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Technical issues associated with deep repositories for radioactive waste in different geological environments

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Science report: SC060054/SR1

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Steve Killeen

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Executive summary

This report reviews technical issues related to the development of a deep geological repository for higher activity radioactive wastes in England and Wales. The study focuses on the post-closure phase and only considers construction and operational issues which could affect the ability to achieve satisfactory post-closure safety.

This project aimed to:

- select a set of geological environments to represent the range of plausible repository host environments in England and Wales and highlight a range of technical issues;
- identify the environment-specific broad technical issues that would need to be considered when evaluating the safety of each environment.

The work was carried out in two phases, each of which included a workshop attended by experts from outside the main project team:

- an initial phase in which geological environments and associated technical issues were defined;
- a second phase in which refinements were made to the definitions of geological environments and technical issues, the state of knowledge on the latter was reviewed and their potential importance was established.

In the first phase of the project, geological environments, wastes, engineered components and disposal concepts were identified, described by the project team and then discussed at the first expert workshop. Subsequently, the classifications and descriptions were reviewed periodically. This iteration was carried out to confirm that the classifications were appropriate for illustrating the range of important technical issues. Classifications made during the first phase were generally found to be adequate for this purpose and only small changes were needed in the second phase.

Nine geological environments were identified:

- Environment 1 – Hard fractured rock to surface.
- Environment 2 – Hard fractured rock overlain by relatively high-permeability sedimentary rocks in which advective transport dominates.
- Environment 3 – Hard fractured rock overlain by a sedimentary rock sequence containing at least one significant low-permeability formation in which diffusion dominates solute transport.
- Environment 4 – Evaporite host rock.
- Environment 5 – Siliceous host rock.
- Environment 6 – Indurated mudrock host rock.
- Environment 7 – Plastic clay host rock.
- Environment 8 – Carbonate host rock.
- Environment 9 – Non-evaporitic rock with hypersaline groundwater.

The precise classification of the environments was less important than making sure that the characteristics of all plausible repository host environments in England and Wales were considered.

Identification of technical issues was undertaken partly in parallel with that of geological environments. The project team initially developed a list of example technical issues, based on prior knowledge and expert judgments of team members, and published literature concerning radioactive waste disposal.

Example technical issues were used to inform participants in the first expert workshop of the kinds of issues and the level of detail needed in the project. Participants then expanded the list of technical issues. Following the workshop, the project team added to the list from further literature reviews and expert knowledge. The resulting notes were circulated to participants, and the feedback received was used to prepare a final list of technical issues and associated descriptions.

In the second phase of the project, team members used their knowledge and literature surveys to prepare a summary of the state of knowledge on each technical issue for the second expert workshop. Participants in this workshop expanded the list of issues, descriptions of these issues and corresponding knowledge summary. This process resulted in the identification of the following technical issues:

- Issue 1: Influence of different wasteform types on the design of the engineered barrier system (EBS).
- Issue 2: Interactions between engineered components.
- Issue 3: EBS/host rock interactions.
- Issue 4: Impact of groundwater/porewater on EBS materials (including the impact of saline water).
- Issue 5: Duration for which EBS materials maintain their function (durability).
- Issue 6: Gas/groundwater (or porewater) interactions.
- Issue 7: Characterising the site adequately.
- Issue 8: Demonstrating long-term stability.
- Issue 9: Impact of resaturation.

Some of these issues are statements of principle that need to be taken into account during site selection and concept design and development. The issues are mostly inter-related. For example, Issue 3 (EBS/host rock interactions) depends partly upon Issue 4 (impact of groundwater/porewater on EBS materials). Inflow of groundwater to a bentonite buffer that forms part of an EBS (Issue 3) will result in the bentonite swelling and exerting a pressure on the surrounding rock (Issue 4).

The list of technical issues is dominated by reference to the EBS; only three issues explicitly focus on the geosphere (Issues 6, 7 and 8). The lack of explicit and more detailed geosphere-specific issues does not imply that the geosphere is less important. Instead, geosphere-specific issues that would impact upon safety are implicit in the descriptions of the geological environments, and discussions of how repository design-related issues will be affected by the characteristics of the host geological environment.

The report concludes that the design of a repository should be matched to the characteristics of its host geological environment with optimum safety, reasonable costs and no undue difficulties in technical implementation.

When designing a repository, it is necessary to take into account the highly coupled nature of many processes. Most issues associated with the performance of EBS materials under repository conditions are reasonably well understood.

There remain, however, significant uncertainties relating to:

- the extrapolation of experimental studies to actual in situ conditions;
- the extrapolation of information gathered by other programmes to conditions in England and Wales;
- the application of repository concepts that have already been proposed to environments different to those in which they have been tested;
- the application of repository concepts that have been proposed elsewhere, but have not yet been thoroughly evaluated.

UK-specific expertise of EBS materials is dominated by experience gained in the development of a cementitious repository design for Sellafield during the 1990s. Much of this expertise may not be transferable to other locations and disposal concepts. UK-specific knowledge of the performance of materials commonly proposed for the EBS of high-level waste/spent fuel (HLW/ SF) repositories is much less mature than in other countries where there have been active HLW/SF repository programmes.

In the UK, issues associated with repository-derived gas have received a great deal more attention than they have in other programmes. Issues associated with gas may be important in all of the environments, but the impacts of these would vary between environments. Generally, these issues relate to the potential for over-pressurisation of the system in environments with low-permeability host rocks and to the potential for rapid release of free gas to the biosphere in environments with high-permeability rocks.

In England and Wales, site investigation may pose problems for all of the environments, given that current practical experience of planning and executing this type of investigation is relatively limited. Compared to many other countries with radioactive waste management programmes, there is relatively little practical experience of underground investigations, such as would be gained in an underground research laboratory.

One of the aims of site investigations will be to demonstrate that any chosen site is sufficiently stable (mechanically, hydrogeologically and geochemically). Experience suggests that with sufficient data, it should be possible to address this issue.

The overall conclusion of this study is that a wide range of technical issues face the programme in England and Wales. This arises partly from the current lack of a site and the great variety of potentially suitable geological environments. The particular nature of the UK waste inventory is also significant. Work has been carried out to address the majority of the technical issues within the UK or within other disposal programmes. However, further work may be required to extrapolate the results from other countries to conditions in England and Wales, especially if the final repository site has different characteristics to the Sellafield site investigated by Nirex in the 1990s.

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Dr Bath participated in the identification of geological environments and helped to convene the first expert workshop, acting as a facilitator of a discussion group. He also helped to document the discussions at this workshop.

Dr McEwen also participated in the identification of geological environments. He helped to convene both expert workshops, acting as a facilitator of a discussion group in each one. Additionally, he helped to document the discussions at each workshop.

Dr Bennett helped to convene the second expert workshop, acting as a facilitator of a discussion group. He also helped to document the discussions at this workshop.

Valuable inputs from the participants in the expert workshops are also gratefully acknowledged. These participants are named in Appendix A.

Contents

1 Introduction

1.1 Background to the project

Throughout the world, developers of deep geological repositories for radioactive wastes are required to satisfy their regulators and other groups that any repository will be safe following its closure. In practice, this goal must be achieved by developing a safety case for each repository. The detailed requirements of a safety case, and the scheduling of its development, vary from country to country. Following the Nuclear Energy Agency (NEA, 2008a), a safety case is defined as *"a synthesis of evidence, analyses and arguments to quantify and substantiate that a repository will be safe after closure and beyond the time when active control of the facility can be relied upon".*

In England and Wales the Environment Agency is responsible for assessing post-closure safety cases associated with the deep disposal of intermediate level waste (ILW), high level waste (HLW) and possibly spent fuel (SF), in the event that SF is declared as waste. It has an agreement to review the work of the Nuclear Decommissioning Authority (NDA) connected with the planning, development, operation and closure of any deep geological repository for these radioactive wastes. As part of any future staged regulatory process associated with the development of such a repository, the Environment Agency will review post-closure safety cases and supporting work prior to any formal submission being made by the developer of the facility under the Radioactive Substances Act 1993 (RSA 93).

This report reviews the current state of knowledge of technical issues important in making a post-closure safety case for a deep geological repository for higher activity wastes (ILW, HLW and SF) in different geological environments that might be suitable to host such a repository in England and Wales. The report also touches on operational and construction issues which might impede a satisfactory post-closure safety case.

1.2 Aims of the project

The overall aim of this work is to help the Environment Agency prepare for the assessment of future regulatory submissions by the developer of a deep geological repository, currently envisaged to be the NDA's Radioactive Waste Management Directorate (RWMD). It will also assist the Environment Agency in carrying out critical reviews of work undertaken by NDA RWMD prior to formal submissions being made. To meet this aim, the following tasks were defined in the project scope (Environment Agency, 2007):

- agree a set of geological host environments as a basis for the study;
- identify key technical issues that would arise in each environment;
- review the current status of each technical issue;
- review the potential safety case arguments that might apply in each geological environment.

1.3 Scope of the project

At the present early stage of the deep geological repository programme in the UK (as described in Committee on Radioactive Waste Management (CoWRM), 2006; Department for Environment, Food and Rural Affairs (Defra), 2007, 2008[1]), no repository site has been selected, nor has any particular kind of site been specified as a preferable repository host. Therefore, this project aims to present conclusions that are not related to specific sites. Consistent with this requirement, it is appropriate to specify generic geological environments, defined in Section 2, only in broad terms, without reference to particular rock formations or localities.

Section 2 also highlights geological environments that are unlikely to be considered as potential repository hosts in England or Wales. Geological environments were deemed unsuitable for further consideration in this project if all of the examples in England and Wales were excluded by the criteria given by Defra (2007). However, site-specific information would be needed to determine whether any particular occurrence of an environment is in fact a suitable repository host. Furthermore, many different factors will influence whether or not an environment is suitable.

Since the Environment Agency has no remit in Scotland and Northern Ireland, it is beyond the scope of this project to consider geological environments that occur only in these parts of the UK. Instead, the study considered environments that could plausibly be identified within England and Wales, including offshore islands and environments within UK territorial waters that are offshore but accessed from onshore.

All the technical issues considered in the project are those that are, or may be, in some way linked to the geological environment. Construction and operation of the facility are regulated by the Nuclear Installations Inspectorate (NII) so the work in this project focussed on post-closure issues. Construction and operational issues are considered on the basis of their influence on post-closure safety, and the treatment of these issues in this report is not comprehensive. Only the impacts of construction and operations on the technical issues that affect safety following repository closure are reviewed.

The work primarily covers ILW and HLW from the nuclear fuel cycle and SF (noting that in the UK, SF is not currently considered to be waste). However, as for SF, the status of certain other radioactive materials has yet to be decided. Limited consideration was thus given to the impact of technical issues on other kinds of material (such as separated plutonium/uranium stocks, submarine fuel).

The project also looked at technical issues of concern for two particular options that might be considered by the repository developer: that of co-located disposal of ILW and HLW/SF[2], and retrieval of wastes.

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[1] It should be noted that Defra (2008), which underpins NDA RWMD's current planning, was not published until after the work reported here was substantially complete. Therefore in some areas, for example inventory, this report may not be consistent NDA RWMD's current proposals.

[2] NDA RWMD's currently preferred option is to develop a single facility that will comprise separate modules for ILW and HLW/SF, with a common access from the surface.

1.4 Approach to the project

There were two main phases to the project:

- an initial phase in which geological environments and associated technical issues were defined;
- a second phase in which refinements were made to the definitions of geological environments and the technical issues, the state of knowledge concerning the technical issues was reviewed and their potential importance was assessed.

In each phase, Quintessa's project team prepared draft outlines based on their own knowledge and published information, which were then reviewed by experts from outside the project team. There were thus two review cycles, each of which involved the following main steps:

- distributing draft outlines from an initial review for comment by Environment Agency external experts who were otherwise unconnected with the project;
- convening an expert workshop attended by members of Quintessa's project team, Environment Agency staff and the external experts;
- modifying the initial outputs to take into account the opinions of workshop participants;
- circulating the modified outputs to workshop participants for final comment;
- making final amendments to take into account any further comments.

These activities, which are described in detail in Sections 2.1 and 4.1, established that:

- the range of geological environments defined in the project covered the range of environments that might plausibly be considered to host a deep geological repository within England and Wales;
- the identified technical issues are appropriate for the project's objectives and no important issues were overlooked;
- the specified geological environments served to illustrate the main technical issues likely to be encountered during an actual repository programme in future.

1.5 Report structure

The structure of this report reflects the task structure suggested by the original scope of work (Environment Agency, 2007):

- Section 2 describes the geological environments and the process by which they were defined.
- Section 3 describes the different waste types that could undergo disposal, or that may be considered for disposal, and the types of engineered structures that might comprise the engineered part of the disposal system.
- Section 4 describes the key technical issues identified during the project and the process that led to their identification.
- Section 5 discusses the current state of knowledge on the technical issues both in the international context and within the UK context.
- Section 6.1 considers the types of safety arguments that might be made in the post-closure safety case for each environment and the potential significance of the different issues in each environment.
- Section 6.2 draws some conclusions on the issues that will need to be addressed by a deep geological disposal programme, regardless of the geological environment and disposal concepts selected and those issues that are more specific to certain combinations of geological environments and disposal concepts.

2 Geological environments

2.1 Approach to identifying geological environments

In the first phase of the project, geological environments, wastes, engineered components and disposal concepts were all defined initially by Quintessa's project team and then discussed at the first expert workshop. These definitions were then reviewed periodically throughout the remainder of the project. This iteration was used to confirm that the classifications of geological environments, wastes, engineered components and disposal concepts were appropriate for illustrating the range of important technical issues. Classifications made during the first phase of the project were found to be generally adequate for this purpose and only small changes were made during the second phase.

The geological environments were selected to collectively represent the *range* of characteristics of plausible deep geological repository host environments within England and Wales. The most important characteristics are the spatial distributions of host and cover rocks, their physical and chemical properties, chemical compositions of groundwater and processes driving groundwater and solute transport. Hence, the study explored the implications of these characteristics for the major technical issues that might affect the development of a safety case for such a repository.

The precise classification scheme used for the identified environments was less important to the project than ensuring all the main environmental characteristics were considered. There are many ways in which geological environments in England and Wales could be classified. A compromise was needed between defining sufficiently few environments to illustrate the key technical issues (where too much subdivision would obscure the main ones), and defining enough environments to show how differences in environmental characteristics would be reflected in technical issues relevant to a repository safety case.

The overall process by which geological environments were defined is shown in Figure 2.1. The figure shows a multi-stage process that made use of: knowledge of project team members and external experts; published literature; and expert judgments made by the project team members and external experts, using their knowledge and outputs from literature reviews.

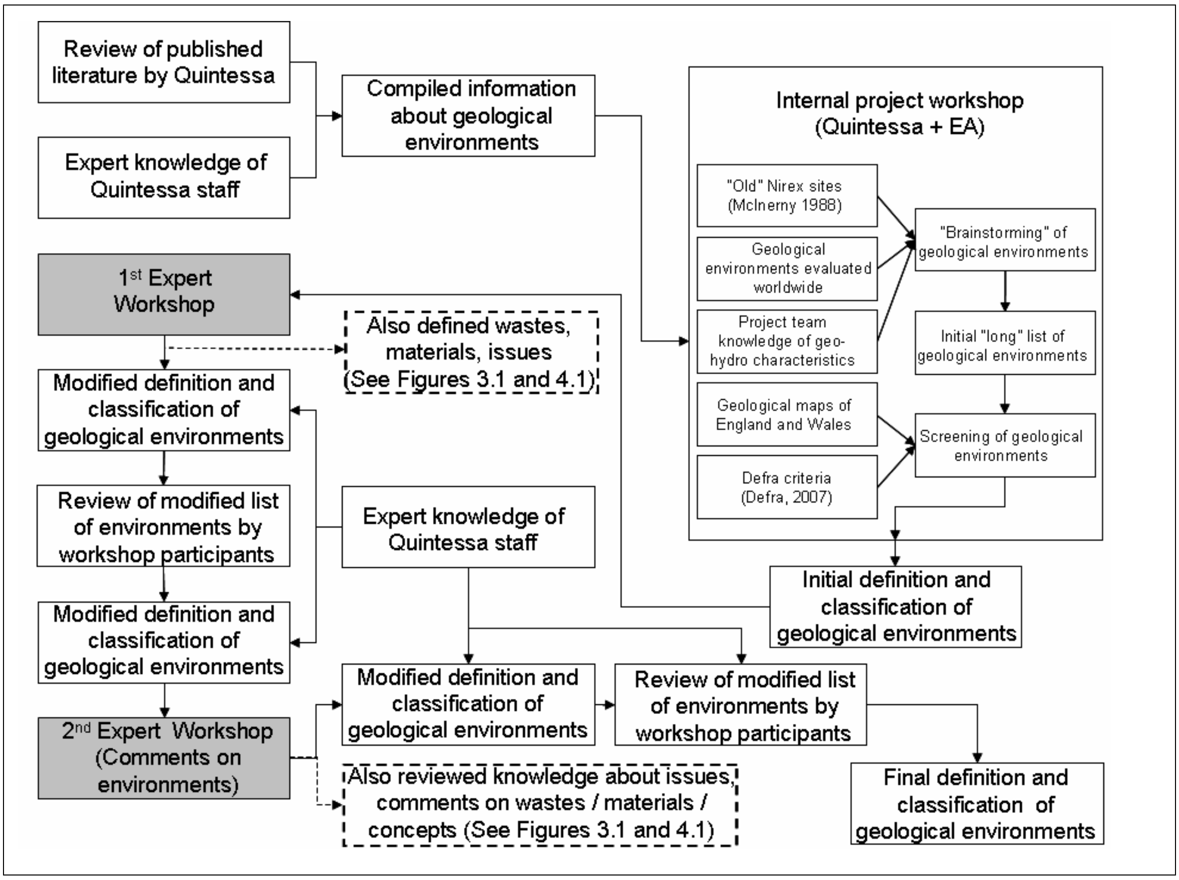

Figure 2.1 The main steps followed to identify geological environments.

At the start of the project members of Quintessa's project team and Environment Agency staff attended an internal project meeting to define an initial list of geological environments. Meeting participants used their extensive geological knowledge to identify geological environments that illustrated all the main hydrogeological settings, large-scale geological structural features (such as sedimentary basins, areas of high relief and so on) and lithological variations occurring in England and Wales. The initial list was then checked against the list of possible radioactive waste repository sites considered by Nirex during the 1980s (McInerny 1988) and geological environments considered by overseas waste disposal agencies. To ensure that coverage was comprehensive, geological, seismic, hydrogeological and tectonic/structural maps of England and Wales were then reviewed (such as on geological maps at 1:250,000 and 1:50,000 scales and regional geological guides produced by the British Geological Survey). This process generated a long list of environments.

The list was then screened to remove:

- those for which it was not possible to find a potentially suitable example within England and Wales.
- environments where all of the examples in England and Wales would definitely be excluded by the Defra criteria (Defra, 2007).

This screening process involved judging whether or not concealed explorable coal deposits and hydrocarbon resources would necessarily occur within each environment. If so, the environment was excluded from consideration as a repository host. These deposits need not be *exploitable* in order to rule out an environment, since exploration by drilling boreholes could lead to human intrusion into any repository that might be constructed there. However, where the existence of such deposits within all examples in England and Wales was uncertain, the environment was retained within the list to ensure that coverage was comprehensive. In these cases, it was more likely than for other environments that any particular example would be ruled out by the Defra criteria. The potential presence of explorable coal or hydrocarbons at depth would then become one of the ‘issues’ associated with the environment.

Descriptions of geological environments included the most important features that would affect a deep geological repository for radioactive waste, but not in sufficient detail to suggest specific rock formations or sites. Some geological environments were subdivided to illustrate important variations in characteristics.

The project team found that the geological environments could be classified in terms of the potential repository host rock and then in terms of the overlying rocks (if any). Should a site selected to host a repository contain more than one potential host rock, the site would fall within more than one of geological environments defined within this project. For example, a hard fractured rock may be overlain by a sequence of sedimentary rocks containing an indurated mudrock in which solutes are transported dominantly by diffusion. At such a site, a repository could be sited within the hard fractured rock (corresponding to Environment 3, described in Section 2.2.4), and/or within the indurated mudrock (corresponding to Environment 6, described in Section 2.2.7). In terms of the issues associated with building a repository, this classification scheme was found to be a more useful way of considering the various repository systems than considering multiple host rock types in a single geological environment.

An initial list of geological environments and their descriptions was presented at the first expert workshop (see Section 1.4 and Figure 2.1). Workshop participants assessed the extent to which this list of geological environments was comprehensive and adequate to illustrate the range of technical issues that would affect a deep geological repository for radioactive wastes. After discussions, the initial list and related descriptions were modified to take into account the opinions of workshop participants. The modified list and descriptions were then circulated to participants for final comment. After further modifications based on the feedback received, final definitions of the geological environments were produced for the second phase of the project. These are given in Section 2.2.

There were some differences of opinion among participants in the first workshop on the classification and detailed subdivision of these environments. However, there was a broad consensus that the specified environments spanned the range of characteristics of plausible deep geological repository host sites in England and Wales. Furthermore, while participants in the second workshop were invited to comment on the degree to which the defined geological environments were appropriate for the objectives of the project, no significant changes to the definitions were recommended.

2.2 Descriptions of geological environments

2.2.1 Terminology

The term ‘geological environment’ is used in this report for simplicity. However, each one is defined not only in terms of geological characteristics, but also hydrogeological and geochemical criteria.

When describing geological environments potentially suitable to host a deep repository, certain descriptive terms are often used interchangeably and sometimes misleadingly. The terms ‘hard rock’, ‘crystalline rock’, ‘hard crystalline rock’ and ‘hard fractured rock’ (although they each have distinct and slightly different meanings) are often used to describe the same broad class of rock: a fractured igneous or metamorphic rock with very low matrix porosity, through which groundwater flows dominantly within fractures. The unfractured rock mass is strong (in the engineering sense) but the overall rock mass strength depends on the frequency and pattern of the fractures.

Geoscientists often use the term ‘basement’ to describe a widespread association of igneous and/or metamorphic rocks, which are overlain unconformably by sedimentary rocks that are either unmetamorphosed or show only low grades of metamorphism. Therefore, in practice ‘hard fractured rock’ is often also ‘basement’ rock. However, the term ‘basement’ does not adequately consider those cases where the ‘hard fractured rock’ is exposed at the surface. Consequently, the more general and descriptive term ‘hard fractured rock’ is used in this report.

The environments described below have been numbered to aid referencing and identification: the numbers allocated to environments do not signify anything about their prevalence or suitability for geological disposal. The descriptions include all of the environments identified before the first expert workshop, together with an additional environment that was defined at this workshop. However, some of these were screened from further consideration in the project. Where this is the case, the reasons for screening them are noted and their presence here records the fact that they were considered by the project team.

2.2.2 Environment 1 – Hard fractured rock to surface

In this environment the repository would be developed in a hard fractured host rock. This rock is likely to be fractured on a range of length scales, from fault and fracture zones at the regional scale (traceable over distances of kilometres) to small-scale fractures with length scales of metres or less. The hydrogeological characteristics will depend upon the connectivity of the faults and fractures. Hard fractured rocks (but not necessarily exactly the same formation as the host rock) extend upwards to, or close to, the ground surface. Rock within the near-surface zone will be weathered to some degree. The depth to which the weathering extends will depend upon the specific characteristics of the site. The weathered rock is expected to extend typically to a few tens of metres from the surface, but the weathering zone could be up to a couple of hundred metres thick. Compared to deeper rocks, those within about 200 m of the surface will probably have higher permeability. The extent of this weathering and enhanced permeability will depend on the details of rock type, topography and geological history (for example glacial history). All of these rocks are likely to be fractured on a range of length scales, from fault and fracture zones at the regional scale (traceable over distances of kilometres) to small-scale fractures with length scales of metres or less. There is also likely to be a surface layer of (recent) Quaternary deposits, which may be up to a few tens of metres in thickness.

This environment was initially subdivided into high- and low-relief variants. However, experts at the first workshop considered that the effect of relief on long-term safety would not necessarily be significant. Therefore, relief would probably not influence the types of wastes that could be disposed in this environment and the overall form of the post-closure safety case. Relief might, however, have a significant effect on the operational phase when, for example, it might be possible to access the repository via horizontal drifts in some high-relief areas.

2.2.3 Environment 2 – Hard fractured rock overlain by relatively high-permeability sedimentary rocks in which advective transport dominates

In this environment the repository host rock would be a hard fractured rock, similar to that in Environment 1 (see Section 2.2.2).

However, in contrast to the host rock in Environment 1, the host rock in Environment 2 is unconformably overlain by a sedimentary rock sequence with a thickness of between about 200 m and 800 m. If this sedimentary cover is less than a couple of hundred metres thick, this environment effectively becomes an example of Environment 1. In contrast, if the sedimentary rock sequence is more than about 800 m thick, adverse rock mechanical factors (principally high stress and insufficient rock strength) will make the development of a repository difficult and expensive. The sedimentary rock sequence is dominated by rocks of moderate permeability and may contain minor aquifers. The key feature of this overlying series of sedimentary rocks is that it does not contain a significant low-permeability formation in which solute transport will occur dominantly by diffusion, although it may contain minor low-permeability rock units. Faults in the sedimentary rocks are likely to be transmissive and thus not to provide barriers to flow and solute transport. Advection will dominate over solute transport in the cover sequence.

Although not an essential feature of this environment, most of the examples in England and Wales generally have moderate relief and are currently located near a coast line.

2.2.4 Environment 3 - Hard fractured rock overlain by a sedimentary rock sequence containing at least one significant low-permeability formation in which diffusion dominates solute transport

In this environment the repository host rock would be a hard fractured rock, similar to those in Environment 1 and Environment 2 (see Sections 2.2.2 and 2.2.3).

As in Environment 2, the repository host rock is unconformably overlain by a sedimentary sequence with a thickness of between about 200 m and 800 m. Once again, if the sedimentary cover rocks are less than a couple of hundred metres thick, this environment effectively becomes an example of Environment 1. In a similar way to Environment 2, if the sedimentary rock sequence is more than about 800 m thick, adverse rock mechanical factors (principally high stress and insufficient rock strength) will make the development of a repository difficult and expensive.

The main difference from Environment 2 is that the sedimentary rock sequence contains at least one significant low-permeability formation in which solute transport occurs dominantly by diffusion. Faults within the low-permeability formation are also expected to have low transmissivities (at least over significant parts of their areas), and thus restrict or provide barriers to groundwater flow and solute transport. The sedimentary rock sequence is likely to be dominated by low-permeability rocks, but may also contain aquifer formations.

Although not an essential feature of this environment, examples from England and Wales are generally located in areas of low relief. Both coastal and inland examples exist.

2.2.5 Environment 4 – Evaporite host rock

In this environment the repository host rock is an evaporite formation, which is most likely to be halite (rock salt), but which could also be another type of evaporite, such as anhydrite and/or gypsum. In the onshore areas of England and Wales, this host rock will be in the form of a bedded formation rather than a salt dome. Salt domes were screened from further consideration because deposits are too far offshore.

Significant thicknesses of low-permeability rocks (most likely mudstones and siltstones) must occur in the vicinity of the evaporite host rock to prevent ingress of flowing water, thereby leading to the host rock's dissolution. The evaporite host rock formation is likely to be bounded by such low-permeability rock formations. However, these rocks do not necessarily need to occur immediately adjacent to the evaporite formation.

Faults are likely to have low transmissivities, at least over significant parts of their areas, and thus restrict or provide barriers to groundwater flow and solute transport.

Examples of this environment in England and Wales are found in areas of low to moderate relief. There are also offshore examples that could be accessed from onshore.

2.2.6 Environment 5 – Siliceous host rock

In this environment the repository host rock is a strong, dominantly siliceous rock, although there may be a carbonate cement. Groundwater advection through the porous matrix may be the dominant transport mechanism, but there may also be a component of fracture-controlled flow. The most likely host rocks are sandstones or siltstones in which a silty lithology and/or diagenetic cementation causes low permeability. The host rock is part of a sedimentary rock sequence that is likely to contain both high- and low-permeability sedimentary rocks.

This environment can be divided into two sub-environments on the basis of the character and tectonic history of the host rock:

- Environment 5a, in which the sequence overlying the host rock does not contain any significant low-permeability formations.
- Environment 5b, in which the sequence that overlies the host rock contains at least one significant low-permeability unit.

Environments 5a and 5b are similar to Environments 2 and 3 respectively. Arguably, it would therefore be appropriate to present these subdivisions as separate geological environments for consistency with the distinction between Environment 2 and Environment 3. However, the contrast between Environments 5a and 5b is likely to be less pronounced, where the host rocks form part of the overall sedimentary sequence and may be of relatively low permeability. In contrast, in Environments 2 and 3, the host rocks are not part of the overlying rock sequence, but are unconformably overlain by the sedimentary rocks.

Distinguishing between Environments 2 and 3 serves to highlight the potentially important role of a cover rock sequence as a control on groundwater flow through the repository site; distinguishing Environments 5a and 5b would serve only to emphasise the same point, but with the disadvantage of complicating the descriptions given in the sections below.

Examples of this environment in England and Wales are found in areas of generally low to moderate relief, although there may also be areas of higher relief. The environment may be inland or coastal. Many, but not all, examples of this environment contain potentially explorable coal or hydrocarbon deposits.

2.2.7 Environment 6 – Indurated mudrock host rock

The host rock in this environment is an indurated mudrock. The host rock has a low permeability and is not significantly fractured. Solute transport within the host rock is likely to be controlled by diffusion.

This environment can be divided into two sub-environments on the basis of the character and tectonic history of the host rock:

- Environment 6a, in which the host rock is a dominantly flat-lying and undeformed, although indurated, mudstone.
- Environment 6b, in which the host rock has been tectonised and may have a well-developed fabric/cleavage (such as tectonised mudstone). This fabric/cleavage may be important in determining its engineering properties.

The main difference between Environments 6a and 6b are the physical properties of the host rock, rather than differences in the overall hydrogeological setting of the host rock as are apparent between Environments 2 and 3. For this reason, Environments 6a and 6b were considered as variations of a single environment.

In Environment 6a, the overlying sequence is a dominantly low-permeability sedimentary sequence, although it is likely to contain some minor aquifers. The environment may be inland or coastal and many of the examples in England and Wales are in areas of low or very low relief.

In Environment 6b, the degree of potential host rock alteration is not necessarily sufficient for the rock to be considered metamorphosed, but metamorphosed examples do exist. The overlying sequence is likely to be a mixed sedimentary rock sequence, which, depending upon the evolutionary history of the basin, may lie unconformably on the host rock.

Examples of such environments exist in both inland and coastal settings in England and Wales.

2.2.8 Environment 7 – Plastic clay host rock

In this environment, the repository host rock is a plastic (non-indurated) clay within which water and solutes would be transported only by diffusion. The plastic characteristics of the rock would lead to the self-sealing of any faults or fractures, which would therefore be non-transmissive.

This environment was originally screened from consideration because there are no suitable plastic clay host rocks onshore in England and Wales. All the onshore occurrences of this lithology are too shallow or not sufficiently extensive. However, some participants in the first workshop were of the opinion that suitable rocks are likely to exist offshore, close enough to be accessed from the land. Given that this environment may raise some distinct issues for engineered barrier system (EBS) design and retrievability, it was considered sensible to include it at this stage for completeness.

2.2.9 Environment 8 - Carbonate host rock

In this environment the host rock is a carbonate (limestone). This environment can be divided into three sub-environments:

- Environment 8a, with a low-permeability carbonate host rock within which water and solutes are transported dominantly by diffusion.
- Environment 8b, with a highly permeable carbonate host rock within which significant water and solute transport occurs dominantly by advection through fractures and/or solution (karst) features.
- Environment 8c, in which the host rock is a relatively massive limestone formation within which the majority of the rock mass supports water and solute transport only by diffusion, but which contains fractures through which water and solutes are transported dominantly by advection, leading to moderate to high overall permeability.

Arguably, Environments 8a, 8b and 8c could have been distinguished as separate environments. However, the main differences between these sub-environments are the physical properties of the host rock, rather than differences in the overall hydrogeological setting of the host rock. For this reason, Environments 8a, 8b and 8c were considered as variations of a single environment.

In Environment 8a, the low-permeability host rock is likely to be overlain by a significant thickness of potentially higher permeability limestone and glacial deposits. Topographic relief is low and the environment is likely to have a coastal location.

In England and Wales, the host rock in Environment 8b typically forms an aquifer. This sub-environment was therefore screened from further consideration as it is clearly excluded by the Defra criteria.

The host rock in Environment 8c is overlain by a mixed sedimentary sequence that is likely to contain both high- and low-permeability formations. By definition there will need to be at least one significant low-permeability formation to protect the host rock from processes such as karstification. Topographic relief is likely to be low to moderate and the location is likely to be inland. Some examples of this environment may contain explorable hydrocarbons.

2.2.10 Environment 9 – Non-evaporitic host rock with hypersaline groundwater

This environment could be considered a variant of any of the other environments apart from Environment 4 (by definition). However, there may be particular issues associated with the presence of hypersaline groundwater at a repository location.

In this environment, the groundwater salinity is significantly greater than seawater salinity but the host rock is not an evaporite. It may be a hard fractured rock, a siliceous rock, a mudstone or siltstone or even a carbonate. However, the high groundwater salinity is most likely to originate in an evaporite rock formation and therefore evaporite deposits of some form are likely to occur relatively close to the host rock. In many cases the high salinity would reflect relatively stable hydrogeological and by inference hydrogeochemical conditions.

2.2.11 Environment 10 – Small islands

Small islands were initially considered as a separate geological environment. However, it was subsequently decided that such islands do not generally offer sufficient stability to be considered a separate environment, and given their geological and hydrogeological characteristics, they could be included in another environment.

On the timescale of post-closure assessment, and taking into account the likely future changes in sea level, it was judged that the majority of small islands are unlikely to remain as islands on the timescales considered in a post-closure safety case. Therefore on the timescales of interest, they are likely to lose the potential advantage of a small island in possessing an independent groundwater flow system.

On balance, it was decided to exclude this environment from further consideration.

2.2.12 Geoscience indicators

Geoscience indicators are qualitative or semi-quantitative characteristics that can be used to describe different geological environments. They are designed to illustrate the similarities and differences between the different environments. They have been used here to describe characteristics that are important for the types of engineered system that can be constructed in the environment.

The geoscience indicators have been divided into a number of groups: geological, geotechnical, geochemical, hydrogeological, gas migration and resources. Table 2.1 gives examples of the types of indicators that might fall into each category.

Table 2.1 Geoscience indicators to describe different geological environments.

Group of Indicators[1]	Specific Indicators
Geological	• Complexity of stratigraphic sequence that will require characterisation • Topographic relief • Likely horizontal extent and thickness of host rock formation • Likely homogeneity of host rock and overlying rocks • Likely frequency and magnitude of faulting and fracturing • Long-term stability of environment – susceptibility to significant erosion, significant alteration by future glaciation and so on
Geotechnical	• Rock strength • Likely stress state • Potential stability of underground excavations in host rock and in any cover rocks – implications for spans and geometries of vaults and construction of access shafts/drifts
Geochemical	• Composition (not just 'salinity') of host rock porewater • Composition (not just 'salinity') of groundwater along likely path of groundwater plume • Fracture and rock matrix materials that will interact with

Group of Indicators[1]	Specific Indicators
	radionuclides along likely path of groundwater plume • Redox state and buffering of host rock groundwater • Any unusual geochemical conditions – high sulphate, unusual pH and so on • Expected geochemical heterogeneity • Likely stability of geochemical conditions
Hydrogeological	• Host rock permeability and mode of groundwater flow (porous- or fracture-controlled) • Cover sequence permeability and mode of groundwater flow (porous- or fractured-controlled) • Likely hydraulic gradients in host rock and cover rocks • Expected dominant solute transport process (advection or diffusion) in host rock • Expected dominant solute transport process (advection or diffusion) in cover rocks • Expected length of groundwater discharge pathway and estimate of groundwater return time • Stability of hydrogeological regime to climate change and so on • Potential for fast pathways • Expected discharge location and extent for natural discharge pathway
Gas migration	• Ease with which gas can migrate through the host rock • Ease with which gas can migrate through cover sequence • Potential for trapping or dissolution of gas within cover sequence
Resources	• Potential for presence of coal or hydrocarbons • Potential for other exploitable resources • Potential for exploitable aquifers in cover sequence

[1]Potential attributes that are not included in the geoscience indicators include seismicity, which is considered to be uniformly low throughout England and Wales.

Table 2.2 provides a brief summary of the major characteristics of the different environments in terms of the geoscience indicators given in Table 2.1.

