2), also means that is has been necessary to develop special tools for waste handling and emplacement. During the course of the EBS Project, both air cushion and water cushion technologies for lifting and moving large mass objects have been tested successfully within the EC ESDRED project (Seidler 2009).

The high radioactivity of the wastes means that appropriate shielding and equipment control systems will be required; this has been factored into the engineering designs for the relevant equipment, but is still an area of on-going development.

### 2.5.2 Quality Assurance of EBS Manufacture and Installation

A range of activities may be used to check that the materials and manufactured components of the EBS meet relevant quality and acceptance standards. For example, various techniques (e.g., radiographic and ultrasonic imaging, and eddy-current testing) may be used to assess the suitability of waste containers and welds, as part of a sequence of activities that leads from the disposal concept, the identification of canister material and welding requirements, to performance and safety assessment (e.g., Ueda *et al.* 2006):

- Identify the requirements of the canister.
- Assess the quality / appropriateness of possible welding methods for canister closure.
- Identify, test and apply non-destructive examination techniques.
- Quantify the number and nature of initial flaws in the canister and weld joints.
- Investigate the corrosion properties of the canister and weld joints.
- Conduct performance and safety assessments to determine the long-term integrity of the canister and consider its implications.

Checking of the quality of supplies of materials used to form EBS components (e.g., of the clays that are to be used for the buffer and for backfilling of tunnels in some disposal concepts) will also need to be conducted, and the approach taken to this may influence the degree of programmatic flexibility to use different sources and suppliers of such materials.

### 2.5.3 Monitoring of the EBS

The relevance and potential role of monitoring within radioactive waste disposal is a wide ranging topic (e.g., EC 2004). Discussions during the EBS project workshops did not attempt to address all aspects of monitoring. Although monitoring may be carried out for non-technical reasons, for example related to public re-assurance, the EBS project focused, in the main, on the technical aspects of monitoring that relate to the EBS characterisation and assessment perspectives (Section 1.2.4).

The discussions confirmed earlier findings that the various disposal programmes are following a range of approaches to monitoring. A common guiding principle, however, is that any monitoring system should not jeopardise operational safety, barrier performance, long-term safety, or the ability to make the safety case (for example by increasing the possibility of preferential radionuclide migration pathways - EC 2004). Where the monitoring of engineered components is part of the objectives of the monitoring programme, then several strategies are available to avoid compromising performance and safety.

A large portion of any monitoring programme is expected to be performed during the early phases of repository development, i.e. during pre-construction, construction, and during repository operation. Monitoring activities performed after waste emplacement should help to support the societal decision making process eventually leading to repository closure, and should help in building confidence in the safety of the disposal system.

Parameters that might be monitored in URL tests and/or repositories for HLW, spent fuel and long-lived ILW might include, for example (EC 2004):

- Convergence of the rock around underground openings.
- Evolution of the temperature field inside the disposal tunnels and the surrounding rock mass.
- Resaturation rates and swelling pressures in bentonite-based materials (backfills, buffers, engineered seals).
- Corrosion and gas production rates.
- Geochemical processes (e.g., pyrite oxidation, cement carbonation).

Information on monitoring presented at the EBS Project workshops came largely from the experience of monitoring activities performed during site investigations and particularly from experiments in URLs. An important practical issue concerns the development and operation of measuring instruments and transmission lines that are sufficiently reliable over potentially long monitoring periods in relatively hostile environments. Several examples were given of instrument failure after a few years in the underground. Additional relevant evidence can be gathered from outside the radioactive waste disposal field, for example, from the monitoring of large engineered structures, such as dams and underground openings, which has taken place over many decades (EC 2004).

The main contribution of monitoring to performance assessment is indirect - an indication that the physico-chemical evolution of the near-field and the EBS are progressing as envisaged. Questions that can usefully be answered by performance assessment, supported by monitoring, include for example: does the backfill become saturated at the expected rate and do the redox conditions evolve from oxidising to reducing at the expected rate?

EC (2004) suggests that monitoring to assist performance assessment should concentrate on:

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

### 2.5.4 Long-Term Performance Experiments

It is important to distinguish between feasibility demonstration trials and experiments designed to increase understanding of the long-term performance the EBS and its components. Experiments on the long-term performance of EBS component are essential because these provide information on the processes and effects that may occur after EBS construction and emplacement. Together with appropriate modelling studies, such experiments allow us to go beyond the question of '*can it be built?*' to address the more important question of '*will the barriers perform well enough to provide long-term safety?'*

A combination of modelling and experimental work is necessary because even though experiments can be conducted over several years, or possibly a few decades, it is not possible to access directly by experiment the much longer timescales (thousands of years) of interest in radioactive waste disposal safety assessment.

Examples of large-scale long-term experiments that have considered the long-term performance of engineered barriers include:

- The Tunnel Sealing Experiment performed in the Canadian URL (Martino *et al.* 2007) (Figure 2.7).
- The German Salzdetfurth Shaft II seal experiment (e.g., Müller-Hoeppe *et al.* 2007).

- The Full-scale Engineered Barriers Experiment (FEBEX) and the Gas Migration in EBS and Geosphere (GMT) experiment performed in the Swiss URL at Grimsel (www.grimsel.com).

- The Prototype Repository, and Backfill and Plug experiments performed in the Swedish URL at Äspö (e.g., Gunnarsson 2006) (Figure 2.7).

Information from this type of experiment can be supplemented with information from smaller-scale laboratory experiments and with information from theoretical studies and studies of systems including materials that are analogous to those of the engineered barriers. For example, studies of naturally-occurring clays or metal deposits (e.g., native copper or uranium ores) may provide more information on the *processes* that affect such materials over longer timescales than are accessible in laboratory or URL experiments. Similar studies may also be made on man-made structures, such as old cements and concretes, and on archaeological artefacts.

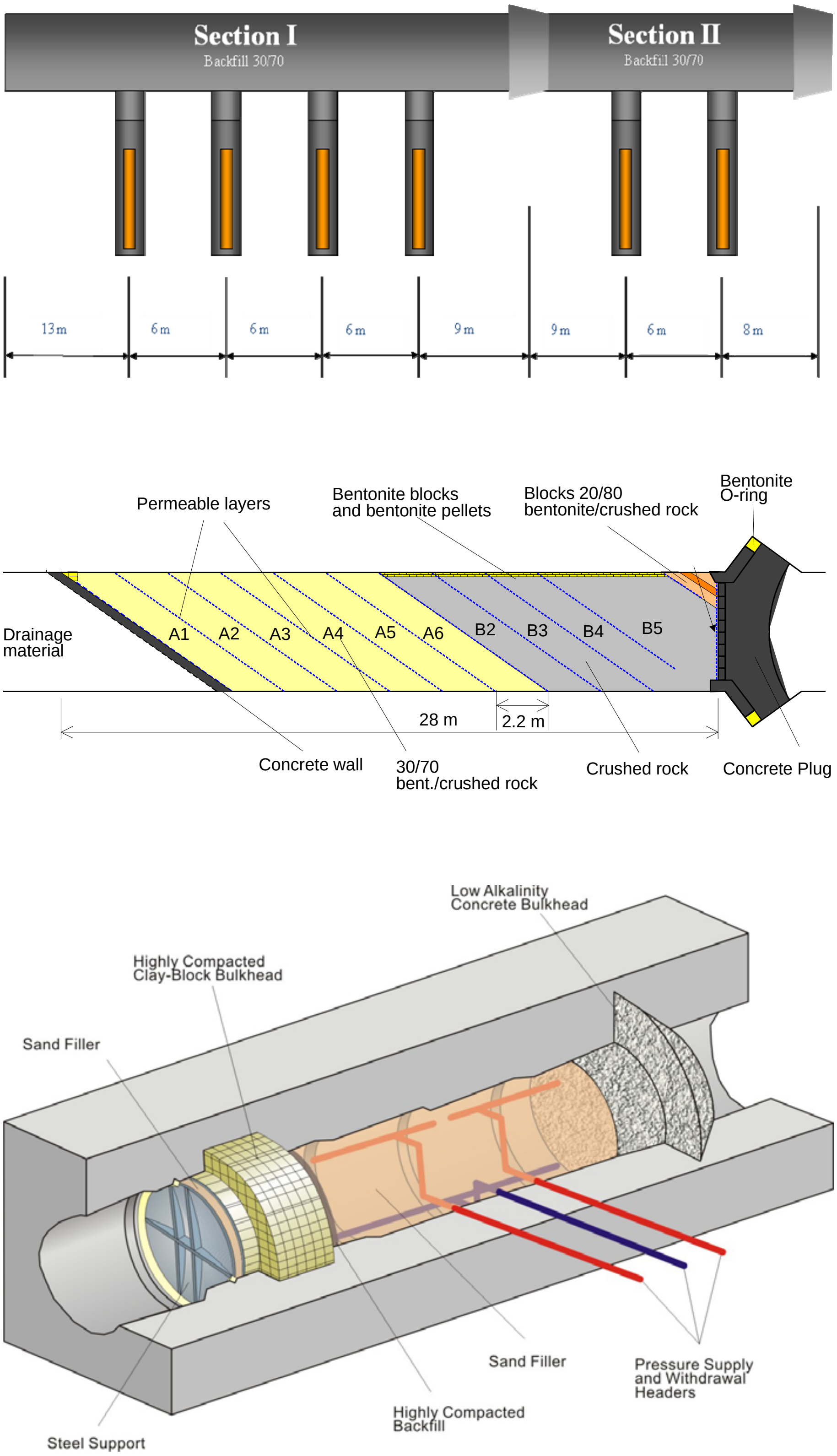


**Figure 2.7** **The Prototype Repository Test (top), Backfill and Plug Test (middle) (SKB 2003), Tunnel Sealing Experiment (bottom) (Martino *et al*. 2007).**

# 3 Examples of EBS Design and Assessment

This section presents several examples to illustrate the process of EBS design and optimisation through development of the safety case.

