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Engineered Barrier Systems and the Safety of Deep Geological Repositories

State-of-the-art Report

In co-operation with the
EUROPEAN COMMISSION

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NUCLEAR ENERGY AGENCY
ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

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NUCLEAR ENERGY AGENCY

The OECD Nuclear Energy Agency (NEA) was established on 1st February 1958 under the name of the OEEC European Nuclear Energy Agency. It received its present designation on 20th April 1972, when Japan became its first non-European full Member. NEA membership today consists of 28 OECD Member countries: Australia, Austria, Belgium, Canada, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Luxembourg, Mexico, the Netherlands, Norway, Portugal, Republic of Korea, Slovak Republic, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The Commission of the European Communities also takes part in the work of the Agency.

The mission of the NEA is:

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

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

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

EXECUTIVE SUMMARY

Geological disposal was defined in a 1995 Collective Opinion of the Nuclear Energy Agency (NEA) Radioactive Waste Management Committee entitled *The Environmental and Ethical Basis of Geological Disposal*. According to page 16 of that publication, geological disposal is provided by a system that will:

(a) "*isolate the wastes from the biosphere for extremely long periods of time*," and

(b) "*ensure that residual radioactive substances reaching the biosphere will be at concentrations that are insignificant compared, for example, with the natural background levels of radioactivity*."

Geological disposal should also "provide reasonable assurance that any risk from inadvertent human intrusion would be very small".

Repositories for the disposal of radioactive waste generally rely on a multi-barrier system to isolate the waste from the biosphere. This multi-barrier system typically comprises the natural geological barrier provided by the repository host rock and its surroundings and an engineered barrier system (EBS). This multi-barrier principle creates an overall robustness of the system that enhances confidence that the waste will be successfully contained.

Ensuring that an EBS will perform its desired functions requires integration of site-characterisation data, data on waste properties, data on engineering properties of potential barrier materials, *in situ* and laboratory testing, and modelling.

The NEA Integration Group for the Safety Case (IGSC) EBS project is intended to provide a greater understanding of how to achieve the integration needed for successful design, construction, testing, modelling and performance assessment (PA) of engineered barrier systems. In addition, the EBS project will help to clarify the role that an EBS can play in the overall safety case for a repository.

Recognising the diversity of engineered barrier systems in various national programmes, the IGSC-EBS project is seeking to share knowledge and experience about the integration of EBS functions, engineering design, characterisation, modelling and performance evaluation in order to understand and document the state of the art, and to identify the key areas of uncertainty that need to be addressed. Specific objectives of the IGSC-EBS project are:

- To understand the relationship between the functions to be served by the EBS and its design in different repository concepts.
- To compare different methods of characterising EBS properties.
- To compare different approaches to modelling the EBS.
- To compare different means of evaluating EBS performance.

- To compare different engineering approaches to similar problems.
- To compare techniques for evaluating, characterising and modelling interactions between the EBS and near-field host rock.

The first NEA-EC workshop on the IGSC-EBS project, entitled “Engineered Barrier Systems in the Context of the Entire Safety Case” was hosted by UK Nirex Limited (Nirex) in Oxford on 25-27 September 2002. It provided a status report on engineered barrier systems in various national programmes and a common basis of understanding from which to plan next steps.

To provide support for this workshop, the members of the IGSC-EBS project steering committee devised a questionnaire, with the aim of establishing a baseline of information at the start of the project. This report presents results from a joint European Commission (EC)-NEA initiative funded by the European Commission and conducted on behalf of the EC and the NEA by David Bennett, Galson Sciences Limited (GSL), to compile the responses to the questionnaire.

Responses to the IGSC questionnaire on engineered barrier systems were received from 13 countries and 17 organisations with responsibility for considering or developing deep underground disposal concepts, or for implementing or regulating radioactive waste disposal programmes. The questionnaire responses consider EBS and disposal systems for a wide range of wastes and a wide range of sites and host rocks.

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

The “engineered barrier system” represents the man-made, engineered materials placed within a repository, including the waste form, waste canisters, buffer materials, backfill and seals. The “near-field” includes the EBS and those parts of the host rock in contact with or near the EBS, whose properties have been affected by the presence of the repository. The “far-field” represents the geosphere (and biosphere) beyond the near-field.

There is generally good consistency in EBS designs for high-level waste and spent fuel, but less for intermediate-level waste (ILW). The greater variation in the ILW disposal systems reflects the greater number of ILW waste streams and the wide range of disposal sites and host rocks considered in the survey.

The main functions of EBS components can be summarised as follows:

- The waste matrix is designed to provide a stable waste form that is resistant to leaching and gives slow rates of radionuclide release for the long term.
- The container/overpack is designed to facilitate waste handling, emplacement and retrievability, and to provide containment for up to 1 000 years or longer depending on the waste type.
- The buffer/backfill is designed to stabilise the repository excavations and the thermo-hydro-mechanical-chemical conditions, and to provide low permeabilities and/or diffusivities, and/or long-term retardation.

The other EBS components (e.g. seals) are designed to prevent releases via tunnels and shafts and to prevent access to the repository.

Lessons learnt include:

- Adopt a methodical, systematic and fully documented approach to repository design and optimisation.
- Peer review is an important positive process that also enhances confidence and should be an active part of the design and assessment process.
- Simple designs and models are easier to implement and verify.
- Maintain close links between EBS design and performance assessment, and include them in iterative cycles of assessment.
- Ensure, and demonstrate, design feasibility.
- Continue to build confidence in performance assessment.
- Focus on the most important issues (e.g. through the use of “risk-informed” approaches).

Performance assessments also suggest that EBS systems are very effective in containing radioactive wastes.

As will become apparent from perusing this compilation regarding the role of the EBS in the safety case, all countries participating in this workshop are considering or pursuing geological disposal as defined above. In doing this, however, the various waste management programmes may place different degrees of emphasis (reliance) on the engineered as opposed to natural barriers. Some choose to rely on the engineered barriers for a longer period of time than others, for example. Regardless of the approach being followed, however, the goal is to provide geological disposal in accordance with the two internationally agreed objectives given above.

Acknowledgements

On behalf of all the participants, the OECD Nuclear Energy Agency (NEA) and the European Commission (EC) Directorate-General for Research wish to express their gratitude to the national organisations that have contributed to the establishment of this report: ONDRAF/NIRAS and SCK•CEN (Belgium), OPG (Canada), RAWRA (Czech Republic), POSIVA (Finland), ANDRA (France), BfS (Germany), NUMO and JNC (Japan), KAERI (Korea), ENRESA (Spain), SKB (Sweden), HSK (Switzerland), UK Nirex Ltd (UK), US-DOE-WIPP, US-DOE-YM and the NWTRB (United States).

The NEA and the EC are also very grateful to the members of the Project Steering Committee for their help in setting up the questionnaire. The programme committee was composed of:

Jesus ALONSO	(ENRESA, Spain)
Richard BEAUHEIM	(SNL, US-DOE-WIPP, USA)
Alan HOOPER	(UK Nirex Ltd)
Bob MACKINNON	(SNL, US-DOE-YMP, USA)
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Hiroyuki UMEKI	(NUMO, Japan), leader of the EBS project
Sylvie VOINIS	(OECD/NEA)
Henning VON MARAVIC	(EC)
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The report was prepared by David Bennett of Galson Sciences Limited. The financial support was provided by the European Commission as part of the European Atomic Energy Community (EURATOM) specific programme on “Nuclear Energy” (1998-2002), Key Action on Nuclear Fission.

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1. INTRODUCTION

Geological disposal was defined in a 1995 Collective Opinion of the Nuclear Energy Agency (NEA) Radioactive Waste Management Committee titled "The Environmental and Ethical Basis of Geological Disposal." According to page 16 of that document, geological disposal is provided by a system that will:

(a) "*isolate the wastes from the biosphere for extremely long periods of time*," and

(b) "*ensure that residual radioactive substances reaching the biosphere will be at concentrations that are insignificant compared, for example, with the natural background levels of radioactivity*."

Geological disposal should also "*provide reasonable assurance that any risk from inadvertent human intrusion would be very small*."

Repositories for disposal of radioactive waste generally rely on a multi-barrier system to isolate the waste from the biosphere. This multi-barrier system typically comprises the natural geological barrier provided by the repository host rock and its surrounding and an engineered barrier system (EBS). This multi-barrier principle creates an overall robustness of the system that enhances confidence that the waste will be successfully contained.

An EBS may itself comprise a variety of components, such as the waste form, waste canisters, backfill, seals, and plugs. The general purpose of an EBS is to prevent and/or delay the release of radionuclides from the waste to the repository host rock, at least during the first several hundred years after repository closure when the fission-product content is high, and where they might be mobilised by natural groundwater flow. In many disposal concepts, the EBS, operating under stable and favourable geosphere conditions, is designed to contain most of the radionuclides for much longer periods.

The specific role that an EBS is designed to play in a particular waste disposal concept is dependent on the conditions that are expected (or considered possible) to occur over the period of regulatory interest, regulatory requirements for waste containment, and the anticipated performance of the natural geological barrier. 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, the pH and redox conditions that are expected, the expected groundwater flux, the local groundwater chemistry, possible interactions among different materials in the waste and EBS, the mechanical behaviour of the host rock after repository closure, and the evolution of conditions over time. Ensuring that an EBS will perform its desired functions requires an integration, often iterative, of site-characterisation data, data on waste properties, data on engineering properties of potential barrier materials, *in situ* and laboratory testing, and modelling.

The NEA Integration Group for the Safety Case (IGSC) EBS project is intended to provide a greater understanding of how to achieve the integration needed for successful design, construction, testing, modelling, and performance assessment (PA) of engineered barrier systems. In addition, the

EBS project will help to clarify the role that an EBS can play in the overall safety case for a repository. A safety case is a collection of arguments, at a given stage of repository development, in support of the long-term safety of the repository. A safety case includes the quantitative results derived from performance assessment modelling, but also considers aspects of barrier performance that are difficult to quantify but can qualitatively be shown to enhance the robustness of the system.

Recognising the diversity in engineered barrier systems in various national programmes, the project is seeking to share knowledge and experience about the integration of EBS functions, engineering design, characterisation, modelling and performance evaluation in order to understand and document the state of the art, and to identify the key areas of uncertainty that need to be addressed. Specific objectives of the IGSC-EBS project are:

- To understand the relationship between the functions to be served by the EBS and its design in different repository contexts.
- To compare different methods of characterising EBS properties.
- To compare different approaches to modelling the EBS.
- To compare different means of evaluating EBS performance.
- To compare different engineering approaches to similar problems.
- To compare techniques for evaluating, characterising, and modelling interactions between the EBS and near-field host rock.

The First Workshop of the IGSC-EBS project, entitled “Engineered Barrier Systems in the Context of the Entire Safety Case” was hosted by UK Nirex Limited (Nirex) in Oxford, during 25-27 September 2002. It provided a status report on engineered barrier systems in various national programmes and a common basis of understanding from which to plan the forward programme.

To provide support for the First Workshop, the members of the IGSC-EBS project steering committee[1] devised a questionnaire, with the aim of establishing a baseline of information at the start of the project. This report presents results from a joint European Commission (EC)-NEA project funded by the European Commission and conducted on behalf of the EC and the NEA by Galson Sciences Limited (GSL) to compile the responses to the questionnaire. In accordance with the remit and scope of the questionnaire compilation project, this report is based solely on the information provided in the questionnaire responses.

The questionnaire had five parts relating to topics for discussion at the workshop:

1. General Overview.
2. Design and Emplacement of EBS.
3. Characterisation.
4. Modelling.
5. Performance Assessment.

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[1] Members of the committee are: Frédéric Plas (ANDRA, France), Henning von Maravic (EC), Jesus Alonso (ENRESA, Spain), Frank Wong (LLNL, US-DOE-YMP, USA), Alan Hooper (Nirex, UK), Hiroyuki Umeki (NUMO, Japan), Patrik Sellin (SKB, Sweden), Oïvind Töverud (SKI, Sweden), Richard Beauheim (SNL, US-DOE-WIPP, USA), Bob MacKinnon (SNL, US-DOE-YMP, USA), Sylvie Voinis (OECD/NEA).

Responses to the questionnaire have been received from 13 countries and 17 organisations with responsibility either for implementing or regulating radioactive waste disposal programmes.

The following sections summarise and discuss the information gathered. The sections correspond broadly to the questions posed in the questionnaire, but the text is designed to highlight the points of particular interest and is not intended to be a comprehensive commentary on the information provided.

As will become apparent from perusing this compilation regarding the role of the EBS in the safety case, all nations participating in this workshop are considering or pursuing geological disposal as defined above. In doing this, however, the various waste management programmes may place different degrees of emphasis (reliance) on the engineered as opposed to natural barriers. Some choose to rely on the engineered barriers for a longer period of time than others, for example. Regardless of the approach being followed, however, the goal is to provide geological disposal in accordance with the two internationally agreed objectives given above.