Table 2.2 Characteristics of the geological environments.

Geoscience Indicator	Environment 1 **Hard fractured rock to surface**	Environment 2 **Hard fractured rock overlain by relatively high-permeability sedimentary rocks in which advective transport dominates**	Environment 3 **Hard fractured rock overlain by sedimentary rocks containing at least one significant low-permeability unit in which diffusion dominates transport**
Geological	At first sight a simple system but in practice potentially complex owing to likely complex tectonic history. Rocks may have fabric relating to past folding etc and comprise a series of hard fractured units. Fractured on all length scales from m to km. Low-relief examples likely to be stable but high-relief examples likely to be subject to active erosion with steep slopes and incised valleys.	Likely to be located near a structurally complex basin margin involving a wide variety of rock types. Host rock similar to that of Environment 1. Many significant structural features may penetrate entire sequence. Volume of suitable host rock may be limited by geometry of basin margin and frequency of major faults associated with basin development.	Similar to Environment 2. Overlying sequences in UK examples are generally relatively simple structurally but may comprise many different units that may vary laterally over length scales of interest. Moderate to low topography protects against denudation.
Geotechnical	Unfractured rock is strong. Overall strength of rock mass depends on pattern of fracturing, stress state etc. Potential for high stresses, especially in tectonic lenses. Potential exists to construct large (10s of metres) stable openings.	Host rocks' mechanical characteristics similar to those of the host rock in Environment 1. Cover sequence contains weaker rocks but most would not be characterised as geotechnically weak.	Host rocks' mechanical characteristics similar to those of the host rock in Environment 1. Cover sequence contains weaker rocks, some of which may be geotechnically weak and may require significant support.
Geochemical	Porewater likely to be low salinity (less than 5,000 mg/l TDS) but weathered zone may contain largely fresh water. Potential for significant heterogeneity if system is compartmentalised. Potentially low stability with glaciation having potential to inject fresh oxidising water to depth.	Host rock porewater likely to be at least low to moderate salinity (high salinities are represented by Environment 9). Potential for significant heterogeneity if system is compartmentalised and for cover sequence to be significantly less saline. Potentially low stability with glaciation having potential to inject fresh oxidising water to depth.	Variations in host rock porewater chemistry and heterogeneity as for Environment 2. Likely to be geochemically stable at repository depths.

Geoscience Indicator	Environment 1 **Hard fractured rock to surface**	Environment 2 **Hard fractured rock overlain by relatively high-permeability sedimentary rocks in which advective transport dominates**	Environment 3 **Hard fractured rock overlain by sedimentary rocks containing at least one significant low-permeability unit in which diffusion dominates transport**
Hydrogeological	Low permeability and matrix porosity with fracture flow dominant. Properties largely determined by connectivity of fracture systems. Advection likely to dominate. Groundwater flow path to surface potentially short (km) and travel time to surface in the order of 10^3 years. Significant potential for fast pathways. Low stability and affected by climate driven changes.	Host rock characteristics are the same as in Environment 1. Cover sequence of moderate permeability and porosity, probably with permeable faults. Advection dominates transport in all cases. Flow pathway to surface potentially short to moderate (km) and and travel time to the surface in the order of 10^3 to 10^4 years. Potential for fast paths up faults and fracture zones.	Host rock characteristics are the same as in Environment 1. Cover sequence dominated by low-permeability units in which diffusion dominates. Low gradients and lack of recharge to host rock mean diffusion may dominate transport here as well. Pathway to surface may be short in length (vertical diffusion) but many millions of years in time. Probably hydrogeologically stable at repository depths.
Gas migration	Gas expected to migrate relatively easily with little or no potential for trapping.	Gas migration characteristics as for Environment 1.	Gas may migrate relatively easily in the host rock but is likely to be trapped in cover sequence.
Resources	Potential exists for economic mineralisation, such as tin, copper, uranium.	Near surface units may be minor aquifers with potable water. Potential for coal and hydrocarbons depends on age and history of basin. Other resources such as iron ore may be present. Resources unlikely to occur in the host rock.	Potential for resources as for Environment 2.

Table 2.2 Characteristics of the geological environments (cont).

Geoscience Indicator	Environment 4 **Bedded evaporite host rock**	Environment 5 **Siliceous sedimentary host rock** **Environment 5a relatively high-permeability cover sequence** **Environment 5b low-permeability unit in cover sequence**	Environment 6 **Mudstone host rock** **Environment 6a flat lying indurated mudstone host** **Environment 6b tectonised mudstone host**
Geological	Relatively simple layered stratigraphy but may be significantly complicated by faulting associated with basin environment. Suitable formations may be only 50-100 m thick and may contain marly (carbonate-rich mudrock) interbeds (thus may not be pure evaporites). Rocks are soft so potential for erosion if significant uplift.	Potential to be in a relatively complex basin setting where strata are cut by faults. Suitable host rock formations could be of limited thickness and of limited lateral extent.	Flat lying indurated host rock (Environmment 6a) likely to be in a simple layered sequence within a basin. Host rock may be relatively thin (50 m or so). Tectonised host rock (Environment 6b) may be in a more complex setting and may be thicker.
Geotechnical	Key characteristic of host rock is that it will creep. Evaporite strength varies greatly depending on composition, impurities and so on. In some examples it may be possible to construct relatively large caverns that remain stable for decades or longer, but others may only allow construction of small openings that will deform significantly on a timescale of years. Cover rocks are likely to require significant support, especially at depths greater than 500 m.	Unfractured rock is moderately strong but overall strength and shape of excavations will depend on pattern of fracturing, especially bedding.	Host rock has low strength which is likely to limit excavation spans to 10 m or less and require excavations to have heavy supports. Some (minor) potential for creep. Tectonic fabric may be a significant control on excavation shape in Environment 6b.
Geochemical	Groundwater in host rock will be brine, with composition depending on evaporite composition. Overlying rock sequence probably contains fresher water. Heterogeneity depends on geology but system probably stable.	Groundwater salinity probably brackish to moderate. Potential for high pCO_2. Geochemical stability could be relatively low as glaciation has potential to inject oxidising water to depth via transmissive fault zones.	Groundwater likely to be brackish to moderate salinity (high salinity is Environment 9) with potential for high sulphate and high pCO_2. Geochemical stability likely to be high.

Geoscience Indicator	Environment 4 **Bedded evaporite host rock**	Environment 5 **Siliceous sedimentary host rock** **Environment 5a relatively high-permeability cover sequence** **Environment 5b low-permeability unit in cover sequence**	Environment 6 **Mudstone host rock** **Environment 6a flat lying indurated mudstone host** **Environment 6b tectonised mudstone host**
Hydrogeological	Majority of sequence (including faults) is low permeability with host rock likely to be essentially impermeable. Any flow in evaporites likely to be along marly (carbonate-rich mudrock) interbeds. Solute transport by diffusion. The system will probably be stable and travel time to surface may be many millions of years.	Host rock probably of moderate permeability with significant porosity but fracture flow may be significant in well-cemented cases. Overall hydrogeology will be similar to Environment 2 for transmissive cover rocks (Environment 5a) and Environment 3 for cover rocks containing a low-permeability horizon (Environment 5b).	Host rock has low or very low permeability and solute transport will be diffusion-dominated. Overlying rocks may include some higher permeability units where advection is important. Travel time to surface likely to be millions of years and hydrogeological regime in host rock likely to be stable.
Gas Migration	Gas does not migrate readily (evaporites are used for gas storage caverns).	Gas will probably migrate easily through the host rock. May be trapped in cover rocks in examples with a low-permeability unit.	Gas migration in host rock probably difficult or very difficult and cover sequence likely to contain units that will either trap gas or allow it to dissolve.
Resources	Evaporites are sources of salts and hosts for gas storage caverns, but Defra concluded they are sufficiently widespread not to rule them out as a potential repository host formation. Coal and hydrocarbons may also be present depending on age and history of basin.	Potential for coal and hydrocarbons depends on basin history. Potential for iron ore and so on.	Moderate risk of coal and hydrocarbons depending on basin age and history. May be evaporites in sequence.

Table 2.2 Characteristics of the geological environments (cont).

Geoscience Indicator	Environment 7 **Plastic clay host rock**	Environment 8 **Carbonate host rock** **Environment 8a low-permeability limestone** **Environment 8c massive limestone**	Environment 9 **Non-evaporitic host rock with hypersaline groundwater**
Geological	Likely to occur at relatively shallow depths in a fairly young basin. Host rock unit may have limited thickness (50-100 m). Relatively soft rock means potential for denudation if in area of active uplift.	Environment 8a is a simple layered rock sequence. Host rock extent is controlled by location of top of low-permeability limestone. Environment 8c is potentially a complex structural environment and likely to be faulted. Actual host formation may be thin (50 m or so).	Could be any of the other environments except for 1, 4, 7, 8a.
Geotechnical	Host rock is weak and subject to creep. Excavation span likely to be limited to less than 10 m and to require full lining.	Environment 8a has strong homogeneous host rock in which large caverns can be constructed but overlying sequence may contain weak rocks. Unfractured host rock in Environment 8c is generally strong, but locally bedding and fracturing control rock strength and hence excavation size and geometry.	Could be any of the other environments except for 1, 4, 7, 8a.
Geochemical	Groundwater likely to be brackish or slightly saline. Low permeability will mean geochemical regime likely to be stable.	Likely to be moderate salinity and will have high pCO_2 and high Mg. Likely to be stable.	Groundwater at repository location is highly saline (probably several times seawater salinity). Likely to be high sulphate and possibly Mg. Key feature is that highly saline (dense) water should be relatively stable.
Hydrogeological	Host rock has low or very low permeability and solute transport will be diffusion-controlled. Travel time to surface likely to be many millions of years.	Environment 8a is low permeability, relatively high porosity, with solute transport probably diffusion-dominated. Advection will dominate in overlying rocks so travel time to surface controlled by time to diffuse out of host rock.	Depends on underlying geological environment. However, probably relatively little flow in dense highly saline water at repository depths. Stability depends largely on environment.

Geoscience Indicator	Environment 7 **Plastic clay host rock**	Environment 8 **Carbonate host rock** **Environment 8a low-permeability limestone** **Environment 8c massive limestone**	Environment 9 **Non-evaporitic host rock with hypersaline groundwater**
		Environment 8c host rock may have moderate to high permeability and high porosity. Fractures will be important controls on flow. Cover rocks include at least one low-permeability unit that will limit recharge to host rock. Solute transport by diffusion in this low-permeability unit, which controls travel time to surface. Both Environment 8a and 8b probably stable at host rock depths.	
Gas Migration	Gas migration will be difficult.	Difficult in low-permeability limestone (Environment 8a) (used as storage caverns in some places) but easy in cover sequence. Gas migration easy in Environment 8c host rock but gas likely to be trapped in cover sequence.	Could be any of the other environments except for 1, 4, 7, 8a.
Resources	Relatively low potential as likely to be in basin or part of basin that is too young for significant hydrocarbons.	Potential for hydrocarbons and/or coal depending on basin age and history.	Could be any of the other environments except for 1, 4, 7, 8a.

3 Characteristics of wastes, engineered materials and disposal concepts

3.1 Importance of wastes, engineered materials and disposal concepts

Within any given geological repository for radioactive wastes, some engineered components are used for structural reasons (such as tunnel supports) and others for fabricating an EBS (barriers to movement of water, gas and solutes, including radionuclides). The nature, spatial distributions and purposes of such engineered materials will depend on the characteristics of the geological environment (lithologies, groundwater chemistry and so on) and properties of the wastes. These dependencies will shape the overall disposal concept at any given site. Interactions between the engineered materials, geological environment and wastes will in turn partly determine the technical issues to be considered when planning, operating and closing a geological repository. Consideration of these interactions was thus an important part of this project.

3.2 Approach to identifying wastes and engineered materials for consideration

The identification of wastes, engineered materials and disposal concepts was carried out at the same time as the geological environments were defined during the first phase of the project. The process by which this was done is shown in Figure 3.1.

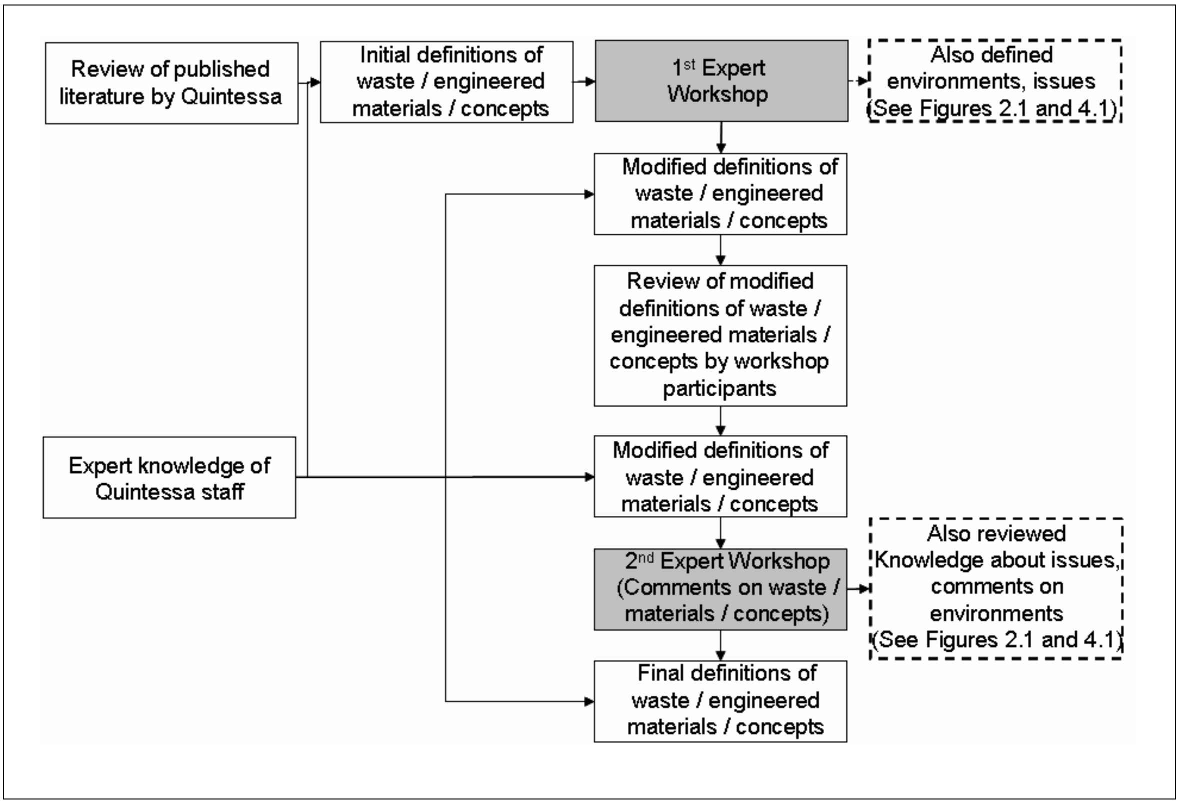

Figure 3.1 Main steps to identify wastes and engineered materials.

Initially Quintessa's project team undertook reviews of:

- the characteristics of UK wastes;
- the characteristics of the engineered components and EBS that have been developed in the UK and elsewhere;
- the disposal concepts within which EBS have been used or proposed in the UK or elsewhere.

The findings of these reviews were presented to participants in the first workshop. The experts then evaluated the findings and suggested amendments to the classification of waste forms, engineered materials and disposal concepts. Their opinions were taken into account by Quintessa's project team when preparing a note of the workshop. This note was circulated to participants for further comment, and the feedback was used by Quintessa's project team to develop final definitions of wastes, engineered materials and disposal concepts. These definitions were used as inputs to the second expert workshop. Participants in this second workshop were invited to comment further on the suitability of the identified wastes, engineered materials and disposal concepts for illustrating the range of important technical issues. As a consequence of the feedback received, Quintessa's project team made some final minor modifications to the definitions of the wastes, engineered components and disposal concepts.

The main results of this process are summarised in Sections 3.3 and 3.4.

3.3 Wastes and waste forms

The types of UK waste that might be considered for disposal in a deep geological repository were given by CoRWM (2006) and Nirex (2003a) and references therein. These inventory estimates do not take account of wastes from any new generation of nuclear power stations. Furthermore, certain materials that are presently not classified as waste may in future be reclassified as waste. The precise characteristics of the packaging for certain wastes have also not yet been fixed. For these reasons there are uncertainties in the kinds and amounts of waste that may require disposal. However, waste materials that were officially declared in 2006, together with indications of alternative packaging options, are:

- high-level waste (HLW) arising from reprocessing activities;
- intermediate-level waste (ILW);
- low-level waste (LLW) that is not suitable for near surface-disposal at the Low-Level Waste Repository (LLWR) near Drigg in Cumbria.

HLW is immobilised through vitrification. The total packaged volume will be about 1,300 m^3, with total activity of approximately 3.8×10^7 TBq. There will definitely be a significant volume of vitrified waste (some has already been produced) and a small possibility that ceramic waste forms could be manufactured in the future.

ILW is generally grouted into 500-litre vented stainless steel drums, 3-m^3 drums and 3-m^3 concrete and steel boxes. Some wastes may be emplaced within a 4-m steel box, which is one of NDA RWMD's 'standard' packages. Other encapsulants are being considered for particular waste streams. The total conditioned waste volume could be up to about 350,000 m^3, with a total activity approximately 2.4×10^6 TBq. The ILW is diverse and arises from a variety of sources including:

- reprocessing;
- reactive metals (uranium and Magnox, aluminium, zinc);
- routine operations at power stations and on nuclear sites;
- ion exchange resins;
- decommissioning wastes dominated by short-lived radionuclides and including concrete and steel-dominated wastes, each with differing volumes and times of arising;
- graphite from reactor cores which will be activated, of a large volume and likely to be contaminated (it may also be relevant to distinguish advanced gas-cooled reactor (AGR) fuel element graphite from bulk core graphite);
- sludges from liquid effluent treatment;
- soil and building foundations that are highly contaminated.

To date, ILW has generally been conditioned in a matrix comprising ordinary Portland cement (OPC) modified with filler, typically comprising blast furnace slag (BFS) or pulverised fly ash (PFA). Small quantities of waste have been encapsulated in polymeric resins. Further use of polymeric encapsulants and alternative cements are being considered for certain problematic waste streams, along with high-temperature processes that may yield non-cementitious waste products (such as glass or slag-like residues). Disposal of some wastes without encapsulation is also being considered.

The conditioned ILW can be broadly divided into:

- cemented wastes, including:
  - cemented wastes with high organics loadings;
  - cemented reactive metals and, more importantly, Magnox swarf;

    - totally encapsulated wastes (cemented sludges and so on);
    - partially immobilised cemented wastes;
- polymer-encapsulated wastes.
- thermally treated wastes.

LLW that is not suitable for near surface disposal has a packaged volume of 37,200 m^3 and a total inventory of below 1 x 10^5 TBq. All of the current LLW packages in this category are cementitious. LLW waste packages may be larger (and heavier) than the average for other kinds of waste (such as the 500-litre drums and 4-m box for ILW). This group of wastes also includes operational ILW that has decayed during storage to the extent that it is LLW by the time of emplacement.

There are other materials which are not currently declared as waste, but which may need to be accommodated in a deep geological repository:

- spent oxide fuel (SF) from both AGR and pressurised water reactor (PWR) stations (SF has been considered by NDA in their recent work);
- spent Magnox fuel that is unlikely to be reprocessed (such as pond-stored legacy fuel that is bare (unclad) following corrosion of the associated cladding);
- submarine spent fuel, which has much greater fissile enrichment compared with 'normal' reactor fuel;
- Naturally occurring radioactive material (NORM) that does not meet the acceptance criteria for the LLWR;
- stockpiled plutonium from reprocessing activities;
- stockpiled uranium from reprocessing;
- natural and depleted uranium.

Spent oxide fuel (SF) from AGR and PWR stations will have a total packaged volume of about 8,150 m^3, with total activity of approximately 3.3 x 10^7 TBq.

The long-term rate of radionuclide release from SF is uncertain and may be significant for a safety case. The release rate would depend partly on the physical form in which the SF might be emplaced in a repository, which is presently uncertain. Radionuclides would be released at different rates if the SF was disposed of in the form of entire fuel elements or as bundles of fuel pins. It is also possible that the SF could be disposed of as fuel pellets produced by destroying the pins (although this operation is unlikely to be carried out as it would be difficult and could potentially release part of the inventory). Consideration could also be given to converting SF to a waste form that immobilises the instant release fraction (IRF).

It is necessary to make the distinction between steel-clad and Zircaloy-clad fuels, since their physical and chemical characteristics are different leading to different influences on future radionuclide releases from the fuel. Zircaloy claddings resist corrosion more readily than steel claddings.

NORMs are produced mainly by the oil and gas industry and are dominated by low-activity radium scales, many of which are generated offshore from Scotland. Disposal of these scales currently takes place to the marine environment and is regulated by the Scottish Environment Protection Agency (SEPA). However, this kind of disposal might not be carried out in the future. It is possible that some of these wastes might be sent to a repository in England, and therefore they were not excluded from consideration in this project. It is useful to divide these wastes into:

- oilfield NORMs which are radium-rich barium/strontium sulphates and carbonates (if disposal of these wastes cannot occur at sea, they will likely be routed to landfills or possibly the LLWR);
- gas field NORMs which are dominated by unsupported lead and polonium and are generally not destined for deep disposal.

If declared as waste, stockpiled plutonium from reprocessing activities is likely to be conditioned to a ceramic or glass waste form. The total packaged volume will be about 3, 250 m^3, with a total activity of approximately 4 x 10^6 TBq. For security reasons, this plutonium might be combined with HLW.

Natural and depleted uranium is currently dominated by stored uranium hexafluoride that would probably be converted to oxide for disposal, if declared a waste. There could be quite a large inventory. One possibility is that the resulting uranium oxide might be added to any future cement-based backfill (as in depleted uranium concrete or DUCRETE). Depleted uranium (DU) makes good radiation shielding and could be used for this purpose in relation to other highly active waste forms.

3.4 Disposal concepts

3.4.1 General characteristics of disposal concepts

A disposal concept for radioactive waste is a generalised description of how disposal will be carried out. The characteristics of disposal concepts that have been proposed to date vary from programme to programme, reflecting largely a programme's maturity and the needs of the end-users. However, disposal concepts typically include general descriptions of:

- the waste forms;
- EBS components and their relationships to one another;
- how a repository will be laid out.

There may also be:

- a description of how the waste will be emplaced;
- some indication of scheduling;
- some indication of the kinds of host rock and/or geological environment within which the repository will be constructed.

Any implementation of a disposal concept would need to be optimised to work with the wastes that are to be placed in the repository, and the host geological environment.

3.4.2 General characteristics of EBS designs

EBS designs for LLW/ILW and HLW/SF are generally different. The differences reflect both the containment requirements of the different waste types and the potential waste volumes involved. For example, if the waste volume is relatively small and the hazard is relatively high, it may be economically viable to use a complex highly engineered system that makes use of relatively exotic materials to provide a high degree of containment. In contrast, for large volumes of less hazardous waste this type of engineering may be unnecessary and impractical.

For LLW/ILW and HLW/SF, the term 'waste package' is sometimes used to describe the 'product of conditioning that includes the waste form and any container(s) and internal barriers (such as absorbing materials and liners), prepared in accordance with the requirements for handling, transport, storage and/or disposal' (IAEA, 2003). A waste package is then surrounded by one or more additional barriers. Generally, the waste package and additional barriers together comprise the EBS.

The EBS designs for LLW/ILW, and the functions required of the various components vary between different concepts. However, an EBS for these wastes may consist of:

- a waste form, which typically consists of the waste itself encapsulated in a matrix that mechanically stabilises the wastes, and provides a chemical environment which retards radionuclide releases;
- a waste container, which may be shielded to lower external radiation and facilitate handling;
- an emplacement container, also termed an overpack, which facilitates handling and acts as an additional barrier to radionuclide release;
- a backfill, which may:
    - limit access of water;
    - provide a chemical buffer which minimizes corrosion of metals and release of radionuclides;
    - sorbs released radionuclides;
    - allows gas to migrate and possibly helps to reduce gas pressures by chemically reacting with the gas (principally CO_2 in cementitious backfill);
- seals and plugs, which help to seal a repository and provide additional barriers to gas, water and solute transport through galleries and shafts.

Emplacement containers/overpacks are not always included in a disposal concept. Similarly, for certain kinds of waste such as large pieces of contaminated industrial equipment that are classified as LLW, there may be no waste containers. Instead, it may be planned to place the waste directly in the repository, perhaps after filling void space with a grout.

It may also not be necessary to employ backfill if the host rock is sufficiently impermeable and has adequate strength. An advantage of this approach is that it makes use of the excavated voids in the repository as reservoirs for gas evolved from the waste. The pressure exerted by the gas is consequently minimised.

The most commonly proposed materials for encapsulating wastes and backfilling repository voids are cementitious. However, other materials such as bitumen have also been proposed.

Similarly, the EBS designs for HLW/SF, and the functions required of the various components also vary between different concepts. However, an EBS for these wastes may consist of:

- a waste form, which is often not regarded as having a barrier function, but which may nonetheless restrict the rate of radionuclide release;

- a waste container, which contains the waste form and enables its safe handling, but which is not usually expected to function significantly as a barrier in the long-term;
- an overpack, also termed a ‘waste canister’ in some programmes, which is designed to prevent the waste from coming into contact with water for long time periods;
- a buffer, which protects the waste containers and their overpacks from physical and chemical processes that would result in their degradation;
- a backfill, which:
  - fills and stabilises excavated void space within the repository that is not already occupied by one or more of the above components;
  - provides a low-permeability and/or low-diffusivity medium that helps long-term retardation of gas, water and solute transport;
- seals and plugs, which help to seal a repository and provide additional barriers to gas, water and solute transport through galleries and shafts.

All these barriers are not necessarily present in all concepts. A number of concepts have no overpack and/or backfill.

Recently, several concepts for HLW/SF disposal have been developed in which barrier components are packaged together to form so-called ‘supercontainers’ (see Section 3.4.4). These ‘supercontainers’ can be constructed at the surface and subsequently transported into the underground repository for disposal. This approach enables barrier components to be assembled under more strictly-controlled conditions than would be possible in the repository. There is consequently an expected improvement in quality assurance (QA) and quality control (QC).

The overall functions that the engineered components may need to perform collectively are similar for ILW/LLW and HLW/SF. However, the nature and function of each individual engineered component will vary between concepts.

During the operational phase, the engineered system may be required to:

- provide physical support of the excavations;
- provide drainage and ventilation of the underground spaces and maintain appropriate environmental conditions for operations and potentially for underground waste storage;
- be suitable for safe waste emplacement, by:
  - enabling safe transport from the surface via shafts and/or drifts;
  - enabling remote handling/emplacement underground;
  - providing radiation shielding;
  - being appropriate for post-emplacement activities such as backfilling between disposal units;
- enable safe waste retrieval, possibly many decades after initial emplacement, should this be required by the developer;
- allow construction and waste emplacement operations to occur at the same time without interfering with each other;

- allow for current and future monitoring and ongoing maintenance.

During the post-closure phase, the engineered system may be required to provide the following functions:

- physical containment of the wastes;
- protecting the primary waste containers and waste forms physically and through chemical buffering of repository porewater (which will influence the characteristics and rates of container and waste form degradation);
- limiting water flow through the waste form;
- chemical containment through retardation and solubility limitation;
- controlling the pressure of any gas generated in the repository, either by preventing gas generation or by ensuring that the engineered system does not become overpressured;
- transferring heat away from the waste containers.

The engineered components that provide these different functions vary with waste type, geological environment and other requirements placed on the system (such as regulatory requirements, cost-effectiveness).

3.4.3 Disposal concepts for ILW and long-lived LLW

Disposal concepts for ILW and long-lived LLW were reviewed recently by Hicks *et al.* (2008). The main features of the disposal concepts identified by Hicks *et al.* (2008) are summarized in Table 3.1.

This table shows that in all concepts, the geosphere and especially the host rock functions prominently as a barrier. However, the nature of this host rock barrier varies between different concepts, depending primarily upon the:

- kinds of waste (principally whether prone to generate gas or not);
- volumes of waste;
- permeability of the host rock.

Some concepts envisage that the host rock will behave as a low-permeability barrier that significantly retards the flow of water into the EBS and within which mass transport occurs only by diffusion (Concepts 1, 2, 3, 4, 5, 8 and 9 in Table 3.1). In contrast in other concepts (Concepts 6, 7 and 10 in Table 3.1) the host rock acts to:

- protect engineered materials and vaults from the effects of surface processes;
- provide a generally low groundwater flux and chemically stable environment;
- provide an environment within which dilution and dispersion of radionuclides may occur.

Table 3.1 Summary of disposal concepts for ILW and long-lived LLW, based on Hicks *et al*. (2008).

No	General concept description	Main Barriers
1	In-tunnel disposal of LILW in a plastic clay host rock, with waste containers shielded in concrete disposal units that are emplaced axially in the concrete-lined tunnels.	• Primary waste packages, containing stabilized waste • Container • Buffer/backfill (whether or not required as a barrier unresolved) • Tunnel liners (primary function is support, but some barrier function) • Seals • Host rock (effectively complete containment) • Overburden (would dilute and disperse any radionuclides that are able to reach it, though this is not expected)
2	In-tunnel disposal of LILW in an indurated clay host rock, with waste containers packaged in concrete overpacks that are stacked in the concrete-lined tunnels; a separate disposal region is included for wastes that contain organic matter.	• Primary waste packages, containing stabilized waste • Container • Tunnel liners (primary function is support, but some barrier function) • Seals and backfill of access tunnels (disposal cells are not to be backfilled) • Host rock (effectively complete containment) • Overburden (would dilute and disperse any radionuclides that are able to reach it, though this is not expected)
3	In-vault disposal of transuranic (TRU)[1] waste in a salt host rock, with remote-handled waste packages inserted in vault walls, contact-handled waste packages stacked on vault floors, and with MgO included as backfill.	• Container (no credit taken for barrier function in safety assessment, but there will be such a function) • Buffer/backfill (MgO absorbs moisture and any CO_2 evolved from the waste, conditions chemistry to retard radionuclides) • Seals and backfill of shafts • Host rock (salt itself offers effectively complete containment, but pathways for fluid flow may exist from the disposal region to surrounding rocks)
4	In-tunnel disposal of TRU waste in an indurated clay host rock, with waste containers packaged in concrete disposal units that are stacked in the concrete-lined tunnels, and with gas-permeable mortar included as a backfill; wastes that contain nitrates and chelating agents are isolated in a single disposal tunnel.	• Waste (conditioned to have low release rate) • Container (complete containment until failure of drums) • Buffer/backfill (similar properties to the grout used to condition waste) • Tunnel liners (primary function is support, but some barrier function since sorbs radionuclides and provides some pH-buffering capacity) • Seals • Host rock (effectively complete for sorbing radionuclides, very significant retardation for non-sorbing) • Overburden (dilution and dispersion)

No	General concept description	Main Barriers
5	In-tunnel disposal of LILW in a marl host rock, with waste containers packaged in concrete disposal units that are stacked in the concrete-lined tunnels, and with gas-permeable mortar included as a backfill.	• Waste (conditioned to have low release rate) • Container (complete containment until failure of drums is expected, but conservatively ignored in safety assessment) • Buffer/backfill (similar properties to the grout used to condition waste) • Tunnel liners (primary function is support, but some barrier function since sorbs radionuclides and provides some pH-buffering capacity) • Seals • Host rock (effectively complete for sorbing radionuclides, very significant retardation for non-sorbing) • Overburden (dilution and dispersion)
6	In-tunnel disposal of TRU waste in hard or soft host rocks, with waste containers grouted into steel emplacement containers that are stacked in the tunnels (concrete-lined in soft rocks), and with grout included as a backfill; a bentonite barrier is included for some wastes, and wastes that contain nitrates are isolated in a separate disposal region.	• Waste (little credit taken except for activation products within stainless steel or zircaloy, when credit taken for corrosion-limited release rate) • Container/packaging/grout (alkaline environment limiting radionuclide release, sorbs/retards radionuclides) • Buffer/backfill (bentonite used around some wastes to ensure diffusion – limited transport) • Seals • Host rock (sorption and matrix dispersion/dilution along flow paths)
7	In-cavern disposal of LILW in a crystalline host rock, with wastes packaged in concrete and steel containers that are stacked in the caverns (low-activity wastes) or grouted in concrete vaults within the caverns (high-activity wastes); the caverns are backfilled with crushed rock that acts a hydraulic cage	• Waste (slow degradation of cement-encapsulated metal wastes) • Container and vault (including grout) with high-activity wastes only (prevent water access to waste long period, until the vault concrete and backfill are significantly degraded and cracked. Prior to this, radionuclide migration out of massive concrete monolith of the vault is diffusion-dominated) • Backfill (crushed rock, acts as a hydraulic cage) • Seals • Host rock (protects vault structures from dynamic surface processes and provides generally low groundwater flux environment, with relatively stable chemistry for several tens of thousands of years)
8	In-room disposal of LILW in a limestone host rock, with LLW and shielded ILW containers stacked in separate rooms (no backfill)	• Seals • Host rock (very low permeability with transport only by diffusion)

No	General concept description	Main Barriers
9	In-cavern disposal of LILW in a sequence of argillaceous formations, with waste containers cemented into steel emplacement containers that are stacked in the caverns; the caverns are backfilled with grout.	• Host rock (very low permeability and essentially dry) • Overburden
10	Phased Geological Repository Concept (PGRC)[2], with waste packages emplaced in large purpose-built vaults in a suitable geological environment. Closure may be up to a few hundred years after waste emplacement. Waste could be retrieved in the pre-closure period. An appropriate time after waste emplacement, the vaults are filled with cementitious backfill. At a suitable later time the repository is sealed and closed.	• Waste (slow degradation of cement-encapsulated wastes) • Containers (limit water access to waste for long enough to prevent significant release of short-lived radionuclides, but do not provide absolute containment, because most will be vented to prevent the build up of internal gas pressure) • Backfill (Nirex Reference Vault Backfill (NRVB), which is cementitious and provides a high-pH environment that inhibits degradation of waste containers and radionuclide release from metal wastes, has a large radionuclide sorption capacity, acts as a significant reservoir for waste-derived gas and can chemically absorb CO_2 evolved by the waste) • Seals • Host rock (protects vault structures from dynamic surface processes and provides generally low groundwater flux environment, with relatively stable chemistry for the assessment period)

1. TRU waste is distinguished as a separate category in some countries and is waste that contains radionuclides with atomic numbers greater than that of uranium. There is no universal definition of TRU waste, but it is approximately equivalent to long-lived low- and intermediate-level waste, as defined by the IAEA (IAEA, 2003).
2. The PGRC is a generic concept developed in the UK by Nirex and subsequently by the NDA RWMD. The concept does not define a specific repository environment. However, it was developed from earlier concepts that were intended to be implemented in a fractured crystalline host rock overlain by a sedimentary sequence that would provide a significant additional barrier to release.

3.4.4 Disposal concepts for high level waste and spent fuel

Disposal concepts for HLW/SF were reviewed recently by Baldwin *et al.* (2008). As for the disposal concepts considered in Section 3.4.3, it is inappropriate to repeat this review here. Instead, the main features of the disposal concepts identified by Baldwin *et al.* (2008) are summarized in Table 3.2.

The different concepts for disposal of long-lived LLW and ILW (Section 3.4.3) emphasise the relative importance of the EBS and host rock/geosphere barriers to different degrees, and at different times. In contrast there is much less variability in the fundamental functions required of the EBS and host rock barriers in the HLW/SF concepts. In all these concepts, the EBS is designed to ensure complete waste containment following repository closure until at least the time when the thermal peak has been reached. Similarly, in all of these concepts the host rock functions as a barrier, but this becomes important only after failure of the EBS.

Among the disposal concepts for HLW/SF are some important relationships between the EBS designs and the characteristics of the host rock, notably between:

- the expected longevity of the waste canister/overpack and the permeability of the host rock, with long-lived canisters/overpack generally favoured in higher-permeability rocks (such as fractured crystalline rocks);
- the length of time that the repository is planned to be open and the mechanical strength of the host rock, with concepts that favour large-span excavations and/or prolonged open periods for mechanically stronger rocks;
- the spatial dimensions of the accessible host rock and the geometry of waste emplacement, with concepts that allow high thermal loadings in cases where the accessible host rock has relatively limited lateral extent.

Table 3.2 Summary of disposal concepts for HLW/SF, based on Baldwin *et al.* (2008).