## 3.1 Canister example

This example looks at the development within the US programme of the design of the EBS and, in particular, of the canister for the disposal of spent fuel in the fractured, and partially saturated, crystalline rocks at Yucca Mountain (Figure 3.1). The example highlights the importance of using performance assessment to guide design reviews, and possible roles of a Performance Confirmation programme.

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 assessment. In addition, the applicable regulations have evolved significantly. The current regulation, US Nuclear Regulatory Commission (NRC) Regulatory Requirement 10 CFR Part 63, is a performance-based regulation that focuses on overall disposal system performance, and requires the US Department of Energy (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 contain the waste.

The evolution of the EBS design during the Yucca Mountain Project is summarised in Box 1 (Mohanty and Ahn 2006).

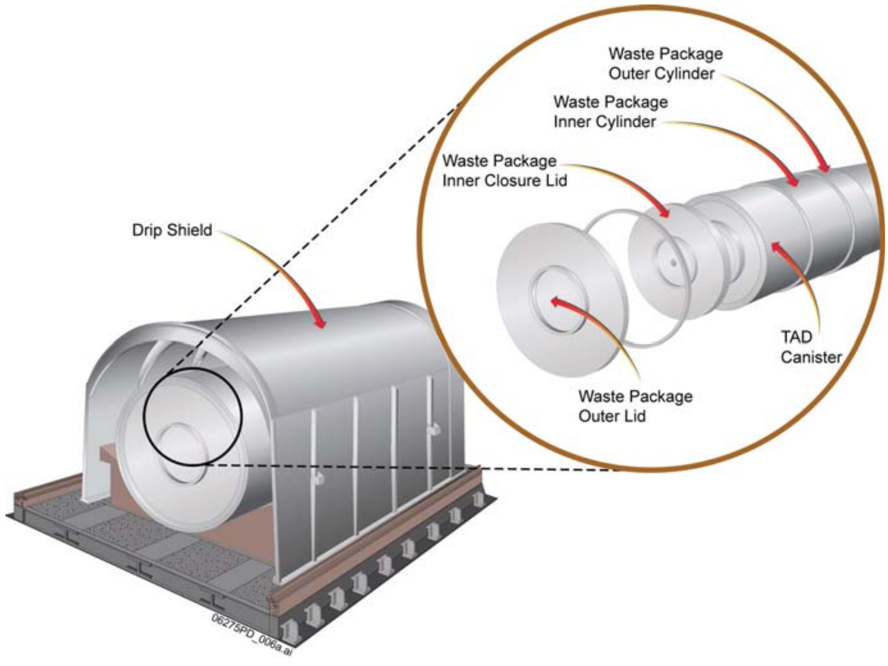


**Figure 3.1 Illustration of the EBS design for HLW and spent fuel disposal at Yucca Mountain, US (USDOE 2008).**

### Box 1 Evolution of the EBS design during the Yucca Mountain Project

In the late 1980's, the concept envisaged involved the disposal of more than 50,000 relatively thin-walled waste packages made from metals, ceramics or composites with a design life of 300 years. Several alternative waste emplacement configurations were considered, including within short or long vertical or horizontal boreholes, possibly with the use of chemical buffers and/or shielding materials. Assessments indicated that the longer boreholes might not be structurally stable, and that waste handling might be difficult unless the waste packages were disposed of at a spacing that would not give ideal repository temperatures.

By 1992, therefore, the waste emplacement concept had changed from the disposal of a large number of relatively small, thin-walled waste packages in boreholes, to the disposal of fewer (~10,000), larger waste packages in horizontal drifts. The 1992 design included a more stable excavation architecture, allowed for easier waste handling, and was also easier to represent in performance assessments.

The 1998 Viability Assessment emphasised longer waste package design lives and containment times, and evaluated several different waste package materials. Fundamental research was conducted on the corrosion behaviour of several alloys (Figure 2.5) and this led to selection of a waste package comprising a 20 mm-thick Alloy 22 inner shell for corrosion resistance, and a 102 mm-thick carbon steel outer shell for structural strength and corrosion allowance. Titanium drip shields were included in the EBS design to prevent water dripping onto the waste packages. Titanium was chosen because it was considered beneficial that the drip shields should be made of a different type of alloy than the waste packages, so that the packages and drip shields would not suffer from a common failure mode.

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. Putting the Alloy 22 component on the outside of the waste package was designed to make the package even more resistant to corrosion.

Since 2005, US DOE has been considering use of a Transport, Aging, and Disposal (TAD) canister, comprising a stainless steel inner barrier to provide strength and an outer barrier consisting of Alloy 22 (Figure 3.1). Waste spent fuel would be placed in the TAD canister at the power plant, and this would then be placed inside the disposal package. Aims of using the TAD canister include eliminating repetitive waste handling activities, and simplifying facility design and operations. The TAD canister design was included in the recently submitted Licence Application.

Performance assessments have been conducted by US DOE and, independently, by the US NRC at each stage of the programme, and this has allowed the development of staff competence, has informed and helped guide the EBS design process, and has facilitated operator-regulator dialogue.

For example, US NRC assessments showed a substantial drop in the fraction of the waste package failing due to localised corrosion by changing from Alloy 625 to Alloy 825, and that by changing to Alloy 22, there should be no localised corrosion failures during the first 10,000 years after closure of the repository (Figures 2.5 and 3.2).

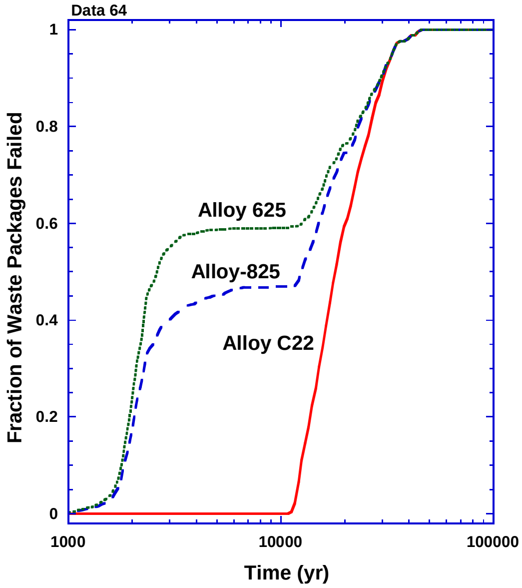


**Figure 3.2 Performance assessment results showing the impact of selecting different waste package materials (Mohanty and Ahn 2006).**

Key lessons from the Yucca Mountain project have included the importance of using performance assessment to guide design reviews. However, post-closure performance assessments are not the only driver for design change, and modelling of long-term performance is not considered sufficient on its own. The applicable regulations, therefore, also require a Performance Confirmation programme of experiments and other activities to confirm the assumptions, data, and analyses that led to findings permitting construction of repository and subsequent emplacement of waste.

Briefly, the Yucca Mountain 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 will function as intended

- Evaluate the effectiveness of design features intended to perform a post-closure function during repository operation and development

- Monitor waste package condition.

## 3.2 Buffer example

This example summarises the main design features and roles of the bentonite-based buffers in the Finnish, French, Swedish and Swiss concepts for spent fuel disposal. Bentonite consists mainly of the smectite mineral montmorillonite, which has a characteristic property of swelling on contact with water. The example highlights how safety functions can be used to improve links between EBS component design and performance and safety assessments. The three cases considered below vary in how much they quantify design requirements as parameter values in safety and performance assessments. They also show that different engineering solutions can be used to fulfil rather similar design requirements.

In France the concept for spent fuel disposal involves use of a bentonite clay buffer (Figures 2.6 and 3.3). In this case it is planned that the buffer will be emplaced in horizontal tunnels and will surround a 55-mm thick carbon steel over-pack containing the primary waste package (Andra 2005; de Bock *et al.* 2006).