1.1 Report structure

This report is structured as follows:

- Section 2 summarises the questionnaire responses for the general overview topic.
- Section 3 summarises the questionnaire responses for the design and emplacement topic.
- Section 4 summarises the questionnaire responses for the characterisation topic.
- Section 5 summarises the questionnaire responses for the modelling topic.
- Section 6 summarises the questionnaire responses for the performance assessment topic.
- Section 7 provides a synthesis of the key messages and lessons to be learnt.

2. GENERAL OVERVIEW

2.1 Facility, facility type and programme status

Responses to the questionnaire have been received from 13 countries and 17 organisations[2] with responsibility for considering or developing deep underground disposal concepts, or for implementing or regulating radioactive waste disposal programmes:

1. The Belgian concept for the disposal of high-level waste (HLW) and spent fuel (SF) in a clay host rock.
2. The Canadian programme considering storage and disposal options for SF.
3. The Czech concept for the disposal of intermediate-level waste (ILW), HLW and SF in a crystalline host rock.
4. The Finnish proposed repository for the disposal of SF in a crystalline host rock.
5. The French concept for the disposal of B and C type wastes (long-lived ILW and HLW), and uranium and mixed oxide (MOX) SF in clay or granite.
6. The Germany repository at Morsleben for disposal of low-level waste (LLW), ILW and sealed sources in a salt host rock.
7. The Japanese concept for the disposal of HLW.
8. The Korean concept for the disposal of HLW.
9. The Spanish concept for the disposal of SF in either granite or clay host rocks.
10. The Swedish, KBS-3, concept for the disposal of SF in a crystalline host rock.
11. The Swiss, Kristallin-I, concept for the disposal of HLW in a crystalline host rock.
12. Nirex's consideration of geological disposal of radioactive wastes, within the broader context of the UK Government's review of policy on all options for the management of radioactive wastes.
13. The US Waste Isolation Pilot Plant (WIPP) for the disposal of transuranic waste (TRU) in a salt host rock, and the US Yucca Mountain Project (YMP) for the disposal of HLW and SF in a volcanic tuff host rock.

Table 2.1 summarises in more detail the status of the programmes considered in the review.

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[2] The organisations from whom responses have been received are: ONDRAF/NIRAS and SCK·CEN (Belgium), OPG (Canada), RAWRA (Czech Republic), POSIVA (Finland), ANDRA (France), BfS (Germany), NUMO and JNC (Japan), KAERI (Korea), ENRESA (Spain), SKB (Sweden), HSK (Switzerland), UK Nirex Ltd (UK), US-DOE-WIPP, US-DOE-YM and the NWTRB (USA).

Table 2.1. **The status of the programmes considered**

Country/ programme	**Disposal programme status**
Belgium	The Belgian programme has recently completed a second phase of research and development (R&D) work with the publication of the SAFIR-2 safety assessment. A third phase of R&D is planned to last until 2010-2015. This may be followed by a 5-year transitional phase, which could lead to a project beginning in ~2017 for the selection of a disposal site.
Canada	The Canadian programme is continuing to conduct generic research and development work in support of geological disposal of SF in crystalline rock. The research activities are being conducted in surface facilities and at AECL's underground research laboratory (URL) in granite near Pinawa, Manitoba. In 2002, the Canadian Government passed the federal Nuclear Waste Act, which mandates that a comparison of approaches (e.g, reactor site storage, centralised storage, geological disposal) for long-term management of SF should be completed in 3 years and submitted to the Government for a decision on the way forward in Canada.
Czech Republic	The Czech programme is in the first phase of R&D, which includes selection of a conceptual repository design, the study of engineered barrier systems, initial safety studies, and consideration of potential site investigations.
Finland	In 2001, the Finnish Parliament ratified the Government's favourable Decision in Principle (DiP) on Posiva's application to locate a spent fuel repository at Olkiluoto. Construction of an Underground Rock Characterisation Facility (ONKALO) at Olkiluoto will be started in 2004. Posiva aims to submit the application for the construction permit of the repository around 2010, and the application for the operation license around 2020.
France	In 2001, ANDRA issued its "Dossier Argile 2001" report, which summarized the status of knowledge on deep geological reversible disposal of long-lived ILW and HLW in a clay formation. A specific clay site in the Meuse-Haute/Marne region had been chosen in 1998, and construction of access shafts for an URL began in 2000. A similar report on geological disposal in granitic host rock is in preparation. However, due to the ultimate rejection of preliminary granitic site choices, this work is not currently focused on a specific formation. The 2001 report serves as a test for the methodology to be used in preparing the 2005 feasibility report, which is to include a complete safety assessment.
Germany/ Morsleben	In 2000, the Federal Government initiated a new plan for radioactive waste management, aimed at developing a new disposal facility for all radioactive waste types by ~2030. The plan includes examination of further potential disposal sites in a range of host rocks. Prior to current policy, a former iron mine at Konrad was selected for disposal of LLW and ILW, and a salt dome at Gorleben was selected for disposal of all types of radioactive waste. In addition, short-lived LLW and ILW was disposed in a former salt mine at Morsleben. Morsleben received waste until 1998. BfS, the operator at Morsleben, is preparing a licencing application for closure of the facility. The licencing procedure is expected to take until 2006. The decommissioning and closure process will take ~10 years.

Country/ programme	**Disposal programme status**
Japan	In 2000, with publication of the H12 progress report, the Japanese HLW disposal programme moved from a 25 year period of generic R&D into an implementation phase. At this point an implementing organisation NUMO was established to select a site, demonstrate disposal technologies, and develop relevant licence applications for repository construction, operation and closure. Repository operation is planned to begin in ~2030.
Korea	The Korean programme is in the process of establishing a reference design for a HLW disposal system. The reference design should be completed in 2006.
Spain	The Spanish programme has identified a large number of sites possessing geological characteristics potentially suitable for deep radioactive waste disposal. Generic and site-specific disposal system designs have been developed for each of the main host rocks under consideration (clay, granite, salt). Currently, the programme is conducting a second phase of safety assessment studies for the conceptual designs in clay and granite.
Sweden/KBS-3	The Swedish programme has over recent years conducted a programme of generic studies for several sites and in 2002 began further detailed site characterisation work at just two sites. Repository construction is planned to begin in 2009, and first disposal of SF is planned for 2015.
Switzerland/ Kristallin-I	The Swiss programme is considering deep geological disposal of HLW and SF in crystalline and clay host rocks. URLs have been developed in crystalline rocks at Grimsel, and in indurated clays at Mont Terri. Currently, the main focus of attention is on disposal in the Opalinus clay. A detailed report on the Opalinus clay option is in preparation. The response to the EBS questionnaire summarised in this report was prepared by the regulator, HSK, and is based on information in the 1994 Kristallin-I project that considered a crystalline host rock. The EBS considered for both types of host rock is similar.
UK/Nirex	UK policy is under review until 2007; and may not necessarily identify geological disposal as a preferred long-term waste management option. The Nirex disposal programme is at the conceptual stage required to provide a basis for assessing the disposability of packaged wastes.
US/WIPP	The WIPP licence application was submitted in 1996. Waste disposal began in March 1999, and approximately 20 000 drums of TRU have currently been disposed. Licence re-certification is required every 5 years. Waste disposal operations are expected to continue for ~35 years.
US/YMP	The U.S. programme is the responsibility of the Office of Civilian Radioactive Waste Management (OCRWM), a unit of the U.S. Department of Energy (US DOE). OCRWM plans to submit a license application in December 2004 to the U.S. Nuclear Regulatory Commission (US NRC) for permission to begin construction of a repository at Yucca Mountain in 2008. According to OCRWM’s timetable, the first placement of waste in Yucca Mountain would be in 2010.

2.2 Definition of engineered barrier system

The questionnaire included proposed definitions for the EBS, the near-field and the far-field, as follows:

> *The "Engineered Barrier System" represents the man-made, engineered materials placed within a repository, including the waste form, waste canisters, buffer materials, backfill, and seals. The "near-field" includes the EBS as well as the host rock within which the repository is situated, to whatever distance the properties of the host rock have been affected by the presence of the repository. The "far-field" represents the geosphere (and biosphere) beyond the influence of the repository.*

The majority of the programmes from which responses have been received agree that the definition of the EBS provided in the questionnaire is consistent with the definitions used in their individual projects, although not all of the programmes account for all EBS components in performance assessment studies (e.g. the US/WIPP project does not account for the potential ability of waste containers to act as engineered barriers in its performance assessments). The Japanese programme defines the EBS as comprising of those components that act as barriers to radionuclide transport. In this way, the Japanese definition of EBS excludes the backfill and seals in the H12 assessment. The Swedish programme does not generally use the term EBS but more commonly applies the terms near-field and far-field. For the Nirex ILW/LLW concept, the "vault backfill" is broadly equivalent to the buffer materials used in HLW/spent fuel disposal systems.

Two of the responses (Belgium, Finland) noted that the proposed definitions of the near-field and far-field were possibly problematic because some effects (e.g. thermal effects) may influence the whole of the host rock formation (i.e., both the near-field and far-field).

The Finnish and Canadian responses support a proposal for an amended definition as follows:

> *The "near-field" includes the EBS and those parts of the host rock in contact or near the EBS, whose properties have been affected by the presence of the repository. The "far-field" represents the geosphere (and biosphere) beyond the near-field.*

The definitions of the near-field used in other programmes are consistent with the definition supplied in the questionnaire.

2.3 Role of the engineered barrier system

Table 2.2 summarises the main roles of the EBS in the disposal concepts/programmes considered.

Table 2.2. **The role of engineered barrier systems**

Country/ programme	**Primary role of EBS**
Belgium	Providing radionuclide containment during the thermal phase, contributing to delaying radionuclide release thereafter, and minimising disturbance to the host rock.
Canada	Providing physical, chemical, hydraulic and biological isolation of the waste and minimising radionuclide release to the geosphere over the long-term.
Czech Republic	Providing a chemical barrier, physical containment, retention and retardation of radionuclides, and control of gas generation and transport.
Finland	Providing isolation and confinement of the waste, and minimising radionuclide releases.
France	Waste packages ensure safety during storage, transport and repository operation, and limit gas release during this period. The overpack and buffer control THM conditions within the repository and protect the host rock from mechanical damage. The seals alleviate radionuclide transport through the excavation-disturbed zone (EDZ) and prevent a “short circuit” pathway through the geosphere.
Germany/ Morsleben	Contributing to radiological safety and other safety goals (e.g. minimising subsidence, protecting groundwater).
Japan	The Japanese programme currently places considerable emphasis on designing an EBS with high containment/retardation capabilities in order that relatively less reliance can be placed on the performance of the geosphere, and a wide range of host rocks can be considered as candidate disposal sites.
Korea	Minimising water inflow, retarding radionuclide release, dissipating heat from radioactive decay, supporting the wastes and protecting the wastes from external mechanical stresses.
Spain	Containing radionuclides during the initial containment period and assuring acceptably low releases during the subsequent controlled release period.
Sweden/KBS-3	The KBS-3 concept emphasises the role of the long-lived waste container in isolating the waste from potential receptors. If the isolation fails, the disposal system still provides adequate performance because the waste form is stable and the bentonite buffer and geosphere provide further barriers to radionuclide migration.
Switzerland/ Kristallin-I	Providing for containment of the overwhelming part of the disposed activity.
UK/Nirex	Short-term physical containment of most fission products in waste packages; more general limitation of radionuclide release from waste packages. Limitation of dissolved levels of radionuclides and hence of release from the near-field by buffering of chemistry. Elimination of preferential pathways for release as a result of excavation. Release of gas without over-pressurisation.

Country/ programme	**Primary role of EBS**
US/WIPP	The WIPP MgO backfill is designed to provide a suitable chemical environment and to remove carbon dioxide. Concrete plugs and shaft seals provide containment and isolation.
US/YMP	Complementing the natural barriers in providing waste isolation by using long-lived drip shields and waste packages and limiting release of radionuclides by retention, retardation and diffusion barriers.

In several of the disposal systems considered (e.g. Finland, Japan, Sweden, Switzerland, US/YMP) the EBS plays a major role in providing the required disposal system performance.

Some of the responses to this part of the questionnaire (e.g. US/WIPP, US/YMP) included more detail on the role of each EBS component than can easily be reproduced here. However, the detailed information supplied has, to the extent possible, been taken into consideration when compiling Section 3 of this report.

2.4 Regulatory consideration of EBS

Most of the responses received indicated that no specific regulatory requirements have been defined for the EBS (Belgium, Canada, Czech Republic, Germany, Japan, Korea, Spain, Sweden). In the other programmes there are regulatory requirements, which largely focus on the need for the EBS to play a role in providing a robust multiple barrier system (Finland, France, Switzerland, US/WIPP, US/YMP, UK) such that overall system performance targets are achieved. The US regulations are also explicit in requiring information about the design, characterisation and approaches to assessing the performance of engineered barriers. In Finland there is a further regulatory requirement to the effect that the EBS must ensure adequate containment and provide for retrievability for several thousand years after disposal.

2.5 Feedback from peer review of EBS design

Several of the programmes (Czech Republic, Germany, Korea, Spain) from which questionnaire responses have been received are at a relatively early stage in development and therefore have not yet undertaken or completed formal peer review cycles. The German response indicates that peer review is foreseen as part of the regulatory licensing process. In other programmes (e.g. Belgium, Finland, France, Japan, Switzerland, UK/Nirex, US/WIPP, US/YMP), key topics have been identified through peer review and these have been considered when planning future R&D.