No	General concept description	Main Barriers
a	In-tunnel (vertical borehole) with long- or short-lived canister Adaptable for HLW or SF and probably for implementation in a variety of host rocks (crystalline, salt, carbonate, indurated mudrock etc), but long-lived canisters would probably only be used in host rocks with significant groundwater flow	• Waste (ensures slow release of radionuclides after overpack or canister failure) • Long-lived canister, typically copper or titanium with iron-insert for strength (if used as an alternative to short-lived overpack, provides complete waste containment for very long time periods (over 100,000 years), after which any failures would be distributed uniformly throughout the repository in space and time) • Short-lived overpack, typically steel (if used as an alternative to long-lived canister, provides complete waste containment until after peak temperature has been reached, which is less than 1,000 years after closure for HLW and greater than this for SF, thereafter the overpack is assumed not to behave as a barrier) • Buffer (protects waste canister or overpack; after waste canister or overpack fails (long-lived canisters may not be expected to fail in the safety assessment time frame), main role is a diffusion/transport barrier) • Backfill (most probably a combination of bentonite and sand which would act as a secondary barrier) • Disposal tunnel seals • Host rock (protects the EBS over the period of containment and afterwards would act as a barrier to the migration of any radionuclides that are able to escape)
b	In-tunnel (horizontal borehole) with long- or short-lived canister Adaptable for HLW or SF and probably for implementation in a variety of host rocks (crystalline, salt, carbonate, indurated mudrock etc), but long-lived canisters would probably only be used in host rocks with significant advective groundwater flow	• As for a)
c	In-tunnel (axial) with short-lived canister and buffer Adaptable for HLW or SF and probably for implementation in a variety of host rocks (crystalline,	• Waste (ensures slow release of radionuclides after overpack or canister failure) • Short-lived canister, typically steel (provides complete waste containment until after peak temperature has been reached, which is less than 1,000 years after closure for HLW and greater than this for SF, afterwards the overpack is assumed not to behave as a barrier) • Buffer (protects waste canister or overpack; after waste canister or overpack fails (long-lived canisters may not

No	General concept description	Main Barriers
	salt, carbonate, indurated mudrock etc), though relatively dry rocks would be favoured	be expected to fail in the safety assessment time frame), main role is a diffusion/transport barrier) • Disposal tunnel seals • Host rock (protects the EBS over the period of containment and afterwards would act as a barrier to the migration of any radionuclides that are able to escape)
d	In-tunnel (axial) with long-lived canister and buffer Adaptable for HLW or SF and probably for implementation in a variety of host rocks with significant groundwater flow (crystalline, carbonate etc), probably would be considered over-engineered for low-permeability host rocks such as plastic clay or salt	• Waste (ensures slow release of radionuclides after overpack or canister failure) • Long-lived canister, typically copper or titanium with iron-insert for strength (provides complete waste containment for very long time periods (over 100,000 years), after which any failures would be distributed uniformly throughout the repository in space and time) • Buffer (protects waste canister or overpack; after waste canister or overpack fails (long-lived canisters may not be expected to fail in the safety assessment time frame), main role is a diffusion/transport barrier) • Disposal tunnel seals • Host rock (protects the EBS over the period of containment and afterwards would act as a barrier to the migration of any radionuclides that are able to escape)
e	In-tunnel (axial) with supercontainer (small annulus) Adaptable HLW or SF and probably for implementation in a variety of host rocks (crystalline, carbonate, indurated mudrock etc), though mechanically weak rocks would not be favoured and it would probably be considered over-engineered for salt	• Waste (ensures slow release of radionuclides after overpack or canister failure) **Supercontainer, consisting of:** • Long-lived canister, typically copper or titanium with iron-insert for strength (if used as an alternative to short-lived overpack, provides complete waste containment for very long time periods (over 100,000 years), after which any failures would be distributed uniformly throughout the repository in space and time) • Short-lived overpack, typically of steel (if used as an alternative to long-lived canister, provides complete waste containment until after peak temperature has been reach, which is less than 1,000 years after closure for HLW and greater than this for SF, afterwards the overpack is assumed not to behave as a barrier) • Buffer (protects waste canister or overpack; after waste canister or overpack fails (long-lived canisters may not be expected to fail in the safety assessment time frame), main role is a diffusion/transport barrier) • Distance block (isolates each waste package within its buffer section, preventing bentonite movement during saturation and ensuring the correct swelling pressure evolution) • Disposal tunnel seals • Host rock (protects the EBS over the period of containment and afterwards would act as a barrier to the migration of any radionuclides that are able to escape)
f	In-tunnel (axial) with supercontainer (concrete buffer)	• Waste (ensures slow release of radionuclides after overpack or canister failure) **Supercontainer, consisting of:** • Relatively thin carbon steel overpack (provides complete waste containment until after peak temperature has been reached, which is less than 1,000 years after closure for HLW and greater than this for SF, after which

No	General concept description	Main Barriers
	Adaptable for HLW or SF and is suitable for implementation in indurated mudstones or plastic clays, but not crystalline rock (since the concept relies on the host rock to provide a buffer) or salt (since the barrier system would be considered over-engineered)	any failures would be distributed uniformly throughout the repository in space and time) • Buffer (provides highly alkaline environment around steel overpack for many thousands of years, passivating steel surfaces and ensuring overpack longevity while providing mechanical protection during containment period and a barrier to transport after canister failure) • Backfill (reduces voids around the supercontainer, improving mechanical integrity of the EBS and protecting buffer from cracking, enhancing the overpack longevity, as well as producing high-pH conditions, reducing steel corrosion rate and hence H_2 gas generation) • Disposal tunnel seals • Host rock (protects the EBS over the period of containment and afterwards would act as a barrier to the migration of any radionuclides that are able to escape)
g	In-tunnel (axial) with supercontainer (large annulus) Adaptable for HLW or SF and probably for implementation in a variety of host rocks with significant groundwater flow (e.g. crystalline, carbonate etc), probably would be considered over-engineered for low-permeability host rocks such as plastic clay or salt	• Waste (ensures slow release of radionuclides after overpack or canister failure) **Supercontainer, consisting of:** • Short-lived overpack, typically steel (provides complete waste containment until after peak temperature has been reached, which is less than 1,000 years after closure for HLW and greater than this for SF, after which the overpack is assumed not to behave as a barrier) • Buffer (protects overpack during period of containment, but after overpack fails, main role is a diffusion/ transport barrier) • Backfill (prevents bentonite extrusion/density loss, bentonite erosion where groundwater inflow and acts as an incompressible medium to enable development of bentonite swelling pressure, may also act as a chemical buffer between bentonite and concrete tunnel liners) • Distance block (isolates each waste package within its buffer section, preventing development of fast, transport pathways along tunnel) • Disposal tunnel seals • Host rock (protects the EBS over the period of containment and afterwards would act as a barrier to the migration of any radionuclides that are able to escape)
h	Caverns with steel multi-purpose transport/storage/disposal containers and bentonite backfill Adaptable for HLW or SF and probably for implementation in a variety of host rocks (crystalline, carbonate, indurated mudrock, salt), but supports needed for weaker rock	• Massive steel containers (ensure complete containment for at least 1,000 years after backfilling, though design lifetime of greater than 10,000 years is feasible, but following failure steel corrosion buffers redox at reducing values that help slow radionuclide release rates) • Backfill (provides mechanical buffering and protects multi-purpose containers (MPCs), ensures diffusive transport around MPCs to slow steel corrosion and radionuclide release and retards radionuclide migration from failed MPCs) • Disposal tunnel seals • Host rock (isolates disposal tunnels from surface conditions, provides a stable environment, retards transport of radionuclides from the waste and provides favourable geochemical and hydrological conditions)

No	General concept description	Main Barriers
i	Caverns with steel MPC or concrete/DUCRETE® Concrete Disposal Casks (CDC) and cement backfill Adaptable for HLW or SF and probably for implementation in a variety of host rocks (crystalline, carbonate, indurated mudrock, salt etc), but supports would be needed for weaker rock	• Waste packages (ensure complete containment for at least 1,000 years after backfilling, though design lifetime of above 10,000 years is feasible if an MPC design or much greater than 10,000 years if a CDC design, high pH would passivate the steel inserts and CDC might resist radionuclide transport even if small cracks exist) • Backfill (provides mechanical buffering and protects MPCs/CDCs, ensures diffusive transport around casks to slow steel corrosion and radionuclide release, and retards radionuclide migration from failed MPCs/CDCs) • Disposal tunnel seals • Host rock (isolates disposal tunnels from surface conditions, provides a stable environment, retards transport of radionuclides from the waste and provides favourable geochemical and hydrological conditions)
j	Mined deep borehole matrix, with waste emplaced in stacks up to 200 m long in vertical boreholes drilled from deep underground either directly from a disposal tunnel or between upper and lower caverns Adaptable for HLW or SF and probably for a variety of host rocks (crystalline, carbonate, indurated mudrock, salt etc), but in weaker rocks, limitations on size of deep openings may limit borehole length	• Waste (ensures slow radionuclide release after overpack degradation) • Overpack (ensures complete containment for at least 1,000 years after backfilling, though design lifetime of above 10,000 years is feasible, but following failure steel corrosion buffers redox at reducing values that help slow radionuclide release rates) • Buffer (during the period of complete containment and after degradation of the handling shell, protects overpack; after waste canister fails, main role is a diffusion/transport barrier) • Load-bearing seals (isolate sections of the boreholes and reduce the potential for transport) • Lower cavern backfilling and lower borehole seals • Host rock (protects the EBS, provides favourable geochemical conditions and low groundwater flux, also provides a radionuclide transport barrier)
k	Hydraulic cage (around a cavern repository)	The hydraulic cage concept could be combined with one of the above cavern concepts (h or i) and implemented in a suitable deep and stable geological environment. An overpack would provide complete containment for a time, and would be surrounded by a low-permeability buffer emplaced. The waste is accessible for a long period following emplacement in the repository (as in h). The key difference from other concepts is that the natural barrier’s properties are modified in the near field, by engineering a high-permeability zone around the EBS.

3.4.5 Terminology for EBS/disposal concepts

In the case of LLW/ILW concepts, there may be no effective EBS (such as for the repository being developed by Ontario Power Generation (OPG) at Bruce in Canada; Concept 8 in Table 3.1). Alternatively, there may be an EBS offering complete containment for up to several hundreds or even thousands of years (such as the concept developed by the Swiss Nationale Genossenschaft für die Lagerung Radioaktiver Abfäller (Nagra) for disposal of TRU waste in indurated mudrock; Concept 4 in Table 3.1). However, even those LLW/ILW EBS that have been designed to provide complete containment are expected to fail earlier than any of the EBS that have been proposed for HLW/SF.

In the case of HLW/SF concepts, there is a clear distinction between EBS that are:

- required to provide complete containment only until after peak temperatures have been attained;
- expected to provide complete containment long after this time and possibly until the end of the time period considered by a safety assessment.

Baldwin *et al.* (2008) describe disposal concepts for HLW/SF that have EBS belonging to the first of these groups as having 'short-lived canisters'. Disposal concepts that belong to the second of these groups are described as having 'long-lived canisters'. In the terminology of Baldwin *et al*. (2008) a 'canister' is synonymous with 'overpack' (although some programmes use 'canister' to mean 'waste container' which is the vessel that contains the waste form, see IAEA, 2003).

A potential problem with this terminology is that the time to the peak temperature is not necessarily short and may conceivably be many thousands of years in some cases. Additionally, in the scheme of Baldwin *et al.* (2008), the concepts with MPCs and/or CDCs (Concepts h, i and j in Table 3.2) have EBS that in their entirety may result in containment for more than 10,000 years. However, these EBS are unlikely to provide complete containment for the same length of time as the 'long-lived canisters'. Therefore, it is inappropriate to describe these EBS as 'short-lived' or 'long-lived'.

Considering LLW/ILW and HLW/SF concepts together, the following groups can be distinguished:

- those that have no effective post-closure EBS;
- those that have an EBS that is expected to provide containment for only a very short time (perhaps a few hundred to a 1,000 years);
- those than have 'short-lived canisters' (in the sense of Baldwin *et al.* 2008);
- those that have EBS that are expected to provide containment for more than 10,000 years;
- those that have 'long-lived canisters' (in the sense of Baldwin *et al.* 2008).

In most cases where the major impacts of the geological environment on the EBS (or vice versa) are to be discussed, there would be few obvious advantages in distinguishing the 'short-lived canisters' from the EBS that can provide containment for more than 10,000 years. However, there are circumstances where it is appropriate to indicate whether, for a given time period, a safety case would require the waste canisters/overpacks alone to provide containment, or whether the requirement is simply for the whole EBS to provide containment.

Consequently, the following sections of this report use the terminology:

- 'longer-lived waste package/overpack' for a waste package (comprising a waste form and waste container, as defined by IAEA, 2003), or waste package in combination with an overpack, that is expected to provide containment for more than 100,000 years, and potentially to the end of the period considered by any safety assessment;
- 'shorter-lived waste package/overpack' for any other waste package, or waste package in combination with an overpack, that is expected to provide some containment following repository closure, but for a much shorter period than a 'longer-lived waste package/overpack';
- 'higher-integrity EBS' for an entire EBS that is expected to provide containment for more than 100,000 years, and potentially to the end of the period considered by any safety assessment;
- 'lower-integrity EBS' for an entire EBS that is expected to provide some containment following repository closure, but for a much shorter period than a 'higher-integrity EBS'.

Cases where there is no barrier function of the waste package/overpack, or where there is no EBS, are distinguished explicitly as they arise. In some cases there is a need to indicate differences in the duration of total radionuclide containment and/or differences in the effectiveness of retardation between two EBS. In these cases descriptions such as 'increased EBS integrity' or 'greater EBS integrity' are used as appropriate, with explanation where necessary.

4 Technical issues

4.1 Approach to identification of technical issues

The overall process by which technical issues were identified is shown in Figure 4.1.

Quintessa's project team initially developed a list of example technical issues. The team then designed a process for expanding this list and identifying knowledge about each technical issue. Use was made of the prior knowledge and expert judgments of team members, and published literature on radioactive waste disposal. These activities were carried out at the same time as the initial identification of geological environments described in Section 2.

The example technical issues identified by Quintessa's project team were not intended to be comprehensive. Instead, the aim was to inform participants in the first expert workshop of the kinds of issues that the project sought to identify. The workshop participants then expanded the list of technical issues.

Following the first workshop, Quintessa's project team summarized the findings and added to them from literature reviews and expert knowledge. The resulting notes were circulated to workshop participants for comment. Feedback was used by Quintessa's project team to prepare a final list of technical issues and associated descriptions, along with a draft summary of the state of knowledge on these issues. The final list and draft summary were circulated at the second workshop. Participants reviewed the issues and state of knowledge, leading to an expansion of the issues list, descriptions and corresponding knowledge summary. Experts at the workshop were invited to make further comments on the descriptions of technical issues and classification of geological environments. These comments resulted in only minor modifications.

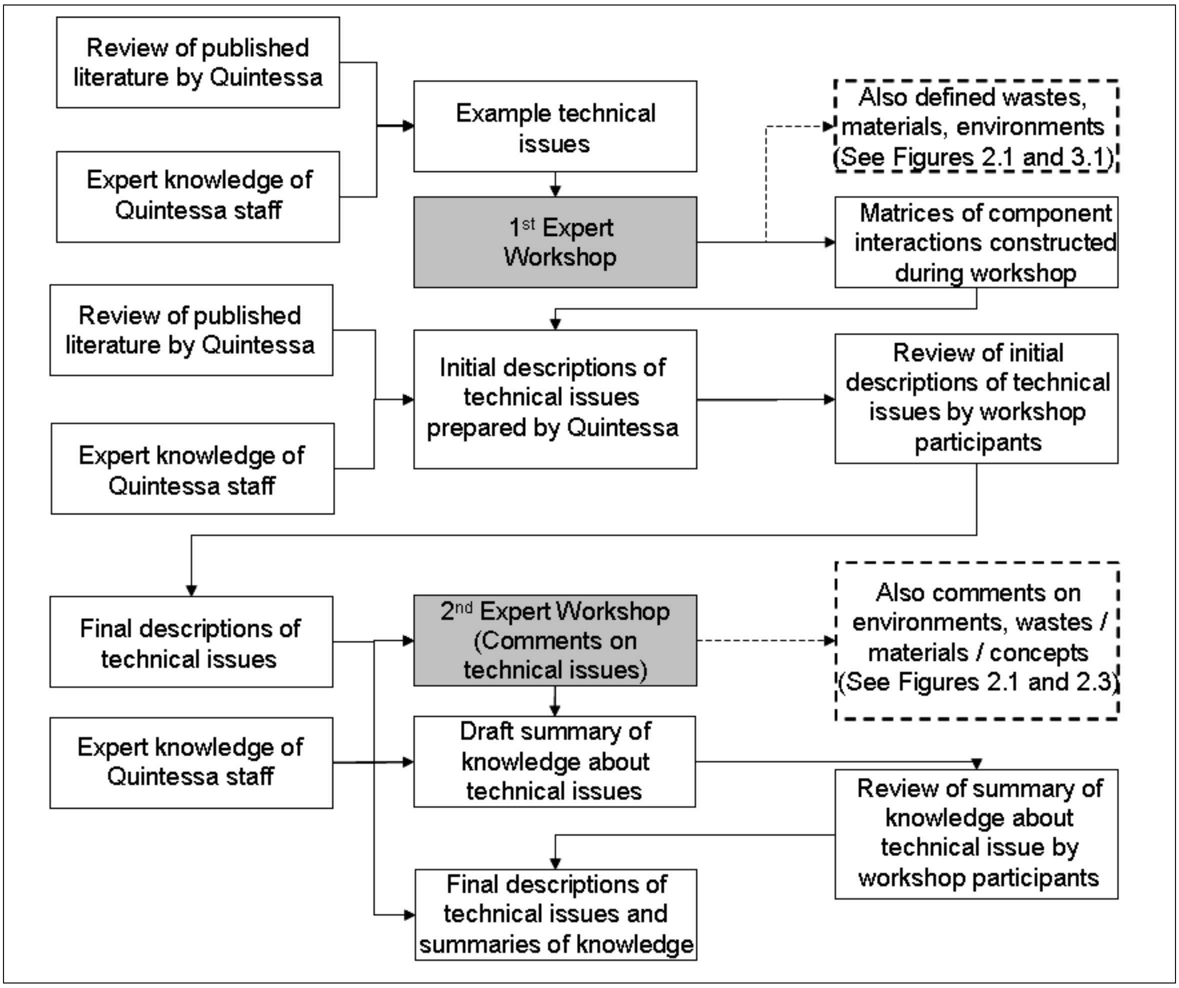

Figure 4.1 Main steps to identify technical issues for detailed review.

4.2 Identification of issues at first workshop

Technical issues can be defined based on knowledge of how a geological environment would interact with components of a geological repository and affect interactions between these components. For example, a waste form will interact with the EBS components (overpack, buffer and so on) that surround it by many processes that depend upon the characteristics of the waste form and particular EBS design, such as:

- density of a waste form affecting the surrounding deformation of EBS components;
- EBS components being affected by gas evolved from the waste form;
- containment required being influenced by the radionuclide release characteristics of the waste form.

These (and other) interactions suggest that the definition of a technical issue should be: the influence of different waste form types on the design of the EBS.

Therefore, the method used to identify issues at the first expert workshop involved a three-step process:

- Quintessa's project team supplying details of the approach to be followed;, briefing materials with draft descriptions of geological environments, wastes, engineered barriers and disposal concepts; and examples of technical issues (to participants of the project goals);

- expert participants reviewing and modifying the definitions and descriptions of the geological environments, wastes, engineered components and disposal concepts (see Sections 2 and 3);
- expert participants determining interactions between each geological environment and repository components, and between different repository components, and hence defining technical issues for further consideration.

To carry out the second and third steps, participants at the first workshop were divided into three discussion groups:

- Group 1 reviewed the waste characteristics and then identified interactions between wastes and engineered components, including EBS components;
- Group 2 reviewed the engineered components and identified interactions between these components, including EBS components, and the geosphere;
- Group 3 reviewed the definitions of the generic geological environments and then identified interactions between wastes and the geosphere.

During the second step, each group agreed on column headings for a table in which interactions between the different system components could be recorded. For example, Group 1 agreed column headings for a table with waste types as column headings.

Before proceeding to the third stage, each group presented its table headings to the workshop and invited comments. The column headings were modified to take into account comments and each table was completed by adding row titles. These latter were column headings decided by one of the other groups (e.g. the row titles for the table to be completed by Group 1 were the column headings decided by Group 2).

In the third step, the discussion groups focused on interactions considered to be of high priority when designing a repository and/or for treatment in performance assessment (PA). The aim was not to describe the interactions in detail, or consider alternative waste management/disposal options (such as long-term storage, deep borehole disposal). Care was also taken not to judge the relative suitability of the geological environments or to consider site selection. Both favourable and potentially adverse characteristics/interactions were identified.

Following the workshop, interactions identified by the groups were summarized by Quintessa and the summaries circulated to participants for comment. During this process, inconsistencies and duplications were removed. The results were used to construct modified tables (or in the case of Group 3 a new table) showing the interactions. The results for Groups 1 and 2 are summarised in Table 4.1 and 4.2.

In addition to the entries given in Table 4.1, Group 1 also noted the following general issues that are not specific to a particular waste type/engineered system combination:

- Co-located disposal is defined as disposal of different waste types in different parts of a repository that have a common access point and surface facilities. Co-located disposal could involve emplacement of different kinds of waste on different levels or in different zones of a repository. Interactions between chemical containment systems in different parts of a facility should be considered, which is not adequately captured by the table. This is probably most significant for co-location of waste forms containing cementitious materials and HLW, but it may also be important for the co-disposal of other waste types.

- Corrosion resistance and durability of repository materials are not well understood, especially when different materials may be interacting with each other. The characteristics (surface areas, geometries, hydraulic properties and so on) of interfaces between different materials are important influences on corrosion resistance and durability.

- If a repository is built in an evaporite and backfilled with evaporitic materials the interfaces between the host rock and the backfill will tend to disappear over time, owing to plastic deformation of the host rock and backfill.

- Thermal degradation, radiolysis, and degradation by water are key issues for polymer waste forms, about which very little is currently known.

- The possibility for criticality occurring outside waste packages will be controlled by many factors, including the local geometry of the packages, groundwater fluxes, geochemical conditions and presence of neutron moderators.

- Gas generated by corrosion of steel components has a different composition to organic-sourced gas. These two sources would be present in different quantities in different repositories and would generate different volumes of gas per unit of source material (whether on a mass or a volume basis). Gas generation from waste may be a major issue that could impact upon safety.

- Super-plasticisers will be required in construction, but little is known about how they might affect radionuclide transport. The new generation of super-plasticisers may be less problematic than those considered a decade ago in the Nirex investigations at Sellafield.

- The local repository environment was assumed to become oxygen-poor to anoxic soon after repository closure and resaturation. This change in redox conditions is important mainly because it influences waste form degradation, metal corrosion and the solubility and transport of those radionuclides that are less mobile in more reduced states.

- The resaturation of the waste will take place over very different lengths of time, depending on the geological environment and the nature of any backfills and seals. The timing of resaturation will be an important influence on the nature, timing and signifcance of interactions between repository components.

Table 4.1 Interactions between wastes and the EBS and issues that influence these interactions, as identified in the first workshop and subsequent review cycle.

	Cemented LLW and NORM	Graphite (treatment unknown)	HLW Glass	SF + HLW ceramic plus U + Pu in ceramic	Cemented ILW with high organics loading	Cemented reactive wastes (Magnox, U, Al, Zn)	Cemented ILW – generic	Polymer encapsulated wastes	Cemented reactor decommissioning wastes (concrete and steel dominated	Misc, carbides, exotics etc
System geometry (depth, access, footprint, caverns, tunnels)	Handling large LLW packages underground. Only separate from cemented ILW if good reason to do so but 'deep' disposal on safety grounds unnecessary. May not be optimal to separate because then would need to characterise more host rock.	Large volume. Maybe a candidate for a separate repository? There is no need for dispersal (no significant heating or criticality risk).	Heat and environmental controls needed during operations. Heat loading dictates spacing. Long-lived radionuclides require long containment (travel times) and so implies disposal at significant depth.	Waste canisters must be spaced so as to reduce temperature. Long-lived radionuclides require long containment (long travel times to biosphere) and so implies disposal at significant depth.	Relatively small volume but gas generating. Gas generation may require engineering for gas release. Care needed in location to prevent unwanted interactions with other waste types (including HLW and SF). Emplacement must be optimised.	Volumes are quite large Care needed in location to prevent unwanted interactions with other waste types (including HLW and SF). Emplacement must be optimised. Engineering for gas release may be needed. (Much gas release possibly within a few decades after closure, therefore an operating and monitoring issue) .	Packaged volumes are quite large. Relatively large volumes of less reactive metals occur. Care needed in location to prevent unwanted interactions with other waste types (including HLW and SF). Gas generation may require engineering for gas release.	Currently a small volume, but could increase as new packaging proposals are developed. EBS/ environmental concerns might push packaging in this direction. Care needed in location to prevent unwanted interactions with other waste types (including HLW and SF). Emplacement must be optimised.	Quite large packaged volumes containing relatively large volumes of less reactive metals Need to think carefully about location – need to optimise emplacement. Interactions with other wastes HLW and SF Engineering for gas release may be needed. Could be an issue with large or awkwardly shaped packages defining tunnel etc dimensions.	No special issues identified
Waste package only (without buffer/	No special issues identified.		Corrosion resistance of exotic materials is not well known at high temperatures so may be an issue if relying on this alone to provide containment.		No special issues identified.					

	Cemented LLW and NORM	Graphite (treatment unknown)	HLW Glass	SF + HLW ceramic plus U + Pu in ceramic	Cemented ILW with high organics loading	Cemented reactive wastes (Magnox, U, Al, Zn)	Cemented ILW – generic	Polymer encapsulated wastes	Cemented reactor decommissioning wastes (concrete and steel dominated	Misc, carbides, exotics etc
backfill)										
Longer-lived waste package/ overpack	No special issues identified.		Copper Ti etc availability.	Copper Ti etc availability.	No special issues identified.		Availability of manufactured boxes etc at required rates may be a practical issue	No special issues identified.		
Shorter-lived waste package/ overpack	No special issues identified.									
Physical buffer and microbial barrier	No special issues identified.		Buffer selection will be controlled by local heat generation. Bentonite availability may be an issue. Need to carry out testing/ experiments with the bentonite to be used in disposal so need to make this decision early or carry forward larger programme to keep options open.	Buffer may be needed to control IRF. Need to ensure saturation on particular timescale to ensure conductivity – sufficient to prevent overheating the buffer. Bentonite availability may be an issue. Need to carry out testing with the bentonite to be used in disposal so need to make this decision early or carry forward larger programme to keep options open.	Possible low-permeability cement buffer. May need to separate these from bentonite buffers around HLW/ SF.	Possible low-permeability cement buffer. May need to separate these from bentonite buffers around HLW/ SF. Waste form expansion likely to be an issue for buffer integrity.	Possible low-permeability cement buffer. May need to separate these from bentonite buffers around HLW/ SF.	No special issues identified.		

	Cemented LLW and NORM	**Graphite (treatment unknown)**	**HLW Glass**	**SF + HLW ceramic plus U + Pu in ceramic**	**Cemented ILW with high organics loading**	**Cemented reactive wastes (Magnox, U, Al, Zn)**	**Cemented ILW – generic**	**Polymer encapsulated wastes**	**Cemented reactor decommissioning wastes (concrete and steel dominated**	**Misc, carbides, exotics etc**
Backfills	No special issues identified.				Backfill may need to be gas permeable.	No special issues identified.				
Chemical containment and conditioning	No special issues identified.		Rely on waste form not chemical conditioning. Conditions rate at which waste form degrades.	Rely on waste form not chemical conditioning. Conditions rate at which waste form degrades.	No special issues identified.					
Linings (including plugs and seals)	No special issues identified.									
Excavation support	No special issues identified.									
Operational infrastructure	Large heavy packages if 4-m box used.	No special issues identified.	Heat removal is a problem. Large heavy packages.	Heat removal is a problem. Large heavy packages.	No special issues identified.	Package integrity issues if they get wet.	More opportunity for standardised containers.	No special issues identified.	Could be an issue with large or awkwardly shaped package.	No special issues identified.
Other	No special issues identified.									

Group 1 started by considering issues and intended to return and grade the issues at the end if time permitted, which it did not. The strategy was to attempt to identify the most important issues and/or those highly specific to a particular waste type first. Thus the entries on the table should reflect a) the most important issues and/or b) issues that are likely to be apparent to a specialist group such as Group 1 and would probably not be apparent to the more general project team. A cell containing 'no special issues indentified' does not mean that there are no potential issues specifically associated with the interaction; it simply indicates that a) the important issues are captured by the general list given in the main text, or b) the issues are of lower importance/more general.

Table 4.2 Interactions between EBS components and the geosphere and issues that influence these interactions, as identified in the first workshop and subsequent review cycle.

EBS Component/ Characteristic	1 Hard fractured rock to surface	2 Hard fractured rock overlain by relatively high-permeability sedimentary rocks in which advective transport dominates	3 Hard fractured rock overlain by sedimentary rocks containing at least one significant low-permeability unit in which diffusion dominates solute transport	4 Bedded evaporite host rock	5 Siliceous sedimentary host rock	6 Mudstone host rock	7 Plastic clay host rock	8 Carbonate host rock	9 Non-evaporitic host rock with hypersaline groundwater
System geometry (depth, access, footprint, tunnels)	Rock stress, depth compromise between stress and low transmissivity, avoid major structures, a large footprint may be required to locate sufficient "good" rock or a multi-layer repository, keeping excavations open for an extended period may be difficult.			Dependent on sedimentary architecture and heterogeneity, variable strength of rock affects size of caverns/tunnels, avoid major structures, circular cross-section tunnel only in plastic clay rock, some environments may be limited in extent compared to required footprint?					May suffer any of Environment 1-8 restrictions. Disturbance to inherently stable system may be a problem
Waste package only (no buffer/ backfill)	NOT FEASIBLE: inadequate geosphere performance.		Unlikely to be acceptable to stakeholders although cover would provide adequate geosphere performance	Barrier provided by impermeable host rock	High degree of package and overpack engineering, gallery / tunnel construction for retrieval, long travel times essential		Closure over canisters, corrosion	Long travel times, engineering, tunnel construction	Very long travel times, corrosion, no reliable buffer available
Longer-lived waste package/ overpack	Corrosion by HS or O_2, high salinity, high dependence on buffer, probability of defective canisters, seismic shearing		Stable groundwater system	With halite / other evaporite backfill	Corrosion by HS or O_2, high salinity, high dependence on buffer, probability of defective canisters, seismic shearing		Closure over canisters, corrosion	Travel times, engineering	Very long travel times, corrosion, no reliable buffer available
Shorter-lived waste package/ overpack	(NOT FEASIBLE?): totally dependent on buffer/backfill retention, short travel time in geosphere		Longer travel time in geosphere	Gas release from ILW is an issue	Totally dependent on buffer/ backfill retention and adequate travel time and retention in geosphere		Corrosion, closure over canisters, irregular closure	Long travel times, engineering, tunnel construction	Very long travel times, corrosion, no reliable buffer available
Buffer as physical, chemical and microbial barrier	Less stable groundwater, buffer erosion	Loss of swelling due to salinity, colloid generation, long-term alteration, emplacement		Not applicable	Stability of groundwater, loss of swelling due to salinity, erosion and colloid generation, long-term alteration		Clay buffer not required unless to bar organics	Swelling pressure, colloids, alteration, erosion	(NOT FEASIBLE): Is there a compatible buffer?

EBS Component/ Characteristic	1 Hard fractured rock to surface	2 Hard fractured rock overlain by relatively high-permeability sedimentary rocks in which advective transport dominates	3 Hard fractured rock overlain by sedimentary rocks containing at least one significant low-permeability unit in which diffusion dominates solute transport	4 Bedded evaporite host rock	5 Siliceous sedimentary host rock	6 Mudstone host rock	7 Plastic clay host rock	8 Carbonate host rock	9 Non-evaporitic host rock with hypersaline groundwater
Backfills in deposition and access tunnels	Less stable groundwater	Cover provides more long-term stability of groundwater		Salt backfill only	Erosion and colloid generation		Backfill not required unless to bar organics	Erosion and colloid generation	Void fill function only
Chemical containment and conditioning	Degradation, loss of high pH, corrosion, sorption	Degradation by groundwater, leaching of alkalinity and high pH, container corrosion, poor retention		Not applicable	Degradation by groundwater, leaching of alkalinity and high pH, container corrosion, poor retention		Not applicable	Degradation, leaching, carbonation	Not applicable
Linings, plugs and seals for deposition holes /tunnels	Rock stress and fracturing, insertion and preservation of linings for efficient emplacement of containers, seal emplacement important in fractured environment and also in Environment 3 to re-instate the diffusive barrier in the access shaft/drifts.			Not applicable	Rock stress and fracturing, insertion and preservation of linings for efficient emplacement of containers, seal emplacement important in permeable horizons and zones		Important to ensure seals effectively re-instate the natural barrier?	Rock stress, fracturing and joints	Fracturing, insertion
Excavation support for galleries and access tunnels	Strong rock, large caverns and tunnels possible, risks of rock falls in fracture zones, rock bolting, grouting of major structures to control water inflows			High creep rate in halite, may need support	Variable rock quality, fracturing	Fracturing, cleavage	High rate of closure, circular tunnel	Fracturing, block joints	Very high corrosion rate of steel support
Operational infrastructure	Excavation methods (drill and blast or TBM)			Corrosion, salt dust in ventilation, exclude water	No special issues		Short time for retrieval	No special issues	Corrosion in brine, salt clogging of pumps, etc
Other aspects of engineering design and operation	Radon hazard and ventilation, rock spoil and sulphide oxidation (acid rock drainage)			Gas hazard	No special issues	Rock spoil, pyrite oxidation	No special issues		Any of Environment 1-8 issues

A key conclusion/observation of Group 2 was that it will be necessary to design the EBS to work with the particular geological/ hydrogeological environment and then optimise the design to the local conditions at the site. It is also clear that there is considerable variation in the significance of some of issues between the different geological / hydrogeological environments. This suggests much more design and characterisation work may be required in some environments to make a safety case.

Group 3 did not consider it possible to analyse in detail the interactions of geological environments with the various waste forms, without reference to the variety of EBS designs that could be employed. This group therefore concentrated on identifying general factors that would influence how each kind of waste would interact with the geosphere in each geological environment. Their results are summarized in Table 4.3. More detailed comments from Group 3 on each environment are given below.

This group noted that investigation programmes and related research and development will need to be tailored to the particular repository concept (bearing in mind the nature of the wastes to be disposed) and the characteristics of the host geological environment. Particularly important issues that will need to be considered are:

- difficulties in investigating host rock bodies/formations that are not exposed at the surface;
- difficulties in investigating host rock bodies/formations that are exposed at the surface, but which at repository depths are likely to have different properties from those at the surface;
- the need to obtain data from an underground research laboratory (URL) to characterise the host rock formation at repository depths (such a URL can be at the selected site and/or elsewhere).

Wastes are likely to interact with the surrounding geosphere by generating gas. When developing a safety case, it will be important to determine whether or not a gas pathway for radionuclide transport will be established. If such a pathway is thought likely, it will be important to establish its significance for safety. If repository-derived gas reaches the surface, there will be a greater impact on the safety case than if the gas does not reach the surface, due to its dissolution in groundwater.

In all the host rocks considered here, there remain uncertainties in the extent and behaviour of the excavation damaged zone (EDZ). Such a zone would develop around any underground excavations. Development of a safety case needs to include a demonstration that the EDZ will not act to conduct radionuclides rapidly from the repository to the surface. For crystalline rocks, understanding of the EDZ is relatively well-developed. However, less is known about the temporal evolution of the EDZ in weaker rocks, such as plastic clays or evaporites.

Similarly, there remain uncertainties in the interactions between host rocks and any high-pH plume that would develop around cement-bearing wastes or barrier components. In particular, it is necessary to establish what mineralogical changes would occur and the corresponding changes in rock porosity. Both the secondary mineralogy and porosity (pore volume and pore geometry) will influence radionuclide migration and retardation. Once again, knowledge is relatively good for crystalline rocks, but there is less information on mudrocks, carbonate rocks and evaporites.

Table 4.3 Factors affecting interactions between wastes and the geosphere, as identified in the first workshop.