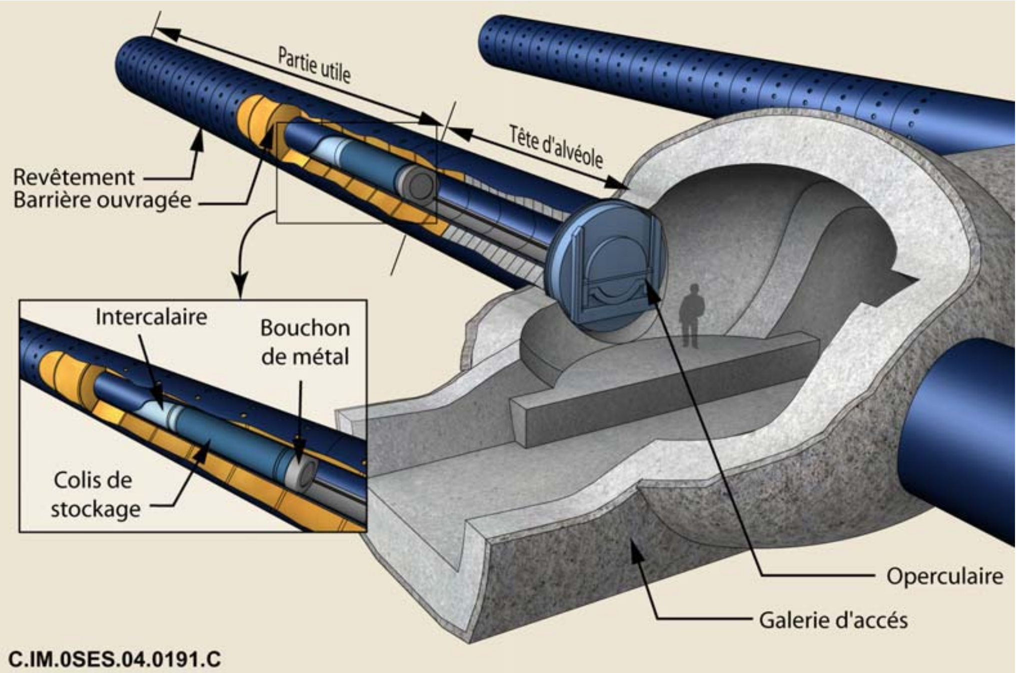


**Figure 3.3 The French concept for spent fuel disposal (Andra 2005)**

In the French design the principal functions of the EBS are (Andra 2005; de Bock *et al.* 2006) to:

- Maintain the favourable properties of the host rock and limiting perturbations. This involves dissipating heat, limiting mechanical deformations in the host rock, protecting the repository from chemical perturbations induced by alteration of certain waste packages, and maintaining sub-criticality conditions.

- Prevent water circulation, for example by using multiple seals and a ‘dead end’ repository layout (see Andra 2005).
- Limit radionuclide release and immobilise radionuclides in the repository. This involves delaying the arrival of water at the waste, limiting the transport of dissolved species near the spent fuel, maintaining chemically reducing conditions and limiting radionuclide dissolution, and filtering colloids.
- Delay and attenuate radionuclide migration towards the environment.

A natural Na-bentonite of Wyoming type (MX-80) has been considered as reference buffer material. A ‘phenomenological analysis’ has been conducted to assess the effects of the various processes that may occur in the disposal system and influence the properties and ability of the buffer to fulfil the required functions. Various practical tests and trials of buffer ring manufacture and handling have also been conducted (e.g., Figures 2.6 and 3.6).

Finland and Sweden are developing the so called KBS-3 disposal concept for spent fuel. In the KBS-3 concept, copper canisters with a cast iron insert containing spent nuclear fuel will be surrounded by a bentonite clay buffer and deposited at approximately 500 m depth in saturated, granitic rock (e.g., SKB 2006).

The buffer is deposited as a series of bentonite blocks below and above the canister and as rings surrounding the canister (Figure 3.4). Each bentonite unit is about 500 mm high and has a diameter of 1,690 mm. The thickness of the rings is 315 mm.

Two different types of bentonite have been considered as reference buffer materials; a natural Na-bentonite of Wyoming type (MX-80) and a natural Ca-bentonite (Deponit Ca-N) from Milos. However, the actual source of the clay to be used has not been firmly decided, potentially leaving flexibility to use any clay that meets the design functions and requirements.

SKB (2006) suggests that to prevent advective transport, the hydraulic conductivity of the buffer in the Swedish KBS-3 disposal system should be less than $10^{-12}$ m/s, and that to ensure that the buffer is sufficiently homogeneous, the swelling pressure should be greater than 1 MPa at all locations within the buffer.

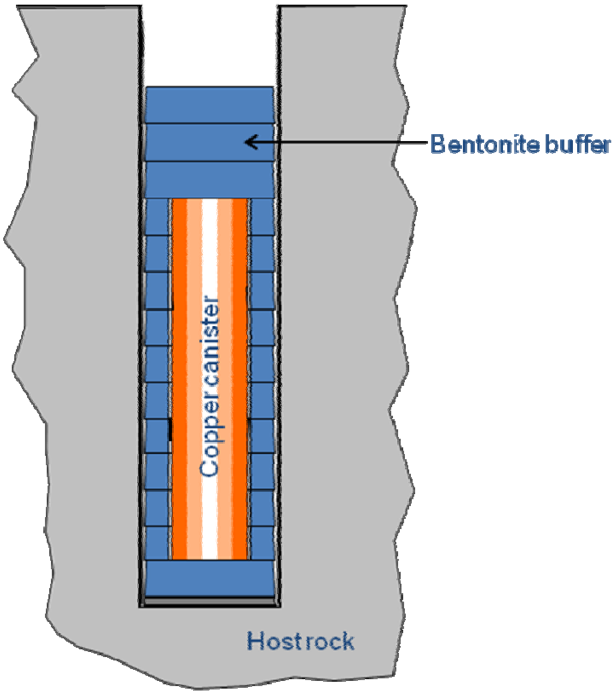


**Figure 3.4 The KBS-3 canister and buffer. After Gunnarsson (2006)**

These properties of the buffer (hydraulic conductivity and swelling pressure) are described as 'safety function indicators' and the quantitative constraints as 'safety function indicator criteria'. Other safety function indicators and criteria that have been proposed for the KBS-3 buffer are (SKB 2006):

- The temperature of the buffer should remain between -5 °C and 100 °C, in order to avoid freezing and limit chemical alteration of the clay.
- The swelling pressure should be greater than 2 MPa at all locations to prevent bacteria surviving.
- The swelling pressure should be greater than 0.2 MPa to prevent sinking of the canister.
- The density of the hydrated buffer should be less than 2,050 kg/m3 in order to protect the canister from rock movements, particularly rock shear.

Thus the key overall aim in the manufacture of the bentonite blocks and rings and their subsequent deposition is to achieve an appropriate final density in the water–saturated buffer. The density requirement for the saturated buffer is 1,950–2,050 kg/m$^3$. The bulk density is dependent on the gaps at the time of deposition between the canister and buffer and between buffer and the host rock.

The gap between the canister and the buffer is nominally 5 mm wide and that between the buffer and the rock is 30 mm. These gaps may be filled with bentonite pellets to limit, although probably not eliminate, the effects of thermal spalling of the host rock and limit the possibility for pieces of rock to fall from the deposition hole wall.

In order to ensure that the buffer can fulfil its various safety functions, it is also necessary to take account of the range of host rock conditions that may be encountered in the repository during buffer installation. At some locations waste deposition holes may be relatively dry, while at others there could be significant water inflows via fractures. A combination of site investigation and performance assessment studies will, therefore, be necessary to determine which locations are suitable, given the distribution of fractures and water flows.

The Swiss design for spent fuel disposal includes a different buffer system design from the block and ring-based designs described above, as it comprises the use of bentonite blocks to support waste canisters which would be placed horizontally along the repository tunnel, in conjunction with highly-compacted granular bentonite material to fill the surrounding void space (Nagra 2002).

In this Swiss design, the bentonite buffer has the following functions:

- To keep the canisters in place and protect them by providing a homogeneous stress field.
- To stabilise the waste deposition tunnels in a mechanical sense.
- To provide a suitable geochemical environment.
- To limit microbial activity.
- To ensure low corrosion rates of both the canister and the waste form.
- To act as a transport barrier to radionuclides and colloids.
- To prevent human intrusion.

In order to fulfil these functions, it is necessary that at least a significant part of the bentonite is not altered in an unacceptable way as a result of high temperatures or through chemical interaction with groundwaters, the host rock or any canister corrosion products. From these general qualitative requirements, several quantitative requirements can be specified:

- The thermal conductivity of the unsaturated buffer, $\lambda_{\text{Buffer}} \geq 0.4$ W/m/K.

- The hydraulic conductivity of the buffer, $k \leq 10^{-12}$ m/s.
- The buffer should achieve a swelling pressure in the range between 2 MPa and the minimum principal *in-situ* stress component.