The main issue identified through peer review of the EBS proposed in the Belgian programme is the need for a demonstration that the construction/emplacement of the EBS is technically feasible.

Topics identified through peer review as potentially requiring further R&D in Finland have included sealing defects in copper-iron waste canisters, copper corrosion, the behaviour of a defective canister in a bentonite buffer, and the alteration and performance of the bentonite buffer itself.

French reviews have identified a range of issues including seal effectiveness, flow and transport in the excavation-disturbed zone (EDZ), the definition of a representative inventory, and the need to consider retrievability.

The peer review of the Japanese H12 assessment pointed towards the need to demonstrate robustness of the multi-barrier concept by working towards an improved balance between the performance of the EBS and of the geosphere. The Japanese programme was encouraged, therefore, to develop a stronger case for the geosphere, as well as continuing to strengthen the case for the EBS.

The Swiss response noted the need to make allowance for uncertainties in the stability and degradation of EBS during its design.

The Nirex response noted that peer review had revealed:

- A lack of visibility of selection criteria for the EBS design.
- That reviewers had a preference for physical rather than chemical containment.
- That reviewers were doubtful about claims made for the long-term performance of engineered barriers.
- That "no physical barrier" dissolved source term models and the exclusion from PA of explicit models for EBS components damaged reviewer's confidence in PA.

The US/WIPP peer review recommended further experimentation on the backfill and further consideration of the long-term behaviour of panel seals.

The US/YMP peer review recommended (i) long-term corrosion tests for waste package materials to investigate the long-term effects of exposure to gamma radiation, salt deposits, microbes and ageing, (ii) further consideration of the mechanisms of radionuclide diffusion through stress corrosion cracks and, (iii) consideration of the possible effects of drift collapse on EBS performance.

Some of the responses (US/WIPP, US/YMP) noted that peer review can provide positive indications that parts of the programme have been conducted successfully and note conservatisms in assessment models, as well as identifying potential requirements for further work.

2.6 Monitoring of EBS

The need for monitoring during the operational phase is recognised in most programmes (e.g. Czech Republic, Canada, France, Germany, Japan, Korea, Switzerland, UK/Nirex, US/WIPP, US/YMP) and in some cases monitoring is also required by regulations for the period in which institutional controls will operating (e.g. Czech Republic, France, US/YMP).

Current Swiss concepts also include an extended period of underground storage during which monitoring would be conducted on a part of the repository separate from the main waste disposal area. In the UK, Nirex has developed a concept of phased geological disposal which includes a period of underground storage that allows relatively straightforward monitoring and retrievability while future generations decide whether to proceed to backfilling, sealing and closure. Other programmes (e.g. Spain, Sweden) have no plans for monitoring of the repository. Monitoring is not planned in any programme for the period after withdrawal of controls.

Where monitoring is planned, details of the monitoring programmes themselves are generally still under development (e.g. Canada, UK/Nirex). The Czech Republic response indicates that monitored parameters may include pressure, temperature, humidity and gas releases. The US/WIPP programme includes monitoring for radionuclide releases and releases of volatile organic compounds. The US/YMP performance confirmation programme envisages development of sub-surface facilities to allow monitoring of the waste emplacement environment and of the performance of the EBS, via seepage tests, temperature measurements and rock mass monitoring.

2.7 Influence of monitoring and retrievability on repository concept

Some countries are in the process of evaluating the influence on the repository concept of monitoring and retrievability requirements (e.g. Canada). Others have made an assessment but have not identified any need to revise the repository concept or design (e.g. France, Germany, Japan).

In the UK, Nirex has developed a concept of phased geological disposal which includes a period of underground storage that allows monitoring and retrievability while future generations decide whether to proceed to backfilling, sealing and closure. The waste containers would be monitored during repository operation and the subsequent storage period, but currently there are no plans to monitor the EBS after closure. The main technical implication for safety assessment is uncertainty over the description of the starting conditions following repository closure, particularly with respect to groundwater chemistry.

2.8 Alternative EBS concepts

Within its consideration of disposal options, the Canadian programme is considering both in-room and in-floor waste emplacement schemes.

The French programme has considered a range of EBS designs and has documented a systematic qualitative assessment of the alternatives considered in arriving at the current design. Research is continuing into some alternative designs in order to provide programmatic flexibility in future years.

The current German programme is not considering alternative EBS designs for the Morsleben site but work on other potential disposal sites includes investigation of alternative EBS materials. The German programme undertook several studies on alternative EBS designs for the Morsleben site (e.g. bentonite seals) before selecting its current design.

The Japanese programme is also considering alternative EBS designs in order to identify the design most suited to the particular geological environments and repository sites under consideration.

In the UK, Nirex undertook several studies on alternatives before selecting its current design. Possible alternatives will be kept under review to demonstrate an “optimised” approach.

3. DESIGN AND EMPLACEMENT OF EBS

3.1 EBS components

Table 3.1 summarises the components of the EBS in the programmes considered.

Table 3.1. **Engineered barrier systems components**

Country/ programme	**Waste type**	**Waste matrix**	**Container/ overpack**	**Buffer/ backfill**	**Others**
Belgium	HLW.	Borosilicate glass.	304 stainless steel container, 316L stainless steel overpack.	FoCa clay, 60% calcium bentonite, 35% quartz sand, 5% graphite.	Disposal tube, tunnel lining.
	Spent fuel.	–	–		–
Canada	Spent fuel.	UO_2.	Carbon steel inner container with a copper outer shell.	Bentonite buffer, bentonite/sand buffer, clay/crushed rock backfill	Tunnel and shaft seals.
Czech Republic	ILW.	Concrete.	Steel.	Bentonite buffer.	Clay seals.
	Spent fuel.	UO_2.			
	HLW.	Glass.			
Finland	Spent fuel.	UO_2 (not considered to be part to the EBS)	Copper-iron.	Bentonite buffer, backfill of compacted crushed rock and bentonite.	Bentonite and concrete plugs.
France	Type B (ILW).	Wide variety.	Stainless steel and concrete containers.	Concrete lining.	Bentonite and/ or concrete seals.
	Type C (HLW).	Borosilicate glass.	Stainless steel container, steel overpack	Optional bentonite buffer.	Bentonite seals.
	Spent fuel.	UO_2 and MOX.	Stainless steel with metal insert.	Bentonite buffer with metal disposal tube.	Bentonite seals.

Country/ programme	Waste type	Waste matrix	Container/ overpack	Buffer/ backfill	Others
Germany/ Morsleben	LLW, ILW and sealed sources.	Not considered to be part of the EBS.	Not considered to be part of the EBS.	Salt concrete.	Seals.
Japan	HLW.	Glass.	Carbon steel overpack.	Bentonite-sand mixture.	Tunnel sealing plugs and grout.
Korea	Spent fuel.	UO_2.	Carbon steel inside, copper or stainless steel outer container	Bentonite or bentonite-sand mixture.	–
Spain	Spent fuel.	UO_2.	Carbon steel.	Bentonite.	Concrete and bentonite seals.
Sweden/KBS-3	Spent fuel.	UO_2.	Copper-iron.	Bentonite.	Tunnel backfill.
Switzerland/ Kristallin-I	HLW.	Glass.	Steel.	Bentonite.	–
UK/Nirex	LLW and ILW.	Cement grout.	Steel drum or box, or concrete box.	Cement-based vault backfill.	Low permeability seals and mass backfill in access ways.
	Shielded ILW	Cement or polymer grout.			
	High-α LLW	Cement grout.			
US/WIPP	TRU.	Various.	208L steel drums. Not considered to be part of the EBS.	MgO backfill.	Concrete panel closures and shaft seals.
US/YMP	Commercial spent fuel.	Fuel rods, Zircaloy or stainless steel cladding, UO_2 fuel pellets.	Stainless steel inside a Ni-based alloy outer container.	None.	Titanium alloy drip shield, granular invert.
	Defence spent fuel.	250 types, e.g. MOX, ceramic-plutonium, Pu/U alloy.	–	None.	
	HLW.	Borosilicate glass.	–	None.	

3.2 Functions of EBS components

Tables 3.2, 3.3, 3.4 and 3.5 summarise the various functions of the EBS components in the disposal concepts/programmes considered.

Table 3.2. **Functions of the waste matrix**

Country/ programme	**Function of the waste matrix**
Belgium	Expected to provide resistance to leaching for 10 000 years in the normal evolution scenario and in most altered evolution scenarios.
Canada	Expected to slow the rate of radionuclide release.
Czech Republic	Expected to contribute to radionuclide retention for 10 000 years in the normal evolution scenario.
Finland	Expected to slow the rate of radionuclide release (waste form is not considered to be part of the EBS).
France	Expected to provide resistance to leaching for 100 000 years in all scenarios.
Germany/ Morsleben	Not considered to be part of the EBS.
Japan	Expected to be stable and provide containment/slow release of radionuclides for tens of thousands of years.
Korea	Expected to provide resistance to leaching in the normal evolution scenario.
Spain	Expected to slow the rate of radionuclide release.
Sweden/KBS-3	Expected to slow the rate of radionuclide release.
Switzerland/ Kristallin-I	Expected to ensure a low radionuclide release rate for 150 000 years in all but the direct human intrusion scenarios.
UK/Nirex	Expected to provide low permeability and to limit radionuclide release for 300 to 500 years in the groundwater release scenario.
US/WIPP	Not considered to be part of the EBS.
US/YMP	Reduce the rate of radionuclide release.

Table 3.3. **Functions of the container/overpack**

Country/ programme	Function of the container/overpack
Belgium	Facilitates waste handling.
Canada	Expected to provide radionuclide containment for at least 100 000 years.
Czech Republic	Expected to provide radionuclide containment for 500 to 1 000 years in the normal evolution scenario.
Finland	Expected to provide a long-term (100 000 years) watertight enclosure for the spent fuel. Canisters with defects are still expected to contribute to limiting radionuclide releases.
France	Expected to facilitate waste emplacement and retrieval, protect the waste from water and limit releases over the long-term in all scenarios.
Germany/ Morsleben	Not considered to be part of the EBS.
Japan	Expected to ensure reducing chemical conditions, to provide a substrate for radionuclide sorption for the long-term, and to provide physical containment for at least 1 000 years.
Korea	Expected to provide radionuclide containment for ~1 000 years in the normal evolution scenario.
Spain	Expected to provide radionuclide containment for ~1 000 years in the normal evolution scenario.
Sweden/KBS-3	Expected to provide radionuclide isolation for ~1 000 000 years in all scenarios.
Switzerland/ Kristallin-I	Expected to provide complete containment during the initial period of elevated repository temperature in all but the direct human intrusion scenarios.
UK/Nirex	Expected to provide physical integrity and to limit radionuclide release for 300 to 500 years in the groundwater release scenario.
US/WIPP	Not considered to be part of the EBS.
US/YMP	Expected to provide resistance to corrosion for >10 000 years in undisturbed scenarios and to provide some degree of performance in disturbed (Igneous Intrusion, and Seismic Ground Motion) scenarios.

Table 3.4. **Functions of the buffer/backfill**

Country/ programme	**Function of the buffer/backfill**
Belgium	Expected to provide biological shielding during the operational phase, to provide a suitable chemical environment to minimise overpack corrosion, and t allow efficient transfer of heat away from the waste
Canada	Expected to provide physical, chemical, hydraulic and biological isolation of the waste and minimise radionuclide release to the geosphere over the long-term.
Czech Republic	Expected to contribute to radionuclide long term retention in the period from 1 000 years after closure, normal evolution scenario.
Finland	Buffer: To isolate the canister from the rock and to protect it against rock displacements. To decouple the canister from the flow and transport processes taking place in the surrounding rock. To limit mass flow rates around the canister. Backfill: To prevent the disposal tunnels and access routes to the repository from becoming major conductors of groundwater and transport pathways of contaminants. To keep the buffer in place around the canister in the deposition hole. To contribute to keeping the tunnels mechanically stable.
France	For HLW and SF: expected to control the THM environment and limit releases. For ILW: expected to ensure a durable and reversible design, to provide chemical buffering and delay release.
Germany/ Morsleben	Expected to ensure long-term stabilisation of the repository excavations and to limit leaching processes at the salt host rock by reducing the volume of voids and reducing brine inflow.
Japan	The buffer is expected to provide low permeabilities, high radionuclide sorption, low radionuclide diffusivities, colloid filtration and low radionuclide solubilities over hundreds of thousands of years.
Korea	Expected to contribute to water inflow minimisation and radionuclide retention and to provide chemical buffering in the normal evolution scenario.
Spain	Expected to contribute to radionuclide retention during the controlled release period of the normal evolution scenario.
Sweden/KBS-3	Expected to provide a mechanical protection and act as a diffusional barrier for ~1 000 000 years in all scenarios.
Switzerland/ Kristallin-I	Expected to ensure only slow radionuclide transport in the phase after failure of the container.
UK/Nirex	The vault backfill is expected to provide a high pH environment and to limit radionuclide release by sorption for up to 1 000 000 years in the groundwater release scenario.
US/WIPP	Expected to provide a suitable chemical environment and to remove carbon dioxide.
US/YMP	Design does not include buffer/backfill.