Factor affecting waste - geosphere interactions	Wastes to which relevant	**1** Hard fractured rock to surface	**2** Hard fractured rock overlain by relatively high-permeability sedimentary rocks in which advective transport dominates	**3** Hard fractured rock overlain by sedimentary rocks containing at least one significant low permeability unit in which diffusion dominates transport	**4** Bedded evaporite host rock	**5** Siliceous sedimentary host rock	**6** Mudstone host rock	**7** Plastic clay host rock	**8** Carbonate host rock	**9** Non-evaporitic host rock with hyper-saline ground-water
Complexity of the geosphere barrier	ILW, HLW/SF	Complexity of fracture network	Challenge to characterise (investigate host and cover)		Maybe challenge to characterise :hetero-geneous lithology, gas and /or water pockets	Maybe challenge to characterise (depending on whether cover rocks required for safety – more likely for ILW)	Relatively uniform, relatively easy to characterise		**Low-permeability:** little variability, easy to characterise **Massive:** fractured, challenge to characterise	Not a priority factor
Barrier function of the geosphere	ILW, (HLW/SF geosphere barrier unnecessary but may be desirable)	Geosphere not reliable physical barrier	Factor affects waste-geosphere interactions							Not a priority factor
Protection of the EBS by the geosphere	HLW/SF (for ILW a suitable EBS may be unfeasible)	Potentially important factor		Not a priority since geosphere could act as barrier and therefore there is less reliance on the EBS		If no low-permeability cover rocks	Not a priority since geosphere could act as barrier and therefore there is less reliance on the EBS		If massive, no low-permeability cover rocks	Potentially important factor
Groundwater- and gas-mediated radionuclide transport delayed by low permeability cover rocks	ILW, HLW/SF	Not a priority factor		Potentially important factor	Not a priority factor	If no low-permeability cover rocks	Not a priority factor		If massive, low-permeability cover rocks	Not a priority factor

Factor affecting waste - geosphere interactions	Wastes to which relevant	**1** Hard fractured rock to surface	**2** Hard fractured rock overlain by relatively high-permeability sedimentary rocks in which advective transport dominates	**3** Hard fractured rock overlain by sedimentary rocks containing at least one significant low permeability unit in which diffusion dominates transport	**4** Bedded evaporite host rock	**5** Siliceous sedimentary host rock	**6** Mudstone host rock	**7** Plastic clay host rock	**8** Carbonate host rock	**9** Non-evaporitic host rock with hyper-saline ground-water
Dilution and dispersion of contaminants in cover sequence	ILW, HLW/SF	Not a priority factor	Potentially important factor	Not a priority factor		If high-K cover rocks	Not a priority factor		If massive, high-K cover rocks	Not a priority factor
Connectivity of the fracture network from the repository to the surface	ILW, HLW/SF	Potentially important factor	Not a priority factor							
Water and/or gas migration through both the matrix and fractures.	ILW (for gas and water), HLW/SF (mainly for water)	Not a priority factor	Cover only	Higher-K cover units only	Not a priority factor	Potentially important factor	Not a priority factor		If massive	Not a priority factor
Poor understanding of EDZ formation and/or significance	ILW, HLW/SF	Not a priority factor			Factor will influence waste-geosphere interactions	Not a priority factor	Potentially important factor		Not a priority factor	
Thermal effects on the host rock	HLW/SF	Not a priority factor			Gypsum dehydration	Not a priority factor	Clay mineral reactions		Not a priority factor	
Geochemical reactions in the rock surrounding open cavities	ILW, HLW/SF	Not a priority factor					Potentially important factor		Not a priority factor	
Reactions between host rock and acids from waste degradation (e.g. CO_2 , organic acids from cellulose, acids from PVC)	ILW	If carbonate fracture fills occur					Not a priority factor		Potentially important factor	Not a priority factor
The gas pathway, and its comparison with the groundwater pathway	ILW (mainly), HLW/SF (much less)	Potentially important factor								Not a priority factor

<table>
<tr><th>Factor affecting waste - geosphere interactions</th><th>Wastes to which relevant</th><th>1
Hard fractured rock to surface</th><th>2
Hard fractured rock overlain by relatively high-permeability sedimentary rocks in which advective transport dominates</th><th>3
Hard fractured rock overlain by sedimentary rocks containing at least one significant low permeability unit in which diffusion dominates transport</th><th>4
Bedded evaporite host rock</th><th>5
Siliceous sedimentary host rock</th><th>6
Mudstone host rock</th><th>7
Plastic clay host rock</th><th>8
Carbonate host rock</th><th>9
Non-evaporitic host rock with hyper-saline ground-water</th></tr>
<tr><td>Gas causing rapid gas and radionuclide migration</td><td>ILW (mainly), HLW/SF (much less)</td><td colspan="2">Factor will influence waste-geosphere interactions</td><td>If gas and/or water pathways occur in the overlying rock</td><td colspan="5">If gas and/or groundwater pathways form in the host rock (e.g. due to gas pressurization) or pre-exist (if fractures occur in Environments 5 and 8) and gas and/or water pathways occur in the overlying rock</td><td>Not a priority factor</td></tr>
<tr><td>Gas solubility</td><td>ILW (mainly), HLW/SF (much less)</td><td colspan="2">Not a priority factor</td><td>Potentially important factor</td><td colspan="5">Not a priority factor</td><td>Potentially important factor</td></tr>
<tr><td>Influence of gas pressurisation on EBS and natural barriers</td><td>ILW (mainly), HLW/SF (much less)</td><td colspan="2">Less than for lower-K geosphere</td><td>Potentially important factor</td><td colspan="5">Potentially important factor</td><td>Not a priority factor</td></tr>
<tr><td>Demonstration that rock properties unaffected adversely by gas flow</td><td>ILW (mainly), HLW/SF (much less)</td><td colspan="3">Not a priority factor</td><td>Potentially important factor</td><td>Not a priority factor</td><td colspan="3">Potentially important factor</td><td>Not a priority factor</td></tr>
<tr><td>Unfeasibility of constructing a sufficiently extensive EBS</td><td>ILW (feasible for HLW/SF)</td><td colspan="2">Potentially important factor</td><td colspan="2">Not a priority since geosphere could act as barrier and therefore there is less reliance on the EBS</td><td>If no low-K cover rocks</td><td colspan="2">Not a priority since geosphere could act as barrier and thus there is less reliance on the EBS</td><td>For massive variety if no low-K cover rocks</td><td>Cementit-ious barriers for ILW</td></tr>
<tr><td>Long-term corrosion/degradation of the EBS</td><td>ILW, HLW/SF</td><td colspan="3">Not a priority factor</td><td>Potentially important factor</td><td colspan="4">Not a priority factor</td><td>Potentially important factor</td></tr>
<tr><td>Interactions between host rock and high-pH plume from any cementitious EBS components</td><td>ILW</td><td colspan="9">Potentially important factor</td></tr>
<tr><td>Difficulty of modelling geochemical processes</td><td>ILW, HLW/SF</td><td colspan="2">Not a priority factor</td><td>Potentially important factor</td><td colspan="5">Not a priority factor</td><td>Potentially important factor</td></tr>
</table>

Factor affecting waste - geosphere interactions	Wastes to which relevant	**1** Hard fractured rock to surface	**2** Hard fractured rock overlain by relatively high-permeability sedimentary rocks in which advective transport dominates	**3** Hard fractured rock overlain by sedimentary rocks containing at least one significant low permeability unit in which diffusion dominates transport	**4** Bedded evaporite host rock	**5** Siliceous sedimentary host rock	**6** Mudstone host rock	**7** Plastic clay host rock	**8** Carbonate host rock	**9** Non-evaporitic host rock with hyper-saline ground-water
Understanding of coupling between mechanical, physical and chemical processes	ILW (especially coupling involving gas), HLW/SF (thermal coupling)	Not a priority factor					Potentially important factor		Not a priority factor	
Effect of rock convergence on groundwater flow (e.g. leading to a pulse of groundwater flow)	ILW, HLW/SF	Not a priority factor			Potentially important factor	Not a priority factor				
Stability of underground excavations	ILW, HLW/SF	Not a priority factor			Potentially important factor	Not a priority factor	Potentially important factor		Not a priority factor	
Impact of rock convergence on retrievability	ILW, HLW/SF	Not a priority factor			Potentially important factor	Not a priority factor	Potentially important factor		Not a priority factor	
Implications of repository's geophysical footprint for human intrusion (investigation of non-natural feature)	ILW, HLW/SF	Potentially important factor								
Resource potential of the rock	ILW, HLW/SF	Not a priority factor			Potentially important factor	Not a priority factor				

Group 3 also made some general comments about underground storage of CO_2. In recent years, this storage has been suggested by many authors as a potential means of mitigating climate change (see IPCC, 2005 and references therein). Most likely, CO_2 would be captured at large industrial point sources (mainly fossil fuel power stations, but potentially also steel works and cement factories) and then injected into rock formations that contain saline water. Thus, it is appropriate to consider the potential implications for radioactive waste repositories in the geological environments considered here.

The storage of CO_2 would most probably occur within permeable, high-porosity sedimentary rocks that are overlain by low-permeability cap rocks. Therefore, Environments 3 and 5 are most likely to contain potential CO_2 reservoirs. However, huge volumes of CO_2 will need to be stored (the average coal-fired power station produces almost four million tonnes of CO_2 per year). CO_2 could migrate many kilometres from an injection point (depending upon the thickness, lateral extent and porosity of the reservoir rock) and affect other geological environments. There would be negative consequences for safety if CO_2 did enter a repository volume, not least because it would tend to corrode barriers and act to transport radionuclides. However, the chances of this occurring are very remote since, to mitigate climate change effectively, CO_2 storage will need to be undertaken over the same time frame as the development of any repository. Thus, CO_2 storage has more implications for repository siting than for long-term performance.

Environment 1 (hard fractured rock to surface) has a fracture network that provides a relatively rapid connection between the repository and the surface, which:

- has implications for EBS design, since the waste form and the EBS will be required to provide the main barrier to radionuclide transport;
- produces a requirement to understand transport processes in fracture networks (including demonstration and modelling of rock matrix diffusion);
- may be relatively difficult to characterise compared to transport pathways in some environments, owing to geological complexity (although this may or may not matter from the point of view of developing a safety case).

In this environment, it might prove difficult to make a safety case for large volumes of ILW, as it will be impractical to enclose the large volume of waste within a low-permeability buffer, as can be done for HLW/SF. This difficulty is in marked contrast with HLW and SF, where there are several existing SF/HLW disposal concepts for this type of environment (e.g. KBS-3 concept and variants developed by Svensk Kärnbränslehantering AB (SKB); SKB, 2006).

In Environment 1, it could also be difficult to make a safety case if large gas volumes and/or rapid gas generation is likely to occur, due to the relatively high host rock permeability (above 10^{-8} to 10^{-9} m/s) leading to potentially rapid gas transport to the surface. Gas-related issues that could impact upon a safety case are the:

- potentially large volumes of gas produced by organic-rich wastes and reactive metal-bearing wastes, requiring the wastes to be specially treated and/or contained within special EBS designs;
- interactions between gas and groundwater flow;
- difficulty of developing robust gas transport models in fracture networks.

In this environment, it is likely to be relatively difficult to argue that the geosphere will provide a major role in containing activity in the long term. Travel times to the surface will tend not to be long and retardation mechanisms may have only limited effects. Therefore, the geosphere barrier may not be as effective as in other environments, and so a safety case will probably need to rely on adequate EBS functioning. However, the geosphere will then be required to ensure that the EBS acts as intended over long periods of time.

Environment 2 (hard fractured rock overlain by relatively high-permeability sedimentary rocks in which advective transport dominates) has many features common to Environment 1, since the host rocks have the same characteristics. However, in Environment 2 any radionuclide releases from the repository would be retarded, diluted and dispersed in the cover rock sequence, so that the:

- thickness and properties of the sedimentary cover influence safety;
- safety case will not place as much reliance on the EBS as Environment 1.

Environment 3 (hard fractured rock overlain by sedimentary rocks containing at least one significant low-permeability rock unit in which diffusion dominates solute transport) has the potential to delay groundwater- and gas-mediated transport of radionuclides. Much of this delay will be due to the cover rock sequence containing one or more low-permeability formations, within which diffusion will be the dominant transport process. The performance of this geological environment will depend upon the:

- thickness of each low-permeability barrier present, which need not be very great to achieve the required function (in contrast to Environment 6 where the host rock itself has this lithology); only a few tens of metres potentially being sufficient for a single barrier in a sedimentary rock cover;
- number of low-permeability barriers present, which also has implications for the potential to separate the different waste types (see below);
- continuity of the low-permeability formation or formations, which could be important because:
  - bypassing of the low-permeability formation or formations by faults or other structures could compromise safety;
  - a large area of continuity may be required as the size of the groundwater flow regime may be considerable (for example, many hundreds of km^2, as at the Bure site being investigated in France by the Agence Nationale Pour la Gestion des Déchets Radioactifs (ANDRA, 2005));
  - a low permeability is required over all of the formation(s) subcrop(s), with no large lithological changes that might allow for the formation of preferential transport pathways.

There is a need to demonstrate that the low-permeability formations maintain their continuity under all future climate states. For example, changes in the hydrogeological regime due to glaciation should not lead to groundwater flow lines intercepting transmissive pathways through the low-permeability formation(s). Similarly deformation due to glacial loading should not lead to the development of pathways. This has important implications for the site investigation programme. Notably, the use of hydrogeochemical/palaeohydrogeological techniques is likely to be necessary to show that past climate variations have not resulted in the low-permeability formation(s) being bypassed.

Environment 3 could be favourable for the vertical separation of different kinds of wastes in different parts of the same deep geological repository. For example, some waste could be placed in the hard fractured basement rocks, while other kinds of waste could be emplaced in the sedimentary sequence. However, such separation is dependent on the thickness, properties and relative location(s) of the low-permeability components of the sedimentary sequence;

There is the potential for the low-permeability formation or formations to trap gas, thereby increasing the likelihood of the dissolution of gas in groundwater.

Environment 4 (bedded evaporite host rock) contains very little free water to interact with the wastes. However, brine lenses can be present and may enhance corrosion of engineered repository components (such as metals, cement). The lack of free water means that the groundwater pathway is likely to have an insignificant impact upon long-term safety following closure. Nevertheless, a pulse of groundwater may be generated around a repository due to convergence of evaporites immediately following repository closure (see German safety cases for Gorleben). It is therefore important to understand deformation of the host rock, which most probably will be halite.

Evaporites are a resource and the effect of human intrusion on evaporites is outlined in the Guidance on Requirements for Authorisation (GRA) (Environment Agency, 2008). Following the approach set out in the GRA might lead to the conclusion that such environments are unacceptable because of the high radiation doses that would result from their exploitation. However, different approaches are possible, as shown by the selection of evaporites as host rocks in other countries and the fact that the presence of potentially exploitable evaporites is not one of the Defra exclusion criteria (Defra, 2007). Although potential exploitation may be a negative factor, in many other respects evaporites can provide a strong safety case.

An evaporite host rock would have very good barrier properties compared to some other host rocks (e.g. fractured crystalline rock). Consequently a safety case for a repository hosted in this environment would probably need to place less emphasis on the EBS compared to the geosphere barrier.

In rock sequences containing bedded evaporites, there may be more than one evaporite formation that could be used to host a repository. It may be possible to place different waste types in separate evaporite horizons, possibly separated by considerable vertical distances. Thus, some instances of this environment may prove suitable for co-location of different kinds of waste.

Long-term retrievability of waste from this environment (should this be required) may be a problem. It may be impractical for some wastes, or at least place severe constraints on retrievability or reversibility.

Environment 5 (siliceous sedimentary host rock) has two variants that are not distinguished here. The majority of comments made about the significance of a low-permeability unit above the host rock in Environment 3 are equally applicable to this environment. Of relevance here is that the host rock in this environment has a greater matrix porosity than the host rock in Environment 1, but possibly similar permeability. Both porous medium and fracture flow may be present. A similar level of understanding is required of groundwater flow in this host rock as for the crystalline host rock in Environments 1, 2 and 3.

Environment 6a (mudstone host rock which is dominantly flat-lying and undeformed, although indurated) has a low-permeability host rock. This low permeability will inhibit gas migration and it is important to establish how such a rock will behave if high pressures are generated by gas evolved from the waste. There is good evidence that in many mudstones any fractures formed by gas pressurisation will self-heal after the pressure dissipates as a result of gas migration (Horseman *et al*., 1996; NEA, 2005a,b). However, many coupled thermal, hydrogeological, mechanical and thermal (THMC) processes will affect the properties of these host rocks and the extent to which fluids can migrate through them. For example, rock strength, pore pressure distributions, permeability and EDZ formation may all depend upon one another. These couplings (dependencies) need to be adequately understood in order to develop a safety case.

The host mudstones of Environment 6a, are "weak" in the engineering sense, which will have an obvious impact on the potential sizes of excavated cavities and/or on the nature and number of engineering supports. These factors will also depend upon the depth of the repository. However, even with limited compressive strength, tunnels that are sufficiently narrow are likely to remain relatively stable to depths of less than 500 m (see evidence from Bure and Benken). Additionally, tunnels in such mudrocks may not prove much more difficult to construct than tunnels in some hard fractured rocks. Note that there are potential repository depth limitations in crystalline rocks at both Forsmark in Sweden and Olkiluoto in Finland, due to the strength/stress ratios of the rocks there.

Relatively narrow widths of excavations have implications for repository designs for certain waste forms, and in particular emplacement of larger packages. If small packages are required, a relatively large repository footprint may be the result for a given volume of waste.

This kind of host rock is likely to be straightforward to characterise. Particularly positive aspects are:

- the preservation of convincing geochemical evidence for low rates of mass transport, and the prospect of confirming diffusion-dominated transport;
- the considerable experience of characterising such rocks developed over the last two decades in France (such as ANDRA, 2005) and Switzerland (such as Nagra, 1997; Pearson *et al.* 2003) in particular.

Group 3 did not provide any conclusions that were specific to Environment 6b.

Environment 7 (plastic clay host rock) has many similar properties to the more indurated mudrock of Environment 6a. However, owing to its plastic characteristics, full tunnel support will be required, and the maximum practicable size of excavations will be limited. The maximum depth is likely to be constrained by the geotechnical properties of the clay. These geotechnical limitations mean that long-term retrievability will probably be a problem and may be impractical, to an even greater extent than in Environment 6a or Environment 4.

Compared to the other host rocks considered, complex coupled THMC processes will probably be more important controls on repository evolution. However, a plastic clay host rock is likely to show a closer approximation to ideal behaviour than other lithologies, which will help us to understand these coupled processes. Particularly important processes are likely to be:

- large geochemical changes to the clay, if excavations are left open for a significant length of time, which are expected to be greater in this host rock; thermal effects on clay leading to excess pore pressures, deformation, and the opening of pathways through the clay.

It may be necessary to manage a repository here differently from one in stronger rock, mainly because the larger openings could not remain open for long periods, the waste packing density is likely to be lower, so the repository footprint is likely to be greater.

Like the indurated mudstone of Environment 6a, plastic clays will probably be relatively straightforward to characterise. There is considerable experience of characterising this kind of rock over the last two decades, notably in Belgium by the Organisme National des Déchets Radioactifs et des Matières Fissiles Enrichies/De Nationale Instelling voor Radioactief Afval en Veriiikte Splijtstoffen (ONDRAF/NIRAS) (see Ondraf/Niras, 2001; Sillen and Marivoet, 2007).

Environment 8a (low-permeability carbonate host rock in which solute transport is likely to be dominated by diffusion) has a host rock that may behave rather like the indurated mudstone of Environment 6a. This kind of host rock would be a potential sink for CO_2

evolved from ILW. However, in contrast to the silicate host rocks of other environments there is relatively little information about the properties of these rocks that would help in assessing the safety of a geological repository for radioactive wastes. OPG of Canada is currently proposing a repository (for ILW and some LLW) in this kind of rock (see Hatch Limited, 2008). A repository for LLW and ILW in very low-permeability oolitic limestone at the disused Konrad iron ore mine in Germany has also been licensed (see Biurrun and Hjarte, 2003).

Compared to silicate host rocks, carbonate host rocks will be more soluble in the groundwater and porewater that will occur in the environs of a deep geological repository. Certain wastes, notably those containing PVC, will tend to produce acid solutions when they degrade. Acids may also be produced by radiolysis or as a result of cellulose degradation. Any safety case will need to consider the potential impact of these acids on the porosity and permeability of the host rock. However, these acids could potentially be neutralised by a suitable backfill.

Compared to clay-rich host rocks, carbonate host rocks are likely to have relatively low sorption capacity. However, significant reduced Fe may occur in the structure of carbonate minerals (for example, there may be a significant component of siderite, $FeCO_3$ present). Oxidation of these minerals in the wallrocks of excavated cavities will produce Fe-oxide mineral phases which may have relatively high sorption capacities. Additionally, carbonate rocks may contain a significant clay mineral component, which could have a relatively high sorption capacity.

Environment 8c (massive carbonate host rock overlain by sedimentary sequence with at least one low-permeability unit) has a host rock with similar chemical properties to the host rock in Environment 8a. However, hydrogeologically, this environment is similar to Enviroronment 3. Thus, the properties of the rocks that overlie the host rock have a significant impact upon safety.

Environment 9 (non-evaporitic host rock with hypersaline groundwater) is not a distinct environment, but rather would occur in combination with one of the other environments. The salinity of the water will influence the corrosion of EBS components in saline groundwater, and the solubility of gas, which will decrease as salinity increases, so that evolved gas is more likely to form a separate gas phase.

Generally, the existence of hypersaline groundwater would tend to indicate relatively stable groundwater conditions (because active groundwater flow would tend to result in dilution by fresher water and because hypersaline water is relatively dense and hence moves relatively slowly). However, this environment may not remain stable once the repository is constructed and operated for a considerable period.

There is a need to develop a good understanding of geochemical processes in these hypersaline groundwater conditions, but few data (such as thermodynamic data for use in geochemical models) exist for situations where the salinity is high. Additionally, conventional geochemical modelling approaches are inapplicable for very high salinities (above that of seawater).

4.3 Compiling the list of technical issues

Following the workshop, the interactions identified were divided into a number of different categories, each of which corresponded to a technical issue to be evaluated further. At the same time, a further review of published literature was undertaken, to determine what technical issues considered important by radioactive waste management organisations across the world. The aim was to audit the issues identified from the first expert workshop, to check that no major issue had been missed. Literature on waste programmes from countries with substantial nuclear power generation was consulted. The reviewed waste programmes were chosen to cover a range of geological environments, waste types and disposal concepts broadly similar to those identified in Sections 2 and 3. However, the history of the UK nuclear industry means that the UK inventory of ILW, in particular, is different to that of other programmes. For example, few countries need to dispose of Magnox or large volumes of wastes arising from reprocessing activities. The programmes that were reviewed are listed in Table 4.4.

Table 4.4 National programmes that were reviewed.

Country	Organisation(s)	Type of waste(s)	Dominant host rocks	Environment[1]
Finland	Posiva	SF	Crystalline igneous/ metamorphic	1
Sweden	SKB	SF and ILW (not operational)	Crystalline igneous/ metamorphic	1
Belgium	ONDRAF/NIRAS	HLW/SF and ILW	Plastic clay	7
Switzerland	NAGRA	HLW/SF and short-lived ILW/LLW	Crystalline igneous and indurated clay	2/3 and 5
		short-lived ILW/LLW	Indurated clay	5
France	ANDRA	HLW and ILW	Granite and indurated clay	1 and 5a
Spain	[2]Enresa	HLW/SF	Granite, clay and Salt	2/3, 5 and 4
Germany	[3]BfS	HLW/SF	Halite	4b
	BfS, [4]GFZ	ILW and some LLW	Halite and oolitic limestone	4b and 8c
USA	[6]US DoE	HLW/SF and TRU	[5]Tuff	1
		TRU	Halite	4a
[7]Japan	[8]NUMO/[9]JAEA	HLW	Crystalline igneous and argillaceous	2/3 and 5/6
UK	NDA RWMD/ Nirex	[10]ILW and some LLW	Volcaniclastic	2
Canada	OPG	ILW and some LLW	Limestone (very low permeability)	8a

[1] Generic environment to which investigated site might be assigned
[2] Empresa Nacional de Residuos Radioactivos SA
[3] Bundesamt für Strahlenschutz
[4] Deutsches GeoForschungsZentrum
[5] Repository in unsaturated zone, so very different to any UK site
[6] United States Department of Energy
[7] Generic research only – no sites actually investigated
[8] Nuclear Waste Management Organisation of Japan
[9] Japan Atomic Energy Agency
[10] NDA RWMD is now considering the disposal of the whole inventory given in the MRWS White Paper (Defra, 2008), Earlier site-specific work considered only ILW/LLW.

Technical issues recognised within the different programmes which would influence a safety case and/or safety itself are listed in Table 4.5. NEA (2008a), the proceedings of a conference entitled *Safety cases for deep geological disposal of radioactive waste: Where do we stand?* provides a good summary of the current state of understanding in the international community and references to the key documents produced by the different waste management organisations. Table 4.5 draws heavily on the material in NEA (2008a) and the references therein, and on reports of the international OECD/NEA project *Approaches and methods for integrating geological information in the safety case* (NEA, 2004, 2007). Many of the table entries use the title given to the topic or issue by a particular waste management organisation, so there is overlap between some entries and the level of detail of the topics/issues is variable.

The results of the literature survey, knowledge of the project team and material generated at the first workshop were used to generate an initial list of topics for consideration in the second phase of the project. These technical issues can be grouped to reflect their relevance to particular aspects of the disposal system or environment. Some of the issues discussed highlight important technical aspects or principles that will need to be considered when developing a deep geological repository, while others relate to technical difficulties that will need to be overcome during the repository programme.

These technical issues were compared with the list of issues identified by the review of national programmes listed in Table 4.4. This comparison is summarised in Table 4.6.

The initial list of technical issues underwent considerable review and refinement during the course of this project. Table 4.7 illustrates the evolution of this list into its final form. Issues on the finalised list (third column in Table 4.7) are described in Section 4.4. Where appropriate, Section 4.4 also discusses some of the important technical aspects/principles that will need to be considered when developing a deep geological repository, but which do not in themselves constitute technical issues that could be explored during the second phase of the project.

Table 4.5 Technical issues and topics considered by other waste management organisations.

Technical issues/topics considered by national programmes	Grouping of technical issues considered by national programmes	Comments
Knowledge management, requirements management Communication with volunteer communities Identification and management of uncertainties Understanding generic controls on safety Understanding safety functions of different repository components Ensuring waste isolation Ensuring radionuclide retardation Ensuring complete containment by EBS for period until after the thermal maximum Understanding mobilisation of radionuclides Limiting the release of radionuclides from the repository Delaying and reducing radionuclide migration towards the environment Thermal evolution Evolution of buffer and backfill Pre-and post-closure evolution Repository closing and sealing issues Inclusion of temporal environmental variations into the model chain Adequate 3D modelling of the repository system Adequate modelling of all repository materials	General principles	• Issues will need to be considered when developing a deep geological repository in any geological environment • Issues cannot be expanded to any great extent during this project • In most cases, issues do not vary in importance in different environments
Siting to avoid tectonic activity Seismicity Siting/design to prevent human intrusion Availability of sufficient space for a repository “Explorability” of a site	Site characterisation, issues	Related to the ease with which the understanding of a site required to make a post-closure safety case can be developed

Technical issues/topics considered by national programmes	Grouping of technical issues considered by national programmes	Comments
Flow paths to and from the repository Possible existence of anhydrite layers forming conductive flow paths “Subrosion” of salt, due to inflows of unsaturated water Excavation damaged zone effects	Geosphere performance (excluding gas)	Issues that affect how the geosphere would influence a safety case, but excluding issues that concern direct interactions between the geosphere and the EBS
Prevention of brine inflows to the repository, resulting in radionuclide migration pathways THMCR transient impacts Effect of cementitious materials on EBS Cement-bentonite interactions influencing EBS performance Glaciation effects on EBS and host rock Buffer freezing Isostatic loading leading to canister failure Intrusion of fresh water during glaciations leading to loss of buffer mass Predictability of chemical reactions in highly saline groundwater Uncertainties in canister durability Buffer swelling Buffer alteration Buffer erosion Defects in canisters Canister failure due to shear loading Canister corrosion leading to failure Microbial sulphide reduction leading to copper corrosion Timescales over which to consider canister durability	Performance of engineered materials	• Issues are related to the likely performance of engineered materials under post-closure conditions • In many cases, issues reflect the expected geosphere performance (characteristics of the geological environment), which influences the choice of EBS
Designing for retrievability Limiting interactions between co-located wastes Convergence of excavations The need to design to accommodate different kinds of waste (HLW, SF) and the impacts on repository size of different waste types	Design and optimisation of the EBS issues	Concern repository layout and the practicalities of its construction and operation

Technical issues/topics considered by national programmes	Grouping of technical issues considered by national programmes	Comments
Preventing water circulation in the repository		
Gas generation by corrosion and/or radiolysis Reaction of cement with gas Volumes and rates of gas evolution Lack of backfill allowing retrievability (if required) and providing a gas reservoir Gas migration mechanisms Gas migration pathways Coupling between resaturation rate and gas generation	Gas issues	Concern gas evolution from the repository (from wastes and/or barrier materials) and which many programmes consider separately from the groundwater pathway
Glaciation effects on the biosphere Glaciation effects on EBS and host rock	System evolution issues	Concerned with the long-term evolution of the system following repository closure

Table 4.6 Comparison of technical issues considered by reviewed national programmes and those from the first expert workshop (some issues are listed more than once to reflect overlaps in definitions made at different stages).

Technical issues/topics considered by the national programmes listed in Table 4.4	Grouping of issues considered by national programmes	Technical issues, based on results from the first expert workshop	Comments
• Knowledge management, requirements management • Communication with volunteer communities (Outside scope of this project) • Identification and management of uncertainties • Understanding generic controls on safety • Understanding safety functions of different repository components • Ensuring waste isolation • Ensuring radionuclide retardation • Ensuring complete containment by EBS for period until after the thermal maximum • Understanding mobilisation of radionuclides • Limiting the release of radionuclides from the repository • Delaying and reducing radionuclide migration towards the environment • Thermal evolution • Evolution of buffer and backfill • Pre-and post-closure evolution	General principles	None explicitly given	Technical issues considered by national programmes would be addressed if the technical issues identified at the first expert workshop and listed below against the other groupings are addressed. Consequently, these general principles identified by other national programmes issues are not addressed explicitly here.

Technical issues/topics considered by the national programmes listed in Table 4.4	Grouping of issues considered by national programmes	Technical issues, based on results from the first expert workshop	Comments
• Repository closing and sealing issues • Inclusion of temporal environmental variations into the model chain • Adequate 3D modelling of the repository system • Adequate modelling of all repository materials			
• Siting to avoid tectonic activity • Seismicity • Siting/design to prevent human intrusion • Availability of sufficient space for a repository • "Explorability" of a site	Site characterisation, issues	• Understanding and characterising heterogeneity will be essential when developing a safety case. • Availability of specialist materials and skills may be an issue (such as the availability of sufficient copper, bentonite, high-quality fabricated boxes and so on). • Generally it is problematical to investigate hard fractured rocks when they are not exposed at the surface. • In some environments, a large geographical area may need to be investigated to 'prove' the homogeneity/continuity of various rock formations.	If the technical issues from the first workshop were addressed, then the technical issues/topics considered by the various national programmes would also be addressed.
• Flow paths to and from the repository • Possible existence of anhydrite layers forming conductive flow paths • "Subrosion" of salt, due to inflows of unsaturated water • Excavation damaged zone effects	Geosphere performance (excluding gas) issues	• The EDZ may be a significant pathway, perhaps bypassing seals. • Repository resaturation is generally not well understood.	Geosphere performance is taken into account by a combination of: • adequate site characterisation; • appropriate EBS design and optimisation (so that the EBS works with the geological/ hydrogeological environment and the waste materials)

Technical issues/topics considered by the national programmes listed in Table 4.4	Grouping of issues considered by national programmes	Technical issues, based on results from the first expert workshop	Comments
• Prevention of brine inflows to the repository, resulting in radionuclide migration pathways • THMCR transient impacts • Effect of cementitious materials on EBS • Cement-bentonite interactions influencing EBS performance • Glaciation effects on EBS and host rock • Buffer freezing • Isostatic loading leading to canister failure • Intrusion of fresh water during glaciations leading to loss of buffer mass • Predictability of chemical reactions in highly saline groundwater • Uncertainties in canister durability • Buffer swelling, alteration and erosion • Defects in canisters • Canister failure due to shear loading • Canister corrosion leading to failure • Microbial sulphide reduction leading to copper corrosion • Timescales over which to consider canister	Performance of engineered materials issues	• QA and QC of the emplaced engineered barriers and knowledge of the state of the waste packages at closure will be very important. • Availability of specialist materials and skills may be an issue (such as the availability of sufficient copper, bentonite, high-quality fabricated boxes and so on). • The performance of the various high-integrity seals is more important in those cases where the geosphere provides significant containment. • Interactions between cement-based and clay-based systems could be significant. • Interfaces between natural and manmade materials will probably influence system performance, but generally are difficult to investigate and relatively poorly understood. • Highly saline groundwater potentially presents many problems such as corrosion, reactions with EBS materials, lower gas solubilities, lowered sorption and so on.	These activities are covered by issues from the first workshop. If the initial technical issues from the first workshop were addressed, then the technical issues considered by the various national programmes would also be addressed.

Technical issues/topics considered by the national programmes listed in Table 4.4	Grouping of issues considered by national programmes	Technical issues, based on results from the first expert workshop	Comments
durability			
• Designing for retrievability • Limiting interactions between co-located wastes • Convergence of excavations • The need to design to accommodate different kinds of waste (HLW, SF) and the impacts on repository size of different waste types • Preventing water circulation in the repository	Design and optimisation of the EBS issues	• It will be necessary to optimise the EBS to work with the geological/hydrogeological environment and the waste materials. • 'Massive' host rock formations increase the flexibility of the repository design compared with more thinly bedded formations. • Weaker rock types restrict the dimensions of excavations, which may be significant for some UK waste packages. • Achieving long-term retrievability is likely to be a major issue for many environments and, as currently defined in the UK, it may be impracticable in some environments (such as evaporites or plastic clays).	If the initial technical issues from the first workshop were addressed, then the technical issues considered by the various national programmes would also be addressed.
• Gas generation by corrosion and/or radiolysis • Reaction of cement with gas • Volumes and rates of gas evolution • Lack of backfill allowing retrievability (if required) and providing a gas reservoir • Gas migration mechanisms and pathways • Coupling of resaturation rate and gas generation	Gas issues	Gas is a common issue but for different reasons in different environments	Technical issues from the first workshop encompass all the technical issues considered by the reviewed national programmes.
• Glaciation effects on the biosphere • Glaciation effects on EBS and host rock	System evolution issues	Issue captured in notes of Group 3, but was not explicitly listed at the first workshop	

Table 4.7 Refinement of the list of technical issues during the project (some issues are listed more than once to reflect overlaps in definitions made at different stages).