Nagra (2002) expect that these requirements can be met using pure bentonite buffer materials if the average *dry* density of the buffer material lies in the range between 1,300 and 1,600 kg/m$^3$. The feasibility of the proposed design has been tested within the URL at Mont Terri and, more recently, some large scale emplacement tests to verify certain proposed improvements and optimize the backfilling technology have been conducted as part of the EC ESDRED project (e.g., de Bock *et al.* 2006; Figure 2.6).

## 3.3 Supercontainer example

This example looks at a relatively recent trend that has been seen in several spent fuel and HLW disposal programmes (e.g., Belgium, Finland, Japan, Sweden) towards adoption of concepts that include ‘supercontainers’. The key feature of these concepts is that the waste, waste container, overpack and buffer are all assembled within a metal shell, or envelope, prior to disposal as a supercontainer. The example highlights the role of process understanding and peer review of a developing safety case as factors motivating a significant design change. The example also illustrates use of multi-criteria decision analysis, supported by research and technology development studies, in design change.

The Belgian radioactive waste management organisation, Ondraf-Niras, had assessed a preliminary reference design for the disposal of vitrified HLW and spent fuel dating from the 1990s (DePreter *et al.* 2005). The design was described in detail in the main SAFIR 2 report (Ondraf-Niras 2002). In the SAFIR 2 design, the disposal tunnels for HLW were lined with concrete and a clay-based buffer surrounded a centralised steel tube into which the waste container and steel overpack would be placed (Figure 3.5).

The SAFIR 2 report identified some weaknesses in the EBS design, which were subsequently confirmed by an NEA peer review (NEA 2003b). In particular, it was considered possible that complex local chemical conditions could promote certain types of corrosion that might threaten the integrity of the overpack during the thermal phase. Experience with the mock-up experiment OPHELIE, and preparations for a large scale *in-situ* heater test, also questioned the practicality of implementing the SAFIR 2 design. These questions related mainly to stress and deformation caused by thermal expansion of the centralised steel tube, and the difficulty of transport and emplacement of an unshielded overpack within the disposal galleries (DePreter *et al.* 2005).

In response to the concerns over the SAFIR 2 design, Ondraf-Niras conducted a review of corrosion and materials issues relevant to the EBS design (Ondraf-Niras 2004a). This review recommended consideration of a

Contained Environment Concept which led to a revised design involving a supercontainer.

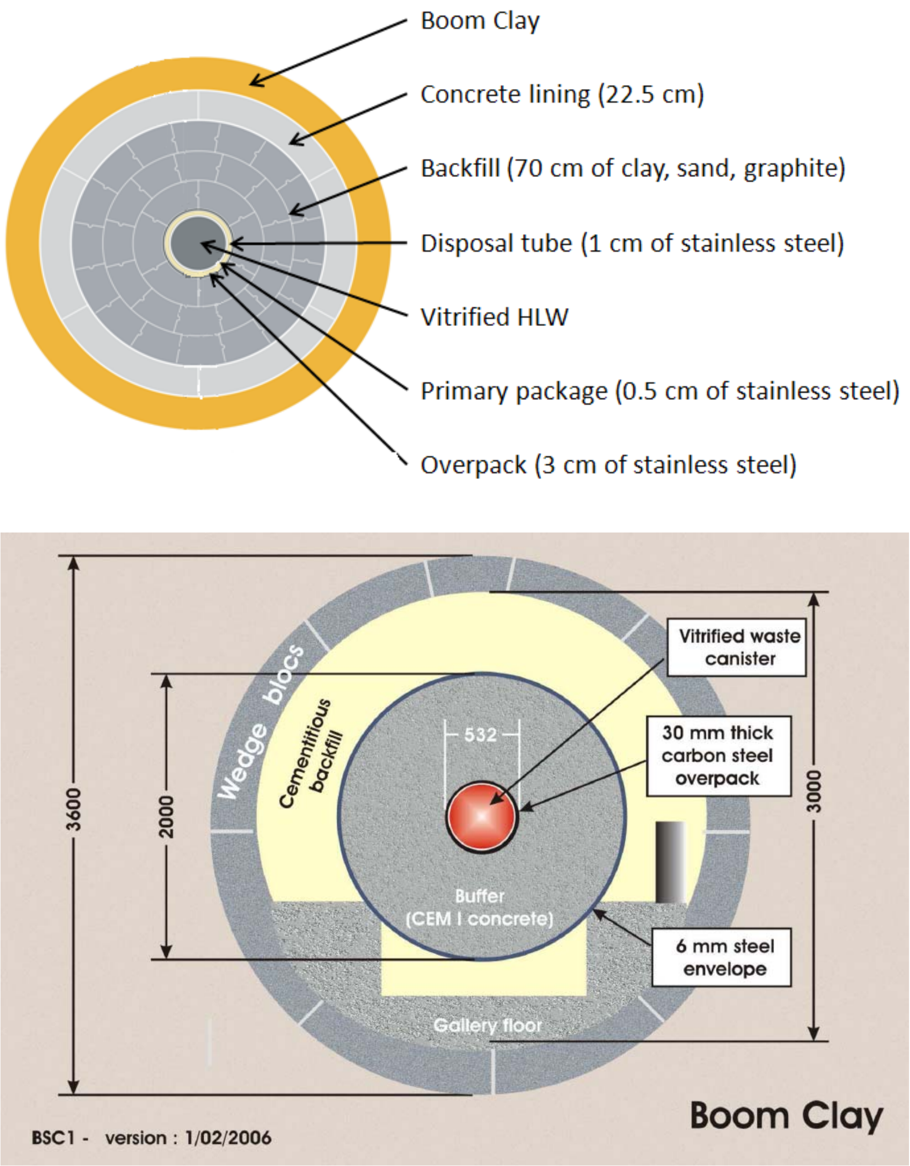


**Figure 3.5 Cross-sections through two EBS designs for disposal of Belgian HLW and spent fuel. Top - the earlier SAFIR 2 design (Ondraf-Niras 2002). Bottom - the later supercontainer design. The supercontainer comprises the stainless steel envelope, the concrete buffer and the carbon steel overpack (Ondraf-Niras 2007).**

In the revised Belgian design the supercontainer comprises a cylindrical container comprising three main components: a stainless steel envelope, a Portland cement concrete buffer and a carbon steel overpack.

- The overpack contains the canisters of vitrified HLW or the spent fuel assemblies, and its primary function is to prevent the release of the radioactive waste throughout the thermal phase.

- The primary function of the concrete buffer is to provide a high-pH environment around the overpack during the thermal phase in order to limit the corrosion rate. Additional functions of the buffer are to provide radiological shielding and to provide a low-hydraulic conductivity environment that slows the infiltration of external fluids to the overpack surface.

- The primary function of the stainless steel envelope is to provide mechanical strength and thereby facilitate fabrication of the buffer and handling of the supercontainer. The envelope may also prevent water ingress from the host rock for a time, and might also facilitate monitoring by allowing instrumentation to be attached to the external surface of the supercontainer. However, no reliance is placed on the envelope for ensuring long-term radiological safety.

Once emplaced in the repository, the supercontainer would be surrounded with a cementitious backfill (Figure 3.5).

Ondraf-Niras included the supercontainer in a multi-criteria decision analysis, which compared several alternative EBS designs (Ondraf-Niras 2004b). Advantages of the supercontainer design that influenced its selection over other possible designs included excellent corrosion protection for the carbon-steel overpack, inherent radiation shielding, easier construction and quality assurance of construction, fewer underground operations, and use of well-known, relatively inexpensive and widely available materials (Ondraf-Niras 2004b).

Subsequent efforts have focused on elaborating and building further confidence in the supercontainer design, and Ondraf-Niras is currently working to conduct a full safety assessment based on the supercontainer design.

The Finnish and Swedish programmes are also considering use of a supercontainer as an alternative method for implementing the KBS-3 disposal concept. In the KBS-3H alternative, wastes would be disposed of in horizontal tunnels in supercontainers. That is each canister is pre-packaged in a special assembly, called a supercontainer, which consists of a perforated steel shell cylinder containing the canister and the bentonite clay buffer (Autio *et al.* 2007; SKB/Posiva 2008; Smith *et al.* 2007). This contrasts with the reference KBS-3V design in which waste containers would not be contained in supercontainers, but would be disposed of in vertical deposition holes drilled in the floors of larger horizontal tunnels (see above). The KBS-3V design involves assembly of the buffer around the waste container in the underground, partly after emplacement of the container in the deposition hole (e.g., Gunnarsson 2006).

According to SKB (2008b), some of the main motivations for considering the KBS-3H design alternative include:

- KBS-3H has been shown to be feasible (e.g., Figure 2.6) and to offer the potential of acceptable long-term safety.

- KBS-3H would be less costly than KBS-3V. The differences in costs between the KBS-3V and the KBS-3H design alternatives mainly relate to the smaller volumes of excavated rock and smaller amounts of backfill required in the horizontal alternative.