Table 3.5. **Functions of other EBS components**

Country/ programme	Function of other EBS components
Belgium	Overpack provides containment. Disposal tube facilitates waste emplacement during operational phase. Tunnel lining provides rock support.
Canada	Tunnel and shaft seals provide mechanical support during the repository monitoring phase, and hydraulic separation of rooms after repository closure.
Czech Republic	The seal components are expected to contribute to radionuclide long-term retention in the period from 1 000 years after closure, normal evolution scenario.
Finland	Sealing structures; To prevent the disposal tunnels and access routes to the repository, and the EDZ around the excavations from becoming major conductors of groundwater and transport pathways of contaminants. To prevent inadvertent intrusion into the repository.
France	The tunnel lining supports the host rock during the operational phase. The tunnel backfill and seals prevent access to the repository, prevent radionuclide transport along tunnels and hold the buffer in place.
Germany/ Morsleben	Drift seals separate different parts of the repository. Shaft seals separate the repository from the biosphere and limit brine flow via the shaft.
Japan	The tunnel plug and grout are expected to restrict groundwater movement for hundreds of thousands of years.
Spain	To block potential release pathways during the controlled release period.
Sweden/KBS-3	The tunnel backfill is expected to provide mechanical support for the buffer and the host rock for ~1 000 000 years in all scenarios.
UK/Nirex	The mass backfill is expected to stabilise the repository excavations for up to 1 000 000 years in the geotechnical instability scenario. Seals are expected to provide low permeability and to limit radionuclide release for up to 1 000 000 years in the groundwater release scenario.
US/WIPP	Shaft seals separate the repository from the biosphere and limit brine flow via the shaft for 10 000 years. Panel closures are emplaced to ensure compliance with regulations relating to non-radioactive hazards during the operational period.
US/YMP	The drift ground support system is designed to provide support for the excavation during the 50-year operational period. The titanium alloy drip shield is designed to reduce the effects of rock fall and to limit the dripping of water onto the waste. The drip shield is designed to function >10 000 years. The granular invert is designed to act as a diffusive barrier to radionuclide transport.

3.3 Key FEPs considered in the design of EBS components

Table 3.6 identifies the main Features, Events, and Processes (FEPs) considered in the design of the EBS components.

Table 3.6. **Key FEPs considered in the design of the EBS components**

Country/ Programme	**Key FEPs**
Belgium	Metal corrosion, heating, chemical and mechanical resistance (e.g. oxidation, effects associated with the EDZ).
Czech Republic	Corrosion, leaching, gas transport, and heat transfer.
Finland	For all components: climate change (e.g. permafrost and glaciation) and THMCB evolution. For the canister: mechanical loads, including loads due to uneven saturation of the buffer and an additional hydrostatic load caused by three kilometres of ice during a glaciation, rock displacements (e.g. due to postglacial earthquakes), corrosion, gas generation and transport, sealing defects. For the buffer, backfill and seals: saturation, swelling, alteration, interaction with cementitious materials, advection, diffusion, gas transport, and intrusion of very saline groundwater.
France	For all components: THMC evolution. For vitrified waste: glass dissolution. For ILW: gas pressurisation/containment. For the container: mechanical and hydrostatic loads. For the buffer, backfill and seals: resaturation, swelling, alteration, interaction with cements, advection, diffusion, gas transport.
Germany/ Morsleben	Mechanical stability, salt creep, dissolution of salt or potash, brine flow, gas production, sorption in the far-field, overburden, and chemical degradation of drift seals.
Japan	For all components: climate change and THMCB evolution. For the waste: dissolution. For the overpack: mechanical loads, corrosion and gas generation/transport. For the buffer: chemical interaction with water, host rocks and cementitious material (e.g. tunnel support, plug and grout), redox processes, radionuclide precipitation adjacent to waste glass, and radionuclide diffusion, solubility and retardation.
Korea	For the waste: the waste type and inventory, dissolution and leaching. For the container: corrosion, gas generation and mechanical stress. For the buffer/backfill: resaturation, groundwater flow, porewater chemistry, radionuclide diffusion and bentonite alteration.
Spain	Buffer saturation and swelling, radiolysis, corrosion, solubility and precipitation, diffusion, advection.
Sweden/KBS-3	For the waste: stability/slow dissolution. For the container: fabrication defects, corrosion, and mechanical loads. For the buffer: diffusion, swelling, physical and chemical degradation. For the backfill: mechanical strength, and physical and chemical degradation.
Switzerland/ Kristallin-I	For the waste: SiO_2 saturation, water flow rate. For the container: integrity/durability, corrosion, redox conditions. For the backfill: diffusion, effects of temperature.

Country/ programme	Key FEPs
UK/Nirex	Reaction/dissolution of the waste matrix in groundwater, anaerobic container corrosion, leaching from the vault backfill, reaction of seals with groundwater.
US/WIPP	Repository structural/mechanical stability, chemical predictability, permeability, durability, and the evolution of MgO in high-ionic strength brines.
US/YMP	Mechanical impacts (e.g. rockfall and seismic ground motion) on waste container and drip shield, general and localized corrosion of waste containers and drip shield, thermal effects, chemical and microbiological changes in the waste and EBS, seepage interactions with corrosion products, degradation of cementitious materials, localized corrosion and creep rupture of cladding, spent fuel degradation, glass degradation, in-package chemistry and sorption, radionuclide solubility and speciation in waste and EBS, and colloid-facilitated transport.

3.4 Baseline design assumptions

Table 3.7 identifies baseline assumptions and constraints underlying the repository design in each of the programmes considered. The variation amongst the types of assumptions in Table 3.7 results, in part, from the different stages of programmatic development in each country and partly from the amount of emphasis placed on the EBS, as opposed to the entire disposal system, when responding to the questionnaire.

Table 3.7. **Baseline assumptions underlying repository and EBS design**

Country/ programme	Baseline assumptions
Belgium	The natural geological barrier is the main isolation barrier. The overpack provides containment during the thermal phase (500 years for vitrified HLW, 2 000 years for spent fuel). In the normal evolution scenario there is no early failure of the overpack. The backfill provides an additional but minor contribution to safety. The disposal tube facilitates retrievability.
Canada	Example of constraints on the design include; the waste type/volume/inventory (e.g. age and burn-up of fuel), the need to maintain container surface temperatures below 100 °C, the need for sufficient, low-permeability, saturated rock above the repository, and the need for dense bentonite near the SF to ensure no microbiologically influenced corrosion of the waste containers.
Czech Republic	Constraints on the design include: waste inventory/volume, radiation safety and minimisation of environmental effects with respect to backfill and host structure compatibility, design feasibility and acceptance by public.

Country/ programme	**Baseline assumptions**
Finland	Long-term isolation of the waste provided by the EBS, which is designed to account for present-day and future conditions at the disposal site, and to minimise disturbances to the host rock caused during construction and operation.
France	Long-term isolation of the waste provided by the EBS, which is designed to account for present-day and future conditions at the disposal site, and to minimise disturbances to the host rock caused during construction and operation.
Germany/ Morsleben	Constraints on the design of the EBS include simplicity (e.g. of geometry) and robustness (e.g. state-of-the-art engineering), compatibility between the backfill and the host rock, site-specific geology, and the requirement to minimise water flow through the repository.
Japan	Constraints on the design of the EBS include the provision of long-term isolation and barrier functions under current and future conditions, and minimisation of construction and operational disturbances.
Korea	Constraints on the design of the EBS include the waste inventory, the order of waste disposal (CANDU spent fuel before PWR spent fuel), and an operational lifetime of 40 years.
Spain	Emplacement of spent fuel (burn up ~40 000 MWd/TU) in long galleries/tunnels excavated at depth in low permeability clay or granite (500 m granite, 250 m clay). Canisters are assumed to have a thermal output of ~1 200 W and so the disposal environment is assumed to be relatively cool (<100ºC).
Switzerland/ Kristallin-I	From a regulatory perspective, the main requirement is one of possessing sufficient understanding of relevant processes (FEPs) with which to make sufficiently confident estimates of repository safety.
UK/Nirex	Constraints on the design of the disposal system include the heterogeneous and chemically reactive nature of LLW-ILW, which make it unrealistic to rely on physical containment in the long-term, and suggest use of a chemical containment system. An additional constraint is the need to allow gas to escape from the repository.
US/WIPP	Constraints on the design of the EBS include feasibility and the use of present-day technologies.
US/YMP	Constraints on the design of the repository include that it should be located above the water table and be capable of supporting staged repository development, receive waste no later than 2010, that the surface temperature of the cladding should remain below 350°C, that there should be thermal operating mode flexibility, and that the waste should be retrievable.

3.5 Contribution of EBS to robustness of multiple barrier system and disposal system performance

All of the programmes recognise that the EBS includes multiple barriers to radionuclide migration, which provide reserves of performance greater than that required for compliance with safety criteria (e.g. dose or risk limits). These reserves of performance may not be explicitly evaluated during safety assessment because of conservatisms incorporated within the safety case.

The US/YMP describes this as a "defence in depth approach", which provides a method of ensuring that the performance of the disposal system is acceptable even if one or more components of the repository system fail to perform as expected. Robustness in this sense, or defence in depth, is provided by having safety components that have different roles and failure modes so that they provide a back-up function to components that may fail (France, Sweden, UK/Nirex, US/YMP).

Examples of EBS components that can provide additional assurance of disposal system safety include:

- The disposal tube in the Belgian concept, which is intended primarily to facilitate retrievability but which also contributes to containment, although this containment is not evaluated in safety assessment calculations.
- The bentonite based buffer in the Finnish, Japanese and Swedish concepts for spent fuel disposal, and in the Japanese concept for disposal of vitrified high-level waste. In these concepts the buffer provides a secondary barrier to radionuclide transport to supplement the primary isolation role of the waste container.
- The long-term containment of many radionuclides within wastes conditioned with cement and grouted inside the Nirex waste package, which backs up the chemical containment function of the vault backfill. The backfill chemistry, which is beneficial to waste container lifetime.
- The multi-component shaft seals in the US/WIPP design, which include several different sealing materials with different potential failure modes.

3.6 Links to URL experiments

Some of the programmes are at too early a stage to have commissioned their own underground research laboratory (URL) experiments (e.g. Czech Republic, Korea), and although several of the other responses did identify programmes of URL experiments (Canada, Finland, Germany, Sweden, Switzerland, US/WIPP, US/YMP – brief details provided below), only the Japanese and US/YMP responses really addressed the issue of *linking* the experiments to the safety case. The US/YMP response describes an iterative process beginning with characterisation and proceeding through conceptual model development and total system performance assessment and leading to design refinement. The experiments identified included:

Canada

- Mine-by experiment.
- Heated failure tests.
- Thermal-hydraulic experiment.
- Buffer/container experiment.

- Isothermal test.
- Excavation stability test.
- Tunnel Sealing Experiment.
- Buffer/coupon long-term tests.
- Moderately fractured rock test.
- *In situ* diffusivity test.
- Quarried block test.
- *In situ* microbial test.

Finland

- Characterisation of the host rock and testing and demonstration of repository technologies (e.g. excavation of deposition holes) in the ONKALO URL.
- R&D, testing and demonstration experiments on the buffer, backfill, plugs, host rock, excavation techniques, and waste transfer and waste emplacement equipment in the Äspö Hard Rock Laboratory and other URLs.

France

- Rock characterisation at the URL at the Meuse/Haute Marne site.
- Participation in studies on EBS components, as well as repository excavation and waste transfer/emplacement equipment, in URLs in Canada, Switzerland (Mont Terri), Belgium (Mol) and Sweden (Äspö) to demonstrate disposal technologies and improve PA methods.

Germany/Morsleben

- Drift seal permeability tests of the contact zone in the Asse mine.
- Permeability tests on the EDZ at Morsleben.
- Handling and operation tests with backfill material (salt concrete) at Morsleben.
- Backfill drop tests.
- Backfill pumping tests.
- Laboratory tests to investigate the mechanical and hydraulic properties of the backfill and drift seal materials, and to investigate their hydration and setting behaviour.

Japan

- Development and validation of THMC models at the Äspö URL and Kamaishi mine to define the initial conditions for the near-field in safety assessment calculations.
- Participation in the Tunnel Sealing Experiment at the Canadian URL with the aim of model and database development for the early physico-chemical evolution of the near-field.
- Participation in the Grimsel URL experiments on colloids and alkaline plumes.
- Initiation of Japanese URLs at Mizunami and Horonobe.

- Conduct of the surface-based “ENTRY” experiments for overpack corrosion, buffer erosion, colloids, alkaline plume effects, low-alkali cements, gas migration in bentonite, THMC processes and possible effects of faulting.

Spain

- The FEBEX programme at the Grimsel URL in Switzerland, which comprises several investigations relevant to the EBS including, canister and bentonite buffer emplacement tests, buffer saturation tests, buffer performance tests under thermo-hydromechanical loads, corrosion tests and code validation tests.
- Reactive transport tests on buffer materials at the Äspö URL.
- Buffer heating tests and further code validation studies at the Mont Terri URL in Switzeland.