Initial Issues Post-first workshop, pre-review	Modified Issues Post-first workshop, post-review by participants	Final Issues Post- second workshop, post-review by participants (reasons for modifying issues given in brackets)
• It will be necessary to design/optimise the EBS to work with the geological/hydrogeological environment and the waste materials. • 'Massive' host rock formations increase the flexibility of the repository design compared with more thinly bedded formations. • Weaker rock types restrict the dimensions of excavations, which may be significant for some UK waste packages. • Achieving long-term retrievability is likely to be a major issue for many environments and, as currently defined in the UK, it may be impracticable in some environments (such as evaporites or plastic clays).	Issue 1: Interactions between different waste form types and the design of the EBS	Issue 1: Influence of different waste form types on the design of the EBS (definition modified since the more general issue of importance is considered to be the influence of different waste form types on the design of the EBS, which to a large extent depends upon interactions between different waste form types and the EBS)
• The performance of the various high-integrity seals is more important in those cases where the geosphere provides significant containment.	Issue 2: Interactions between cement and clay-based systems	Issue 2: Interactions between engineered components (interactions between cementitious and clay-rich EBS components (included originally in definition of "interactions between cement and clay-based systems") considered a subset of "interactions between engineered components")
• The EDZ may be a significant pathway, perhaps	Issue 7: EBS/host rock interactions Issue 2: Interactions between cement and clay-based	Issue 3: EBS/host rock interactions

Initial Issues Post-first workshop, pre-review	Modified Issues Post-first workshop, post-review by participants	Final Issues Post- second workshop, post-review by participants (reasons for modifying issues given in brackets)
bypassing seals. • The performance of the various high-integrity seals is less important in those cases where the geosphere provides significant containment. • Interactions between cement-based and clay-based systems could be significant. • Interfaces between natural and manmade materials will probably influence system performance, but generally are difficult to investigate and relatively poorly understood.	systems	(interactions between cementitious EBS components and clay-rich host rocks (included in the original definition of “interactions between cement and clay-based systems”) merged with”EBS/host rock interactions”)
• Highly saline groundwater potentially presents many problems such as corrosion, reactions with EBS materials, lower gas solubilities, lowered sorption and so on.	Issue 9: Impact of saline water on EBS materials	Issue 4: Impact of groundwater/porewater on EBS materials (including the impact of saline water) (definition made more general to acknowledge that all interactions between EBS components and water could potentially be important)
• Highly saline groundwater potentially presents many problems such as corrosion, reactions with EBS materials, lower gas solubilities, lowered sorptionand so on.	Issue 8: Durability of EBS materials	Issue 5: Duration for which EBS materials may maintain their functions (durability) (definition modified to indicate what is meant by “durability”, specifically to make clear that the term does not imply that an EBS is necessarily required to be unchanging)
• Gas is a common issue but for different reasons in different environments: - In ‘wet’ environments, high gas generation rates may cause rapid breakthrough to the surface or an overpressurised engineered	Issue 6: Gas/groundwater interactions	Issue 6: Gas/groundwater (or porewater) interactions (definition modified to include porewater since several national programmes consider groundwater to be only that water which flows by advection, water contained in pores that flows by diffusion being classified as porewater)

Initial Issues Post-first workshop, pre-review	Modified Issues Post-first workshop, post-review by participants	Final Issues Post- second workshop, post-review by participants (reasons for modifying issues given in brackets)
system, depending on rock type - Estimating gas generation rates is difficult - Modelling multi-phase flow is difficult - The interaction between gas and groundwater flow is not well understood.		
• Generally it is problematical to investigate hard fractured rocks when they are not exposed at the surface. • In some environments, a large geographical area may need to be investigated to 'prove' the homogeneity/continuity of various rock formations. • Understanding and characterising heterogeneity will be essential when developing a safety case. • Availability of specialist materials and skills may be an issue (such as the availability of sufficient copper, bentonite, high-quality fabricated boxes).	Issue 3: Characterising the site adequately Issue 5: Availability of resources	Issue 7: Characterising the site adequately (evaluating availability of resources could be an aspect of site characterisation and therefore is not considered separately)
Issue captured in notes of Group 3 but not explicitly listed.	Issue 4: Demonstrating long-term stability	Issue 8: Demonstrating long-term stability
• Repository resaturation is generally not well understood.	Issue 10: Impact of resaturation	Issue 9: Impact of resaturation
QA and QC of the emplaced engineered barriers and knowledge of the state of the waste packages at closure will be very important.	Not carried forward in this form	

4.4 Descriptions of technical issues

4.4.1 Issue 1: Influence of different waste form types on the design of the EBS

It will be necessary to design/optimise the EBS to contain the UK waste inventory for the particular environment selected to host a repository. A wide range of engineering solutions which provide the required degree of containment for different wastes is available for the type of environments that occur in England and Wales. It is important to consider the waste form, EBS and geosphere as a coupled system. Thus, our discussion touches on the role of the geosphere in determining the EBS design as well as the influence of the different waste form types.

Different types of waste require different levels of containment by the surrounding waste package/EBS. An optimised EBS is likely to include different engineering solutions to suit different waste types. There are likely to be different optimised engineering solutions not only for LLW/ILW and HLW/SF, but also for different kinds of waste within each of these broad groups. In addition to making best use of the available rock volume and minimising interactions between the LLW/ILW and HLW/SF portions of the repository (if there is co-location), different waste forms will interact with the surrounding engineered materials (and possibly each other) in different ways. A 'one size fits all' EBS design is unlikely to be appropriate. It is likely that any repository to take all of the UK inventory would need to be subdivided at a more detailed level than a simple split between ILW and HLW/SF zones (see for example the design by ANDRA (ANDRA, 2005), where the EBS is tailored to the waste characteristics).

Interactions between the waste forms and EBS components are an important consideration when designing an EBS. The design must minimise any potentially detrimental aspects of these interactions and at the same time maximise any potential positive aspects. This issue is therefore closely related to Issue 2 (Section 4.4.2; see also Section 4.5 on relationships between technical issues). Particularly important potential interactions are:

- interactions involving alkali pore fluids released from cement-encapsulated wastes which can accelerate the dissolution of glasses, cause embrittlement and cracking of bentonite, and reduce the swelling pressure of the bentonite;
- interactions between EBS components and radiolytic degradation products of polymer encapsulants, primarily acids and organic complexants;
- increased dissolution rates of glass, ceramic SF, Pu and U by interactions involving acids derived from polymer breakdown;
- 'capture' of C-14 evolved from wastes by cementitious barriers (see also Issue 6, Section 4.4.6);
- corrosion promoted by galvanic coupling between graphite and metals and alloys of lower rest potential;
- complexation of radionuclides with miscellaneous waste materials (such as co-located complexing agents) and waste degradation products (such as cellulose degradation products like short chain fatty acids). Radionuclides might also be entrained within oils, greases and other non-aqueous phase liquids.

Interactions between different waste forms are important in terms of the performance required of the system (EBS and geosphere), which may need to isolate some wastes from others for as long as possible. These interactions are also affected by the geological environment because two key controls on waste form evolution are the rate of flow and composition of groundwater. The EBS may isolate the wastes or buffer the incoming water but with time the effectiveness of this barrier will degrade. Chemicals (such as organic degradation products including acids and colloids) released from a waste package may have a detrimental effect on the performance of neighbouring packages or on the mobility of radionuclides after they have been released from a waste package. If packaging proposals for different waste streams are considered in isolation, potential interactions between the package contents and substances that may be released from neighbouring packages may not be properly taken into account. It is unlikely to be possible to rely on the waste packaging alone to avoid interactions between waste packages that are placed close together. Therefore, it will probably be necessary to identify potentially detrimental interactions and design emplacement strategies to mitigate these. However, not all interactions between waste packages will be negative. For example, a high-pH plume emanating from a cement-bearing waste package could lead to passivation (decreasing corrosion rate) of nearby steel waste packaging materials.

Thermal loading may be important in determining both the repository layout and the choice of EBS materials. The thermal conductivity of waste forms and EBS materials generally increases with saturation. Therefore it is necessary to understand the likely resaturation timescales (Issue 9, Section 4.4.9) and their potential heterogeneity when designing the layout and selecting EBS materials.

The gas generation potential of wastes is an important factor in repository design. This issue is considered in detail as Issue 6 (Section 4.4.6).

The volumes of the different kinds of wastes will also shape the characteristics of the EBS. Costs and availability of specialist materials may be an important consideration in the design. For example, these issues may influence whether copper or carbon steel is chosen as a canister material for HLW/SF at the design stage.

The overall performance of the geosphere is important in determining the type of EBS required to provide the level of containment needed for each waste stream (see Section 6.1). Once the overall 'style' of the EBS has been decided, the structure and properties of the host rock will be very significant in determining the design/layout/operational options that are viable. These are discussed in the context of generic geological environments in Section 6.2. Host rock heterogeneity/variability will be a key factor in determining how much effort is required to optimise the EBS design/layout to suit the site and the different waste types. The effort required to achieve this goal will depend strongly on the properties of the host rock, notably its heterogeneity at the sub-vault/tunnel scale, and the role it plays in the safety case. This in turn will influence the detail with which it will be necessary to characterise the host rock (see also Issue 7, Section 4.4.7).

One consideration when specifying the environments (Section 2) was that they should provide an adequate volume of rock for disposal of the full UK inventory, and indeed Environment 7 (plastic clay host rock) was initially screened out by the project team on the basis that it was unlikely to provide the required volume (see Section 2.2.8). Any UK repository designed to accommodate all the various waste types that require disposal would be among the larger repositories being considered worldwide. It is possible that some examples of generic environments considered in the future may prove to have insufficient volumes of rock to accommodate all the wastes.

The design and layout of the repository will need to take account of all the different phases in the facility lifecycle: construction, operation and post-closure performance. A repository built with multiple zones to optimise post-closure performance may introduce significant additional complexities as it may be necessary to operate a number of different 'disposal fronts' at the same time, rather than simply emplacing wastes at a single disposal face in the order in which they arrive. This may be more of a problem for weak host rock or those subject to creep because of potential problems with maintaining multiple stable openings for long periods of time. It may also significantly complicate construction and operation if it is planned that construction of new disposal vaults will proceed in parallel with emplacement of wastes in earlier vaults. However, a number of operators (such as ANDRA, 2005) have developed schemes that allow emplacement in multiple zones in parallel with construction of future disposal tunnels.

4.4.2 Issue 2: Interactions between engineered components

This issue covers interactions between any engineered components used within a repository, as part of an EBS or for other purposes, such as tunnel supports.

The potential interactions between engineered components are diverse and include:

- physical interactions, such as the pressurisation of waste canisters by the swelling of bentonite buffers;
- chemical interactions, which typically involve solid and fluid phases.

Most kinds of engineered components within an EBS will to some extent be able to interact with one another if they are in sufficiently close proximity. These interactions may be direct, when one component is in physical contact with another enabling the two components to react chemically. Alternatively, interactions may be indirect, when two components are not in direct physical contact, but are both able to react with porewater that diffuses from one to the other.

The main components which are typically proposed and that may interact are:

- metalliferous components of the EBS, which may include canisters, canister inserts (such as steel inserts in copper canisters) and overpacks;
- waste encapsulants, for example cement, glass or asphalt/bitumen (although these are typically not considered to be part of the EBS);
- buffers, most commonly of bentonite or mixtures of bentonite with other materials, such as sand;
- backfills of excavated cavities (including tunnels and shafts and/or drifts), which may be cementitious, bentonite or mixtures of bentonite with other materials (such as crushed rock or sand), crushed rock (which may be rock salt in repositories within evaporitic host rocks), and MgO;
- seals, typically proposed to be composed of similar materials to those proposed for backfills, although asphalt/bitumen has also been chosen by some programmes;
- engineered materials used to stabilize excavations, including shotcrete, rockbolts and steel liners.

The interfaces between different materials (natural and manmade) are likely to be key to system performance. Many of the interactions between engineered barriers will occur at these interfaces. Some may have a positive effect on safety (the increase of porewater pH at an interface between a cementitious component and a steel component may slow down the corrosion rate of the steel, for example). Others may be detrimental (such as a decrease in the swelling capacity of bentonite backfill next to a cementitious seal).

4.4.3 Issue 3: EBS/host rock interactions

Potential interactions between EBS components and the host rock are diverse:

- physical interactions, such as pressurisation and sealing of an EDZ by swelling of bentonite buffers, or erosion of bentonite buffers by flowing groundwater;
- chemical interactions within the host rock, which typically involve water emanating from the wastes / waste forms/EBS and solid phases.

The expected degree of interaction may have a direct impact on the safety case and the resources required to characterise it adequately. The effects of groundwater and porewater on the properties of individual EBS components and on interactions between them are covered by Issue 4 (Section 4.4.4).

The main interactions will usually be between the host rock and EBS components that contact the rock directly. However, indirect interactions are also possible. For example, gases that might be generated by corrosion of metalliferous barrier components can contribute to pressurisation of the host rock (see also Issue 6, Section 4.4.6). The potential for chemical reactions will generally be greatest where the barrier materials and host rocks are chemically and/or physically most dissimilar. For example, there will be relatively large mineralogical changes in a clay-rich host rock adjacent to a cementitious barrier (although the spatial extent of such changes will be limited owing to the generally low permeability of clay). In contrast, there may be little interaction between a backfill that is composed of crushed host rock and the host rock itself (such as crushed rock salt backfill used in a rock salt host rock).

The extent to which the EBS and host rock interact chemically will also depend strongly on the geological environment and EBS concept. Those concepts that minimise contact between wastes and flowing groundwater (for example, using low-permeability buffers/backfills to isolate wastes) will result in less interaction than concepts where the backfill/buffer plays a more active role in providing chemical containment (such as a porous, permeable cementitious buffer).

The most spatially extensive chemical reactions are anticipated around repositories in relatively permeable host rocks (such as fractured crystalline rocks) that employ extensive cementitious barriers. In these cases, an alkaline plume will extend beyond the repository leading to some alteration of the host rock in a zone termed the alkaline disturbed zone (ADZ). The spatial extent of the ADZ will depend upon the permeability of the host rock and the potential gradients driving groundwater flow, which will be a combination of natural hydraulic gradients and hydraulic gradients that result from disturbance by the repository. Interactions are likely to be more spatially extensive in more active flow regimes (such as fracture zones crossing repository footprint) and minimised in environments where there is very little flow (such as in salt host rocks).

The characteristics of the host rock may influence the physical form of the interface between the EBS and the rock. For example, in fractured rocks bentonite composing tunnel seals will to some extent penetrate fractures. The nature of the fracturing may therefore control the spatial distribution of the bentonite.

The lithology of the host rock may also affect the chemical reactions that occur. For example, in many mudstone host rocks, pyrite oxidation during the aerobic phase of the repository may generate acid which then interacts with EBS materials (although this process will affect only small volumes of the EBS). Potentially of more significance is the effect of water/rock interactions within the host rock on the chemistry of groundwater and/or porewater that may then interact with the EBS. An extreme case of such an influence may occur in host rocks that contain evaporite minerals (which may occur in lithologies other than evaporites). Dissolution of these minerals may influence the salinity and composition of the groundwater and/or porewater. Examples of these kinds of interactions are:

- decreasing swelling capacity of Na-bentonite barriers due to Na^+ exchange for Ca^{2+} in the groundwater;
- carbonation of cementitious barriers by carbonate dissolved in the groundwater.

Excavation of the repository will result in an EDZ in which the properties of the rocks have been disturbed by the excavation process (usually by 'drill and blast' or tunnel boring machine), the stress relief associated with the excavation and chemical interactions that occur during the operational period. The characteristics and extent of the EDZ, which depend upon the host rock lithology, excavation methods used and repository design (such as the diameters of tunnels) will be an important influence on interactions between the EBS and the host rock. The EDZ will contain freshly exposed rock and mineral surfaces that can contact the outermost component of the EBS. The EDZ may also be a significant pathway for the transport of groundwater/porewater into the EBS and for the transport of fluids or gases originating in the repository away from the EBS (see also Issue 6, Section 4.4.6). Potentially, the EDZ could bypass seals, unless suitable preventative design measures are taken. .

4.4.4 Issue 4: Impact of groundwater/porewater on EBS materials (including the impact of saline water)

Issue 4 is closely related to Issue 3 (Section 4.4.3). The primary difference between them is that Issue 4 concerns the impact of water originating in the host rock and surrounding rock formations on EBS materials, whereas Issue 3 covers the impact of water emanating from the EBS on the surrounding host rock.

Similarly, there are some relationships between Issue 4 and Issue 9 which concern the impacts of resaturation (Section 4.4.9). In the period immediately following its closure, resaturation of the repository will supply groundwater/porewater to the EBS. Hence, the impacts of resaturation will include the effects of this introduced groundwater/porewater on the EBS components. However, the EBS will also be affected by groundwater/porewater before resaturation (for example, water will be included in any bentonite slurries used in the sealing system) and after resaturation. Rather than splitting the impacts of groundwater/porewater on the EBS among several issues, it was decided to cover all these impacts by Issue 4.

The chemistry of the groundwater/porewater will potentially affect the behaviour of EBS materials in several ways. Particularly important are likely to be influences on:

- evolution of swelling pressure in any bentonite-bearing materials (principally buffer and backfill);
- corrosion characteristics (principally rates and spatial scales of variability) of metals;
- degradation of cementitious materials.

These processes will be affected by the:

- pH of the groundwater/porewater;

- oxidation state (redox condition) of the groundwater/porewater
- overall groundwater/porewater salinity (concentrations of solutes);
- the natures and proportions of the solutes (for example, whether the water is bicarbonate-rich, Cl-rich or SO_4-rich).

The pH of the natural groundwater/porewater will generally be near-neutral to slightly alkaline, depending upon the nature of the host rocks. Generally, groundwater in crystalline rock sequences will tend to have slightly more alkaline characteristics than groundwater from sedimentary rock sequences. However, over the range of pH values likely to occur in a repository environment, there are likely to be only small variations in the behaviour of engineered barrier components.

The redox state of the groundwater/porewater immediately surrounding a repository would be relatively oxidizing immediately after closure, owing to the ingress of atmospheric oxygen from excavated voids. However, the spatial extent of such oxidizing conditions would be very limited due to chemical buffering by the host rock and the expected low permeability of the host rock. It is expected that in all the geological environments considered here, conditions would become reducing (anoxic) very soon after closure (most probably within a few years to tens of years). This return to reducing conditions would most probably be caused by one or more of the following:

- ingress of reduced groundwater/porewater from beyond the EDZ;
- corrosion of metals (in structural components and in the EBS);
- oxidation of minerals in the host rock and/or barrier materials (such as small quantities of pyrite in the host rocks and/or bentonite backfill);
- degradation of organic materials within the host rock and EBS, which would probably be microbially mediated.

However, all these processes are expected to result in insignificant changes to the properties of the barrier materials, owing to the proportionately small quantities of oxygen that would be sealed within the repository at closure.

Of much greater significance will be the overall salinity and solute load in the groundwater/porewater. The precise changes that occur will be a complex function of the concentrations and proportions of the solutes present. For example, where it is able to access buffer-forming bentonite, very low-salinity (fresh) water could remove cations, leading to a decrease in swelling pressure. On the other hand, Ca-bentonite of a specified dry density would tend to exhibit a smaller swelling pressure in the presence of highly saline Na-Cl dominated groundwater than in more dilute Na-Cl dominated groundwater.

Highly saline groundwater in particular potentially presents many problems, since under highly saline conditions there is a tendency for:

- the rate of metal corrosion to be enhanced;
- cementitous materials to be degraded (for example by formation of high-specific volume minerals such as ettringite if SO_4 concentrations are high);
- gas solubilities to be lowered;
- sorption of radionuclides to become less effective.

It is likely that EBS materials can be designed to function adequately in low to moderate salinities (possibly up to a salinity equivalent to about twice that of seawater). However, hypersaline water such as would be expected in Environments 4 (bedded halite, Section 2.2.5) and 9 (non-evaporitic host rock with hypersaline groundwater, Section 2.2.10) would present greater problems, although other properties of the bedded halite host rock may render the EBS largely irrelevant (see also Section 5.10).

Groundwater salinity also impacts upon the predictability of EBS evolution. The behaviours of most commonly proposed EBS materials under highly saline groundwater conditions have not been investigated experimentally. Furthermore, conventional thermodynamic models are inapplicable for solutions with salinities greater than seawater. While the so-called 'Pitzer approach' is applicable for modelling reactions at higher salinities, it is strictly applicable only for waters with similar compositions to those used in the laboratory experiments from which the underlying thermodynamic data were obtained. Additionally, reliable thermodynamic data are lacking for many minerals under likely repository conditions.

Saline water may prove to be more of a problem during the operational phase than the post-closure phase. Chloride, and in particular thiosulphate, must be kept away from the stored drums to prevent corrosion during operations. Clearly, the longer the operational phase, the more difficult this requirement becomes.

4.4.5 Issue 5: Duration for which EBS materials may maintain their functions (durability)

The importance of this issue depends strongly on the geological environment, EBS concept and nature of the wastes. Between them, these factors determine the safety functions that the various EBS materials are required to perform and therefore the durability that is required of them. These points are discussed further in Section 5.10.

In general terms, greater durability will be required from EBS materials when the repository is constructed in an environment where the geosphere is expected to provide relatively little containment. For example, SKB has designed a highly engineered and durable EBS to work in a fractured hard rock environment (SKB, 2006) that is an example of geological Environment 1. In this case the geosphere can be reasonably assumed to protect the EBS, but on its own cannot be relied upon to provide the containment necessary to achieve regulatory targets. In contrast ANDRA's safety case, which is for a geological environment of type 5a, is able to place much more reliance on the geosphere (ANDRA, 2005).

Durability requirements will also vary with waste type. An optimised solution will take the different requirements of the various wastes into account. Evaluating the durability of EBS materials will require a good understanding of the evolution with time of the coupled near-field system. This must include an understanding of the degree of heterogeneity that will develop, since this may determine the degree to which degradation processes (such as localised corrosion) affect the integrity of the EBS. In some cases it may be necessary to determine/demonstrate the extent to which radiation influences the durability of the EBS. This will be more important for HLW/SF than for ILW.

Understanding the evolution of interfaces between the different materials in the system is a key challenge. Interfaces are always likely to be the 'weak links' in the structure so there is likely to be merit in ensuring that the EBS is as simple as possible (consisting of as few components as possible), thereby minimising the number of interfaces.

It will be important to demonstrate that large-scale emplacement of waste material underground is possible to adequate levels of QA/QC. In practice this will usually mean demonstrating that attainable levels of QA/QC will be similar to that reached in the smaller-scale testing that would have underpinned repository design. In Sweden, SKB has experienced difficulties in producing compacted bentonite rings on a sufficiently large scale for repository operations rather than simply for testing/demonstration.

To meet this goal it will probably be important to demonstrate in a URL or similar facility that the selected EBS can be emplaced with the required level of consistency and quality prior to finalising the detailed design. It may also be advantageous to manufacture as much of the EBS as possible above ground where it is likely to be easier to assure and verify quality. For example, it may be advantageous for above-ground packaging of drums into 'disposal units' that already contain a backfill, as is done by most European programmes. An alternative approach could be for the buffer to be emplaced around HLW/SF above ground, as in the Belgian supercontainer concept.

Demonstrating durability requires one or more of:

- long-term demonstration experiments, combined with a demonstration that the results can be scaled to repository conditions and timescales;
- use of natural analogues;
- carefully targeted modelling work that builds on the experimental results and analogue observations.

Durability of the EBS is one post-closure issue that could be influenced by pre-closure activities. In particular, the duration for which a repository remains open (un-backfilled) prior to final closure could influence the length of time for which the EBS components may subsequently perform their functions. For example, metal components may undergo greater pre-closure corrosion if there is a prolonged period of operation before backfilling, as in certain cavern disposal concepts (such as the Japanese Cavern Retrievable Concept, CARE).

Various processes may influence durability, including:

- water/solid reactions;
- heat (generated mainly by the wastes themselves);
- radiation, which is likely to be significant only for HLW/SF and which will influence the barrier components closest to the wastes themselves;
- progression towards more stable forms of solids in the EBS that are initially not at thermodynamic equilibrium (for example, solids present in cement gradually transform to more stable phases as the cement ages);
- mechanical stress on the engineered barrier components, which may be applied to barrier components:
  - gradually, for example as excavations re-equilibrate with the natural stress field following closure;
  - rapidly, for example if a previously unidentified active fault displaces a vault (an event that should be extremely unlikely if repository siting and design have been carried out effectively);
- erosion of bentonite barriers by flowing groundwater.

The first of these processes will generally be important, since groundwater/porewater will be present and will influence the effects of the other processes. For example, the main effect of heating will be to increase the rates of the water/solid reactions. Thus, this issue is closely related to Issue 4 (Section 4.4.4).

4.4.6 Issue 6: Gas/groundwater (or porewater) interactions

Gas is likely to be generated in a repository as a result of the corrosion of metals and degradation of organic wastes. A small proportion of this gas will be radioactive (mostly ^{3}H or ^{14}C compounds) but the bulk inactive gas (mostly H_2) has the potential to result in transport from the repository of these trace radioactive gases. Interactions between repository-derived gas and groundwater or porewater are important for different reasons in different environments (see Issue 9 on resaturation). In ‘wet’ environments high gas generation rates may lead to rapid gas-mediated radionuclide breakthrough to the surface or overpressurisation of the engineered system. If gas cannot easily escape from the repository, overpressurisation could compromise the engineered structure and host rock integrity. It may therefore be necessary to design the EBS specifically to allow gas pressures to disperse or to limit the potential for gas generation through the choice of materials used in construction and waste packaging or even through careful selection of the actual waste form. One strategy could be to design the EBS to minimise water inflow and another could be to encapsulate certain waste streams in an impermeable matrix such as a polymer so that gas generation rates are limited by water availability.

Coupling between the processes that control gas evolution and migration is difficult to simulate. There are fundamental limitations in our understanding of the couplings and their detailed modelling is computationally difficult. These limitations are reflected in uncertainties in the best ways to take these couplings into account in assessment-level models. For example, it may be difficult to make conservative assumptions. Because gas migration is highly site-specific, it is difficult to assess the potential importance of repository-derived gases in the absence of a specific, characterised site.

The salinity and chemistry of the groundwater/porewater are important controls on the evolution and migration of gas and the pressures attained. Broadly, salinity influences gas solubility, with gas being generally less soluble in more saline solutions. Consequently, assuming that all other parameters are equal, higher gas pressures might be expected in more saline groundwater/porewater systems. Similarly, the pH of the groundwater will affect the solubility and migration of CO_2. For example, in fractured crystalline rocks the groundwater is typically more alkaline than in clastic sedimentary rocks. The CO_2 will tend to dissolve more readily in the more alkaline waters.

The physical characteristics of the rocks, including the extent to which they are water-saturated, will also influence interactions between migrating gases and groundwater/ porewater. The porosity structure of a rock (such as the extent to which flow occurs through the rock matrix or through fractures and/or the interconnectivity of the fracture network) influences the effective contact area between gas and groundwater. The greater the contact area the greater the potential for gas dissolution, if all other factors are equal. Similarly, lithological heterogeneity will influence the potential for migrating gases to become trapped and therefore the residence time available for interaction with groundwater and/or porewater. For example, upwardly migrating gas might accumulate beneath a low-permeability horizon within the cover sequence overlying a repository host rock. There is then a much longer time for the accumulated gas to interact with the surrounding groundwater than would be the case in the absence of such a low-permeability horizon.

Gas generation and migration may have important consequences during the operational phase as well as during the post-closure phase. The duration of the interval between waste emplacement and closure, and the conditions during this period, are important in determining both ‘operational risk’ and the nature of the gas-generating inventory that needs to be considered during the post-closure period.

In the cases of the UK ILW, waste packages are vented to reduce the possibility that gas generated within the package might result in package failure. Unfortunately, these vents also provide pathways for the migration of dissolved radionuclides from the waste package. These pathways are active before the package has been breached by corrosion.

4.4.7 Issue 7: Characterising the site adequately

Site characterisation is the process by which information is acquired from a site to provide inputs into the design process and support the development and demonstration of a safety case. Site characterisation encompasses several different stages which vary in different radioactive waste management programmes, but which typically include:

- an initial phase of 'desk' studies, including literature studies;
- a phase of surface-based investigations, including surface mapping; borehole drilling, sampling and testing; and geophysical surveys (seismic, electro-magnetic and so on);
- a phase of underground investigations, within a purpose-built URL at or near the repository site and/or during the phased construction of the repository itself.

These different phases typically overlap to some degree (for example, seismic surveys can continue after underground investigations commence). They are also carried out iteratively with design and safety assessment activities; the outputs from each phase of design and safety assessment are typically used to guide subsequent site characterisation, the results of which are used in further refinements of designs and up-dating of the safety assessment. The precise phasing and iteration schedules will depend upon a large number of factors, including the availability of equipment and personnel, regulatory requirements, planning applications, and political influences. Planning and executing a site characterisation therefore presents many difficulties, not least of which is how to decide (and justify) when sufficient information of a particular type has been collected.

The kinds of data that need to be obtained in a site characterisation exercise are typically diverse, including:

- geological data (basic information about the spatial distributions of different lithologies, and characteristics and distributions of geological structures);
- rock core data, including mineralogical information, rock porosities;
- hydrogeological data, including hydraulic conductivities, rock porosities and groundwater heads;
- geochemical data, including groundwater analyses, naturally-occurring gas analyses, mineral analyses and whole-rock analyses;
- surface-based geophysical data, including seismic data, electromagnetic data, and gravity data;
- borehole geophysical data, including seismic tomographic data, temperature and electrical conductivity data.

The site characterisation programme should be designed so that the different activities are performed in the most efficient way possible. Here 'efficient' means that ideally the site characterisation programme should produce only data that are useful to its various stakeholders and in particular to the repository design and safety assessment teams.

The applications of information that are obtained from site characterisation will be different depending on the role that the geosphere plays in the safety case (see also Section 5.10). Clearly, if the safety case relies on a geosphere barrier then the site characterisation will need to acquire data that allow this barrier function to be demonstrated. Alternatively, in the extreme where the safety case relies to a large extent on the EBS system, site characterisation will need to demonstrate that geosphere conditions are appropriate for the adequate functioning of the EBS. If the main function of the geosphere is to protect the EBS and ensure that it functions as intended, then the investigation area may be smaller than if the geosphere has a barrier role. As with all aspects of a deep geological repository, the investigations required will be concept- and site-specific.

The design of the site investigation (area covered, techniques used, relative focus on host rock versus cover sequence and so on) will vary according to the geological environment. Although there will be similarities between programmes for different environments, there is no 'one size fits all' design for site investigation programme. For example, characterising fractured igneous host rocks will involve expending much effort in fracture characterisation, which will require:

- hydraulic tests on fractures identified in rock core and/or wireline logs;
- groundwater sampling from fractures identified in rock core and/or wireline logs;
- petrographical and mineralogical data from individual fractures.

In contrast, characterisation of a plastic clay will involve obtaining porewater data, which will require:

- sampling of rock so as to minimise perturbations (for example, removing from core barrels under anaerobic conditions followed by immediate sealing from the atmosphere to prevent oxidation);
- squeezing of samples to remove porewater.

For some environments, a large geographical area may need to be investigated to understand sufficiently the geological and hydrogeological environment and to obtain the data necessary for a safety case. In general, the more permeable the host rock and surrounding rock formations, the greater the area to be investigated.

Obtaining sufficient information to support the consideration of a particular combination of waste form, EBS and environment through a staged siting/regulatory process may be a factor in site selection. It will be necessary to identify at an early stage those site characterisation observations that will be required to discriminate between potential candidate sites or which will clearly demonstrate that a site is not suitable for further investigation. Some environments will be more difficult and time-consuming to investigate than others. In addition, some combinations of environment, EBS and waste may not be practicable. For example, it will be difficult to gather enough information to propose with sufficient confidence that Environment 1 is a suitable host for a repository of large volumes of ILW with an EBS that does not provide substantial containment.

In general, geological environments that are simpler to investigate would be preferable to more complex environments, all other factors being equal. There are likely to be fewer uncertainties in simpler environments. Those uncertainties that do occur can probably be reduced more readily. This preference for simplicity relates also to the practicalities of carrying out the investigation programme (and is referred to as the 'explorability' of a site by Nagra).

Linked to site characterisation is the ability to collect data that would provide convincing evidence of features and processes that would recommend the site for repository development. Such features include mechanical, geochemical and hydrogeological stability, slow groundwater movement and suitable long-term redox conditions at depth (see Issue 8; Section 4.4.8). The likelihood of obtaining such information varies significantly between environments.

It may be difficult to obtain the required level of understanding without carrying out investigations in a URL, even if the rock formations of interest are exposed at the surface. Additionally, it will be necessary to develop an adequate understanding of the site in 3D, which can be aided enormously by obtaining data from a URL.

Many rock mass and hydrogeological parameters are site-specific and cannot be simply transferred from apparently analogous sites elsewhere, so the advantage of having a separate research-based URL may be limited in site-characterisation terms (although distinctly advantageous for other reasons, such as developing data acquisition methods and training personnel). Experience points to the need for a URL at the proposed repository site, possibly in addition to a separate research-based URL.

The level of detail with which the host rock must be characterised depends on the geological environment and proposed EBS design. If the host rock displays significant heterogeneity on a length scale of less than a vault/module (such as fracture zones, which are hydrogeologically or geotechnically significant) then it may be necessary to characterise these structures deterministically on a similar length scale. This could be problematic for a fractured host rock with a thick sedimentary cover that reduces the effectiveness of remote imaging techniques. On the other hand, in relatively uniform lithologies such as certain plastic clays, it may be adequate to characterise the site at larger length scales, perhaps comparable to individual vaults (10s of metres).

An additional issue related to site characterisation is the provision of appropriate monitoring before construction begins, during construction and operations and following closure. Difficulties that will be faced during the monitoring programme include:

- defining appropriate monitoring indicators or trigger indicators that can be interpreted unambiguously;
- specifying and installing instrumentation that will operate under repository conditions or at depth within the geosphere for very long periods of time (hundreds of years or more);
- ensuring that any monitoring system cannot provide a potential pathway to the surface during the post-closure period, which means it will not be possible to replace or upgrade components as they fail or become obsolete.

There is no point in collecting monitoring data that indicates that a measured quantity is changing, without having defined the threshold values that indicate that the system is not evolving according to design and some intervention is required.

In the UK, little work has been done to develop site characterisation methods since 1997, when a decision was taken not to proceed with developing a repository for ILW and some long-lived LLW near Sellafield in North West England. Consequently, the situation in the UK is not directly comparable with that in most other European countries with developed nuclear industries. In France, Switzerland, Sweden and Finland, for example, there have been continuous repository programmes for several decades which are still ongoing. However, UK personnel have had some involvement in these overseas programmes, and the UK participates in international collaboration projects, for example research projects organised by the EU.

4.4.8 Issue 8: Demonstrating long-term stability

Demonstrating long-term stability may be an important element of both the site investigation and research programmes. It may be necessary to demonstrate a wide range of different types of stability: geological, seismic, geotechnical, hydrogeological and geochemical.

The term 'stability' is not the same as 'predictability' and does not necessarily mean that the site remains unchanged with time. 'Stability' in the context of radioactive waste management means that changes occur sufficiently slowly to ensure there are no negative consequences for safety over the time frame of a safety assessment. NEA (2008b) states that "*the stability of a hard fractured rock has been broadly defined as the presence of THMC conditions considered favourable for the safety of a nuclear waste repository*." For radioactive waste disposal, stability does not imply that steady-state conditions exist; the geosphere is constantly evolving and such evolution is perfectly acceptable for safe geological disposal. What is important is that this evolution is understood. Thus, future changes need to be 'predictable' in order for a site to be shown to be 'sufficiently stable'. However, 'predictable' does not mean that the effects of all aspects of change can be estimated accurately, but rather that they are shown to lie within acceptable limits. From these definitions it follows that many sites that are inherently transient may well be adequate as hosts for a deep geological repository.

4.4.9 Issue 9: Impact of resaturation

When the repository is finally closed, it will resaturate. The timescale for resaturation varies significantly between geological environments and EBS designs, with predictions ranging from a few years to many thousands or even hundreds of thousands of years.

Controls on the duration of the resaturation period include:

- the groundwater flow rate through the host rock;
- the void volume to be resaturated, which is a function of design and layout;
- the degree to which the resaturating repository is pressurised by repository-generated gas (which is related to Issue 6, Section 5.6);
- the properties of the EBS, including liners and so on;
- the degree to which the host rock has become de-saturated during the operational phase, which is a function of host rock properties, EBS design and operating conditions (ventilation and so on);
- the degree to which the rock has been chemically and physically altered during this phase (see Issue 3, Section 5.3).

The last two factors are likely to depend on the length of the operational period, with effects being greater for longer periods of operation.

The relationship between gas generation and resaturation is complex (see Issue 6, Section 5.6). In vaults where there is a significant potential for gas generation, there may be a complex coupling between resaturation and gas generation. Water from resaturation is a major control on the gas generation process, but a build-up of gas pressure within the vault may inhibit resaturation. However, it is generally expected that at least some gas will be generated before significant resaturation occurs, owing to some waste and/or barrier degradation being facilitated by:

- humid atmospheric conditions within the repository;
- the presence of residual water within certain wastes and/or barrier components (notably cement).

As a consequence of this process, gas generation that is independent of resaturation may influence the resaturation rate.

While resaturation is occurring, radionuclides cannot leave the repository by advection or diffusion. However, relatively rapid resaturation may be necessary to ensure the correct functioning of the EBS, because the EBS is likely to be optimised for long-term conditions (saturated and reducing). This has potential implications for strategies that plan to keep the vaults open for a length of time following waste emplacement. In this case it may be necessary to design an EBS that can function under two different sets of environmental conditions. Such a strategy is likely to add cost and uncertainty.

Understanding the rate of resaturation is particularly important for predicting the evolution of compacted bentonite buffers. Rapid resaturation is favourable because it:

- allows the bentonite to attain its full swelling pressure, thereby maximising its ability to function as a seal;
- enhances the thermal conductivity of the bentonite.