- KBS-3H would have lower environmental impacts. A reduction in the excavation of rock and need for backfill would bring associated benefits in terms of a decrease in the consumption of resources and less transportation, which leads in turn to less air pollution, etc.

SKB's and Posiva's comparison of the KBS-3H and KBS-3V designs shows the KBS-3H design to be positive in all aspects that have been assessed at this stage, with the exception of steel and iron consumption.

In the Japanese programme, the use of a pre-fabricated carbon-steel and bentonite supercontainer (Figure 3.6) has been considered, partly on the basis that it would be easier to assemble and demonstrate acceptable supercontainer quality on the surface than it would be to emplace the waste and buffer components in the underground, and partly because it would simplify waste handling operations and reduce the overall time for waste emplacement. Ueda *et al.* (2006) suggest that the time for waste disposal using a supercontainer design could be half of that for a design involving deposition of waste containers in horizontal tunnels.

It is also interesting to note that some other disposal programmes that do not envisage use of a supercontainer (e.g., the French disposal programme) have been testing of methods for handling and emplacing several bentonite rings at a time.

In summary, the trend towards supercontainer type disposal concepts can be seen as part of the overall drive for optimising disposal methods and may bring increased ease, efficiency and QA of waste handling, buffer assembly and waste emplacement. The adoption of supercontainer designs also very much emphasises the need to regard the engineered barriers as a system rather than as a set of independent barriers.

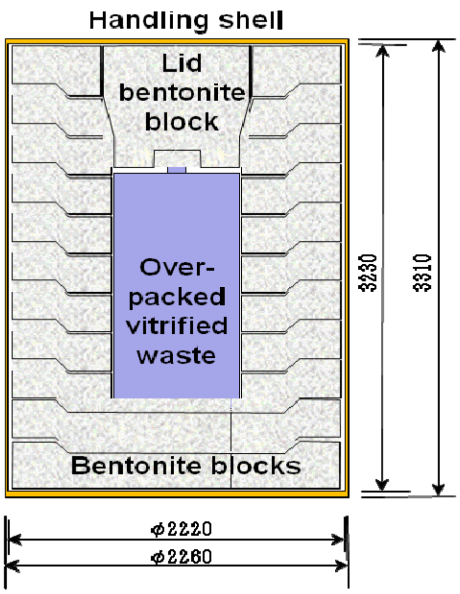


**Figure 3.6** **Cross-section through the Japanese supercontainer concept (Ueda *et al.* 2006).**

## 3.4 Backfill example

This example looks at the development and refinement within the Swedish programme of the design and methods for backfilling of repository tunnels in fractured crystalline rocks. The example illustrates the roles of engineering feasibility trials and large-scale experiments, coupled with the conduct of iterative safety assessments in refining the backfill design and methods.

In Sweden, the development of systems for the encapsulation and final disposal of long-lived waste from nuclear power plants was initiated in the mid-seventies. During the period 1977 to 1983, work resulted in a series of reports that gradually focused on encapsulation of the spent nuclear fuel in copper canisters and the deposition of these canisters surrounded by highly compacted bentonite clay at a depth of approximately 500 m in the Swedish bedrock. The resulting disposal concept, known as KBS-3, has, since 1984, constituted the reference method in the Swedish programme, and later also became the reference method in the Finnish programme (SKB/Posiva 2008).

In the reference KBS-3V design it is envisaged that the deposition tunnels will be backfilled so that the hydraulic conductivity of the backfilled tunnels would be such that they would not form preferential pathways for groundwater flow. Initially SKB planned to achieve this by the placement and subsequent *in situ* compaction of a suitable mix of bentonite clay and crushed rock backfill in the tunnels (Figure 3.7).

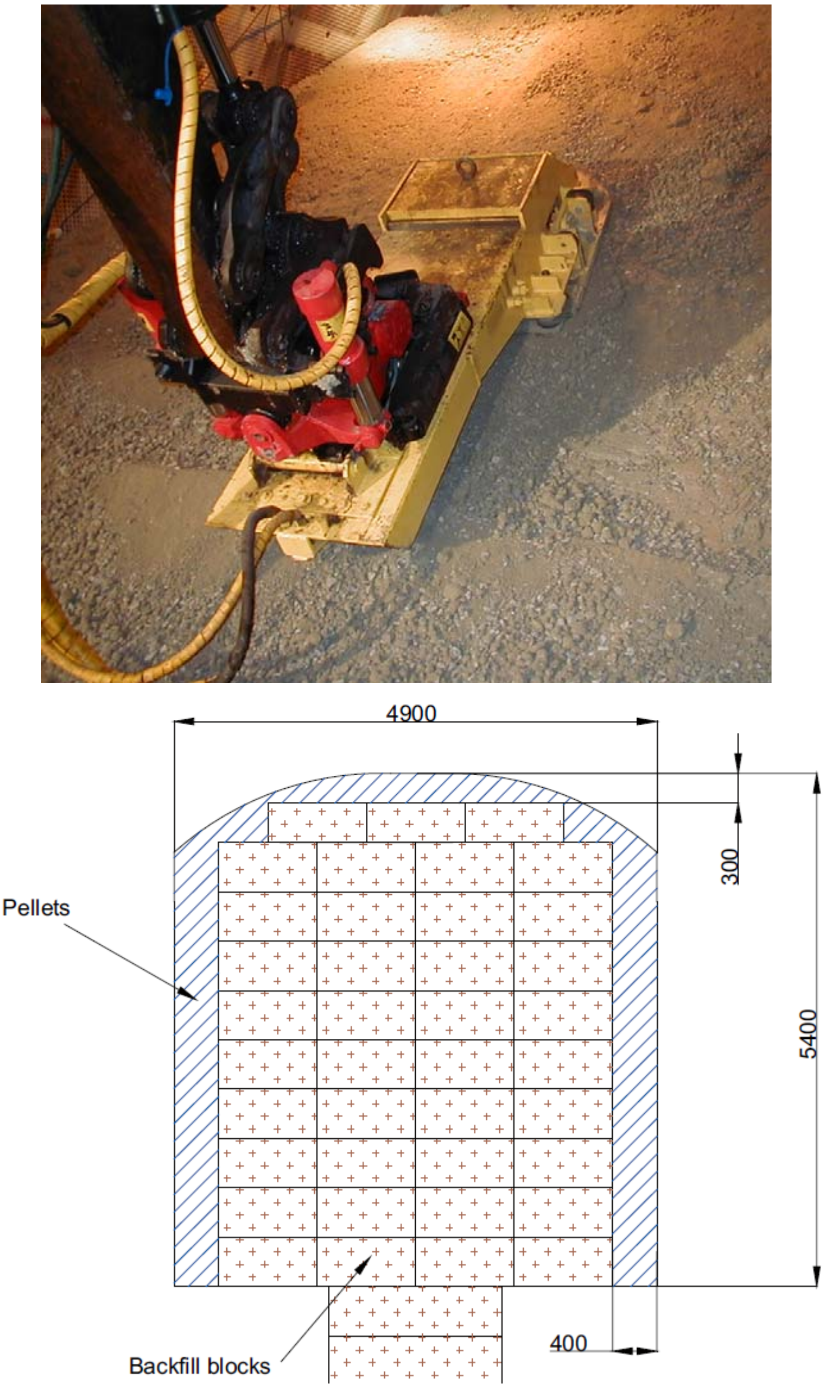


**Figure 3.7 Top – mechanical compaction of granular tunnel backfill material according to SKB's earlier concept (Gunnarsson 2006). Bottom – SKB's later concept for backfilling of waste deposition tunnels using clay blocks and pellets (see SKB 2008a).**

The feasibility of emplacing two such mixtures of granular materials, with different bentonite to rock ratios, was tested during the Backfill and Plug Test (Figure 2.7). The Backfill and Plug Test showed that it was feasible, although not always straightforward, to emplace the backfill as a granular mixture, and to compact the backfill materials to suitably high densities. The test also examined the hydration of the backfill, the swelling of the bentonite clay, and the resulting densities and hydraulic performance of the backfill.

Safety function indicator criteria had been established for the backfill including that its average hydraulic conductivity should be less than $10^{-10}$ m/s, and that its swelling pressure should be greater than 100 kPa (SKB 2006). However, average measurements of hydraulic conductivity from the Backfill and Plug Test were found to lie in the range $1.4 \times 10^{-9}$ to $1.4 \times 10^{-8}$ m/s, above the safety function indicator criterion for hydraulic conductivity. This, in combination with new findings relating to the influence of groundwater salinity on bentonite performance, and predictions of groundwater salinity at the potential repository sites led SKB to re-assess its backfilling concept.

SKB assessed several revised backfilling concepts for their potential to meet the safety functions, as well as for engineering feasibility, robustness and cost. The currently favoured concept involves the emplacement of pre-formed blocks, which would be surrounded by pellets (Figure 3.7).