Sweden/KBS-3

- Buffer resaturation tests at the Äspö URL.
- Reactive transport tests on buffer materials at the Äspö URL.

US/WIPP

- An initial series of URL tests in the experimental part of the WIPP aimed at addressing thermal and structural interactions.
- A later series of laboratory and metre-scale plugging and sealing tests, emplacement tests and fluid flow studies, including gas flow testing of the EDZ.

US/YMP

- Drift seepage tests.
- Large block tests to examine thermally driven coupled processes (temperatures and water saturations in heated rock).
- Heater tests at different scales to investigate the thermo-hydrological, thermo-mechanical, and geochemical behaviour of the host rock.
- Long-term corrosion tests on container materials under repository conditions.
- Tests of drip shield effectiveness under representative thermal conditions.
- Tests to examine the processes of degradation for cladding, spent fuel and vitrified HLW glasses.
- Tests to examine the generation, and sorptive properties, of colloids.
- Ventilation tests.

3.7 Key design uncertainties

Table 3.8 identifies the key uncertainties in the design and emplacement of EBS identified in the questionnaire responses.

Table 3.8. **Key uncertainties in the design and emplacement of EBS**

Country/ programme	**Key uncertainties**
Belgium	• The deformation of the disposal tube under thermal loads and heterogeneous swelling pressures. • The design of the disposal gallery seals to take account of thermal loads and swelling pressures. • The relation between corrosion and overpack thickness and welding requirements. • The relation between disposal tube design, water tightness and durability. • Backfill design in terms of characterisation, maximum temperature/swelling pressures, emplacement as powder, blocks or pellets, costs, availability, swelling capacity, and how to achieve appropriate levels and rates of hydration. • The long-term strength and chemical compatibility of the lining. • The relation between disposal gallery geometry and dimensions, and optimal sealing. • Backfill materials and emplacement methods.
Canada	• Material properties, performance and emplacement methods for clay-based sealing materials (dense buffer, buffer, gap backfill, light backfill and dense backfill). • Confirming the assumption that the copper container will not fail in a repository from creep, stress-corrosion cracking, or microbiologically influenced corrosion. • Ensuring no microbial activity in the sealing materials near the container surface. • Copper container fabrication, welding and inspection methods. • Demonstration of in-room container emplacement and retrieval methods. • Tunnel seal requirements and demonstration of seal lifetimes (e.g. clay, concrete). • Effect of long-term monitoring phase on EBS system.
Czech Republic	• The durability of the waste matrix and its ability to retain radionuclides over ~100 000 years. • The durability of the container over ~500 to 1 000 years. • The durability of the backfill and its ability to retain radionuclides over ~10 000 years.
Finland	• The emplacement and transient-phase behaviour of the packages containing the canisters and buffer in the horizontal deposition holes in the KBS-3H concept. • The medium-term to long-term behaviour of cement in the backfill and seals. • The performance of backfills in saline groundwaters.
France	• The emplacement and transient-phase behaviour of the packages containing the canisters and buffer. • The effects of cement on bentonite EBS components. • Construction of a “key” through the EDZ to prevent flow and transport. • EDZ evolution.
Germany/ Morsleben	• Proof of sealing between the backfill and the surrounding host rock. • The permeability behaviour of the EDZ. • The construction of drift seal dam structures using backfill injection technologies. • The limits of adequate mechanical and hydraulic behaviour of salt concrete seals. • The chemical composition of inflowing brines.

Country/ programme	**Key uncertainties**
Japan	• Overpack corrosion in the first 1 000 years, including the effects of high pH. • Overpack weld resistance. • The transient behaviour of the overpack and buffer during the resaturation period. • Long-term chemical alteration of the buffer. • Long-term deformation and erosion of the buffer.
Spain	• Interactions of canister corrosion products. • Gas transport in bentonite. • Bentonite concrete interactions. • Retrievability of waste from the bentonite buffer. • Monitoring. • Seal design.
Sweden/KBS-3	• Canister welding and sealing.
UK/Nirex	• Physical and chemical heterogeneity of the waste matrix. • Container fabrication defects. • Longevity of the vault backfill.
US/WIPP	• The chemical reaction behaviour of the MgO backfill. • The degree to which the shaft seal design can be simplified while ensuring adequate performance. • Construction of the panel closures.
US/YMP	• Coupled thermal-mechanical, thermal-chemical, and thermal-hydrologic processes and their relation to the EBS design. • Groundwater seepage into the emplacement drifts. • Host rock mechanical and fracturing properties and the relationship with drift stability.

3.8 EBS design criteria and constraints

In the French concept, the following design criteria apply:

- The disposal system should protect public health and the environment as specified in regulatory guidelines.
- The EBS design must not compromise the contribution of the geosphere to the safety case.
- The EBS must make an important contribution to radionuclide confinement during the period of higher activities and temperatures (up to 10^4 years).
- The repository design must allow safe handling of waste packages.
- The EBS design should control the waste package environment.
- The EBS design should control the release of radionuclides from the near-field.

- The EBS design should be functional, flexible and reversible.
- The EBS design should avoid unnecessary complexity and should not rely on complex models in which confidence might be low.

Examples of design constraints considered in France include:

- Minimisation of mechanical perturbation to the host rock.
- Accommodation of a variety of waste types.
- Minimisation of any thermal pulse to ensure that temperatures in the far-field do not rise above 100°C.
- Minimisation of any geochemical perturbation.
- Promote very slow resaturation (~10^5 years) and return to equilibrium.

The German Morsleben disposal facility is largely constrained by the nature of the former mine excavations in which it is located.

In the Japanese concept, the following criteria and constraints apply:

- Physical containment of radionuclides by the overpack for at least 1,000 years.
- Effective filtration by the buffer of colloids and microbes.
- Restriction of maximum near-field temperature to below 100°C.
- Low permeability of buffer material to ensure diffusive solute transport.
- Constructability.

In Nirex concept, the following criteria and constraints apply:

- Use of existing technologies and qualified materials.
- Quality assurance to ISO 9000.
- Use of cement encapsulants in waste packages.
- Weight and dimensions of waste packages.
- Remote placement of waste packages and backfill.
- Compliance of waste packages with operational and transport safety cases.

3.9 Critical parameters for design and construction

In the French concept the most important parameters relate to:

- The extent of the EDZ and any long-term deformation.
- Temperature.
- Saturation.
- Gas generation.

- The ability to re-seal tunnels.
- The ability to seal access wells.

The German Morsleben disposal facility the most important parameters relate to the permeability of the seals and the contact of the seals with the host rock.

In the Japanese concept the most important parameters include:

- Overpack thickness (for mechanical stability and corrosion allowance).
- Maximum temperature of the buffer (below 100°C).
- Permeability of the buffer material.

In the Nirex concept the most important parameters apply to the vault backfill and include:

- Sufficient short-term strength to support packages.
- Relatively low long-term strength to facilitate retrievability.
- Sufficient workability for reliable emplacement (filling all voids).
- Pumpable to facilitate remote delivery.
- Low “bleeding” settlement to avoid the formation of gaps.

3.10 Areas of optimisation and optimisation drivers

The French and Nirex programmes have identified several areas for potential optimisation to improve the reliability of the disposal system and envisage long-term research programmes to investigate where and how improvements can best be made.

Optimisation work for the German Morsleben disposal facility focuses on the potential cost savings that might be made by optimising the length of the seals.

Optimisation work for the Japanese disposal concept focuses on balancing potential cost savings against the constructability and performance of the buffer, overpack, plug and grout by considering alternatives in the materials and barrier properties.

4. CHARACTERISATION

4.1 Key parameters that characterise EBS behaviour

Table 4.1 identifies the key parameters that characterise the behaviour of the EBS in the disposal systems under consideration.

Table 4.1. **Key parameters that characterise the behaviour of the EBS**

Country/ programme	**Key parameters**
Belgium	Overpack permeability, backfill swelling pressure and thermal conductivity, liner strength, disposal tube permeability and strength.
Canada	EBS geometry and material composition and thermal/saturation/corrosion properties, near-field temperatures, groundwater flow rates and salinity.
Czech Republic	Geotechnical characterisation parameters, radionuclide migration parameters.
Finland	Corrosion rates of copper, iron and fuel assembly, canister strength, buffer and backfill strengths, thermal conductivities, permeabilities, radionuclide retardation coefficients in buffer and backfill.
France	Metal corrosion and glass leaching rates. Mechanical parameters for the container. THMCB and gas parameters for the buffer and backfill.
Germany/ Morsleben	Drift seal geometry. Mechanical parameters for sealing materials (e.g. Young's modulus, compressive and tensile strengths). Hydraulic properties of sealing materials (porosities and permeabilities). Rheological properties of sealing materials (e.g. concrete consistency, hydration heat and setting properties).
Japan	Glass dissolution rate, overpack thickness and material, radionuclide solubilities, retardation coefficients and diffusivities, long-term properties of the buffer, plug and grout.
Korea	Constraints on the design of the EBS include the waste inventory, the order of waste disposal (CANDU spent fuel before PWR spent fuel), and an operational lifetime of 40 years.
Spain	Leach rate, canister thickness and corrosion rate, buffer thickness and dry density, bentonite suction, seal width, radionuclide solubilities and diffusion coefficients.
Sweden/KBS-3	Radiation intensity, temperature, pressure and water flow, EBS geometry, mechanical stress, radionuclide inventory, EBS material and properties (e.g. swelling), water and gas compositions.

Country/ programme	Key parameters
Switzerland/ Kristallin-I	HLW glass corrosion rate, steel corrosion rate, buffer conductivities and rheological parameters, radionuclide diffusivities in buffer.
UK/Nirex	Container corrosion rates, cement porewater pH, radionuclide solubility and sorption in cementitious systems, encapsulant and backfill permeability.
US/WIPP	EBS component permeabilities and porosities.
US/YMP	Thermal loading. Drip shield general corrosion rate. Waste package general corrosion rate. Radionuclide solubilities, effective diffusion coefficients, and colloid stability in invert. Rate of water inflow (seepage) into emplacement drift, evaporation rate for seepage water, and water saturation in invert. Flow of seepage through breached waste package. Chemical composition of seepage entering emplacement drift during thermal period. Radionuclide diffusivities and sorption coefficients in waste package.

4.2 Key characterisation uncertainties and issues

Many of the key uncertainties have already been identified in Tables 3.8 and 4.1. The key issues identified in response to this question fall into just a few groups.

There is a group of issues relating to the **application of data to safety analysis**. For example, the responses from the Czech Republic and Spain noted the uncertainties associated with the extrapolation of short-term experimental data to longer assessment periods (see also Section 6.2), and with the use of data from analogues.

The Belgian, Finnish, French, Japanese and Spanish responses identified issues relating to the swelling capacity of clays, the heterogeneity of swelling and, more generally, the thermo-hydro-mechanical-chemical-biological **(THMCB) properties of** clay-based **buffers and backfills**. Similarly, the German response noted uncertainties associated with the parameters describing the mechanical and hydraulic properties of salt-concrete sealing materials. The German response also noted that the ***evolution*** **of properties and parameter values** was a further uncertainty.

The Japanese, Spanish and US/YMP programmes raised **spatial heterogeneity** as an issue. The US/YMP programme is investigating the complex coupled processes that result from spatially heterogeneous and uncertain parameters describing the thermal and mechanical properties of the host rock.

A group of issues exists in relation to **gas generation**. The US/WIPP response identified microbial gas generation as a key issue: gas generation could lead to acidification of brines and thereby to increased radionuclide solubilities. Gas generation rates were also noted as being uncertain in the Korean and Finnish responses. Uncertainties in related parameters, such as iron corrosion rates, may compound gas generation rate uncertainties (e.g. Spain). The Japanese response noted the uncertainties associated with the processes of, and pathways for, gas migration. The Finnish response noted that uncertainties associated with fuel assembly corrosion rates might be significant because they influence rates of **^{14}C release**, and the French and Spanish responses also noted the importance of the waste matrix and the waste container in containing ^{14}C.

Other issues identified were **EBS degradation rates** and interactions of the EBS with the host rock (Czech Republic) or among EBS materials (e.g. cement-bentonite interactions – France, Japan), the **radionuclide retention properties** of buffer and backfill (Finland), canister corrosion rates (Finland, UK/Nirex) and canister defects (Sweden), and the **characteristics and behaviour of the EDZ** (France).

4.3 New characterisation methods and techniques

The questionnaire responses identified the following areas where new or improved characterisation techniques are sought:

1. Techniques to characterise the extent and fracture density of the EDZ (France).
2. Techniques for remote monitoring (France).
3. Techniques for improved geochemical characterization (France).
4. Techniques for determining more accurate and representative short-term and localised corrosion rates (France, UK/Nirex).
5. Improved methods for building confidence in models of THMC and cement-bentonite interactions (Japan).
6. Techniques to characterise the quality of container seals, fabrication defects and the propagation of container failure mechanisms (UK/Nirex).

4.4 Key scenarios affecting characterisation requirements

Responses to this question suggest that all of the main scenario types can lead to characterisation requirements, depending on PA assumptions and the balance between the assumed performance of the various disposal system components.