If a bentonite buffer resaturates more slowly than allowed for by the design, it may not be able to conduct heat away from the waste canister sufficiently well and may become ‘baked’. This overheating would reduce the swelling pressure, promote crack formation and could lead to mass redistribution (notably of silica) by causing mineral dissolution and precipitation, and mass transport (along the thermal gradient) within the buffer. All of these processes may impair the function of the buffer.

On a larger scale, understanding the dependence of material properties, in particular thermal conductivity, on saturation is important in determining repository layout for heat-generating wastes, especially when the thermal peak will occur during or before the end of resaturation.

Most models assume uniform resaturation but this is unlikely to be the case in practice. For example, resaturation experiments carried out by SKB have shown a large variation between adjacent deposition holes. The implications of this heterogeneity for the long-term safety case are unclear.

4.5 Relationships between technical issues

The different technical issues discussed above are inter-related. In certain cases, the main reason for distinguishing issues is the degree to which they are defined in relation to a particular concept and/or safety case. Issue 2 (interactions between engineered components, Section 4.4.2) and Issue 5 (duration for which EBS materials may maintain their functions (durability), Section 4.4.5) are closely related. However, the interactions between engineered components do not necessarily affect the duration for which barriers will maintain their functions. Indeed, the interactions may be positive with respect to safety. In contrast, the precise functions of a particular barrier will also be concept- and/or safety-case dependent and in fact may change over the course of a project.

Table 4.8 sets out some of the main relationships between the different issues. The key point illustrated by Table 4.8 is that the disposal system is strongly coupled at all levels such that an apparently minor change in specification or design of one component can have far reaching consequences for other parts of the programme.

4.6 The significance of issues for the staged authorisation process

At present, any deep geological repository for radioactive wastes that might be developed in England or Wales will be authorised by the Environment Agency via a staged process (Environment Agency, 2008). At each stage, decisions may be taken and/or events might occur that:

- could affect the significance of each issue for safety later, during the post-closure phase (for example, changes to the proposed operating period or the inventory and waste types to be disposed); and
- could influence the extent to which the effects of the issue can be estimated and their significance for safety judged, both in the pre- and/or post- closure phases (for example, a decision not to proceed with a particular investigation).

The influence on the programme of these decisions will to some extent be site-specific. It should possible to suggest activities that might be carried out by the developer and the regulator at each stage of the authorisation process, to determine the influence on safety of each issue and, where necessary to ensure that these influences do not prevent overall safety targets being met. It may be necessary to'bank' certain decisions at a relatively early stage in the design and investigation programme. These general issues are stated in Table 4.9.

The extent to which these activities will be carried out will depend partly on the specific requirements for authorisation that are in force when the activities are developed (here assumed to be an unmodified version of the current draft guidance). A presumption is that some kind of safety assessment will be carried out at each stage, allowing full evaluation of the issues. However, whether this is done, and the characteristics of each assessment have not yet been decided.

Implicit in Table 4.9 is that it is best to maximise flexibility in the concept, design and scheduling. The concept and/or design and/or scheduling may need to be modified to minimise potentially adverse impacts of the issues, whether identified or caused by activities at each stage of the process. For example, major water-conducting features in the rock mass that intersect the vaults may only be identified at the stage of construction. In this case, grouting that was not initially planned may be required or it may be necessary to review, and possibly modify, the EBS. Indeed, in most radioactive waste programmes to date, some adjustments to the concepts and/or design and/or scheduling have been made.

Data acquisition should normally be carried out throughout all stages of authorisation.

Table 4.8 Major relationships between the technical issues (influences of row headings on column headings).

Technical Issue	1 Influence of different waste form types on the design of the EBS	2 Interactions between engineered components	3 EBS/host rock interactions	4 Impact of groundwater on EBS materials (including the impact of saline water)	5 Duration for which EBS materials may maintain their functions (durability)	6 Gas/ groundwater (or porewater) interactions	7 Characterising the site adequately	8 Demonstrating long-term stability	9 Impact of resaturation
1 Influence of different waste form types on the design of the EBS		EBS materials depend on wastes	EBS materials depend on wastes	EBS materials/ layout depend on wastes.	EBS materials/ layout depend on wastes	EBS properties control gas release	Layout and role of geosphere depends on EBS design	None	EBS properties influence resaturation
2 Interactions between engineered components	Interactions may influence EBS feasibility		Chemical/ physical properties of EBS affected	Chemical/ physical properties of EBS affected	May affect EBS durability	EBS properties control gas release	None	None	EBS properties influence resaturation
3 EBS/host rock interactions	Interactions may influence EBS feasibility	May affect chemical/ physical properties		May affect chemical/ physical properties	May affect EBS durability	May affect water composition	None	None	EBS/host rock properties influence resaturation
4 Impact of groundwater/ porewater on EBS materials (including the impact of saline water)	Impact may influence EBS feasibility	Impact may affect chemical/ physical properties	Impact may affect chemical/ physical properties		Water will react with EBS materials	May influence ability of EBS materials to react with/remove gas	Groundwater/ porewater compositions must be obtained	None	None
5 Duration for which EBS materials may maintain their functions (durability)	Durability may influence EBS feasibility	Influences change in chemical/ physical properties	Influences change in chemical/ physical properties	Influences change in chemical/ physical properties		Durability of EBS will affect gas release	None	None	None
6 Gas/groundwater (or porewater) interactions	Design may need to accommodate gas	Affect EBS porefluid chemistry/ pressure	Affect EBS porefluid chemistry/ pressure	Affect EBS porefluid chemistry/ pressure	Affect EBS porefluid chemistry/ pressure		Impact on parameters to be gathered	None	Resaturation influences gas evolution
7 Characterising the site adequately	Input into which designs are feasible	None	None	None	None	None		Site characterisation demonstrates stability	None
8 Demonstrating long-term stability	None	None	None	Variable water chemistry affects EBS	Variable water chemistry affects EBS	Variable water chemistry affects solubility	Influences types of information required		None
9 Impact of resaturation	EBS properties depend on saturation	Influences EBS interactions	Influences EBS/ host rock interactions	A control on water access to EBS	A control on water access to EBS	A control on water access to EBS	None	None	

Table 4.9 Major activities at each stage of the authorisation process (Environment Agency, 2008) to determine the influence on safety of each issue and, where necessary, to ensure that these influences do not prevent overall safety targets being met.

Technical issue	Desk-based studies	Site investigations (surface-based)	Site characterisation (underground)	Construction	Operation
1 Influence of different waste form types on the design of the EBS	Determine waste/EBS options; theoretical evaluation of compatibility of each option with the environment.	Determine environmental constraints on design. Modify design/concept if required.	Determine environmental constraints on design. Modify design/concept if required.	None	None
2 Interactions between engineered components 3 EBS/host rock interactions 4 Impact of groundwater on EBS materials (including the impact of saline water) 5 Duration for which EBS materials may maintain their functions (durability)	Theoretical evaluation and literature review[1].	Theoretical evaluation using site data. Parallel laboratory research programme. Potential design/concept modification if needed to ensure safety.	Theoretical evaluation using site data. Demonstrations in URL. Potential design/concept modification if needed to ensure safety.	Acquisition of monitoring data to determine interactions as expected[2]. Ongoing demonstrations ein URL. Potential modification to design/concept/scheduling to ensure safety.	Acquisition of monitoring data to determine interactions as expected. Potential modification to design/concept/scheduling to ensure safety.
6 Gas/groundwater (or porewater) interactions	Theoretical evaluation and literature review[1].	Theoretical evaluation using site data. Measurement of relevant properties. Potential design/concept modification if needed to ensure safety.	Theoretical evaluation using site data. Potential design/concept modification if needed to ensure safety.	Acquisition of monitoring data to confirm water chemistry. Theoretical modelling of consequences. Potential modification to design/concept/scheduling to ensure safety.	Acquisition of monitoring data to confirm gas generation rates, gas chemistry and water chemistry interactions as expected. Potential modification to design/concept/scheduling to ensure safety.

Technical issue	Desk-based studies	Site investigations (surface-based)	Site characterisation (underground)	Construction	Operation
7 Characterising the site adequately	Planning of site characterisation taking into account environmental characteristics and literature review[1].	Gathering site-specific data. Planning further site characterisation taking into account results of surface-based investigations and design/ research activities.	Gathering site-specific data. Planning further site characterisation taking into account results of underground investigations and design/ research activities.	Acquisition of hydrogeological and geochemical monitoring data. Potential modification to design/concept/scheduling if needed to ensure safety.	Acquisition of hydrogeological and geochemical monitoring data. Potential modification to design/concept/scheduling if needed to ensure safety.
8 Demonstrating long-term stability	Qualitative evaluation taking into account environmental characteristics and literature review[1].	Quantitative evaluation using site data.	Quantitative evaluation using site data.	Quantitative evaluation using site data.	Quantitative evaluation using site data.
9 Impact of resaturation	Theoretical evaluation and literature review[1].	Theoretical evaluation using site data. Laboratory based research programme. Potential design/concept/ scheduling modification if needed to ensure safety by minimising desaturation.	Theoretical evaluation using site data. Demonstration experiments. Potential design/concept/ scheduling modification if needed to ensure safety by minimising desaturation.	Monitoring to confirm hydrogeological impact. Potential modification to scheduling to minimise construction period if needed to ensure safety by minimising desaturation.	Montoring to confirm hydrogeological impact. Potential modification to scheduling to minimise operational period if needed to ensure safety by minimising desaturation.

[1]Literature review includes evaluation of experience in other radioactive waste management programmes, especially international experience.
[2]Applicable only if components of the EBS are deemed to be emplaced during the construction phase.

5 State of knowledge about technical issues

5.1 Issue 1: Influence of different waste form types on the design of the EBS

5.1.1 International state of knowledge about Issue 1

Knowledge of Issue 1 is well-developed internationally (NEA, 2003a,b, 2006a and references therein). Most national radioactive waste management organisations have developed EBS designs that are tailored to work with the specific radioactive wastes and geological environments present within their countries. Arguably the regulatory environment within which a repository is to be sited, constructed and operated has an influence on EBS design that is at least as great as the characteristics of the wastes (NEA, 2003a). Different radioactive waste management programmes rely to different degrees on the EBS and natural barrier systems. Furthermore, the time interval for which the EBS must function varies between programmes, as a consequence of the differing roles of the geosphere in the overall safety case and the different regulatory regimes, some of which place a fixed time limit on the period for which potential discharges must be assessed; others, for example, state that the maximum in dose/risk must have been captured in the safety case calculations.

In different countries, the EBS is defined to include different components. For example, in the PA for the Waste Isolation Pilot Plant (WIPP) project in New Mexico, USA, the waste containers are not considered to act as engineered barriers (USDoE-WIPP, 2004). In contrast, the generic (not site-specific) Japanese programme of the Japan Nuclear Cycle Development Institute (JNC), as described in JNC (2000), defines the EBS to include only those components that act as barriers to radionuclide transport, thereby excluding the backfill and seals.

There is significant variability between the EBS designs for HLW and SF that have been proposed in different countries (for example, Baldwin *et al.*, 2008). While many countries favour a design that incorporates a bentonite buffer, ONDRAF/NIRAS's design for a repository in the Tertiary plastic Boom Clay uses a cement buffer (Bel *et al*. 2006). The German designs for disposal in salt have an EBS that is sufficient only for safe handling (Bollingerferr *et al*. 2008).

EBS suggested for ILW also differ widely between countries (see Hicks *et al.,* 2008). Many are cement-based, but there are also examples where the EBS is almost absent (such as OPG's proposals for disposal in 'tight' limestone; Hatch Limited, 2008). This variation is a consequence of the range of host rocks considered by different waste management organisations. In the ILW systems, the large number of ILW waste streams also contributes to the variability.

Extensive research into the influence of waste forms on the design of the EBS has been carried out both in national programmes and international collaborative research. Between 2002 and 2006, the EBS project of the NEA Integration Group for the Safety Case (IGSC) sought to boost our understanding of how to integrate successful design, construction, testing, modelling and performance assessment (PA) of engineered barrier systems (NEA, 2003a,b; NEA, 2006a).

The NF-PRO project, which was funded by European radioactive waste management organisations and the Commission of the European Communities between 2003 and 2007, investigated key processes affecting the long-term barrier performance of the near-field system of a HLW/SF repository (details are given on the NF-PRO web page at: http://www.nf-pro.org/). The main focus of the project was to improve understanding of the key processes within the near-field (the volume surrounding the disposed waste).

Research has focussed on achieving and demonstrating the required functions of the different EBS components. The main EBS components and their functions are:

- waste matrix, which provides a stable waste form that is resistant to leaching and gives slow rates of radionuclide release for the long term;
- container/overpack, which facilitates waste handling, emplacement and retrievability, and provides containment for a period suitable to the waste type;
- buffer/backfill, which stabilises excavations and THMC conditions, and provides low permeabilities, diffusivities and/or long-term retardation;
- other components (such as seals), to prevent releases via tunnels and shafts and to prevent access to the repository.

There are no major uncertainties in the influence of waste forms on the EBS. The processes controlling the functions of each EBS component are sufficiently well understood to design an adequate EBS for any major HLW/SF waste type in any geological environment where an EBS is required for safety. The feasibility of manufacturing and emplacing engineered components that have been proposed for disposal systems to date has been confirmed by large-scale experiments (NEA, 2006a). Therefore, the main aims of ongoing research are to:

- demonstrate overall design feasibility (that is, feasibility of emplacing a large number of waste packages within a full-scale repository and of implementing the overall repository layout);
- build further confidence in performance assessment;
- optimise the design of the EBS, so that costs and wider environmental impacts (for example, from the waste rock which is excavated so as to emplace the EBS) can be reduced without compromising safety.

A number of programmes (see SKB, 2006; Smith *et al.* 2007; ANDRA, 2005) have moved beyond the stage where the feasibility of constructing an EBS is demonstrated. These are now at the stage of designing detailed layouts that take account of the requirements of the local environment and EBS/waste system. The WIPP repository for TRU waste (US DoE) is operating (Matthews and Eriksson, 2003; US DoE, 2004).

5.1.2 State of knowledge in the UK about Issue 1

In the UK, NDA RWMD currently bases its quantitative work (for example, assessment of packaging proposals) on an illustrative concept for ILW/LLW that is based on the Nirex PGRC (Nirex, 2003b, 2005a) and an illustrative concept for HLW/SF that is a slightly modified version of the SKB KBS-3V concept (Nirex, 2005b). The current concepts assume a single EBS design for all wastes within a given category (ILW or HLW/SF) with no design variants to suit individual waste form types or different geological environments. The illustrative concepts are used together with a generic environment that comprises hard fractured rock overlain by sedimentary rocks (the environment would be classified as Environment 2 in this project) to assess packaging proposals.

The UK programme to date has necessarily focused on generic aspects of the repository design. NDA RWMD has begun to explore the range of EBS concepts that might be applicable for different waste types and geological environments (Baldwin *et al.*, 2008, Hicks *et al.*, 2008, Watson *et al.*, 2007a). The NDA RWMD is now developing strategies to optimise the EBS design to these local geological conditions and specific waste types (NDA, 2008).

An additional complication is that in the UK, the waste form remains undetermined for a number of key waste streams (such as graphite). There is also the potential to modify some currently proposed waste forms to work better with any disposal system that is ultimately developed for use in England and/or Wales. New waste forms may also emerge, which will have implications for EBS design. Consideration will need to be given to the potential interactions between these new waste forms and how to take these interactions into account in the EBS design and repository layout.

Many of the ILW packages endorsed by Nirex/NDA as suitable for disposal are vented to reduce the potential for overpressuring within the package. These vents mean that the packages do not to provide complete containment of radionuclides in the post-closure period. The vents also provide an easy route by which substances released from other packages can enter the waste package. This feature will need to be factored into the final repository design.

5.2 Issue 2: Interactions between engineered components

5.2.1 International state of knowledge about Issue 2

It will be important to characterise parameters using the actual materials that will be used in the EBS. For example, different bentonites have different properties and results obtained for one bentonite composition are not directly transferable to another (Metcalfe and Walker, 2004, and references therein).

Interactions may occur between a wide range of barrier materials that are juxtaposed to one another, notably:

- copper and bentonite;
- iron/carbon steel and bentonite;
- dissimilar metals and alloys with different rest potentials, where contact results in galvanic corrosion;
- cement and bentonite;
- cement and stainless steel.

The state of the art report for component 2 of the recent EU NF-PRO project (de la Cruz *et al.*, 2005) provides a good summary of recent work on the interactions between different materials in the near field of a HLW/SF repository. In general, the major interactions have been identified and studied in isolation but it has often proved difficult or impossible to simulate repository conditions. Significant uncertainties therefore remain in the extrapolation of experimental data to real repository conditions after closure.

Copper and bentonite interactions are not well-understood, but have been identified as an issue for investigation by Carlsson and Muurinen (2007). Interactions between iron/carbon steel and bentonite have received more attention, for example by Charpentiera *et al*. (2006), Wilson *et al*. (2006a,b), Smart *et al.* (2006) and Vokal *et al.* (2006). The results have indicated that while Fe-phyllosilicates may form very close to the interface between the bentonite and the iron, thereby reducing the swelling capacity of the bentonite, the overall effect is likely to be too localised to influence buffer performance. Furthermore, the thick layers of iron corrosion products that had previously been assumed to form at the interface between the metal and bentonite do not appear to be present in systems where compacted bentonite is in direct contact with the steel. Instead, a thin layer of corrosion products is formed and the corrosion process (and rate) appears to be controlled by the diffusive transport of iron species.

Probably the most studied interactions are those that may take place between cementitious and clay barrier components (Metcalfe and Walker, 2004). Cement-clay interactions have been recognised and investigated by most national radioactive waste management programmes. There has also been considerable international research on this topic, notably the European Ecoclay (*Effects of cement on clay barrier performance*) and Ecoclay-II projects (European Commission, 2000, 2005). These projects assessed the effect of an alkaline plume on the chemical and mineralogical properties of the clay and on the migration of radionuclides released from a cementitious repository into clay.

Major interactions between cement and bentonite are fairly well understood. Cement affects bentonite mainly by buffering the pH of the pore fluid entering the bentonite at high (above 12.5 initially) values. The actual mineralogical effects depend on the concentration of OH^- ions and the flux of these ions into the bentonite. However, the fluxes of cations into the buffer (most importantly Ca^{2+}, Na^+) at least partly govern the characteristics of the alteration and the buffer's physical properties.

The functions of a highly compacted bentonite buffer may be affected by two important, inter-related effects of the high-pH plume on montmorillonite and accessory minerals:

- mineralogical alteration of bentonite components, which will consume the bentonite's chemical buffering capacity and influence pore water chemistry;
- osmotic effects (differing ion activities in the external solution and porewater), which depend on the external pH and influence the temporal sequence of mineral dissolution and precipitation.

Low-pH cements have recently been developed for use in areas where there are concerns about the potential for detrimental interactions with bentonite. This is a relatively new research area, but initial modelling indicates that the expected amount of degradation is significantly reduced compared with conventional cement (see Benbow *et al.*, 2007; Watson *et al.*, 2007b).

Temporal changes in porosity, permeability and mechanical properties of bentonite will be caused by the varied and inter-related mineral dissolution, precipitation and alteration reactions. A more holistic understanding of these changes is needed to evaluate the overall safety implications.

Major outstanding uncertainties are:

- dissolution rates under alkaline conditions;
- effects of bentonite compaction on mineralogical reactions, which means laboratory experiments on uncompacted bentonite are to some degree inaccurate representations of processes in an actual buffer;
- effects of alteration on the mechanical properties of bentonite;

- effects of alkaline plume chemistry on diffusion rates through compacted bentonite;
- effects of gas on interactions.

Work in many countries is focussing on developing integrated interpretations using available data and improved coupled models of bentonite alteration.

Interactions between cements and steels are relatively minor and well understood. The corrosion rate of steel is greatly reduced under the alkaline reducing conditions that are expected in the near field of a cementitious repository. General anaerobic corrosion of steels is a well understood and characterised process. Corrosion of stainless steels is more complex. These processes are considered under Issue 5 (durability) in Section 5.5.

5.2.2 State of knowledge in the UK about Issue 2

The UK has a good understanding of the potential interactions between cementitious backfill and stainless steel waste canisters (Nirex, 2001a and references therein). Broadly, these interactions are positive in terms of safety. That is, rates of corrosion of metal waste containers will be decreased by the alkaline porewater conditions within the cement; indeed, this is the primary reason for using cement. However, interactions between waste degradation products and cement are less well understood. In the Nirex 97 assessment (Nirex, 1997a), carbonation of the cementitious backfill was invoked as a mechanism by which C-14-bearing CO_2 released from certain wastes might be locked up and thereby kept from entering the geosphere. However, there is considerable uncertainty in the effectiveness of this process. Although research is ongoing, it has not yet been shown that the process will act in the assumed way under repository conditions. Notably, CO_2 is expected to migrate preferentially through fractures in the cementitious backfill and react only with the cement immediately adjacent to these features to produce calcite. However, this process would effectively armour the cement from further reactions. Thus, the cement might not be as effective a barrier to CO_2 migration as might be predicted.

There has been no UK-specific research into interactions between the barriers that might be employed in deep geological repositories for other kinds of waste (HLW, SF that might be declared as waste, and other wastes such as Pu/U), although the UK has participated in some international projects such as NF-PRO. Furthermore, there has been little reported research into interactions that might occur if a future repository for ILW and long-lived LLW had a substantially different barrier system to that envisaged for the proposed Nirex repository at Sellafield, and the PGRC developed from earlier work. Backfill compositions remain as originally specified when the concept was first developed in the early 1990s (Nirex, 2001a). Similarly, potential interactions between the different barriers that might be employed in a repository for co-located LLW/ILW and higher-activity wastes, in the UK context, have not been investigated.

5.3 Issue 3: EBS/host rock interactions

5.3.1 International state of knowledge about Issue 3

Work on EBS/host rock interactions has mainly involved the development, evolution and properties of the EDZ. The evolution of the EDZ was the subject of technical component 4 of the recent EU NF-PRO project (see Alheid *et al.*, 2005).

The EDZ could be a significant transport pathway, perhaps bypassing seals. Such behaviour would be a greater potential problem in hard fractured rocks than in less fractured and/or more plastic lithologies. It is currently difficult to prove that the EDZ does not form a continuous high-permeability pathway in hard fractured rocks, although SKB concluded that such a pathway appears unlikely (SKB, 2006). On the other hand, tests in the Canadian URL at Whiteshell in Manitoba clearly showed that the EDZ provided a continuous pathway (Fairhurst 1999). Whether these results are site-specific (reflective of the characteristics of natural fractures) or dependent on the local stress field needs to be resolved by comparing results from different sites using an integrated approach. Until this question has been resolved, safety cases will generally assume that there is a higher-permeability pathway. Nevertheless, the significance of this potential pathway is not thought to be great, even if its permeability is up to 30 times greater than the host rock (SKB, 2006). SKB also believe that it may be possible, with the correct QA control, to prevent the formation of a continuous EDZ.

There is broad agreement that an EDZ with an enhanced permeability will develop around voids excavated in indurated clay host rock, but that the extent of the EDZ can be limited through prompt installation of appropriate excavation support. Work by ANDRA and Nagra in particular indicates that with time, creep appears to close the fractures and reduce the permeability of the EDZ (Bossart *et al.*, 2002; Bauer *et al*., 2004; Alheid *et al.*, 2005). Using evidence from the Mt Terri URL, Nagra conclude that in the Opalinus Clay the EDZ is likely to be self-sealing and have a permeability below 10^{-10} m/s within a few decades of tunnel backfilling (Blümling *et al*. 2007).

During the early part of the post-closure period, the presence of a transmissive EDZ may be an advantage as it offers a pathway for gas to migrate through the engineered system, reducing the potential for damaging overpressures. However, it is likely that the impact of an EDZ on post-closure safety will decrease with time. The results of PA by ANDRA (ANDRA, 2005) and Nagra (Nagra, 2002) have shown that, even for rather unfavourable EDZ conditions, the performance of the repository is not adversely affected.

In plastic clay, recovery is likely to be more rapid and the EDZ will not provide a preferential pathway. Alheid *et al*. (2005) summarise the results of several experiments and accompanying analyses carried out at the Belgian URL at Mol to investigate EDZ formation and healing. Again, the results indicate that an EDZ will form but that the extent can be minimised through careful excavation techniques. Significant healing appears to take place on timescales that can be observed in long-term experiments (years) but the impacts of geochemical changes from extended operations and heat from disposed wastes on the healing process is less well understood. Work continues at Mol.

Alheid *et al*. (2005) also summarise work to support the German programme. Research at Asse salt mine has shown that the hydraulic conductivity of the EDZ in halite reduces to approximately 10^{-11} m/s in 100 years (permeability (unaffected salt) = around 10^{-14} m/s). It may be necessary to remove the existing EDZ shortly before inserting a seal, before a new EDZ has time to develop (mining in salt does not produce a sudden stress pulse and stress relief as would be produced by blasting in hard rock). Work to understand the constitutive relationships in the halite, to allow the observations to be modelled, has matured in recent years.

The second area of EBS/host rock interaction that has received significant attention is the potential impact of cements on the properties of the host rock. Despite the well known deleterious impact of cementitious pore fluids on clays, there seems to be a general consensus that cements used in the EBS of radioactive waste repositories will not significantly impact on the host rock performance. ANDRA's design makes extensive use of concrete linings and the ILW disposal concept involves stacking concrete boxes in concrete lined tunnels. ONDRAF/NIRAS have recently adopted a cement buffer for their HLW/SF disposal concept (see Baldwin *et al*., 2008, for a summary) and have a cement-based ILW disposal concept for use in the Boom Clay (Hicks *et al*. 2008).

More attention has been paid to the potential for an alkaline plume to develop downstream of a cementitious repository in higher flow environments. The two organisations that have been most concerned with these interactions are SKB and UK Nirex Ltd. SKB have given serious consideration to the consequences of the development of an alkaline plume from their Final Repository for Radioactive Operational Waste (SFR) for ILW (see Karlsson *et al*., 1999; Benbow *et al*, 2004). Probably the most significant body of work in this area was carried out by UK Nirex in support of their proposed development of a cementitious repository in the predominantly volcaniclastic rocks at Sellafield. This work is considered further in Section 5.3.2.

5.3.2 State of knowledge in the UK about Issue 3

A cementitious backfill is characteristic of the repository concepts developed in the UK for an ILW and long-lived LLW repository (Nirex, 1997a,b, 2001a,b, 2003b, 2005b). The principal EBS/host-rock interactions will be reactions between the alkaline plume that originates in the cementitious backfill and the host rocks. For this reason, during the 1990s Nirex conducted extensive research into the characteristics of this alkaline disturbed zone, including experimental and theoretical modelling and natural analogue investigations at Maqarin in northern Jordan (all summarized in Nirex, 2001b). However, this research focussed on the lithologies that occur at Sellafield in North West England and additional research would need to be considered before employing a cementitious barrier in different host rocks at a future repository site elsewhere.

There has been no UK-specific research into the interactions between the different kinds of EBS that would need to be employed in a repository for HLW, SF that might be declared as waste and other highest-activity wastes.

During the Sellafield investigations, consideration was given to the extent and properties of the EDZ that might develop around the excavations for a repository in the predominantly volcaniclastic host rocks there (the Borrowdale Volcanic Group, BVG) and this understanding was represented in the Nirex 97 safety assessment (Nirex, 1997a). This representation was consistent with the state of the art understanding in 1997, but little work seems to have been carried out since then. For example, Nirex/NDA RWMD did not participate in the EDZ component of the recent NF-PRO project which explored our current understanding of EDZ development and evolution for a range of host rock types. Thus, UK understanding of EDZ development in hard fractured rocks may not be comparable to that in many other countries. Understanding of EDZ development in other lithologies besides hard fractured rocks appears to be based on reviews of literature published by other organisations.

5.4 Issue 4: Impact of groundwater/porewater on EBS materials (including the impact of saline water)

5.4.1 International state of knowledge about Issue 4

Interactions between groundwater/porewater and EBS materials have been extensively studied internationally. All PAs that have been carried out to date account for these processes explicitly or implicitly (see Atomic Energy of Canada Limited (AECL), 1994; Nagra, 1994; Nirex, 1997a; Vieno and Nordman, 1999; JNC, 2000; ONDRAF/NIRAS, 2001; Nagra, 2002; NEA, 2003a,b; USDoE-WIPP, 2004; NEA, 2006a; SKB, 2006; Smith *et al*. 2007).

As a consequence of this research, the impact of fresh to moderately saline groundwater on EBS materials and the degradation processes of all major barrier components (carbon steel, iron, copper, bentonite, cement/concrete and crushed rock) are fairly well understood. When the water has relatively low salinity (ionic strength about one, about the same as seawater), interactions between the EBS components and water may be modelled with reasonably reliability. Many studies have shown that the chemical changes that occur may be predicted or reproduced under these circumstances (see references in Metcalfe and Walker, 2004; Vuorinen *et al*. 2006).

Much research has been undertaken into the corrosion of metal components under repository conditions (such as King *et al*. 2001; Kursten *et al*. 2004a,b; Watson *et al*. 2007a). Depending upon the disposal concept, the dominant metals that have been proposed for use in an EBS are varieties of iron/steel and/or copper.

Several different Fe-based metals have been considered (mainly passivated and unpassivated carbon steels, galvanized steels, or stainless steels), each of which could exhibit slightly different corrosion characteristics. Under oxic conditions, iron will be oxidized to Fe-oxyhydroxide phases, the precise compositions of which will depend upon the water composition; the solid structure of the hydroxide can accommodate certain species dissolved in groundwater, such as Cl^-, SO_4^{2-} and CO_3^{2-}. Under anoxic conditions, iron will initially corrode to a ferrous hydroxide phase with simultaneous reduction of water and the liberation of hydrogen gas. Later, the ferrous hydroxide will tend to transform to magnetite (Fe_3O_4) and produce more hydrogen gas. The precise characteristics of the corrosion (in particular its rate and whether uniform or localised (pitting) corrosion occurs) will depend upon the composition of the metal phase and the groundwater/porewater with which it is in contact. Overall corrosion rates are heavily dependent on the rates at which aqueous species are transported to and from the metal's surface, the availability of O_2 (during the oxic phase), and the rate at which $Cl^–$ ions are supplied by the groundwater. Steel will tend to corrode more rapidly if the concentration of Cl^- is high.

The rate of copper corrosion is influenced by similar processes to those that affect the rate of iron corrosion. However, the rate at which sulphide ions are supplied to the surface of a copper component could be an important control on the rate and characteristics of copper corrosion. Under oxic conditions copper will oxidize to cuprous oxide (Cu_2O), copper hydroxide and/or copper hydroxides containing other anions, for example malachite ($Cu_2CO_3(OH)_2$) or atacamite ($CuCl_2.3Cu(OH)_2$), depending upon the water composition.

Under oxic conditions, chloride ions stabilize dissolved Cu(I) in the form of complex anions, such as $CuCl_2^-$ and $CuCl_3^{2–}$. At sufficiently low pH in $Cl^–$ solutions, Cu corrosion occurs with the evolution of H_2. The stability field of $CuCl_2.3Cu(OH)_2$

increases in size relative to the stability fields of Cu_2O and CuO. Under anoxic conditions, copper corrosion will be accompanied by reduction of water to produce hydrogen gas, the solids produced being Cu-bearing hydroxide phases that will typically contain some chloride within their structures; the concentration of Cl in a solid corrosion product depends upon the concentration of Cl^- in the aqueous phase. If sulphide occurs in the water, corrosion of copper to Cu_2S and CuS is also possible. Thus, if there are high SO_4^- concentrations and conditions are reducing, producing reduced sulphur, there may be a detrimental impact on the longevity of copper.

Cementitious components will undergo leaching and hydrolysis in the presence of groundwater (Berner, 1992; Karlsson *et al*. 1999; Metcalfe and Walker, 2004 and references therein). Potentially important with respect to safety will be interactions with SO_4 dissolved in the groundwater, which may affect the chemical buffering capability of the cement and its physical properties (Metcalfe and Walker, 2004). Notably, formation of high-specific volume secondary mineral phases such as ettringite gypsum ($CaSO_4.2H_2O$), monosulphoaluminate ($3CaO.Al_2O_3(CaSO_4).12H_2O$), or ettringite ($3CaO.Al_2O_3.3(CaSO_4).32H_2O$) may lead to cracking of the cement .

Similarly, interactions between bentonite and porewater derived from the groundwater/ porewater in the surrounding rock have been considerably researched (see JNC, 2000; Pusch and Kasbohm, 2002; Metcalfe and Walker, 2004 and references therein; Arthur *et al*. 2005; Savage, 2005; Karnland and Birgesson, 2006). Ion exchange will occur on smectite, in particular exchanges of Na^+ ions with Ca^{2+} ions from the groundwater and calcite dissolution in bentonite. Alteration of smectite to illite has also been studied. At higher salinities, the functioning of bentonite barriers may be impaired because smectite swelling pressures decrease compared to fresher-water environments.

Compared to the impacts of fresh to moderately saline water, the impacts of highly saline water on most EBS materials are more uncertain. While highly saline groundwater conditions are encountered in evaporite-hosted repositories, in these cases relatively little weight is given to EBS performance, the geosphere providing the main barrier. The EBS in evaporite-hosted repositories for HLW/SF is generally designed for safe emplacement only and has little function in the post-closure period. In contrast, in the case of the WIPP for TRU waste in New Mexico, the only significant long-lived EBS component is MgO which is used as backfill. A combination of experimental studies and theoretical modelling using the so-called ‘Pitzer approach’ (Pitzer, 1991) was used to establish that this barrier would perform as required (USDoE-WIPP, 2004). At the Morsleben repository for wastes, backfills and seals will be composed of cement-salt mixtures (Preuss *et al*. 2002). The primary functions of these structures are to physically stabilize the excavations and prevent the development of pathways for brine migration.

Thus, in a salt formation the proposed EBS, if any, is relatively simple and designed to function under extremely low-flow conditions. Highly saline waters in non-evaporite host rock have been considered by the Canadian HLW/SF disposal programme (AECL, 1994; Gascoyne, 2004) and the Deep Geological Repository (DGR) programme for LLW and ILW being undertaken by OPG at Bruce in Ontario (Hatch Limited, 2008). However, in these cases the host rocks have extremely low permeabilities and consequently interactions between brine and EBS components will be limited. There is relatively sparse information on how more complex EBS materials would perform in highly saline groundwaters and porewaters and/or where groundwater fluxes are relatively high.

A major difficulty caused by the presence of saline water (ionic strength above one, greater than seawater) is accurately predicting the reactions that occur, because:

- there have been relatively few experimental investigations of these reactions for proposed EBS materials under repository conditions;

- conventional thermodynamic modelling approaches, such as the Debye-Hückel approach (Debye and Hückel, 1923) and variants of it, including the so-called b-dot extension (Helgeson, 1969), are inaccurate at these high salinities;
- the fundamental thermodynamic data needed to carry out theoretical predictions are lacking or of uncertain or poor quality.

For these higher salinities other approaches are required, such as the so-called specific ion interaction or Pitzer approach (Pitzer, 1991). As for the Debye-Hückel and similar approaches, the Pitzer approach is strictly valid only if the system is in equilibrium. An additional requirement is that the thermodynamic data used should be obtained under conditions similar to those being modelled. In the cases of repository minerals, little data is available for:

- cementitious barriers;
- metal barriers;
- redox-sensitive species that occur in these barriers.

The most comprehensive Pitzer database available is the one developed for the Yucca Mountain Project (US DoE, 2007). However, this database is not internally consistent.

Evaporation during the open phase of the repository and/or resaturation could lead to local development of high salinities. High salinities may then influence the durability of EBS components. Such influences have been considered by the Yucca Mountain Project, which has modelled reactions using the Pitzer approach (US DoE, 2007).

However, the presence of highly saline water often implies low groundwater flow rates. Low flow rates would generally be advantageous with respect to safety, and these advantages would need to be set against any disadvantages from the difficulties in predicting chemical reactions.

Whatever the salinity of the groundwater/porewater, there remain uncertainties in the reaction kinetics. At the low natural temperatures (generally up to a few tens of degrees) that will occur within a repository host rock, water-solid systems will not attain thermodynamic equilibrium (although some minerals may equilibrate with the coexisting fluid phase). These disequilibrium conditions need to be adequately addressed in chemical models. Rates of reactions usually depend on the chemistry of the water and physical form of the solid reactants and reaction products. In particular, the surface areas of these solids are important controls on the rates of reactions, but are notoriously difficult to estimate accurately. Usually, the approach taken is to make bounding assumptions conditioned by experimental observations.