Two such backfills were analysed in SR-Can safety report (SKB 2006):

- Natural swelling clay. The tunnels were assumed to be filled with pre-compacted blocks of natural swelling clay (not necessarily bentonite) with the gaps between the rock and the backfill blocks filled with pellets of the same material. Friedland clay was used as an example of such a material in SR-Can. Friedland clay is a naturally occuring clay, mainly consisting of mixed layer smectite/illite.

- Bentonite and crushed rock. The tunnels were assumed to be filled with pre-compacted blocks made from a mixture of bentonite and crushed rock, with a weight ratio of 30/70. The gaps between the rock and the backfill blocks were assumed to be filled with bentonite pellets. The bentonite component in the mixture was assumed to have the same composition as that of the buffer bentonite. The crushed rock was assumed to be taken from the residues from the excavation of the repository and to have a maximum grain size of 5 mm.

Results from the SR-Can safety assessment indicated that the concept involving clay only backfill blocks had several advantages from the point of view of long-term performance as compared to the blocks made from a mixture of bentonite and crushed rock (SKB 2006).

Since the SR-Can safety report was published, SKB has continued to test and further develop its approach to backfilling, and has conducted various large-scale tests and trials at a new bentonite clay laboratory at Äspö (Figure 3.8).

**Figure 3.8 Large-scale testing of water uptake by backfill emplaced according to SKB's current concept involving bentonite blocks and pellets (SKB 2008b).**

The work is on-going and issues being investigated currently include:

- How to achieve a sufficiently high density of backfill materials. This has caused SKB to consider clays, such as the Milos clay, that contain a higher proportion of bentonite than Friedland clay.

- How to manage the effects of water inflows to the tunnels via fractures, which can cause piping and erosion of the backfill materials. This has led SKB to conduct a considerable programme of fundamental research on the processes of piping and erosion and to consider how such processes should be represented in safety assessment.

## 3.5 Seals example

This example looks at the development within the German waste disposal programme of the design of drift seals for sealing repository tunnels in salt host rocks. The example illustrates the use of the EBS Project optimisation cycle, and highlights the role of safety assessment in integrating various types of information and providing a basis for uncertainty analyses. The example also illustrates the use of information from relevant analogue systems, in this case from trials of seals in existing salt mines, to help confirm the performance of the engineered barriers.

The German programme has been developing concepts for disposing of HLW and spent fuel in massive steel canisters within a salt host rock at Gorleben. Two main disposal concepts have been considered (Figure 3.9):

- Emplacement of HLW canisters and spent fuel in vertical boreholes drilled several hundred meters beneath repository drifts.

- Emplacement of spent fuel in drifts surrounded by crushed salt backfill.

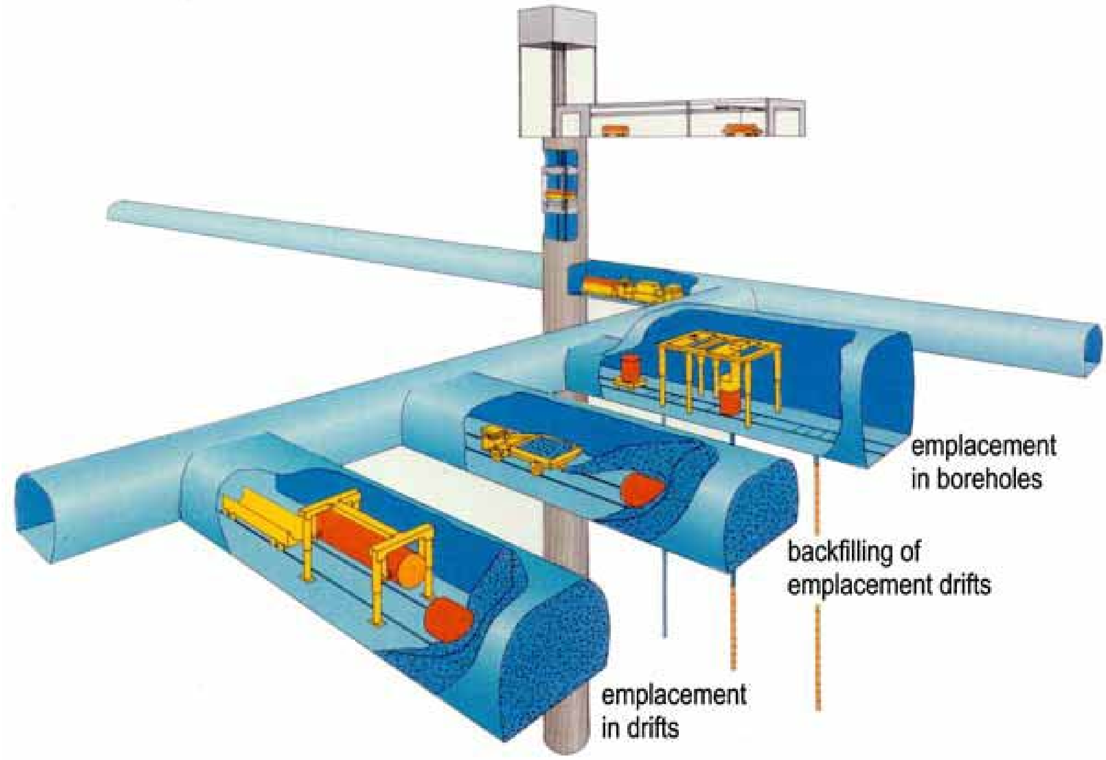


**Figure 3.9 German concepts for disposal of spent fuel (Graf and Filbert 2006).**

Both concepts rely on the use of crushed salt backfills to conduct radiogenic heat to the host rock, to stabilize the process of drift and borehole closure, and to provide long-term barriers against inflowing brines or other waters.

Further from the disposed wastes, seals would be constructed to seal the repository drifts. One candidate material for the drift seals is salt concrete. Salt concrete consists mainly of cement, crushed salt and fly ash, with the crushed salt replacing more commonly used aggregates (e.g., sand and gravel).

A series of complementary papers and presentations from the German programme to the EBS Project (Müller-Hoeppe *et al.* 2003; Herbert *et al.* 2004; Noseck *et al.* 2005; Mauke *et al.* 2006):

- Described the establishment of the functions and requirements of the drift seals.
- Examined the various processes that may affect the behaviour of the candidate drift seal materials.
- Described modelling and assessment of the potential performance of the drift seals.

- Considered the experience of investigations into the use of salt-concretes for sealing of mines, including at the low- and intermediate-level waste repository that has been developed within a former rock salt and potash mine at Morsleben.

The facility at Morsleben is known as the Endlager für Radioaktive Abfälle Morsleben, or ERAM. The safety strategy for the ERAM facility includes comprehensive backfilling of all mine openings, and the use of drift seals using salt concrete. The drift seals (Figure 3.10) are a particularly important element of the engineered barrier system at the ERAM and play a fundamental role in the long-term safety of the facility. Waste emplacement at ERAM has been completed and the licensing process for backfilling and sealing of the repository has been initiated.

The functions and requirements of the backfills at ERAM are the stabilisation of drifts and tunnels, the reduction of void volume and, in the case of brine intrusion into the mine openings, reduction of convergence-driven fluid movement.

The functions and requirements of the drift seals at ERAM are to hydraulically separate the disposal areas from the rest of the openings and potential pathways to the groundwater system (e.g., anhydrite and potash seams in the central part of the mine).

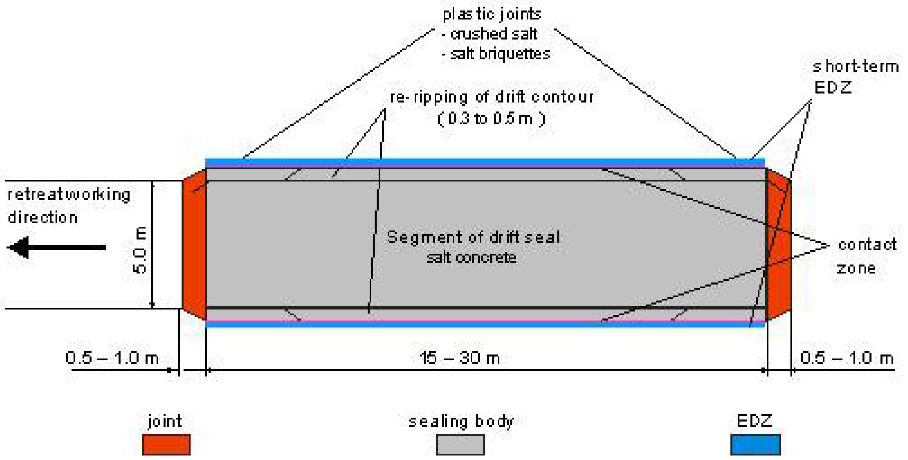


**Figure 3.10 German design for a tunnel seal composed primarily of salt-concrete for use in a salt host rock (Mauke *et al*. 2006).**

In more detail, various processes relating to their mechanical properties (e.g., ability to withstand rock and fluid pressures), their permeability, and their resistance to potentially corrosive brines will determine the behaviour and long-term properties of the salt-concrete. For example, Herbert *et al.*

(2004) discuss the potential influence on the hydraulic and mechanical properties of the seal materials resulting from interactions with NaCl or Mg-rich brines, which may involve mineral dissolution and precipitation.