Characterisation of the EBS is important in disposal systems where the geosphere is assumed to provide little containment and for scenarios where it is assumed that geosphere performance is compromised by disruptive events. Conversely, in disruptive scenarios where the EBS is assumed to provide little containment, the emphasis of characterisation activities is on the geosphere.

Specific examples of how scenarios affect characterisation requirements include:

- Modelling of certain human intrusion scenarios requires characterisation of the physical properties of the waste form (UK/Nirex, US/WIPP).
- Scenarios involving seawater influx to the repository may require different near-field K_ds (Japan).

5. MODELLING

5.1 Research models

Table 5.1 summarises the responses to the questions on research models. Key points of generic relevance (as opposed to programme-specific or site-specific relevance) are noted below:

- A wide range of Thermo-Hydro-Mechanical-Chemical (THMC) processes are modelled using research models (e.g. Belgium, Canada, Finland, France, Germany, Japan, Spain, Sweden, US/YMP). Processes not always explicitly included in the models include biological (e.g. Belgium, Finland, France) and colloidal processes (e.g. Belgium, France, Spain). The Canadian programme, however, is developing a capability to model biological processes, and models of gas generation that include biological processes are included in some performance assessment models (e.g. Germany, UK, US-WIPP).

- In general, process couplings are modelled where this is feasible and where the couplings are significant (e.g. Belgium, Canada, Finland, France, US/WIPP, US/YMP). Explicit representation of process couplings in research models can sometimes be necessary to gain adequate understanding and acceptance, and can also provide support for, and build confidence in, simplified performance assessment models.

- Geometrical simplifications are often made when applying research models (e.g. Belgium, Canada, Czech Republic, France, Germany, Korea, Switzerland, UK/Nirex). Some programmes justify this by arguing that, when applying research models, the focus is on developing process understanding rather than simulating the details of effects related to geometry (e.g. Belgium):

- Relatively few sensitivity studies are made with research models because usually these are directed at developing process understanding (e.g. Belgium). Those sensitivity studies that are conducted typically involve investigating the effects of varying just one or a few parameter values all a time (e.g. France, Japan).

- Different methods are used when defining boundary conditions for models of the EBS and near-field. The choice of approach tends to depend on programmatic or site-specific issues, such as the nature of the host rock. One common approach, however, is to use models of the disposal system at a larger scale to define the boundary conditions for smaller scale EBS or near-field models (e.g. Canada, Finland, France, Germany, Japan, US/YMP).

Table 5.1. **Processes, process couplings, simplifications and boundary conditions in research models**

Country/ programme	**Processes modelled**	**Coupled or individual process modelling**	**Repository geometry/Spatial variability**	**Model simplifications**	**Sensitivity studies**	**Boundary conditions**
Belgium	Water and gas flow, heat and mass transport, buffer swelling, canister corrosion, waste dissolution, chemical reactions.	THM processes are coupled where possible. Separate reactive transport calculations.	1-D, 2-D and 3-D models are used as needed to represent repository geometry.	Geometrical simplifications are made in research modelling because the focus is on the process understanding.	Few sensitivity studies are made with research models as these are more directed at process understanding.	For clay host rocks it is sometimes necessary to include part of the host rock in the near-field model.
Canada	A wide range of processes.	Different models include different THM and bio-chemical couplings.	3-D models are used as needed to represent repository geometry.	Simplifications vary according to the model (e.g. bio-chemical models are 1-D).	Key parameters are varied.	Boundary conditions are defined based on assumptions about the far-field.
Czech Republic	Geotechnical processes, radionuclide migration.	Processes are modelled separately.	The repository is represented as a spatially homogeneous source	A 1-D model is used.	None.	Boundary conditions are defined using reference data for granite.
Finland	THMC processes.	Different models include different THM and TC couplings.	Some THM models represent repository geometry explicitly. Some models include deterministic host rock features. Stochastic modelling of flow and transport.	Only the most important couplings are included.	Key parameters are varied. “What if?” calculations are also made.	Boundary conditions are defined from larger scale geohydrogeological models and chemistry measurements.

Country/ programme	Processes modelled	Coupled or individual process modelling	Repository geometry/spatial variability	Model simplifications	Sensitivity studies	Boundary conditions
France	Water and gas flow, heat and mass transport, buffer swelling, canister corrosion, waste dissolution, chemical reactions.	Different models include different THM, TC and HC couplings.	Some 3-D THM models. 1-D or 2-D axisymmetric chemical models.	Only the most important couplings are included.	Deterministic sensitivity studies in which single parameters are varied.	Boundary conditions are defined from larger scale geohydrogeological models and measurements.
Germany/ Morsleben	Water and gas flow, heat and mass transport, waste dissolution, chemical reactions, gas generation.	TM couplings and HC couplings are evaluated independently	The EBS is modelled in 3-D but this model does not encompass the whole repository.	Geometrical simplifications are made and conservative parameters values applied.	Sensitivity studies are included in PA.	Boundary conditions are defined from larger scale far-field models.
Japan	Glass dissolution, overpack corrosion, gas generation and migration, resaturation, porewater chemistry, radionuclide solubility and retardation, mechanical stability of the EBS.	THM couplings are modelled, other couplings tend to be neglected.	Repository geometry is accounted for using models with multiple sources. Spatial variability is not modelled.	Many simplifications are made. These are justified using reasoned arguments or by reference to experimental observations.	Parameters variations for key parameters.	Boundary conditions are defined from larger scale models.
Korea	Radionuclide leaching, waste dissolution, container corrosion and failure, diffusion in buffer, decay.	Some couplings are modelled.	The THM model accounts for an array of waste containers in vertical deposition holes.	A 2-D approach is used. Other simplifications depend on the particular model.	Parameters variations for buffer thickness, geometry and spatial variability.	Boundary conditions are defined using assumptions for the far-field.

Country/ programme	Processes modelled	Coupled or individual process modelling	Repository geometry/spatial variability	Model simplifications	Sensitivity studies	Boundary conditions
Spain	THMC processes, radionuclide leaching and transport, buffer resaturation, canister corrosion and movement.	THM couplings and hydrogeochemical couplings are modelled.	The THM modelling accounts for the geometry of the repository. Spatial variability is not modelled.	All wastes are assumed to exhibit the same behaviour.	Parameter variations for models of buffer saturation and geochemistry.	Part of the far-field is included in models of the near-field.
Switzerland/ Kristallin-I	Heat transport, resaturation, glass corrosion and radionuclide release, gas generation, particulate transport.	Processes are mainly modelled separately. Gas generation is coupled to corrodant diffusion.	Accounted for implicitly by conservative approximation.	Homogeneity, symmetry.	Parameter variations for rate parameters.	It is assumed that the access of water to the outer surface of the buffer is uniform.
UK/Nirex	Corrosion, backfill leaching, groundwater flow, thermal evolution.	Processes are modelled separately.	The source-term modelling considers repository geometry in a simplified way. Spatial variability is considered by modelling backfill cracking and preferential flow.	The source-term modelling assumes that solid phases in the backfill are pure crystalline solids.	Sensitivity studies are used to investigate the effects of cracking and preferential flow.	Boundary conditions are defined based on the hydraulic gradient and permeability of the far-field, and typical groundwater compositions.
US/WIPP	Mechanical and hydrological processes.	Most models include significant couplings.	Host-rock stratigraphy is represented explicitly in the PA model. A statistical approach is used for actinide concentrations.	Numerous simplifications are made. Peer review is used to demonstrate acceptability.	Many. Both individual parameter variations and probabilistic approaches.	The PA model grid extends for several kilometres from the waste and EBS.

Country/ programme	Processes Modelled	Coupled or individual process modelling	Repository geometry/spatial variability	Model simplifications	Sensitivity studies	Boundary conditions
US/YMP	TH, THM, and THC processes, seepage, chemical interactions and evolution, EBS structural behaviour, drip shield and waste package degradation, radionuclide solubilities and transport.	Processes are coupled or treated individually depending on the importance of the coupling and whether a bounding approach is acceptable.	These factors are accounted for directly in some cases or a bounding approach to capturing their impacts is taken.	Process models and abstraction models are used. Simplifications are justified by showing that a process is not important, taking a bounding approach, or providing justification that the important processes are captured adequately.	For process models sensitivity studies typically assess the impact of one or a few key parameters. TSPA sensitivity analyses are used to determine uncertain EBS parameters important to performance.	Stress boundary conditions at the drift-scale are derived from a larger, mountain-scale model. TH and THC boundary conditions to the near-field are established by modelling the near-field and far-field together.

5.2 Modelling EBS in performance assessment

The following points summarise the responses to the questions about PA modelling of EBS:

Uncertainties are handled in one or more of four ways:

- Through the use of conservative assumptions and parameter values (Belgium, Canada, Czech Republic, Finland, Germany, Japan, Switzerland, UK/Nirex).
- Through probabilistic modelling (Canada, Germany, Japan, UK/Nirex, US/WIPP, US/YMP).
- Through deterministic sensitivity studies to explore the effects of varying parameter values (Belgium, Canada, Finland, Germany, France, Japan, Korea, Switzerland).
- Through the conduct of “what if?” calculations (Canada, Finland, France, Japan).

Some programmes employ bespoke forms (e.g. Data Collection Forms, Belgium) on which to record best estimate values of parameters and associated uncertainties as a means to provide a documented treatment of uncertainties.

Typical simplifications include:

- Reduced dimensionalities, such as 1-D and 2-D approaches (e.g. Czech Republic, France, Germany, Japan, Korea, Spain), radically symmetric approaches (e.g. Japan, Switzerland, US/WIPP).
- Spatial homogeneity (e.g. Switzerland).
- Consideration of only part of a repository, such as modelling of a single deposition hole (Finland), or modelling of radionuclide release from a single canister and then upscaling this to apply to the whole repository (Japan).
- Making steady-state assumptions (e.g. Belgium, Finland, Japan).
- Linearisation of non-linear processes such as radionuclide sorption (all).

Assessment programmes justify simplifications using a combination of some or all of the following:

- Arguments that the modelling assumptions and parameter values are conservative.
- Arguments that steady-state models are parameterised in a manner that encompasses the possible effects of time-dependent processes.
- By showing that a process is not significant to disposal system performance.
- By taking a bounding approach, i.e., making scoping calculations separately from the PA analysis.
- By providing justification that the important processes are captured adequately using other model parameters.
- By using peer review to demonstrate acceptability.

EBS sub-models may be linked to, or used in, PA in several ways:

- The EBS sub-model may be directly incorporated within the PA model (Belgium, US/WIPP). For example the model of the seal elements in the WIPP disposal system is directly included in PA model.
- Models of EBS components may be used to provide data tables, which can be sampled during probabilistic PA runs (e.g. the WIPP salt convergence model).
- Results of regional groundwater flow calculations can be input as boundary conditions to the near-field sub-model (e.g. France).
- Results of radionuclide release calculations may be used as the source term for far-field radionuclide transport calculations (e.g. France, Japan, Spain).

5.3 Key modelling uncertainties – areas for confidence building

Table 5.2 provides examples of the responses received on the identity of key modelling uncertainties and planned/ongoing routes to the reduction of those uncertainties.

Table 5.2. **Addressing key modelling uncertainties**

Country/ programme	**Modelling uncertainty**	**Route to reducing uncertainty**
Belgium	Adequate understanding/modelling of processes.	Additional URL and laboratory observations and experiments.
	Lack of data (especially geochemical data, unsaturated hydraulic parameters, rheology of EBS materials).	Further characterisation of EBS materials and use of conservative assumptions.
	Correct understanding/modelling of process couplings.	Comparison of model results with experiments and benchmark tests.
Finland	THMCB evolution of the buffer-canister system in the transient phase and potential alteration of the buffer in the long-term.	URL and laboratory experiments, modelling studies, and by employing conservative assumptions in PA.
	Behaviour of a defective copper-iron canister surrounded by a highly compacted bentonite buffer (including effects of gas generation and transport).	URL experiments and by developing models for gas transport through compacted bentonite, and by employing conservative assumptions in PA.
	Time-dependent effects in radionuclide transport analyses.	By introducing step-wise changes in the parameter values, concerning e.g. the growth of an initially small defect in the canister.
France	Transient phase THMC evolution of the buffer-container system and long-term buffer alteration.	URL and laboratory experiments, modelling studies, natural analogues, and by employing conservative assumptions in PA.

Country/ programme	**Modelling uncertainty**	**Route to reducing uncertainty**
Germany/ Morsleben	Behaviour of the contact between the backfill and the host rock.	URL experiments.
	Time-dependent changes in mechanical and hydrological parameters used to represent sealing materials. Uncertainty in possible geochemical conditions.	By employing conservative/pessimistic assumptions in PA.
Japan	Glass dissolution rate.	By using conservative data based on experimental observations.
	Expansion of overpack corrosion products and intrusion of bentonite into fractures.	By employing conservative assumptions.
	Long-term stability of bentonite.	By undertaking experiments, modelling studies and by employing conservative assumptions.
	THMCB behaviour of buffer and overpack in transient phase and long-term.	As above.
	Gas generation and transport effects	As above.
Spain	Corrosion rates under repository conditions. Concrete-bentonite interaction. Gas generation and release. Buffer resaturation. Radionuclide migration.	URL experiments.
UK/Nirex	Spatial and temporal evolution of near-field chemistry.	Improved modelling of spatial variability and of the first 1,000 years post-closure. Research into organic complexation. Confidence building in waste package traceability.
US/WIPP	The behaviour of the EDZ.	URL experiments, drawing on industry experience, laboratory work and exploiting international collaborations.
	The actinide source term.	Laboratory studies and monitoring of inventory placed in the repository.