5.4.2 State of knowledge in the UK about Issue 4

The focus of previous research within the UK has been on barrier systems for ILW and some long-lived LLW that are unsuitable for disposal in the LLWR. Extensive knowledge about the durability of stainless steel and cementitious barriers in the presence of saline water has been accumulated (see Nirex, 2001a, 2005a and references therein). However, the maximum groundwater salinities investigated are similar to those of seawater, reflecting the fact that at Sellafield, the maximum groundwater salinity in the potential repository zone (PRZ) was about 0.8 times that of seawater (while noting that the actual origin of the salinity was not marine). Thus, there is limited knowledge on the stability of these barrier materials in more saline waters, such as those that might be encountered in closer proximity to evaporite-bearing rock sequences, and/or at greater depths/more central locations in Mesozoic sedimentary basins.

There has been almost no UK-specific research to date on the effects of groundwater/ porewater on barrier materials for HLW, SF (should this be declared as waste) or other wastes. Instead, to demonstrate that a repository for HLW could be developed within the UK, Nirex (and more recently the NDA RWMD) have investigated the applicability of SKB's KBS-3 disposal concept (see Nirex, 2005b). Simple, semi-qualitative arguments have been made to show that the different groundwater compositions found in potential UK repository locations would not adversely affect the performance of a KBS-3 repository. However, these generic studies have not yet considered the very saline groundwaters that occur in parts of England and Wales, notably at depth within Mesozoic basins. Many of these brines are expected to have relatively high sulphate levels which could become an issue if an EBS system used copper disposal canisters.

5.5 Issue 5: Duration for which EBS materials may maintain their functions (durability)

5.5.1 International state of knowledge about Issue 5

All the international knowledge outlined for Issue 4 in Section 5.4.1 is also applicable to Issue 5. However, Issue 5 covers the safety implications of processes described by Issue 4. This knowledge has been summarized in a wide range of PA documentation (see Atomic Energy of Canada Limited (AECL), 1994; Nagra, 1994; Nirex, 1997a; Vieno and Nordman, 1999; JNC, 2000; ONDRAF/NIRAS, 2001; Nagra, 2002; NEA, 2003a,b; USDoE-WIPP, 2004; NEA, 2006a; SKB, 2006; Smith *et al*. 2007).

The wide variety of materials used by the different waste management organisations means that information is available for most materials of interest under laboratory conditions. The way in which the materials evolve under repository conditions is less well understood, although this is not necessarily a problem for safety because the uncertainties can be addressed within a PA by making conservative assumptions. For example, it is often assumed that carbon steel will corrode relatively rapidly under repository conditions to produce a thick layer of corrosion products. However, recent experimental and theoretical work (see Smart *et al.*, 2006; Vokal *et al.*, 2006) suggests that no corrosion product layer is formed when carbon steel corrodes under repository conditions in contact with compacted bentonite. Uncertainties of this kind can be treated within a PA by specifying a conservatively rapid corrosion rate for the canisters. Thus, the uncertainties are more of an issue for optimisation of repository designs/ concepts than they are for demonstrating that safe disposal can be achieved.

When reviewing the general topic of EBS durability, related sub-issues are:

- the possibility of changes in the reasons for using particular materials over the lifetime of a project (for example, in SKB's KBS-3 concept, initially the bentonite buffer was not assigned the function of excluding microbes, but this function has recently been specified (SKB, 2006));

- the possibility of changes in the materials to be used for a particular purpose as a result of technological developments or shortages in supply during the project (SKB, 2006);

- heterogeneities in engineered barriers, for example, the spatial distribution of density and hydraulic properties of clays, and the history/characteristics of cracking in cements;
- knowledge gaps on the durability of certain cements under environmental conditions that might be considered for a repository (such as so-called 'low-pH' cements under highly saline conditions (Watson *et al*. 2007b));
- a knowledge gap on the way in which such cements will interact with other materials, for example bentonite (see Watson *et al*. 2007b);
- possible uses of alternative kinds of materials, besides those that have traditionally been proposed for the EBS (such as polymers; see discussion in Metcalfe and Walker, 2004);
- incompatibility of certain waste types with certain EBS, for example, the possible incompatibility of bentonite with certain gas-producing wastes;
- whether the durability of the system is based on a 'corrosion allowance' (typically carbon steel overpacks for HLW/SF) or a 'corrosion resistance concept' (typically copper canisters with cast iron inserts for HLW/SF).

The most recent research indicates that canister lifetimes of the order of 100,000 years could be achieved using either of the corrosion concepts.

In the corrosion-allowance concept, the canister materials considered generally have a relatively low corrosion resistance. However, these materials are sufficiently inexpensive to be used economically in thicknesses adequate to prevent corrosion penetration during the desired lifetime. These materials also corrode at a predictable corrosion rate. No localised corrosion such as pitting or crevice corrosion is expected and standard manufacturing techniques can generally produce the canisters. Recent research (such as the NF-PRO project) suggests that the long-term corrosion rate for such canisters could be sufficiently slow that lifetimes in the order of 100,000 years are plausible.

In the corrosion-resistant concept, the canister materials have a very high corrosion resistance in the disposal environment. These materials corrode passively at a very low uniform corrosion rate. Therefore, a relatively small thickness of such a metal can be used to achieve the desired canister lifetime. The relatively small amount of material required at least partially offsets the typically higher cost. However, for these materials the risk of localised corrosion, such as pitting and crevice corrosion, has to be taken into account, because the protective film that gives them their low overall corrosion rate may break down locally.

If retrievability of the wastes is needed, this will have implications for the durability of EBS materials. The EBS pre- and post-closure is exposed to very different environmental conditions. It may therefore be necessary to demonstrate that materials are durable under a number of different conditions. There are major knowledge gaps on the impacts of a repository being kept open for a long period, and hence on our understanding of the durability of engineered materials in the open and subsequent post-closure phases. These uncertainties need to be accounted for or reduced in the overall safety case. The impact on the durability of the EBS of keeping a repository open for a prolonged period is being considered by ANDRA in context of the French disposal concept (ANDRA, 2005). It is recognised that how a repository is operated will affect the post-closure durability of the barriers.

5.5.2 State of knowledge in the UK about Issue 5

The focus of previous research within the UK has been on barrier systems for ILW and some long-lived LLW that are unsuitable for disposal in the LLWR (Nirex, 1997a,b, 2001b, 2005a). Extensive knowledge on the durability of stainless steel waste canisters and cementitious backfill has been built up as a result of this research. UK knowledge of localised corrosion of stainless steel under likely Sellafield conditions was state of the art during the Sellafield investigations and more generic work has continued since 1997. However, it is likely that much of this knowledge will be inapplicable to geological environments dissimilar to that at Sellafield, which was the target of most previous research, owing to differences in groundwater composition and flow rate.

There has been little UK-specific research to date into the durability of barrier materials for HLW, SF (should this be declared as waste) or other wastes. Instead, to show that a repository for HLW could be developed within the UK, Nirex (and more recently the NDA RWMD) have adapted the KBS-3 disposal concept of SKB would be employed (Nirex, 2005b).

Thus, compared to many programmes in other countries, knowledge of the performance and durability of repository materials under likely repository conditions in England and/or Wales is relatively unadvanced. One reason for this is that the exact conditions (like groundwater chemistry, flow rates, temperatures) at an actual site are presently unknown. It will be important to characterise these parameters using the actual materials that will be used in the EBS in the actual environment that is eventually considered to host a repository. For example, different bentonites have different properties; results obtained for one bentonite composition are not directly transferable to another.

A particular issue faced by the UK programme is the potential for relatively rapid degradation of packages that contain reactive metals (mainly Magnox swarf). Reactive metals encapsulated in cement will corrode and swell, resulting in cracking and rapid degradation of the cement encapsulant. This process has long been recognised within the programme as a potential problem. Packages were originally designed to remain intact under controlled store conditions for periods of tens of years to allow safe emplacement within the Nirex repository. An issue is the extent to which the original package specifications would be compatible with the longer storage periods now envisaged, especially if retrievability is an integral part of the disposal concept. The post-closure performance assessments undertaken by Nirex (see Nirex, 1997a and later generic studies) took little or no credit for package integrity so rapid package failure was highlighted as a potential safety issue. Some data on the extent of this issue may be available from studies of 'failed' packages currently in store.

The performance of cementitious encapsulants as a barrier will generally decrease with time. Super-plasticisers to promote cement mobility and ensure void filling may be required in construction cements. These super-plasticisers may also be required in backfills if the design requires the primary backfill for entire vaults to be emplaced after the vaults have been filled with wastes. Super-plasticiser technology has advanced significantly since the Sellafield investigations but the impact of modern super-plasticisers on very long term durability and on radionuclide mobility is not well understood.

5.6 Issue 6: Gas/groundwater (or porewater) interactions

5.6.1 International state of knowledge about Issue 6

International research on the behaviour of gas is less mature than the research on aqueous solutes. The principal reason is that not all waste forms are considered to potentially cause gas problems and the possible issues associated with repository-derived gases were not recognised initially. Research has tended to be undertaken only by those agencies intending to dispose of LLW/ILW, notably Nirex (Nirex, 2005a), ANDRA (France; ANDRA, 2005), Nagra (Switzerland; Nagra, 2002), and USDoE (for WIPP; USDoE-WIPP, 2004).

Gas/groundwater (or porewater) interactions within the EBS and surrounding geosphere have been investigated. In the case of HLW/SF repositories, interactions involving gas and porewater within the EBS will be of relatively greater significance to safety than interactions between gas and groundwater/porewater in the geosphere. In these repositories, H_2 gas will be generated principally by corrosion of the metal containers and to a lesser extent by radiolysis of water. Of major concern is the potential effect of this gas on the integrity of low-permeability bentonite buffers and backfills. A considerable amount of work has been done to demonstrate that the gas will be able to migrate through the buffer without causing significant damage (see Harrington and Horseman, 2003; Hoch *et al*. 2004). Key findings have been that it is possible for:

- gas to pass through initially water-saturated bentonite buffers;
- little water to be expelled from the buffer by the migrating gas;
- the buffer to reseal as it resaturates following gas migration;
- the transport properties of the buffer to be unaffected.

Compared to repositories for HLW/SF, repositories for ILW will generally contain much large volumes of potentially gas-generating materials. These materials will include not only metals, both in canisters and in the wastes themselves, but also large quantities of organic-bearing materials. Thus, a major goal of research on gas generation in repositories has been to:

- ensure that evolved gas pressures will be insufficient to compromise the integrity of the EBS and surrounding rock, generally by:
  - ensuring that the repository (including any buffer and backfill) has a sufficient total pore volume to act as a large gas reservoir;
  - ensuring that the gas can leave the repository sufficiently easily;
  - ensuring that the gas (or components of the gas) may be locked up by reactions with cementitious components of the barrier system.
- ensure that gas does not break through to the near-surface environment, generally by:
  - siting the repository where there are natural barriers to gas migration in the geological sequence overlying the host rock;
  - siting the repository in rocks that have hydrogeological properties favouring gas dissolution;

- ensuring that the gas cannot leave the repository (but does not lead to detrimental overpressuring, owing to one or more of the design measures described above).

Several international projects have investigated gas/groundwater interactions:

- Rodwell *et al*. (2003) recorded the views of GASNET, a network of researchers concerned with gas issues in safety assessments;
- NEA (2001), the proceedings of an international workshop on safety issues related to gas generation and migration in radioactive waste disposal;
- Rodwell *et al*. (1999), a review of our understanding (in1999) of gas migration and two-phase flow through engineered and geological barriers in deep repositories for radioactive waste;
- Horseman *et al*. (1996), a review of the fundamental processes governing water, gas and solute migration through argillaceous media.

Each of the above documents considers gas generation in repositories for all the main kinds of radioactive waste (LLW, ILW and HLW/SF) and gas migration from these repositories.

Rodwell *et al*. (2003) cover the possible impacts of gas migration on PA and safety, providing recommendations for further research on gas generation, migration and biosphere issues. The focus of Rodwell *et al*. (1999) is on gas migration topics, although there is a shorter review of gas generation and its modelling. This report makes no formal recommendations for further research, but observations are made at various points in the text. In contrast, the report by Horseman *et al*. (1996) deals with fundamental physico-chemical processes that control gas migration through clay barrier systems (including engineered bentonite-based systems and natural mudrocks). The main conclusion relating to gas was that further research should be undertaken to understand the mechanism by which gas moves through clays. This recommendation is repeated in the report by Rodwell *et al*. (2003).

NEA (2001) comprises an overview and separate papers on a range of issues relating to gas generation and migration in a variety of host rock lithologies, including non-indurated clays, indurated clays, crystalline rocks and salt.

Key outstanding areas of uncertainty concern:

- the definition of truly conservative assumptions about interactions of gas and groundwater/porewater, in view of the highly coupled nature of flow and chemical interaction;
- evaluation of the degree of pessimism/conservatism associated with parameterisation of individual features and processes, to ensure that future assessments are not unrealistic, as has been the case in the past;
- the significance of heterogeneities in gas generation within a repository;
- the coupling between gas generation, groundwater flow and accessibility of water to corroding/degrading waste;
- the coupling of the convergence behaviour (collapse of excavated voids) of the host rock to the processes in the previous bullet point (particularly if consideration is to be given to disposal in salt);
- the influence of salinity on gas solubility (and hence transport);
- the potential importance of any space between the backfill and the EDZ;

- the potential importance of any EDZ as a pathway for enhanced gas migration;
- demonstration that upscaling of two-phase flow in fractured crystalline rocks is possible in such a way as to capture the key processes relevant to gas migration in the context of a radioactive waste repository;
- the possibility of future temporal changes in rock properties.

5.6.2 State of knowledge in the UK about Issue 6

A recent Quintessa review for NWAT provides an overview of the current position in the UK (Metcalfe *et al.*, 2008). Understanding of gas generation from UK ILW wastes under water-unlimited conditions is relatively well developed. Recently, the focus has been on the release of C-14 from metallic and graphite wastes.

Gas has to date been more prominent in safety-related work in the UK than in other countries (see Hicks, 2006). This emphasis seems to result from a combination of relatively pessimistic gas generation assumptions and the fact that the fractured rock geosphere considered by Nirex in its models offered relatively little containment. Other organisations have generally proposed to dispose of gas-generating ILW within geospheres that are more capable of containing, dissolving and/or dispersing gas.

Gas migration in the geosphere is strongly influenced by the detailed structure of the site itself, so the absence of a UK site for study has limited progress in this area in recent years. Recent Nirex and NDA RWMD work has continued to use the Sellafield datasets (for example. Bate *et al.*, 2006) because there is no other site which has the required level of detailed data. However, an issue is the extent to which this work will be applicable to sites other than Sellafield.

In the UK, there has been no extensive research programme on gas-generating systems other than for ILW in fractured crystalline rock, as most recently represented in the PGRC (Nirex, 2003b, 2005a). However, the UK has participated in various international programmes such as GASNET (Rodwell *et al.*, 1999) and GAMBIT (Hoch *et al.*, 2004) that have considered these issues.

5.7 Issue 7: Characterising the site adequately

5.7.1 International state of knowledge about Issue 7

Current methods and technologies are capable of characterising a site sufficiently well to construct and license a deep repository in a variety of different host rocks (see Biurrun and Hjarte, 2003; USDoE-WIPP, 2004; SKB, 2006; Smith *et al*. 2007). For example, a successful site characterisation programme in hard fractured rock enabled SKB of Sweden to develop the operating SFR repository for LLW/ILW. SKB is also in the final stages of characterising two potential sites for a Swedish HLW/SF repository, both sites having crystalline potential host rocks Similarly, in Finland, the characterisation of a potential repository site for HLW/SF is well advanced and has not encountered any significant problems that suggest future characterisation will not meet its goals.

In the USA, a successful site-characterisation programme enabled US DoE to develop the WIPP repository for TRU in a bedded salt formation. While the programmes in indurated and plastic clays are less advanced, programmes in several countries have shown that it is possible to characterise these lithologies adequately. For example, ANDRA's programme in France has clearly shown that it is possible to characterise an indurated clay environment to the level required to develop significant underground structures (the URL at Bure; ANDRA, 2005, 2007). Similarly, extensive investigations have been undertaken in Switzerland, notably in the Mont Terri Tunnel URL (see Pearson *et al*. 2003) and at Wellenberg (see Mazurek, 2000; Nagra, 2002). These investigations lead to the development and testing of a wide range of characterisation techniques (such as porewater squeezing). Methods that are particularly suited to plastic clays have been developed by the Studiecentrum voor Kernenergie/Centre d'Etude de l'Energie Nucléaire (SCK/CEN) in Belgium, notably at the Mol URL (see. Marivoet *et al*. 2000).

Much less well-developed is experience of investigating limestone host rocks. However, OPG is currently characterising a limestone-dominated host rock formation at the proposed site of a repository for LLW/ILW at Bruce in Ontario (see HATCH, 2008). Investigations in the Konrad Mine in Germany have, on the other hand, already resulted in successful licensing (Biurrun and Hjarte, 2003).

In many countries, extensive use has been made of URLs to improve our understanding of repository host rocks. Two main approaches have been adopted:

- development of one or more URLs *not* located where a repository will be constructed, with the aims of:
    - developing investigation methods in rocks that are similar to potential repository host rocks at an actual repository site elsewhere;
    - improving our understanding of the general properties of potential repository host rocks at an actual repository site elsewhere (such as 3D variability in fracture characteristics at a range of spatial scales);
- development of a URL at an actual repository site, or immediately adjacent to an actual site, with the same general aims as above, but with the further aim of providing more site-specific information.

Examples of the first kind of URL are:

- Äspö, Sweden, located in crystalline (mainly granitic) rocks, close to one of the sites being considered as a possible HLW/SF repository site, but developed long before this repository site was suggested and operated independently of the site investigations;
- Whiteshell, Manitoba, Canada, located in crystalline (granitic) rocks;
- Tono, central Japan, located within crystalline rock (granite) situated beneath a sedimentary rock cover;
- Grimsel, Switzerland, located in crystalline (granitic) rocks;
- Mont Terri Tunnel, Switzerland, located largely in indurated mudstone;
- Mol, Belgium, located in plastic clay;
- Horonobe, northern Japan, located largely in diatomaceous (indurated) mudstone;
- Asse Mine, central Germany, located predominantly in halite.

Examples of the second kind of URL are:

- ONKALO, Finland, located in crystalline (granitic) rocks adjacent to the proposed Olkiluoto HLW/SF repository;
- Bure, France, located in indurated mudstone, possibly adjacent to the proposed Bure HLW/SF repository (although the repository could potentially be sited further afield, within an area of some 250 km^2 that surrounds the Bure URL);
- Yucca Mountain, located in volcaniclastic rocks within a rock volume that will become part of the proposed Yucca Mountain HLW/SF repository;
- Rokkasho, northeastern Japan, located in argillaceous and arenaceous sedimentary rocks adjacent to a proposed repository for certain long-lived LLW;
- Gorleben, Germany, located dominantly in halite (which though planned to be adjacent to a repository is now more likely to be an off-site URL since the final repository site will probably be selected elsewhere).

Two areas where the majority of programmes continue to struggle are:

- the most appropriate way to characterise heterogeneity and uncertainty and how to determine whether or not sufficient data have been collected;
- the development of long-term monitoring systems that will function adequately during the very long monitoring period required following closure.

5.7.2 State of knowledge in the UK about Issue 7

The most recent UK experience of site characterisation was the Sellafield investigations that ended more than 10 years ago, in early 1997 (Nirex, 2001b and references therein). More limited investigations were conducted by Nirex in the early 1990s at Dounreay in northern Scotland (Nirex, 1994 and references therein). Some UK experts have been involved in overseas site characterisation programmes but the level of involvement has been limited (UK experts have provided consultancy support, but UK contractors have not generally been involved in site work). An issue is whether there are sufficient numbers of personnel to plan and execute a site characterisation programme, especially if the site requires significantly different approaches to those employed at Sellafield. Furthermore, the UK needs sufficient practical resources such as laboratory facilities, suitable drilling rigs and the personnel required to run them.

Since the Sellafield investigations, Nirex and subsequently NDA RWMD have carried out some general planning of site characterisation programmes as part of their generic repository programme (Littleboy and Degnan, 2003). The focus of this work has been to document an overall approach to site characterisation with examples of how various investigation techniques might be employed, and in particular how site characterisation could be integrated within a step-wise repository development process.

The UK has only limited experience in URLs, Nirex and its successor NDA RWMD not having played an active role in foreign URL programmes in the last decade. The current NDA programme does not have provision for a URL to develop the required underground skills but includes the potential to make use of URLs operated by other programmes.

5.8 Issue 8: Demonstrating long-term stability

5.8.1 International state of knowledge about Issue 8

The presence of geologically stable conditions at depth is an important element in demonstrating that radioactive waste can be disposed of safely. Stability, in this sense, does not imply that steady-state conditions exist, as it is recognised that no natural system is likely to be in equilibrium. The geosphere is constantly evolving, although in many cases rather slowly, especially at depth, and such evolution is perfectly acceptable for safe geological disposal. The concept of geological stability implies that the changes that occur in the geological system do so to an extent and at such a rate that their effects are unlikely to compromise the short- or long-term safety of the disposal system. What is perhaps of greatest importance in this regard is that we understand this evolution and the effects it could have on the safety of a repository.

The stability of the hydrogeological and hydrogeochemical system is more difficult to demonstrate, but there is considerable consensus around the world that it is possible to demonstrate such stability. There have been two recent NEA workshops on stability, the first on argillaceous rocks in 2003 (NEA, 2005a) and the second on crystalline rocks in 2007 (NEA, in press). The NEA is understood to be preparing a brochure on geological stability for all geological environments in the context of radioactive waste disposal.

Demonstrating long-term stability of the geosphere system in which the repository is to be developed has received considerable attention in recent years. Especially in northern European environments which have been glaciated, but also in areas of low-permeability rocks, heads at depth are likely to be out of equilibrium with current surface conditions because the timescale on which the driving forces (ice loading and so on) vary is shorter than the timescale on which the rock can respond. This will apply to any rock which has a hydraulic conductivity below around 10^{-10} m/s which is unlikely to have recovered from the last glaciation. Therefore, the process of demonstrating long-term stability is often a case of establishing the degree of disequilibrium with present-day surface conditions and then demonstrating the degree to which the system has evolved since the last glaciation. This is, however, complicated in many rocks because the disequilibrium reflects earlier events.

Knowledge on long-term stability varies from country to country, depending on the environment types being considered, and the potential impacts of environmental changes on the safety case. For example, the timing and nature of future glaciations is of key importance in the safety case for a repository hosted in a Swedish crystalline rock environment, where the change in surface conditions might impact directly on the conditions in the EBS (NEA, 2008b). However, these changes are likely to be of lesser importance for a repository located in an indurated mudstone formation, as at Bure in France (NEA, 2006b), or in a plastic clay such as the Boom Clay in Belgium (ONDRAF/NIRAS, 2001). The main reason is that mudstones and plastic clays tend to have very low permeabilities and therefore would prevent penetration of recharge waters to the environs of the wastes. A subsidiary reason is that indurated mudstone and especially plastic clay tend not to undergo brittle deformation during loading and unloading by glaciers. Consequently, glaciation and deglaciation is unlikely to generate new fluid flow paths through a host rock of indurated mudstone or plastic clay.

Evidence of stability is likely to be better preserved over long periods of time in clays than in hard fractured rocks. Therefore, it is almost certainly more straightforward to demonstrate stability in clays. It is also likely that these very low-permeability rocks at depth are less susceptible to exogenic changes.

Internationally, there has been extensive research into clay host rocks for geological repositories. This research has covered a wide spectrum of argillaceous media, including plastic, soft, poorly indurated clays to brittle, hard mudstones or shales. The properties of these lithologies are summarised in NEA (2005b). Examples of specific studies are:

- investigations of indurated mudrocks in Switzerland by Nagra during the Mont Terri Project (Pearson *et al*. 2003) and at Wellenberg (Nagra, 1997; Mazurek, 2000);
- investigations of indurated mudrocks in France at Bure, by ANDRA (ANDRA, 2005);
- investigations of the plastic Boom Clay at Mol, Belgium by SCK/CEN (Marivoet *et al*. 2000);
- investigations of silica-rich (diatomaceous) mudrock by JAEA at Horonobe, Japan (JNC, 2005; Hama *et al*. 2007).

As a result of these and other studies, extensive experience has built up over the last decade on the mechanical and chemical stability of clays at depth. There is considerable evidence for their general stability from:

- chemical profiles through clays;
- pressure profiles through clays;
- evidence of self-healing;
- lack of transmissive fractures at depth.

There is also confidence that sufficiently stable conditions can be found at depth in hard fractured rocks, if the site has been selected carefully. There are several examples of safety cases for a repository in hard fractured rock where a comprehensive account of geosphere stability issues is given (see Nagra, 1994; AECL, 1994; SAM, 1996; Vieno and Nordman, 1999; JNC, 2000; SKB, 2006;). These assessments have shown that compliance with regulatory criteria can be achieved and that the geoscientific understanding of stability issues was found sufficient and not detrimental to safety.

Hard fractured rock formations that are not located near the margins of tectonic plates are generally regarded as being geologically stable. The rocks of the Canadian Shield have ages in the order of billions of years (see Berman *et al*. 2000) as do the rocks of the Scandinavian Shield (see Milnes, 2002). Such shield rocks show little evidence for major structural changes over timescales of many tens or even hundreds of millions of years. However, much younger hard fractured rocks can show considerable evidence of stability, even near to tectonic plate margins. For example, Yoshida *et al*. (2005) compared fracture frequencies in Japanese granitic plutons ranging in age from around 117 million years to 1.8 million years and found that there were insignificant differences. The conclusion is that once formed soon after intrusion, fracture patterns may be relatively insensitive to further modification. Generally, changes in the stress field appear to be accommodated by movements on existing fractures, rather than by generation of new fractures. Thus, the overall geometry of a fracture network may undergo relatively little change even in an active tectonic belt.

Geosphere phenomena (processes and events) that could perturb stability in hard fractured rock are well known; no fundamentally new phenomena have been identified in recent years. The geoscientific understanding of these phenomena is also relatively well advanced. Plate tectonic processes have been studied extensively, most notably in Japan which lies in an active tectonic belt (JNC, 2000, 2005), but also in the USA, for example in the repository programme at Yucca Mountain (O'Leary, 2007). Elsewhere, the focus has been on the potential impacts of sea level change and/or climate change, most notably glaciations, on the repository environment (Bath *et al*. 2000; Marivoet *et al*. 2000; Boulton *et al*. 2001; Degnan *et al*. 2005).

Any assessment of the long-term safety of a repository in hard fractured rock will have to take into account uncertainties relating to geosphere stability. To support these safety assessments, the radioactive waste agencies have developed assessment tools (deterministic, bounding and probabilistic) to address these uncertainties in a safety case and a wealth of examples of how these tools have been applied to address geosphere stability issues in safety cases.

Evaporites have been studied in investigations related to the WIPP in New Mexico, USA (USDoE-WIPP, 2004) and the Gorleben and Asse salt domes in Germany (NEA, 2006c, 2008a). These programmes have demonstrated that, like clays, evaporites have many characteristics that favour inherent stability.

5.8.2 State of knowledge in the UK about Issue 8

In the UK tectonic stability is not an important issue, since over PA timescales only relatively small changes in crustal stress are expected (Nirex, 2001b). The level of seismicity is also low and likely to remain so.

During its investigations in the Sellafield area during the 1990s, Nirex carried out research to understand the impacts of climatic variations on the deep geosphere. This research involved determining the climatic history of the area during the Quaternary period and then assessing whether or not the deep groundwater/rock system shows evidence for these fluctuations (Heathcote and Michie, 2004). While the work was site-specific, the fundamental methods developed and/or demonstrated in the Sellafield area could be employed elsewhere within England and Wales.

Nirex also investigated future climate scenarios and their implications for the post-closure phase of a Sellafield repository. Although the understanding of future climate change has evolved significantly since that time, most notably in terms of the likely timing of the next glaciation, much of the previous work would still be relevant, especially for a site in an area that would be expected to be glaciated (broadly speaking, areas to the north of a line from the Severn to the Wash).

Nirex also participated in several international projects to develop methods for assessing whether or not climatic variations, and in particular glaciations, had affected the deep geosphere (see Bath *et al*. 2000). A major output from these studies was the recognition that mineralogical features could be correlated with past groundwater movements, specifically:

- spatial distributions of oxidised and reduced Fe-minerals (Fe-oxides and Fe-oxyhydroxides, and sulphides, principally pyrite);
- spatial variations in the crystal morphologies of carbonate minerals, which were shown to be correlated with variations in groundwater salinity;
- spatial variations in the chemistry of carbonate minerals, which were interpreted in terms of past variations in groundwater compositions.

The overall conclusion from these studies was that the groundwater system at Sellafield had probably varied little at repository depths during the Quaternary period. Although glaciations had introduced relatively fresh, oxidizing groundwater to the groundwater system, water/rock reactions along flow paths caused conditions to become reducing before repository depths were reached. Furthermore, the deep groundwater system responded more slowly to changes in boundary conditions than the shallower groundwater system. Therefore, although the groundwater system has probably remained in a transient state, never in true equilibrium with the boundary conditions, the rates of change in deep groundwater flow patterns have been too slow to be affected significantly by changing climatic conditions.

The investigations at Sellafield focussed on fractured volcanic rocks and dominantly arenaceous cover rocks. In the UK, there has been relatively little experience in evaluating the stability of mudrocks. However, during the late 1980s several mudrock sites were investigated, leading to a demonstration that they are inherently stable. Additionally, researchers in the UK have been involved in international programmes investigating indurated clays.

5.9 Issue 9: Impact of resaturation

5.9.1 International state of knowledge about Issue 9

The fundamental processes controlling resaturation and its impacts have been investigated widely by national radioactive waste management programmes throughout the world and are well understood (see Ledesma and Chen, 2003; NEA, 2003a; Poppei *et al*. 2003; Alonso *et al*. 2005). However, these processes and impacts are highly coupled, making them difficult to model and predict on the excavation scale. A particular issue is obtaining adequate site-, concept- and design-specific data to enable accurate models to be developed. Typically, large uncertainties in these data are reflected in very large uncertainties on the timing of resaturation and its impacts. Nevertheless, knowledge, data acquisition and modelling have been successfully used by many programmes to demonstrate that limiting worst-case impacts of resaturation will be acceptable.

Owing to the very complex nature of resaturation and its impacts, most programmes have to date made broad assumptions about the timing and homogeneity of resaturation. Experimental work has not always confirmed the accuracy of the assumptions (for example, Alonso *et al*. 2005).

5.9.2 State of knowledge in the UK about Issue 9

In the UK, Nirex considered the impact of resaturation on the post-closure safety case but this treatment was generally simple (see Nirex, 1997a). Since then, resaturation has been considered in the context of gas generation. Additional calculations have been carried out for Sellafield (Bate *et al*., 2006) and there has been some consideration of the way in which an indurated clay might resaturate.

5.10 Uncertainties about the issues at each stage of the staged authorisation process

During the course of the staged authorisation process proposed by the Environment Agency (2008), knowledge on the technical issues at the investigated site should generally improve with time. The impact on safety of uncertainties in technical issues should also become better understood over time. However, unexpected technical issues may arise at any point when investigating an actual site and designing a disposal concept for it. Apparent uncertainties will not necessarily decrease as more information is gathered. There is a tendency for personnel who carry out data interpretations to give greater weight to ‘known unknowns’ rather than ‘unknown unknowns’. That is, there is a general tendency for uncertainties in site data and information to be interpreted, while lack of information is simply ignored. For this reason, additional data acquisition may show a site to be more complex than initially thought, leading to an impression of greater uncertainty; in the absence of data, the site may be interpreted as being relatively simple. There is a general expectation that uncertainties critical to safety will decrease progressively during the course of a well-designed investigation programme.

Uncertainties associated with the technical issues of any future repository programme will depend on the geological environment, disposal concept and repository design. However, it is easier to identify the kinds of uncertainties that might plausibly be resolved at each stage of a site-characterisation process. Activities that can be undertaken to resolve these uncertainties are:

- desk-based studies in which the overall disposal concept and key features of safety cases are defined, allowing:
    - planning of site investigations;
    - planning of supporting research and design programmes;
    - development of more than one concept or variant carried forward;
- surface-based site investigations, in which design/concept possibilities are resolved and repository footprint areas are decided, and which include:
    - progress with research and design programmes;
    - sufficient site characterisation to allow planning and construction of underground structures;
    - sufficient confidence in safety cases being developed to justify the considerable time and expense of underground operations;
    - establishment of monitoring networks;
- underground (URL) site investigations, including:
    - verification of surface-based investigations;
    - additional studies that require large-scale exposure of rock at depth, in particular resolution of uncertainties on interactions of excavations with geosphere – EDZ, resaturation and so on;
    - development and refinement of concept and construction/emplacement techniques and strategies;
    - acquisition of monitoring data to confirm surface-based understanding of the repository’s impact on the whole geosphere system;
    - building of sufficient confidence in safety cases to proceed to full-scale construction;
- construction, involving:
    - large-scale verification of work carried out from the surface and underground;

  - monitoring, which provides information on long-term impacts of the repository on the repository-geosphere system as a whole;
- operations, which are likely to proceed in parallel with construction, as vaults are likely to be completed as needed, including:
  - verification at a large scale of work carried out from the surface and in URL;
  - monitoring, which provides information about the long-term impacts of the repository on the repository-geosphere system as a whole; and
- refinement of closure plans.

6 Safety arguments and synthesis

6.1 General safety arguments in each environment

The development of a deep geological repository will entail the design of an EBS that will work with the geological environment to provide the required level of containment for the wastes under consideration. These may be existing (already conditioned and packaged) wastes or wastes that have not yet been prepared for disposal. The type of EBS required to provide adequate containment for a particular waste type varies with environment. The structure of the post-closure safety case will also differ significantly between systems. In some cases, the role of the EBS may be little more than providing a ‘safe’ environment for waste emplacement, with the geosphere providing the main containment. In others cases, the EBS provides the main containment barrier and the role of the geosphere is largely to protect the EBS and ensure it is able to function as designed. In some cases, the characteristics of the environment will dictate the EBS design and form of the safety case whereas in others, the developer will have more flexibility over the design of the EBS and the form of the safety case.

Given the range of environments considered in the project (see Section 2) and the range of waste types, waste forms and EBS components (see Section 3) it is clear that not all combinations of EBS and environment will provide the required degree of containment for all waste types. There are particular EBS/environments for which it is likely to be impracticable to make a post-closure safety case (or construct a repository). For example, a safety case for the combination of an EBS and geosphere that both provide minimal containment and would be unfeasible. Alternatively, from a technical and economic point of view, some combinations might be considered to be ‘over-engineered’ and therefore not optimised solutions. The combination of an EBS that includes longer-lived waste packages/overpack and a geosphere that provides a high degree of containment is unlikely to be considered an optimised system. However, the extent to which such ‘over-engineering’ is acceptable will depend largely on non-technical factors, such as the extent to which a robust multi-barrier concept is required to build public confidence, and/or regulatory and political circumstances.

The relative importance of the various issues discussed in Sections 3.4.5 and 5 depends in many cases on the role of the different system components in the safety case. In order to evaluate whether or not an issue is ‘important’ for a particular site, it is necessary to know the environment/EBS combination being considered and the likely role/ importance of each component in the safety case. In the sub-sections that follow, an assessment is made of the combinations of environment and general EBS type that might be considered for UK wastes. Note that it is always possible to use an EBS of increased integrity compared to that suggested below. However, this option may not constitute an optimised solution as increased integrity generally results in increased costs, which might not be justified if the resultant improvement in safety is negligible. An assessment is also made of the likely features of the post-closure safety case and of any characteristics of the system that might give rise to ‘issues’ or are specifically required to address ‘issues’. What follows is not an attempt to rank the different environments. It is simply an exercise to help identify the key issues for each one. Other issues outside the scope of this project may be equally important in any future site selection process.

Table 6.1 provides a summary of key safety arguments and counter-arguments.

6.1.1 Environment 1 – Hard fractured rock to surface

In this environment, the host rock is likely to be relatively strong and therefore place few constraints on the physical dimensions of the excavation, although it may be necessary to allow for high stresses. However, the presence of fracture zones and other large-scale heterogeneities may prove significant in determining the repository layout, and hence footprint. It may be necessary to understand the possibly complex structure of the target area in some detail. Current groundwater chemistry is likely to be relatively 'benign' but it may be difficult to demonstrate the required 'stability'[3] of the groundwater geochemistry and hydrogeology.