In terms of post-closure performance, the most important property of the salt-concrete drift seals is their long-term permeability. Herbert *et al.* (2004) presented results from Monte Carlo sensitivity studies that assessed the effect on calculated potential dose of different long-term drift seal permeabilities (Figure 3.11). The reference case identified in Figure 3.11 corresponds to the design requirement established for the drift seals (i.e., a long-term permeability of less than $10^{-18}$ $m^2$). The ability to achieve this value of seal permeability has been supported by gas measurements (Noseck *et al.* 2005).

In the reference case calculated dose rates before ~20,000 years result from brine flow out of unsealed mine areas with residual contamination. The sharp decrease in the dose rate seen at ~20,000 years is caused by the failure of the seal and the consequent transient flow of brine into the waste containing south western section of the mine. Once this section of the mine has filled with brine, the dose rate increases to a higher level than before because of brine flow out of the waste filled areas.

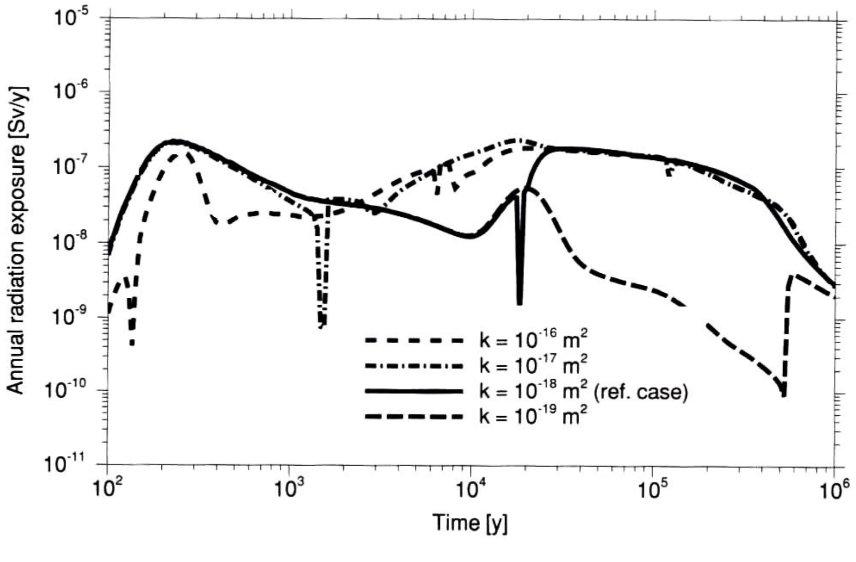


**Figure 3.11 Calculated potential annual radiation exposures for four different drift seal permeabilities (from Noseck *et al.* 2005): an example of the use of safety assessment in determining the significance of barrier properties and performance, and establishing barrier design requirements.**

# 4 Conclusions

## 4.1 Project Achievements

The EC/NEA EBS Project has provided:

- A valuable forum, particularly for senior disposal programme managers and safety assessors, to discuss EBS design and assessment issues.

- The opportunity to draw together and take an overview of detailed information from a range of engineering design, assessment, and research and development studies conducted in related projects and programmes.

- Improved understanding of the relationships between EBS and repository design, and performance and safety assessment.

- An on-going view of the ‘state of the art’ in radioactive waste disposal within OECD countries.

- An opportunity for valuable sharing of experience, knowledge and lessons learnt.

- An understanding of current strengths and uncertainties.

- A series of high-quality published reports and papers.

## 4.2 Key Messages

### 4.2.1 The EBS is a System, not a Series of Independent Barriers

The EBS is best regarded as a *system* of components that functions in conjunction with the surrounding rock and thus provides acceptable levels of safety. The EBS and the host rock have different safety functions and the EBS should be tailored to the waste and to the host rock in which it is required to function. Each component of the EBS will have its own functions, but it is the functioning of the system as a whole that is most important.

The importance of regarding the EBS as a system can be readily understood from examples in which the function of one EBS component is to protect a neighbouring component. For example, the concrete buffer in the Belgian supercontainer protects the cast iron overpack by passivating its outer surface and effectively preventing its corrosion. Another example, this time from the Finnish/Swedish KBS-3V disposal concept, is the role of the backfill in preventing upward swelling of the buffer, which ensures that the buffer retains sufficient density so that it can fulfil its functions in protecting the copper canister. Similarly, the drip shield in the US Yucca Mountain concept has a role in protecting the waste containers.

It may be better, therefore, to describe the principal means of achieving safe radioactive waste disposal in terms of designing a system that will fulfil multiple safety functions.

### 4.2.2 The EBS has a Central Role in the Safety Case for Disposal

The EBS has a central role in the safety case for disposal. Even in situations where the host rock offers the potential to provide significant performance (e.g., in terms of limiting groundwater flow and retarding radionuclide transport), a well-designed EBS that will fulfil multiple safety functions is essential.

First, operational issues dictate that reliable engineering solutions must be found for waste transport, handling and disposal, and these solutions must of course be conducted whilst offering adequate worker protection (e.g., through shielding). Second, the safety case for disposal cannot rely on a single barrier; confidence in the safety of disposal derives from the provision and fulfilment of multiple safety functions and defence in depth. Third, the EBS plays an important role in other key safety case arguments, such as those relating to feasibility, to monitoring, to the reversibility of waste disposal operations and to waste retrievability.

A well designed EBS is even more important in cases where, on its own, the host rock offers relatively less performance in terms of long-term containment and retardation (e.g., in fractured rock systems). That is not to say that the host rock is unimportant, as even fractured geological systems still provide isolation of the waste from the biosphere, and may contribute significantly to assessed safety for some nuclides (e.g., by allowing matrix diffusion and dispersion and thereby delaying the return to the biosphere of mobile anionic species such as iodide). Such host rocks may also play important roles by providing reasonably stable and desirable chemical conditions (e.g., reducing conditions) and appropriate hydrological and mechanical properties which allow the EBS to perform as intended.

### 4.2.3 EBS Design and Optimisation Requires a Considered Iterative Programme of Design and Assessment Work

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 the EBS and its components, taking account of waste-specific and site-specific constraints that 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 after repository closure.

This process of design and optimisation requires a significant programme of work, typically lasting at least several years to several tens of years. During such a programme, it is essential to maintain good links all the way from fundamental understanding of the processes and phenomena that may affect the behaviour of the wastes, the EBS materials and the host rock, to their representation in safety assessment. It is also important to develop and maintain relevant expertise in repository and EBS design, and in safety and performance assessment, and to manage the knowledge amassed.

Several, if not the majority, of the waste management organisations in the OECD countries are actively following the approach to EBS design and optimisation that has been discussed within the EBS Project. The approach is considered to be useful and not only enables EBS design, but also plays 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.

The justification for simplified safety assessment models and for assessments or demonstrations of a particular disposal system's compliance with applicable regulatory (e.g., potential dose or risk) standards, rests and relies on sound scientific understanding of the materials comprising the disposal system and their possible future behaviour in response to credible external factors.

In broad terms it can be said that the physico-chemical processes that may occur in repository systems and influence the behaviour of the EBS have been identified. The potential effects of these processes need to be assessed on a concept- and site-specific basis.

Simplifications are often necessary during safety assessment modelling and sometimes it is appropriate to make such simplifications by adopting conservative assumptions or parameter values for example. Whilst the use of such conservatisms can be appropriate for certain purposes (e.g., demonstrating compliance), the use of assessment models that are as realistic as possible assists with optimisation. If used inappropriately, results from conservative models may lead to sub-optimal decision-making over EBS design and lead to unnecessary costs.

## 4.3 Trends in EBS Design and Safety Case Development

During the period of the EC/NEA EBS Project several trends have been discernable:

- There has been increased consideration of disposal concepts for spent fuel and high-level wastes of EBS designs involving supercontainers.

- Increasing use is being made within safety case development programmes of requirements management systems.

- Increasing use is also being made within safety assessments and safety cases of safety function indicators and criteria. Safety functions are beginning to be used as the basis for the structure of safety assessments (e.g., as a means to scenario development and analysis), with FEPs analysis being used more as a means of comprehensiveness check, rather than as a main driver for scenario development.

- Increasing use has been made of structured, inclusive decision-aiding processes and options appraisals, for example, over EBS design choices. These processes allow a more explicit recognition of the wide range of factors that can influence such choices, including technical assessments, stakeholder needs, feasibility and cost.