Country/ programme	**Modelling uncertainty**	**Route to reducing uncertainty**
US/YMP	Seepage into emplacement drifts.	*In-situ* niche tests.
	Thermally driven coupled processes.	URL experiments.
	Long-term drip shield and waste package corrosion rates.	Laboratory studies.
	Commercial spent fuel degradation.	Laboratory studies.
	Colloid generation and stability.	Laboratory studies.
	Natural convection in EBS.	¼-scale laboratory studies.
	Ventilation efficiency during pre-closure.	¼-scale laboratory studies.
	Thermal, mechanical and fracture properties of host rock.	Field and laboratory tests.

The French response also noted that design simplicity may lead to increased confidence in modelling results, and that natural analogues present the only means of verifying estimates of long-term material behaviour.

5.4 Relative roles of research and PA models

The responses to this question indicated that research models are intended to justify, or demonstrate the scientific and technical basis for PA models. PA models are used to develop an assessment of the overall system’s performance for comparison with safety standards and other requirements.

6. PERFORMANCE ASSESSMENT

6.1 How EBS performance is assessed

Table 6.1 provides a summary of the responses received regarding performance measures, timescales and links to performance assessment.

Table 6.1. **Performance measures, timescales and links to PA**

Country/ programme	**Performance measure**	**Timescale**	**Link to performance assessment**
Belgium	Canister lifetime.	Few thousand years.	Physical confinement.
	Radionuclide flux from EBS.	Millions of years.	Slow release/retardation.
	Fractional release from EBS.	Millions of years.	Slow release and decay.
Canada	Container lifetime.	>100 000 years.	Input to model of radionuclide transport in the geosphere and biosphere.
	Radionuclide flux from EBS.	1 000 000 years.	
Czech Republic	Radionuclide transport times.	At least until peak release.	–
	Radionuclide flux leaving near-field – source term.	Throughout analysis.	–
Finland	Canister lifetime (complete containment).	Target of 100 000 years.	Long-term isolation.
	Radionuclide flux from canisters.	Several hundred thousand years.	Release to biosphere, dose rates.
France	Canister lifetime (complete containment).	Targets of 1 000 years for HLW and 10 000 years for SF.	Demonstrates isolation concept.
	Radionuclide flux from defective canisters.	Operational and post-closure phases.	Direct link to safety criteria.

Country/ programme	**Performance measure**	**Timescale**	**Link to performance assessment**
Germany/ Morsleben	Radionuclide dose	Beyond peak release (100 000 years).	Slow release/retardation. Demonstrates isolation concept.
Japan	Overpack lifetime.	Target of at least 1 000 years.	Defines start of radionuclide release from the waste.
	Radionuclide release rate from EBS.	Very long-term.	Input to model of radionuclide transport in the geosphere. Allows comparison of alternative EBS concepts.
Korea	Radionuclide leach rate from waste matrix.	~ 1 000 years.	Input to model of radionuclide transport in the buffer.
	Time of container failure by corrosion.	~ 1 000 years.	Determines the beginning of radionuclide release.
	Release to the host rock.	~ 1 000 years.	–
Spain	Activity release.	Between 1 000 and 10 000 000 years.	–
Sweden/ KBS-3	Radionuclide release.	Unlimited.	Estimates of radionuclide release from the near-field are input to the far-field radionuclide transport model.
Switzerland/ Kristallin-I	Radionuclide release rates from the near-field.	Unlimited.	Input to model of radionuclide transport in the far-field.
UK/Nirex	Container integrity.	300-500 years	No credit is taken in PA for this containment.
	Radionuclide flux from the near-field.	1 000 000 years.	Estimates of radionuclide release from the near-field are input to the far-field radionuclide transport model.
US/YMP	Waste package/drip shield degradation.	> 10 000 years.	Determines flow in and out of the waste form and radionuclide release.
	Waste form degradation.	> 10 000 years.	Determines source term.
	Radionuclide release from EBS.	> 10 000 years.	Input to model of radionuclide transport in the near-field.

6.2 Data uncertainties in PA

Data for use in PA is typically gathered from the literature, from laboratory and URL experiments, from modelling studies and, in a few cases, from analogue studies. The responses indicate that from the perspective of PA, uncertainties often arise because of the need to extrapolate data to conditions and spatial and temporal scales different from those of experiments and observations. Specific examples of PA data uncertainties identified include:

- Extrapolation in time of the results from corrosion experiments and empirical models (Belgium, France).
- Upscaling in space, and extrapolation in time, of processes that can enhance radionuclide migration, such as colloidal transport (Belgium).
- The long-term stability of the buffer (Belgium), and of the backfill and sealing material (Germany).
- Reliability, completeness and applicability of thermodynamic databases to the disposal system (Belgium).
- Geochemical conditions (and speciation/thermodynamic databases) and, for SF, the effects of radioactivity on waste dissolution (France).
- The long-term mechanism and rate of overpack corrosion (Japan).
- Interactions between glass dissolution products and the overpack (Japan).
- Porewater chemistry and radionuclide retardation (Japan).
- Spatial variability within the bentonite buffer (Spain).
- The application of laboratory data on glass corrosion rates to repository conditions and timescales (Switzerland).
- The application of laboratory data on radionuclide transport in the backfill to the repository environment (Switzerland).
- Extrapolation of radionuclide transport data to the disposal system scale (Switzerland).

6.3 Key results from PA

The following general points can be identified regarding the role of the EBS in contributing to the overall safety of the disposal system:

- For a repository in a clay host rock, the contribution of the EBS to overall performance of the disposal system is minor when considering the normal evolution scenario. This is because the path length for radionuclide transport in the buffer (the EBS component that hinders radionuclide migration most efficiently) is much shorter than in the host rock (e.g. Belgian and French responses). However, the properties of the EBS can be of paramount importance to the overall safety of the repository in altered evolution scenarios, such as those involving poor repository sealing or human intrusion. For such scenarios, key issues relate to the hydraulic/mechanical properties of the buffer, the waste form dissolution rate and the canister lifetime. The EBS also plays an important role during the operational phase.

- For a repository in a granite host rock, the contribution of the EBS to overall performance of the disposal system can be very significant when considering the normal evolution scenario (e.g. Canada). For example, in the Finnish and Swedish KBS-3 disposal concepts, the intact copper-iron canisters are expected to preserve their integrity for more than one million years, and radionuclide releases from the repository into the geosphere are low even if a large number of canisters fail because the buffer is also expected to retain its function for periods on the order of millions of years.

More specific responses to the questionnaire, relating for example to the identity of key radionuclides and the timescales over which they may be important were provided for some disposal systems. As an example, in the Japanese HLW disposal system:

- ^{135}Cs dominates calculated release rates from the EBS in the period 1 000 to 500 000 years post-closure, with a peak impact at ~70 000 years post-closure. After 500 000 years ^{93m}Nb becomes dominant.
- Isotopes with large inventories and low solubilities precipitate in the vicinity of the HLW glass and, therefore, exhibit a long-term near steady-state release function at low concentrations.
- Short-lived isotopes, which are readily sorbed (^{240}Pu, ^{241}Am), decay significantly within the buffer.

In other disposal concepts/systems other radionuclides (e.g. ^{129}I) may be important (e.g. Canada, UK/Nirex).

6.4 EBS design issues

Specific examples of where problems have been found in EBS designs include:

- It was not clear that the reference composition of the Canadian upper buffer material would reliably prevent microbially induced corrosion of the waste containers, and this led to suggestions that a denser buffer material would be necessary.
- The backfill originally planned for the KBS-3 concept – a mixture of crushed rock and 10-30% of bentonite, compacted *in situ* in the tunnels – may not have an adequate swelling pressure and hydraulic conductivity if exposed to saline groundwater. Alternative backfilling and sealing concepts are being developed (Finland, Sweden).
- Poor access to drift seal locations as a result of reusing an old mine as a waste repository (Germany).
- Ambitious EBS specifications (e.g. seal permeability of 10^{-18} m^2, Germany).
- The need to ensure that the UK/Nirex backfill provided sufficient pH buffering capacity led to the proposal to emplace a further peripheral backfill to condition inflowing groundwater before it contracted the backfill surrounding the waste packages (UK/Nirex).
- Addition of the MgO backfill (US/WIPP).
- Modification of the waste package design to place the corrosion-resistant Alloy-22 layer on the outside (US/YMP). Carbon steel was outer layer in earlier design and was subject to localised corrosion and releases prior to 10 000 years.

- The waste loading strategy for the Yucca Mountain repository was changed to reduce the complexity of coupled thermal processes and to maximise the redirection of water away from the emplacement drifts. In addition, drip shields were added to minimise the potential for dripping water to contact waste packages.
- And the backfill was removed to reduce peak cladding temperatures and creep failure (US/YMP).

6.5 Difficult scenarios and FEPs

The responses indicate that "difficult" scenarios are those that include many processes and process couplings, or essentially unpredictable events. Specific examples of difficult scenarios identified include:

- The early canister failure scenario, involving the release of radionuclides from the waste package during the thermal phase (Belgium).
- Scenarios involving destructive events (Czech Republic).
- Intrusion of deep, very saline groundwater; glacial effects (permafrost, high flow of meltwater, postglacial earthquakes); effects of gas generation; quantitative estimation of the effects of cement (Finland).
- Unknown timing and quantity of brine inflow to unsealed mine openings; unknown geochemical conditions in the mine openings due to access of brines to different salt minerals at different locations (Germany).
- Scenarios including large amount of gas generation (Spain, Switzerland) or imperfect backfill emplacement (Switzerland).
- Scenarios involving earthquakes (Sweden).
- Scenarios involving evolutionary processes and those including unpredictable events (e.g. criticality) (UK/Nirex).
- Igneous intrusion; volcanic disruption; seismic ground motion (US/YMP).

It is apparent that the identity of difficult scenarios tends to be rather site-specific, although some groups of scenario types are evident (e.g. scenarios involving disruptive events, scenarios involving gas generation).

6.6 Lessons learnt from PA: input to future programmes

Based on the questionnaire responses, lessons from the analysis of EBS and safety analysis include:

- Future safety cases might usefully place greater emphasis on demonstrating the capacity of the disposal system to isolate the waste and less on radionuclide release from the repository (Finland, France, UK/Nirex).
- Follow a methodical, systematic approach to EBS design and optimisation (Germany).
- Simple and robust EBS designs are most easily proven (and licensed) (Germany).

- A correctly manufactured EBS is very effective in containing/retarding radionuclides (Finland, Japan, Spain, Sweden, Switzerland, UK/Nirex), but this can be difficult to demonstrate in PA (UK/Nirex).
- It is beneficial to promote close links between EBS design and PA, while ensuring engineering feasibility (Japan).
- Demonstration of engineering feasibility and model validation at URLs helps to increase confidence in EBS performance (Japan).
- Confidence can be established through the application of an iterative model development process that begins with a demonstrably conservative approach and then, in successive iterations, relaxes conservatism to the extent defensible and necessary (US/YMP).
- There is a need to document the process of model development, choices of conservatism, and the representation of uncertainty in a systematic and consistent manner (US/YMP).
- Risk-informed, performance-based prioritisation of models and uncertainties helps in the development of the post-closure safety case by allowing the programme to focus on those technical issues that are most important to the performance objectives required for licensing (US/YMP).

7. SUMMARY AND KEY MESSAGES

Responses to the IGSC questionnaire on engineered barrier systems have been received from 13 countries and 17 organisations with responsibility for considering or developing deep underground disposal concepts, or for implementing or regulating radioactive waste disposal programmes.

The questionnaire responses consider EBS and disposal systems for a wide range of wastes (SF, HLW, ILW, TRU, LLW) and a wide range of media (crystalline, salt, clay, clay tuff). The status of the programmes surveyed can be summarised as follows. For intermediate, transuranic and low-level wastes:

- 1 facility is approaching closure and decommissioning (Morsleben, Germany).
- 1 facility is operating and approaching re-certification (WIPP, USA).
- 1 programme is in a review phase (UK/Nirex).

For spent fuel and high-level wastes:

- 2 programmes are approaching a licence application “soon” (Olkiluoto, Finland ~2010, Yucca Mountain, USA ~2004).
- 3 programmes are in the siting phase or where the potential repository site has been identified (France, Japan and Sweden).
- 6 programmes are in review or concept development/R&D phases (Belgium, Canada, Czech Rep., Korea, Spain and Switzerland).

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

> The “Engineered Barrier System” represents the man-made, engineered materials places within a repository, including the waste form, waste canisters, buffer materials, backfill, and seals. The “near-field” includes the EBS and those parts of the host rock in contact or near the EBS, whose properties have been affected by the presence of the repository. The “far-field” represents the geosphere (and biosphere) beyond the near-field.

All of the programmes surveyed include at various level of importance an EBS and multiple barriers to radionuclide migration, which provide reserves of performance greater than required for compliance with safety criteria (e.g. dose or risk limits). Although the EBS plays a significant role in providing the required level of disposal system performance, there are few specific regulatory requirements of the EBS that go beyond the requirement for a robust system of multiple barriers.

There is generally good consistency in EBS designs for HLW and SF, but less for ILW:

- For HLW, the main components of the EBS are a borosilicate glass matrix, steel containers/overpacks, and bentonite or bentonite-based buffers.[3]
- For spent fuel the main components are UO_2, MOX and other waste matrices, steel or copper-iron containers, copper, steel or Ni-alloy overpacks, and bentonite or bentonite-based buffers (except for salt host rocks).[3]
- For ILW the main components of the EBS include a wide variety of waste matrices, including concrete-conditioned wastes, steel or concrete containers, and a wide variety of backfill materials including, concrete, bentonite-based materials, salt-concrete and magnesium oxide.

The greater variation in the ILW disposal systems reflects the greater number of ILW waste streams and the wide range of different disposal sites and host rocks considered in the survey.

The main functions of EBS components can be summarised as follows:

- The waste matrix is designed to provide a stable waste form that is resistant to leaching and gives slow rates of radionuclide release for the long-term.
- The container/overpack is designed to facilitate waste handling, emplacement and retrievability, and to provide containment for up to 1 000 years or longer depending on the waste type.
- The buffer/backfill is designed to stabilise the repository excavations and the thermo-hydro-mechanical-chemical conditions, and to provide low permeabilities and/or diffusivities, and/or long-term retardation.
- The other EBS components (e.g. seals) are designed to prevent releases via tunnels and shafts and to prevent access to the repository.

Many Features Events and Processes (FEPs) can influence the EBS depending on the particular waste types and site characteristics. Potentially important FEPs include:

- The THMCB (Thermal, Hydro, Mechanical, Chemical and Biological) evolution and climate change.
- Glass dissolution/waste leaching rates.
- Container corrosion rates, container defects.
- Buffer re-saturation, swelling, and long-term alteration.
- Radionuclide transport through the buffer, backfill and sealing material.
- Gas generation in container and transport through the buffer/backfill.

The need for monitoring of the repository during the active control phase is recognised in most programmes, but monitoring plans are generally in an early phase of development. Some programmes are considering extended monitoring phases (e.g. Switzerland, UK/Nirex).

Many programmes are actively involved in experiments in Underground Research Laboratories (URLs). This is an area of extensive international collaboration and there are clear links

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[3] An exception occurs for repositories in salt host-rock for which bentonite and bentonite-based buffer materials are not considered to be the preferred option.

between URL experiments, laboratory experiments, process modelling and data gathering. Some programmes (e.g. Finland, France, Japan, US/YMP) include URL experiments in an iterative process of PA and design refinement. It is less clear how well URL experiments act to build stakeholder confidence (e.g. through demonstration).

Peer review is an important positive process that also enhances confidence and should be an active part of the design and assessment process. Issues identified through peer reviews include:

- The need for a demonstration of technical feasibility.
- The need for further R&D on particular topics.
- The need for a balance between EBS and natural barriers.
- The need to account for uncertainties in expected performance.

Remaining design uncertainties relate mainly to issues of how to link EBS design and emplacement methods to disposal system performance. Key characterisation uncertainties include the THMCB properties of buffer and backfill materials and the evolution of those properties, the effect of gas generation, the determination of (e.g. corrosion) data for safety analysis and the release and uptake mechanisms of ^{14}C.

Research models are intended to demonstrate detailed mechanistic understanding of processes. Their results are used to demonstrate understanding of experiments and to natural analogues, for providing confidence in long-term predictions, and to justify, or demonstrate the scientific and technical basis for simplified PA models. PA models are used to develop an assessment of the overall system's performance for comparison with safety standards and other requirements. PA models are used to account for uncertainties in disposal system performance by using conservative assumptions, probabilistic techniques, deterministic sensitivity studies, and "what if?" calculations.

PA uncertainties often relate to the determination of parameter values that are representative of the large spatial scales and long time scales of interest to radioactive waste disposal (e.g. long-term metal corrosion and glass dissolution rates, large scale radionuclide dispersion coefficients). Other relevant PA uncertainties include parameter values for thermodynamic data, geochemistry and radionuclide retardation, long-term buffer stability and spatial heterogeneity.

Lessons learnt from performance assessment include:

- Adopt a methodical, systematic and fully documented approach to repository design and optimisation.
- Simple designs and models are easier to implement and verify.
- Maintain close links between EBS design and performance assessment, and include them in iterative cycles of assessment.
- Ensure, and demonstrate, design feasibility.
- Continue to build confidence in performance assessment.
- Focus on the most important issues (e.g. through the use of "risk-informed" approaches).

Performance assessments also suggest that EBS systems are very effective in containing radioactive wastes.

Annex I

EBS QUESTIONNAIRE

1.1 General context

Repositories for disposal of radioactive waste generally rely on a multi-barrier system to isolate the waste from the biosphere. This multi-barrier system typically comprises the natural geological barrier provided by the repository host rock and an engineered barrier system (EBS) constructed within the repository. This multi-barrier principle creates an overall robustness of the system that enhances confidence that the waste will be successfully contained.

An EBS may itself comprise a variety of components, such as the waste form itself, waste canisters, backfill, seals, and plugs. The general purpose of an EBS is to prevent and/or delay the release of radionuclides from the waste to the repository host rock, at least during the first several hundreds of years after repository closure when fission-product content is high, where they might be mobilised by natural groundwater flow. In many disposal concepts, the EBS, operating under stable and favourable geosphere conditions, is designed to contain most of the radionuclides for much longer periods.

The specific role that an EBS is designed to play in a particular waste disposal concept is dependent on the conditions that are expected (or considered possible) to occur ("scenarios") over the period of regulatory interest, regulatory requirements for waste containment, and the anticipated performance of the natural geological barrier. 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, the pH and redox conditions that are expected, the expected groundwater flux, the local groundwater chemistry, possible interactions among different materials in the waste and EBS, the mechanical behaviour of the host rock after repository closure, and the evolution of conditions over time. Ensuring that an EBS will perform its desired functions requires an integration, often iterative, of site-characterisation data, data on waste properties, data on engineering properties of potential barrier materials, *in situ* and laboratory testing, and modelling.

The EBS project is intended to provide a greater understanding of how to achieve the integration needed for successful design, construction, testing, modelling, and performance assessment of EBS's. In addition, the EBS project will help to clarify the role that an EBS can play in the overall safety case for a repository. A safety case is a collection of arguments, at a given stage of repository development, in support of the long-term safety of the repository. A safety case includes the quantitative results derived from performance assessment modelling, but also considers aspects of barrier performance that are difficult to quantify but can qualitatively be shown to enhance the robustness of the system.

Recognising the diversity in EBS in various national programmes, the project will seek to share knowledge and experience about the integration of EBS functions, engineering design, characterisation, modelling and performance evaluation in order to understand and document the state of the art, and to identify the key areas of uncertainty that need to be addressed. Specific objectives are:

- to understand the relationship between the functions to be served by the EBS and its design in different repository contexts;
- to compare different methods of characterising EBS properties;
- to compare different approaches to modelling of the EBS;
- to compare different means of evaluating EBS performance;
- to compare different engineering approaches to similar problems; and
- to compare techniques for evaluating, characterising, and modelling interactions between the EBS and near-field host rock.

The First Workshop entitled "*Engineered Barrier Systems in the Context of the Entire Safety Case*" serves to provide a status report on EBS in various national programmes and develop a common basis of understanding for the possible subsequent workshops.

1.2 Scope of the questionnaire

This questionnaire was devised by the members of the steering committee, aiming to establish a baseline of information at the time the project begins, i.e., the first workshop planned on 25-27 September 2002 in Oxford, UK.[1] A follow-up questionnaire will be distributed near the end of the EBS project before the last workshop and used to evaluate the progress that has been made as a result of the project. Information that is provided by each contributing organisation would also provide a basis for general planning of the first workshop structure.

In answering the questions listed below, a brief description of the key information will suffice. Use of tables should be encouraged so that comparison among the national programmes can be made easily and bibliographic references are welcome. The answers might indicate if the topics already identified in the proposal [NEA/RWM/IGSC(2001)6] are relevant for a presentation and/or for discussions during the working group sessions.

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[1] Members of the committee are: Jesus Alonso (ENRESA, Spain); Alan Hooper (UK Nirex Ltd, UK), Hiroyuki Umeki (NUMO, Japan), Richard Beauheim (SNL, USDOE-WIPP,USA), Patrik Sellin (SKB, Sweden), Frederick Plas (ANDRA, France); Oïvind Töverud (SKI, Sweden), Henning von Maravich (EC), Bob Mac Kinnon (SNL,US-DOE-YMP, USA).

Topic 1 – GENERAL OVERVIEW

Q1: What is the current stage of your disposal programme in your overall schedule?

Q2: Is the definition of the EBS adopted in the project* consistent with the one in your programme? If not, does the difference have any implications for comparing your EBS concept with the others?

> *"The "Engineered Barrier System" represents the man-made, engineered materials placed within a repository, including the waste form, waste canisters, buffer materials, backfill, and seals. The "near field" includes the EBS as well as the host rock within which the repository is situated, to whatever distance the properties of the host rock have been affected by the presence of the repository. The "far field" represents the geosphere (and biosphere) beyond the influence of the repository."*

Q3*:* What is the role played by the EBS in your overall PA and safety case?

Q4: Does regulation exist in your country regarding the performance of the EBS? If so, please describe. Are there any regulatory considerations concerning the EBS performance and its contribution to the robustness of the multiple barrier system?

Q5: What are the key lessons learnt through peer review (internal or external) of your EBS design, modelling and its treatment in PA? How were they fed back into your programme?

Q6: Do you plan to monitor the EBS during and/or after the operation of the repository? What is the scope of the monitoring? Does the regulator require it?

Topic 2 – DESIGN AND EMPLACEMENT OF EBS

Q1: What are the components of your EBS?

Type of waste	Waste matrix	Container	Backfilling	Others

Q2: What is the function of each component? Specify the phase in which the function applies and for how long you need this function. For which type of scenario do you need this/these function(s)?

Component	Function	Duration /phase	Scenario	Alternatives (please give the main reason: (e.g. uncertainties,)

Q3: What are the main FEPs, i.e., expected behaviour of the barrier components and potential effects operating against them, considered in design?

Q4: What are the baseline assumptions underlying the design?

Q5: How does the EBS contribute to enhancing the robustness of the overall multiple barrier system? Is there any emphasis in your design to back-up the function of one component of the EBS by another, to increase robustness in the overall performance of the EBS?

Q6: How are the EBS design, modelling and PA linked with URL experiments? What are the main EBS-related experiments you plan in the URL? Are they related to modelling aspects, the characterisation of parameters, or performance assessment of the EBS?

Experiment	Objective	Components studied	

Q7: Please list key uncertainties/outstanding issues regarding the design and emplacement of the EBS?

Component	Key uncertainty	Time period	Planning to resolve these uncertainties (in a few words (e.g. URL tests planned, benchmark comparison for modelling, alternatives.)

Topic 3 – CHARACTERISATION

Q1: Please list the main parameters that characterise the EBS and its behaviour.

Please prepare a table by type of waste and/or design

Parameter	Nature of the parameter (design, modelling, performance.)	Period of time during which it is needed	Associated experiments (surface, URLs)	Usefulness of natural analogues

Q2: What are the key uncertainties regarding the characterisation? Please describe their origins, e.g. time scale, spatial heterogeneity, measurement errors. What are the main issues?

Topic 4 – MODELLING

Q1: Regarding research models (as opposed to safety assessment models) of the EBS that aim to understand its behaviour:

Which processes are modelled and which are not?	
Are processes coupled or treated individually?	
How are repository geometry and spatial variability handled?	
What model simplifications are made and how are they justified?	
What sensitivity studies have been performed?	
How are boundary conditions established with respect to the far field	

Q2: Regarding the approaches to EBS modelling for system performance assessment:

How are uncertainties handled?	
What model simplifications are made and how are they justified?	
How is the EBS submodel connected to other submodels?	
What sensitivity studies have been performed?	

Q3: What are the key uncertainties associated with your current modelling? How do you think they could be resolved (e.g. by verification through URL experiments, benchmarks, use of conservative/pessimistic assumptions.)?

Topic 5 – PERFORMANCE ASSESSMENT

Q1: How is the EBS performance evaluated?

Performance measure	Time scale	How is it linked with the overall performance evaluation?

Q2: What are the sources of data for this evaluation?

Data	Source	Key uncertainties

Q3: What are the key results of your previous performance evaluation of the EBS?

Q4: What kinds of problems have been found with the original design? How did you or will you resolve them?

Q5: What types of scenarios or FEPs create particular difficulties?

Q6: Please describe the main lessons learnt on EBS performances? How do you feed them into the future programme?

Annex II

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