- There has been increasing recognition of the importance of operational issues and feasibility assessments and demonstrations, as essential complements to performance and safety assessment, and the associated research and development work.

- Significant progress has been made (within related projects) in large scale trials and demonstrations of EBS component manufacture and installation. Discussions within the EBS Project have re-emphasised the importance of considering feasibility in the EBS design and assessment process. Feedback of lessons learnt from large-scale trials and experiments provides invaluable information for EBS design and disposal concept development.

## 4.4 Future Activities

At the last EBS Project workshop there was consensus that it would be valuable to maintain an international forum under the auspices of the NEA for collaborative work on the EBS and the safety case.

Reflecting recent trends and observations, suggestions for areas where further discussions could be valuable include:

- Disposal concepts involving supercontainers or pre-fabricated EBS systems.

- Requirements management and safety functions.

- Feasibility assessment.

- The management of safety case development programmes.

- The development of safety cases, particularly with an emphasis on safety arguments other than the details of quantitative safety assessment.

- The role of post-licensing performance confirmation programmes.

- The degree of design flexibility that can remain after licensing, and the management of design changes.

- The use of operational experience and safety case maintenance.

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# 6 Appendix AEBS Project - Participating Organisations

| | |
|---|---|
| Belgium | Agency for Radioactive Waste and Enriched Fissile Materials (Ondraf/Niras)<br>Studiecentrum voor Kernenergie - Centre d'Etude de l'Energie Nucléaire (SCK/CEN) |
| Canada | Atomic Energy Canada Limited (AECL)<br>Ontario Power Generation (OPG) |
| Chinese Taipei | Atomic Energy Council (AEC)<br>Institute of Nuclear Energy Research (INER) |
| Czech Republic | Radioactive Waste Repository Authority (RAWRA) |
| Finland | Posiva Oy<br>Säteilyturvakeskus (STUK)<br>VTT Processes |
| France | Agence Nationale pour la gestion des Dechets Radioactifs (ANDRA)<br>Commissariat à l'Énergie Atomique (CEA)<br>Direction Générale de la Sûreté Nucléaire de la Radioprotection (DGSNR)<br>Électricité de France (EDF)<br>L'institut de Radioprotection et de Sûreté Nucléaire (IRSN) |
| Germany | Bundesamt für Strahlenschutz (BfS)<br>Bundesantalt für Goewissenschaften und Rohstoffe (BGR)<br>Deutsche Gesellschaft zum Bau und Betrieb von Endlagern für Abfallstoffe mbH (DBE)<br>Gesellschaft für Anlagen- und Reaktorsichereit mbH (GRS) |
| Hungary | ETV-EROTERV Rt.<br>Golder Associates Hungary Limited |
| Italy | Agenzia Nazionale per la Protezione dell'Ambiente (ANPA)<br>Società Gestione Impianti Nucleari SpA (SOGIN) |

| | |
|---|---|
| Japan | Central Research Institute of Electric Power Industry (CRIEPI)<br>Institute of Applied Energy<br>Japan Atomic Energy Agency (JAEA)<br>Japan Nuclear Cycle Development Institute (JNC)<br>Japan Nuclear Energy Safety Organization (JNES)<br>Nuclear Safety Research Association<br>Nuclear Waste Management Organization of Japan (NUMO)<br>Radioactive Waste Management Funding and Research Centre |
| Korea | Korea Atomic Energy Research Institute (KAERI) |
| Slovak Republic | VUJE Trnava, Inc. |
| Spain | Consejo de Seguridad Nuclear (CSN)<br>Empresa Nacional de Residuos Radioactivos SA (ENRESA)<br>University of La Coruña |
| Sweden | Svensk Kärnbränslehantering AB (SKB)<br>Swedish Radiation Safety Authority (SSM)<br>Swedish Geological Science Park Ideon<br>Tekedo AB |
| Switzerland | BMG Engineering Limited<br>Hauptabteilung für die Sicherheit der Kernanlagen (HSK)<br>Nationale Genossenschaft für die Lagerung radioaktiver Abfälle (NAGRA) |
| UK | British Geological Survey<br>Galson Sciences Limited<br>Nexia Solutions Limited<br>Quintessa Limited<br>TerraSalus Limited<br>Nuclear Decommissioning Authority |

| | |
|---|---|
| US | Centre for Nuclear Waste Regulatory Analyses (CNWRA)<br>Lawrence Livermore National Laboratories (LLNL)<br>Monitor Scientific LLC<br>Nuclear Waste Technical Review Board (NWTRB)<br>Sandia National Laboratories (SNL)<br>US Department of Energy (US DOE) |
| Others | European Commission (EC)<br>OECD Nuclear Energy Agency (NEA) |

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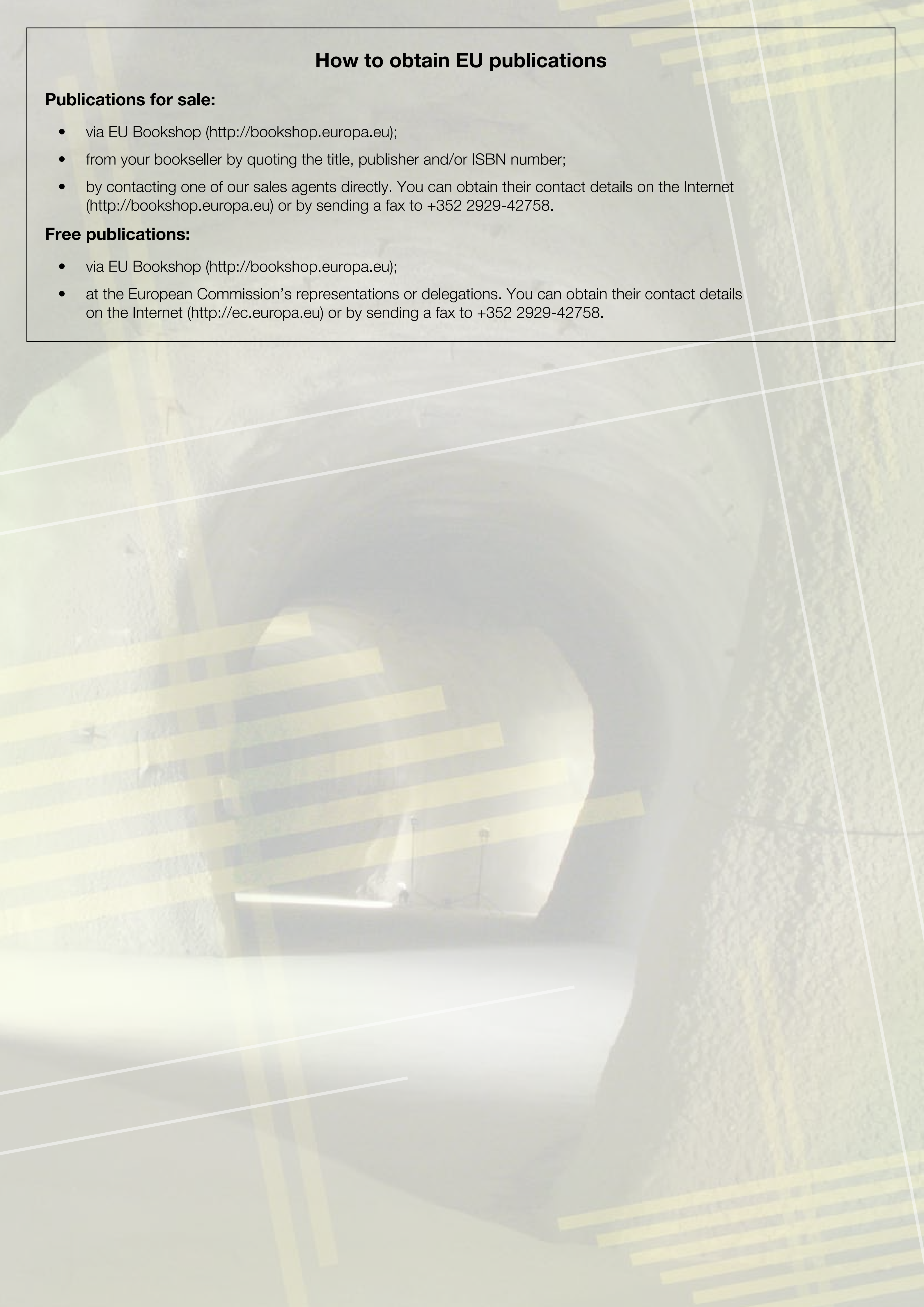

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The European Commission (EC) and the OECD Nuclear Energy Agency (NEA) have, over the past several years, sponsored a project on the engineered barrier system (EBS) used in geological disposal of long-lived radioactive wastes. The EC/NEA EBS Project has examined how to design, characterise, model and assess the performance of engineered barrier systems, and how to integrate these aspects within the safety case for geological disposal of long-lived radioactive wastes. This report provides a synthesis of the EBS Project, and summarises its main results and findings.

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