For this environment, it is likely to be difficult to argue that the geosphere will play a major role in containing contaminants for the groundwater or gas pathway. Therefore the primary containment barrier is likely to be the EBS with the main role of the geosphere being to protect the EBS and ensure that it functions as intended in the long-term.

A repository developed in this environment is likely to require a longer-lived waste package/overpack to provide the required level of containment for the UK's longer-lived and higher activity wastes. It may make significant use of high performance materials such as bentonite and copper/titanium or relatively sophisticated engineering to isolate the wastes from groundwater. The KBS-3 (V and H) concept developed by SKB is an example of the type of higher-integrity EBS suitable for HLW/SF that might be required for this environment.

SKB has also developed an ILW disposal concept for this type of environment. However, the extent to which a similar concept could be used for UK ILW is unclear because the:

- Swedish ILW inventory differs significantly from the UK inventory, with a significantly smaller potential for gas generation;
- the Swedish EBS incorporates a hydraulic cage to reduce interactions between the wastes and the groundwater.

A concept that includes a hydraulic cage may not provide the level of containment that would be required for all components of the UK ILW inventory. A particular difficulty may be caused by the UK ILW waste containers typically being vented to prevent over-pressurisation. These containers will have very little effective barrier function from the point of view of the groundwater pathway. On the other hand, the presence of a hydraulic cage might restrict the ingress of water to the wastes, which conceivably could reduce the rate of gas generation. These potential merits and demerits would need to be investigated in more detail when deciding whether this concept is viable for UK wastes. If an ILW repository was developed in this environment for UK ILW, it might be necessary to adopt special measures to mitigate the impacts of repository-derived gas.

The safety case for this environment is most likely to be based on showing:

- that the integrity of the EBS is sufficiently great;
- a good understanding of the way that the EBS is likely to evolve during the post-closure period.

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[3] See discussions of Issue 8, Section 4.4.8 for what is meant by geosphere stability here.

Demonstrating that the host rock environment is sufficiently stable and that the groundwater is compatible with the engineered components will be important in building confidence in EBS performance.

This environment would provide relatively little containment for repository-derived gas. Therefore, it is unlikely that a safety case could argue successfully that the geosphere on its own would prevent gas migration or retard it sufficiently. Instead, a gas safety case would probably need to demonstrate that the gas is generated sufficiently slowly to prevent a separate radionuclide-bearing gas phase from reaching the biosphere in significant quantities. That is, the gas generation rate would need to be sufficiently small that any gas produced could be dispersed and dissolved in the groundwater, whereupon it would migrate more slowly as a solute. Thus, it follows that in order to develop a safety case it will be necessary to show how the EBS design can sufficiently restrict gas evolution. A higher-integrity EBS would most likely be unsuitable for these gas-producing UK wastes because:

- waste volumes are large, probably making construction of a higher-integrity EBS impracticable;
- prevention of gas release by a higher-integrity EBS could cause very high pressures, which could then result in physical damage to the EBS.

6.1.2 Environment 2 - Hard fractured rock overlain by relatively high-permeability sedimentary rocks in which advective transport dominates

The host rock is likely to have similar engineering and containment properties to the host rock in Environment 1. However, compared to locations with Environment 1, locations with Environment 2 are more likely to have saline water at repository depths. In Environment 2, the overlying sequence has the potential to provide some additional containment for both groundwater and gas pathways, but at the same time may make it more difficult to characterise the host rock. This additional containment is likely to take the form of a combination of increased travel time and dilution/dispersion.

The safety case for this type of environment is likely to be built around the concept of multiple barriers working together to contain or attenuate the release of radionuclides with different properties. Within the safety case, it is likely that both the EBS and the geosphere will play a significant role in providing containment; the precise balance will depend on both the waste concerned and the characteristics of the site. The function of the host rock is likely to protect the EBS and it will be necessary to build confidence in the durability of at least some components of the EBS. The thickness and properties of the sedimentary cover will be important for determining the degree to which it is able to delay or dilute any releases from the host rock, but it is unlikely to provide all of the containment required for all UK wastes. It may therefore be necessary to characterise both the host rock and the overlying cover sequence in considerable detail.

To some extent, the degree of containment required from the EBS can be selected by the developer to meet a required minimum level. There may be a trade-off between:

- investing in a higher-integrity EBS (complex and more expensive) while investing less in building confidence in geosphere performance;
- investing less in a lower-integrity EBS while investing more in building confidence in geosphere performance.

Thus, the EBS might contain any or all of the engineered components listed in Section 3.4.

Sellafield, which was extensively investigated by UK Nirex Ltd during the 1980s and 1990s, would be classified as Environment 2. The major challenges to the post-closure safety cases that have been proposed for Sellafield relate to the migration of repository-derived gases and the complexity of the environment (see Nirex, 2005a).

6.1.3 Environment 3 - Hard fractured rock overlain by sedimentary rocks containing at least one significant low-permeability unit in which diffusion dominates solute transport

The host rock is likely to have similar engineering and containment properties to the host rock in Environment 1 and Environment 2. As for Environment 2, it is more likely that saline water will be encountered at repository depths than in Environment 1. The overlying sequence has the potential to provide significant additional containment but at the same time may make it more difficult to characterise the host rock.

It is probable that the low-permeability unit(s) in which diffusion dominates solute transport will provide the main barrier to radionuclide release in the safety case for both groundwater and gas pathways. The unit(s) could also help prevent the EBS from being affected by external challenges, for example the penetration of sub-glacial water in a future glacial period. It will therefore be necessary to characterise any low-permeability units in some detail to build confidence in their continuity and performance. The spatial extent over which characterisation will be necessary will depend upon the characteristics of the flow system at the particular site. However, the areal extent is likely to be greater than in Environments 1 or 2.

While the EBS will provide some degree of long-term containment, its primary function may be to ensure that the waste can be disposed of safely. A lower-integrity solution that uses simple and less durable materials such as cement and steel and makes only limited use of more exotic (and durable) materials may therefore be acceptable.

The safety case for this type of environment is likely to be based around demonstrating the expected good performance of the geosphere barriers in the units overlying the host rock. Strength in depth (multiple barriers) will be provided by the performance of the EBS in limiting releases to the geosphere. The greatest contributor to risk that needs to be addressed by the safety case is likely to be the potential for the repository accesses to provide pathways for groundwater and/or gas through the low-permeability unit. Experience from programmes in other countries has shown that these risks are likely to be extremely small, but they will naturally tend to influence safety case development. Building confidence in the sealing of the repository access shafts and drifts and site investigation boreholes may therefore be important.

The project did not identify any organisation that is currently developing a safety case for a deep geological repository in this type of environment.

6.1.4 Environment 4 - Bedded evaporite host rock

Given the likely excellent performance of the geosphere for this environment, the EBS probably only needs to provide the integrity required to ensure operational safety. However, the bedded evaporite host rock may present a number of engineering problems that are not present in other environments (although there are some similarities with the plastic clay host rock environment). The strength of the host rock may influence the tunnel span and/or cavern geometry that is/are practicable. Most significantly evaporites are subject to creep, which influences the engineering measures needed to keep the excavations open for any significant length of time.

Depending upon the particular characteristics of the salt, timescales longer than a few months to a few years may be impracticable, although caverns excavated in some formation have been stable for decades. This creep property will also present problems should the disposal concept need to include retrievability. However, the extent to which this lack of strength may be an issue for repository design will depend on the particular characteristics of the salt (like the presence or absence of impurities such as clay), natural stress state and depth.

Some of the properties that would potentially make an evaporite host rock an engineering challenge contribute to its likely excellent behaviour as a barrier to the release of radionuclides. It is likely that the host rock would converge and that any excavation damage would self-heal on a timescale of a few hundred years. The host rock is expected to be of extremely low permeability and to be within a low-permeability rock sequence; this is necessary for the long-term preservation of the halite host rock. Thus, it could reasonably be expected that the geosphere in this environment would provide the required degree of containment for the groundwater pathway, despite the potentially corrosive nature of the groundwater (brine). Building confidence in the performance of repository seals will be important. However, the extremely low permeability of the host rock could result in potentially damaging overpressures if any significant volumes of gas were generated in the repository. There are significant uncertainties regarding gas generation in this environment, since gas generation rates will depend upon water availability, which is likely to be very limited.

The safety case for Environment 4 is likely to be based on demonstrating the good containment properties of the host rock and overlying strata. The only aspect of the EBS that is likely to feature prominently in the long-term safety case is the performance of the seals and backfill. It will be necessary to demonstrate that the EBS seals do not provide a weak point in the containment system and that any repository-generated gas cannot compromise the system integrity. In some cases, it may also be necessary to show that the seals and/or backfill function to restrict the inflow of brine to areas of the repository within which the wastes are emplaced.

The most significant problem in the safety case may relate to human intrusion. Evaporites are a potential resource both for salts and as host environments for storage caverns (because of their excellent containment properties).

The US DoE has successfully developed a safety case for the WIPP facility for TRU in a bedded salt environment. The German programme has spent many years investigating and developing a disposal concept for HLW and SF in a salt dome. Also in Germany, a closure concept was developed for the Morsleben repository for LLW/ILW, which is located in folded bedded salt.

While there are no salt dome formations in England and Wales that would be accessible for repository construction, some of the lessons learned during the German investigations of salt domes may be relevant to a bedded salt environment. The German experience at Morsleben and the US experience at WIPP may also be relevant to potential bedded salt host rocks in England and Wales. There is also experience within the UK of developing and operating a deep (greater than one km) mine in salt (dominantly halite and sylvite) at Boulby in North East England.

6.1.5 Environment 5 - Siliceous sedimentary host rock

The siliceous sedimentary host environment has many similarities to Environments 2 and 3. Two variants have been defined, depending on whether or not the overlying cover sequence contains a low-permeability unit. As with Environments 2 and 3, the overlying rocks may make it relatively difficult to adequately characterise the host rock using surface observations alone. Any suitable host rock is likely to be of similar or greater overall permeability to the hard fractured host rock of Environments 1-3. However, the greater matrix porosity will result in a very different style of groundwater flow through the host rock. In Environment 5, flow will probably be relatively uniform rather than focused within only a few fracture zones. However, fracture flow and flow along bedding planes is also possible, especially for fine-grained or well-cemented rocks.

The geotechnical properties of the host rock may impact upon the repository design, particularly so if it is strongly bedded. The host rock may dictate the shape of the openings and the maximum permitted span and it may be necessary to install (and maintain) excavation support.

The form of the safety case, and hence the types of materials that might be used in the EBS will depend on whether or not there is a low-permeability unit in the cover sequence. If such a unit is present, a lower-integrity EBS should be sufficient but if the cover sequence consists entirely of higher-permeability rocks then a higher-integrity EBS will be required. Likewise, the safety case will take a similar form to either Environment 2 or 3, depending on the presence or absence of a low-permeability barrier or barriers in the overlying sequence.

The project did not identify any organisation that is currently developing a safety case for a deep geological repository in this type of environment.

6.1.6 Environment 6 – Indurated mudstone host rock

For this environment, the most likely host rock is a dominantly flat-lying and un-deformed, although indurated, mudstone. The host rock unit may be relatively thin (possibly only 50 m thick). The geotechnical properties of the host rock will to a large extent influence the repository design and layout because they are likely to influence the maximum practicable excavation spans (possibly 10 m or less) and result in the need for (potentially significant) excavation support. The other potential host rock is a tectonised mudrock. In this case, cleavage and other structure may further impact upon the geometry of the excavations.

The host rock is expected to be low or very low permeability, such that solute transport is likely to be dominated by diffusion. Porewater within the host rock will probably be at least moderately saline since these rocks are:

- typically marine in origin and their porewaters may contain at least a component of fossil seawater;
- evaporite deposits which are relatively common within the UK sequences that contain this kind of rock

The case where the groundwater is highly saline (a brine) falls under the category of Environment 9.

The host rock is expected to provide significant containment. Therefore, the safety case is likely to be based on the host rock being the primary barrier to radionuclide release. Strength in depth (multiple barriers) will be provided by the performance of both the EBS and the host rock. The overlying rock strata may also contain low-permeability units that could act as additional barriers. Consequently, it may be possible to achieve the required performance using a lower-integrity EBS.

The main challenge to the safety case is likely to arise from the potential for repository-generated gas to damage the EBS and form preferential pathways through the host rock. Within the UK, the possible presence of hydrocarbons or coal may be an issue.

A number of waste disposal organisations are currently developing safety cases in this type of environment, most notably ANDRA and Nagra which are developing safety cases for the disposal of HLW/SF and some ILW.

6.1.7 Environment 7 - Plastic clay host rock

Like the indurated mudstone host rock of Environment 6, the plastic clay host rock is likely to be dominantly flat-lying and un-deformed. The host rock unit could be relatively thin (possibly only 50 m thick).

The plastic clay host rock may present a number of engineering problems. It is a relatively weak rock which, combined with a tendency to creep, may influence the tunnel span and/or cavern geometry that is/are practicable. It may prove impracticable to construct tunnels of greater than 5-10 m span and all excavations will probably need to be fully lined. Thus, the characteristics of the host rock will largely define the repository design and may influence waste package size.

The host rock is expected to be of low permeability and its tendency to creep is likely to result in excavation and other damage being self-healing. Thus, it would be reasonable to expect the host rock to provide the primary barrier to radionuclide release in the safety case. From the post-closure point of view, a lower-integrity EBS is likely to be adequate. However, the EBS performance will still contribute to overall confidence in the safety case by providing additional barriers. It will be easier to defend a safety case that relies on multiple barriers than one relying on only a single barrier. It will be necessary to build confidence in the performance of the EBS seals to demonstrate that these do not form preferential pathways. Over-pressurisation of the EBS and host rock as a result of repository-derived gas may be a major challenge to the safety case.

The Belgian waste disposal organisation ONDRAF/NIRAS is currently developing safety cases for the disposal of HLW/SF and ILW in this type of environment.

6.1.8 Environment 8 - Carbonate host rock

The low-permeability carbonate host rock environment (Environment 8a) is likely to have many similarities to the mudrock host rock (Environment 6, Section 2.2.7), although it may be possible to construct larger openings in the carbonate. The safety case is likely to have similar characteristics to those of the Environment 6 safety case.

The massive host rock variant (Environment 8c) is likely to pose many of the same problems as the siliceous host rock overlain by a sequence containing a low-permeability unit (Environment 5c, Section 2.2.6). The safety case for Environment 8b will therefore have the same overall characteristics as the one for Environment 5c. This type of environment will tend to be located within the Mesozoic basins of England and Wales where the potential for coal or hydrocarbons may result in a risk of human intrusion. In relatively permeable examples, carbonate-dominated groundwater chemistry and the nature of the host rock mean that significant effort may be required to demonstrate that interactions between the EBS and host rock will not impact on system performance. For example, it may be necessary to consider the carbonation of cementitious barrier components.

OPG is currently developing a safety case for the disposal of LLW and ILW in a very impermeable limestone formation at the Bruce site (Hatch Limited, 2008). In Germany, DBE has developed a concept and safety case for the disposal of LLW and ILW in very low-permeability oolitic limestone at the disused Konrad iron ore mine (Biurrun and Hartje, 2003).

6.1.9 Environment 9 - Non-evaporitic host rock with hypersaline groundwater

This environment has a wide range of potential host rocks and therefore potentially shares features with other environments in terms of the control the host rock exerts on repository design/layout. The key feature of this environment is that the likely low groundwater flow rate associated with the hypersaline groundwater in the repository environment may be significant in terms of providing containment. This low-flow regime is likely to be an important component of the safety case.

The key challenges for this environment will be to gain adequate confidence in the durability of the EBS components in the highly saline groundwater, and demonstrate the stability of the hydrogeological regime (particularly when it has been disturbed to characterise, construct and operate the repository).

The only organisation that is currently developing a safety case for a deep geological repository in this type of environment is OPG in Canada, where the Bruce site contains brine porewaters. However, in this case the host rock has an extremely low permeability, so low-flow rates are not thought to be caused primarily by the high density of the saline porewaters.

Table 6.1 Summary of key safety arguments and counter-arguments.

Environment	Key arguments	Key counter-arguments
Environment 1 – Fractured rock to surface	• Provides a 'stable' environment with relatively benign conditions in which highly engineered EBS can operate	• Highly dependent on EBS integrity – in the long term, geosphere contributes little to multiple containment barriers • Potential for relatively rapid migration of gas • May be difficult to demonstrate host rock stability
Environment 2 - Fractured hard rock overlain by relatively high-permeability sedimentary rocks	• Multi-barrier system likely to be used, with geosphere enhancing and adding to containment provided by the EBS	• May be difficult to characterise owing to its complexity • Complex safety case • Potential for rapid gas migration
Environment 3 - Fractured hard rock overlain by a sedimentary rock sequence containing at least one significant low-permeability formation	• Geosphere performance is able to dominate safety arguments • EBS performance provides multiple barriers	• May be difficult to characterise owing to its complexity • Access shafts and so on may compromise low-permeability barrier
Environment 4 – Evaporite host rock	• Existence of host rock is an indicator of its likely stability • Good containment properties	• Human intrusion possibly more likely than in other environments • May be difficult to guarantee EBS seals, especially with respect to gas generation
Environment 5 – Siliceous host rock	• See Environment 2 or 3 depending on whether or not low-permeability layer in overlying sequence	• See Environment 2 or 3 depending on whether or not low-permeability layer in overlying sequence
Environment 6 – Mudrock host rock	• Host rock can provide primary barrier • EBS performance provides multiple barriers	• Gas overpressurisation

Environment	Key arguments	Key counter-arguments
Environment 7 – Plastic clay	• Host rock can provide primary barrier • EBS performance provides multiple barriers	• Gas overpressurisation
Environment 8 – Carbonate host rock	• See Environment 5 or 6 depending on host rock	• Interactions between carbonate-rich groundwater and cements
Environment 9 – Non-evaporite with hypersaline groundwater	• Stable low-flow hydrogeological regime	• Durability of EBS materials may be questionable in hypersaline water

6.2 Implications of identified technical issues for safety arguments in each environment

This section discusses each of the technical issues in the context of the geological environments and the likely form of the corresponding safety case. The aim is to highlight in which environments an issue (or aspect of an issue) is likely to be important and in which environments it is likely to be less so. Table 6.3 and Table 6.4 summarise the influence of the different technical issues in each environment. Table 6.5 lists some of the major uncertainties relating to the technical issues.

6.2.1 Issue 1 - Influence of different waste form types on the design of the EBS

The geological/hydrogeological environment and the EBS (which may include the waste form itself) must function as a combined system to achieve acceptable overall performance. The choice of environment and host rock both defines the functions the EBS must fulfil within the safety case and places constraints on the EBS components that can be used to achieve this. Most obviously, the degree of containment provided by the geosphere and hence the credit that can be taken in the safety case for the performance of the geosphere defines the 'type' of EBS that will be suitable. Environments 1 and 2, in which the geosphere provides relatively little containment, will require EBS designs to have greater integrity than environments where there is one or more low-permeability layers to provide containment. It could be difficult to make a safety case for some wastes in some environments.

For the UK inventory, the greatest difficulty is likely to be designing an EBS to provide sufficient containment for the relatively large volume of long-lived ILW, in environments where it is impracticable for the post-closure safety case to rely on geosphere containment (in Environment 1, and to a lesser extent Environments 2, 5a, and possibly 8c). Some of these waste form types have significant potential to generate gas and the vented design of the standard UK ILW waste containers provides little containment for soluble, mobile species such as Cl-36 and I-129. Gas generation is considered in more detail in Section 6.2.6. The potential for the waste form to generate gas is, however, an important factor that will influence EBS design, as it may be necessary to design the EBS to withstand high gas pressures, allow gas to escape or have sufficient void space to prevent over-pressuring.

The properties of the waste packages will define the minimum dimensions of the underground openings and the types of equipment required to handle them. It is likely that most packages will need to be handled remotely. The heat-generating properties of HLW and SF packages will determine their spacing within the repository. Some UK packages have large dimensions (such as the 4-m box) and packages may be very heavy (especially for LLW). These considerations impact on layout and aspects such as the feasibility of implementing a disposal system that incorporates full retrievability (as defined by Nirex). Clearly, stronger and more massive host rocks (Environments 1, 2, 3, 5, possibly 8) offer more options than the weaker, and generally more thinly bedded, host rocks (Environments 4, 6, 7).

In a hard fractured host rock (Environments 1, 2 and 3) and probably to a lesser extent in a siliceous or carbonate host rock (Environments 5 and 8) it may be desirable to ensure a minimum distance (termed a 'respect distance' by some programmes) between major structural features (such as fracture zones) and the disposed wastes.

Not only will this requirement strongly influence the layout, it also means that the locations of potential layout determining features will need to be established during the site investigations (see also Issue 7, Section 6.2.7). To allow this flexibility in design, it will be necessary for the host rock to be sufficiently extensive.

The weaker host rocks (notably Environments 4, 6 and especially 7) may influence the maximum practicable dimensions of the underground openings and therefore impact upon the layout and operational approach. Tunnel/vault spans may need to be less than 8-10 m, which will affect the maximum size of package that can be handled underground. The minimum practicable vault span for the currently authorised UK packages is five metres (limited areas with larger span may be required for handling). Environment 7 is the only environment where there is a significant possibility that the maximum practicable tunnel span will be close to or smaller than five metres. However, as a general rule, as the tunnel span decreases the footprint increases or the underground layout becomes more complex or both.

Creep may be a significant issue in the evaporite (Environment 4) and plastic clay (Environment 7) host rocks, and to a lesser extent in other rocks. This process has implications for the design of the infrastructure and linings and it may not be practicable to keep vaults open for more than a few tens of years, owing to the need for ongoing maintenance. Conversely, high rock stresses may be an issue for the stronger host rock types. These may control the span and geometry of the excavations and influence the repository layout and practicalities of keeping excavations open for extended time periods.

Achieving long-term retrievability (retrievability or reversibility as proposed in NDA's PGRC concept, Nirex, 2003b) is likely to be a major issue for many environments. As currently defined in the UK, retrievability would involve simple reversal of the waste emplacement process during the period prior to backfilling, which could last for up to several hundred years (Nirex, 2003b). This kind of retrievability may be impracticable in some environments (such as evaporites or plastic clays), or achievable but extremely costly in others (such as indurated clays). Small span tunnels/vaults will preclude the use of overhead crane systems such as proposed by Nirex for package emplacement and mean that packages will have to be emplaced on a first in-last out basis. If the option of retrievability is to be maintained in these environments, there may need to be relatively early backfilling. However, in this case there may need to be available methods that could remove the backfill later to gain access to the waste if necessary.

6.2.2 Issue 2 - Interactions between engineered barrier components

Interactions between engineered barrier components will be of most significance in those disposal systems where the safety case depends strongly on the performance of the EBS (Environments 1 and 2, 5a, possibly 3 and 8c and, depending on the characteristics of the rock sequence, perhaps 9). In these cases, the EBS components may need to be extremely durable (Issue 5, Section 5.5). Unfortunately, as outlined in Section 4.4.3, the magnitudes of most of the interactions of interest increase with the groundwater flow rate through the repository, because the interactions require solute transport to occur. Environments 1, 2, 5b and 8c are most likely to have the highest groundwater flow rates. Thus, the magnitude of the interactions is likely greatest in these environments. These relatively extensive interactions may increase the difficulty of making a safety case, since it will be harder to demonstrate that there is no net negative effect of the reactions than in a case where groundwater flow is slower.

6.2.3 Issue 3 – EBS/host rock interactions

The relative importance of EBS/host rock interactions depends on the role of the host rock in the safety case. This issue is therefore most significant in environments where the EBS or host rock plays a major role in the safety case. The EBS potentially provides the primary containment in Environments 1, 2, 5a, possibly in Environments 3 and 8c and, depending on the characteristics of the rock sequence, Environment 9. As discussed in Section 6.2.2 these are the environments where chemical interactions, mediated by flowing groundwater, are likely to be largest. The host rock provides a key barrier in Environments 4, 6, 7, and 8a. However, groundwater flow rates are expected to be low in these environments so the extent of EBS/host rock chemical interactions will be much more limited.

The other major EBS/host rock interaction is the development of and evolution of the EDZ. The general consensus is that the EDZ is likely to have only a limited impact on post-closure safety. The largest impacts are likely to be in hard fractured rocks (Environments 1, 2 and 3).

6.2.4 Issue 4 - Impact of groundwater on EBS materials (including the impact of saline water)

There will be some degree of interaction between the host rock groundwater/porewater and the EBS materials because the water will not be in chemical equilibrium with the solids present. These interactions are usually considered to result in degradation of the EBS materials, as discussed in Section 5.4. However, some of the degraded materials and their degradation products may be beneficial to system performance and form part of the design of the system. For example, bentonite swells when it comes into contact with groundwater and most EBS designs that use bentonite assume that this process will occur.

The one environment where this issue may not need to be considered is Environment 4, evaporite host rock. In this environment it is possible to imagine a system with minimal engineering and an evaporite backfill. Further, it would be expected that such a system would contain minimal free groundwater and overall water flow would be negligible. Thus, this issue may be of limited significance in Environment 4.

As with Issue 2 (Section 4.4.2), the impact of groundwater on EBS materials will be of most significance in those disposal systems where the safety case depends strongly on the performance of the EBS (Environments 1, 2 , and 5a, and possibly 3 and 8c). This issue is also important for Environment 9 where the groundwater is by definition hypersaline and, apart from being a non-evaporite host rock, the geology is undefined. Environments that fall into the category of Environment 9 include those where:

- the post-closure safety case can rely on the presence of low-permeability barriers in the geosphere to provide containment;
- the safety case depends heavily on the combination of EBS performance and the hydrogeological regime that results from the presence of hypersaline water.

In this second case, the impact of saline groundwater on EBS materials may be a particular issue.

The potential for poor seal performance due to degradation by interactions involving groundwater / porewater could be an issue in some cases of Environment 9. This could be the case if the host rock is of low permeability and the safety case depends on the containment properties of the host rock.

6.2.5 Issue 5 - Duration for which EBS materials may maintain their functions (durability)

When discussing durability, there is often an underlying assumption that the safety case depends on the durability of the EBS and therefore it is necessary to use only highly durable materials in its construction. However, the extent to which overall safety depends upon the durability of EBS materials will depend upon the nature of a particular disposal concept and the characteristics of the disposal site. For many of the environments considered in this project (such as Environments 3, 4, 6, 7) the primary containment barrier is likely to be provided by the geosphere and the role of the EBS in providing containment will be secondary. The primary function of the EBS in these cases will be to provide a safe environment in which to emplace the waste and perhaps in the case of HLW/SF to provide containment until the thermal peak associated with the decay of short-lived species has passed.

Optimising the disposal system will involve optimising the materials used in the EBS so that they are sufficiently durable to perform their safety case functions but not over-engineered such that there is a large cost penalty. As with the other issues that address EBS materials (Issues 2, 3, 4 in Sections 4.4.2, 4.4.3 and 4.4.4 respectively) this issue will be of most importance in environments where the containment provided by the EBS is a major safety argument. These environments are Environments 1, 2 and 5b, possibly 3 and 8c and some cases of 9. In each of these cases, the EBS will need to have sufficient integrity.

6.2.6 Issue 6 – Gas/groundwater interactions

Gas/groundwater interactions are least likely to be a potential threat in Environment 3, Environment 5a, with a low-permeability layer in the overlying sequence, and Environment 8c, with a massive carbonate host rock. In the other environments, gas is more likely to be problematical and may present three different challenges to a safety case.

Firstly, in environments where the geology provides little containment for the gas, there is the potential for relatively rapid release of a free gas phase to the surface. This may be an issue for Environments 1 and 2, Environment 5b, which has no low-permeability layer in the rock sequence above the host rock and, depending on geology, Environment 9. In addition to the geological sequence providing relatively little gas containment, the gas generation processes are not likely to be water-limited. That is, generation rates will be governed by reaction rates rather than water availability.

Secondly, in environments where the host rock has a low permeability, it may be difficult for any gas generated within the repository to escape and there is the potential for damaging overpressures to build up. The gas pressure has the potential to disrupt the EBS and perhaps the host rock. These processes could result in a loss of containment both for gas and for dissolved radionuclides, which would exploit the pathways created by the gas. However, it is also possible that the low permeability of the host rock would limit the availability of water to the gas-generating reactions. These latter will be dominantly corrosion reactions in HLW/SF repositories and a combination of corrosion and organic-matter degradation reactions in LLW/ILW repositories. The restricted water supply could potentially limit the rate of gas production to a level where damaging pressures cannot build up. The analyses required to understand these phenomena are particularly difficult. This category covers Environments 4, 6 and 7, Environment 8a, with a low-permeability host rock, and, depending upon the host rock type, potentially Environment 9.

Thirdly, many EBS designs (such as KBS-3, the ANDRA and Nagra designs) for HLW/SF rely on a bentonite buffer to protect the waste canister and provide the primary containment within the EBS. Corrosion of the inner liner in the KBS-3 concepts or the carbon steel overpack in the French and Swiss concepts will result in the generation of hydrogen gas. If the rate of gas generation exceeds the rate at which it can diffuse away, a free gas phase will develop. Experimental studies have shown that this free gas phase is likely to escape by fracturing the bentonite buffer. It is generally assumed that the fractures reseal and do not provide a preferential path for the migration of dissolved radionuclides, although this process has yet to be demonstrated under in situ repository conditions. This issue may be significant for systems that rely on a bentonite buffer where the safety case is strongly dependent on EBS performance (Environments 1, 2 and 5a, possibly 3 and 8c and, depending upon host rock type, 9).

6.2.7 Issue 7 - Characterising the site adequately

The requirement to characterise a site adequately applies to all of the geological/ hydrogeological environments but the emphasis placed on different aspects of the system will depend on the role that the geosphere plays in the post-closure safety case. The discussion below is applicable to any UK environment, except where comments are made regarding a specific environment.

Whichever geological/hydrogeological environment is being considered, it is important to avoid quickly concentrating on a small area which is believed to show greatest promise, based on pre-existing information. Instead, it is important to develop a broad understanding of a proposed repository site from the inception of investigations. That is, it is desirable to study the entire geological/hydrogeological system surrounding the site at the start. Here, the geological/hydrogeological system refers to the volume of rock occupied by the groundwater flow paths that could potentially affect the proposed site of the repository. Initially the system boundaries must be judged largely using existing data and desk studies. It is important to ensure that uncertainties in the locations and characteristics of the system boundaries do not result in the area of general investigation being too restricted. To achieve this goal the initial area estimated from existing data and desk studies should be greater than the actual area within which groundwater flow could impact upon the repository. When defining the area of general investigation, it is also important to consider not only the present groundwater flow system but also how the flow system might evolve in future.

This approach requires analysis of the regional geological and hydrogeological setting, which implies that studies such as the regional water balance would be required (in contrast to concentrating on obtaining as many hydraulic conductivity data as possible). There are also implications for the area over which investigations may be required. Where the groundwater flow system is of relatively limited lateral extent, and/or the groundwater fluxes are very small, such investigations may include mainly geological mapping and limited hydrological and hydrogeological studies. The latter condition follows because small groundwater fluxes mean that over timescales relevant to safety, only groundwater that is presently relatively close to the repository need be considered. These circumstances are most likely to occur where relatively permeable host rocks extend to the surface (Environment 1) or the entire geological sequence is dominated by low-permeability rocks (some instances of Environment 4 and possibly 6).

In contrast, in some sedimentary rock environments investigations could be required over an extensive area, possibly of several hundreds of square kilometres. These environments are those where the geology includes relatively permeable rocks interstratified with less permeable ones (the host rocks themselves would be chosen to be of low permeability). Such investigations are likely to require deep boreholes, perhaps at considerable distances from where the repository might eventually be sited. The investigations carried out by ANDRA are a good example of this type of investigation. For the geology of England and Wales, all environments except Environment 1 probably fall into this category. However, a coastal location may significantly limit the area of investigation as the saline interfaces limits flow paths by forcing discharge in the coastal zone.

In a fractured rock environment such as is being investigated by SKB in Sweden (Environment 1), the geographical extent of the area to be characterised is relatively small, covering only a few tens of square kilometres. The SKB investigations at Laxemar and Forsmark use approximately the same number of deep boreholes (25-30) as the ANDRA investigations at Bure in France, despite the very different geographical extents and focuses of the investigations.

When designing the site investigation, it is important to ask questions such as:

- What do we need from the site?
- What does the geosphere need to offer in order to demonstrate that radioactive waste could be disposed of here safely?

These are rather similar to the questions posed in the early stages of SKB's repository programme in their report entitled *What requirement does the KBS-3 repository make on the host rock?* (Andersson *et al*., 2000).

An integrated approach to the investigations is good practice. For this to take place, a dedicated team would need to be set up well in advance of the investigation itself. This team should include representatives from the various components of the investigation programme (geology, hydrogeology, geochemistry and so on), together with representatives from safety assessment and repository design/engineering. Good examples of such an approach, and the methods they employ to work collectively, are provided by several existing waste disposal programmes (such as ANDRA, Nagra, SKB and OPG). One very important point here is the considerable time that is required to set up such a team and for it to function efficiently. Again, considerable experience is available from other waste disposal programmes. The integration team would have an important function through all phases of the investigations and would be intimately involved in all aspects of the modelling.

A similar approach needs to be followed in the development of any URL programme. Since the conclusion of the Sellafield investigations in 1997, the UK has put little effort into developing experience in URLs, although this may be changing with the Government's decision to implement geological disposal. Many programmes elsewhere have gathered much experience in designing and operating these facilities (Äspö in Sweden, Onkalo in Finland, Mont Terri Tunnel and Grimsel in Switzerland, Mol in Belgium, Tono and Horonobe in Japan, Yucca Mountain in the USA and Whiteshell in Canada). UK scientists have participated, as consultants to overseas programmes, in some of the experiments that have been carried out in these overseas facilities but have generally had little or no involvement in the development and operations of such facilities. It would be desirable to learn from the overseas experience, well in advance of the construction of any new facility. This approach would allow proper planning of facility construction and subsequent investigations to be carried out.

International experience has shown that the planning of URLs must be closely matched to the geological environment being evaluated. For example, construction of URLs in fractured crystalline rocks needs to take into account relatively high groundwater inflows, which may need to be minimised using grouting. However, the grout impacts upon the geochemical investigations that can be done. A URL in a plastic clay would need to be constructed with relatively narrow tunnels that can readily be supported for the duration of the underground investigations. These investigations then need to be planned taking into account the locations and characteristics of the supports.

Modelling should be kept as simple as possible, consistent with achieving its objectives. If this is not done, too much time is spent in model development and complex models are likely to require data that are difficult to obtain at the density required. Considerable time constraints are likely to exist, especially in the earlier stages of the investigations, and it is better to be able to run several phases of relatively simple models, rather than only a limited number of complex ones.

The kinds of models that are needed, and the ways in which the models should be used, will vary between the different environments. For example, in fractured crystalline host rocks (Environments 1, 2 and 3) it will generally be necessary to use fracture network models to simulate groundwater and/or radionuclide flow. In contrast, in plastic clays (Environment 7), equivalent porous medium models in which transport of water and solutes (including radionuclides) is modelled by diffusion will be appropriate.

It is important to learn as much as possible from other industries (such as mining, mineral assessment, hydrocarbons industry) and from other waste disposal organisations.

6.2.8 Issue 8 - Demonstrating long-term stability

There are important differences between the geological environments in the ease with which it may be demonstrated that the system at depth is stable. It is likely to be easier to demonstrate such stability in argillaceous rocks than in any other rock type (although the argillaceous rock in this regard does not necessarily have to be the host rock itself, but could be one or more of the low-permeability barriers in the geological succession).

The relative ease with which stability can be demonstrated depends on:

- the likelihood of being able to find evidence in the rock that will convincingly demonstrate the past existence of stable groundwater (for at least the last 100,000 years);
- the likelihood that all elements (THMC) of the geologically stable conditions at depth have been maintained.

The likely ease with which stability can be demonstrated for each environment is given in Table 6.2, which indicates the relative level of ease on a scale of one to five, with one being the easiest and five the most difficult. These scores do not imply that environments with a score of five are definitely unstable, but rather that:

- demonstrating stability in such environments is likely to be more difficult;
- such environments possess some characteristics which tend to reduce their capability to buffer the effects of external events, such as climate change.

Stability is only one of many issues that need to be considered when evaluating the suitability of a site for a repository. Furthermore, the extent to which a demonstration of stability actually matters for a safety case will probably vary from environment to environment and from concept to concept. Thus, the scores in no way reflect an overall ranking of the environments in their suitability to host a deep geological repository.

Table 6.2 Ease with which stability might be demonstrated.

Geological/hydrogeological environment	Ease of demonstration of stability
1	4-5
2	4-5
3	1-3
4	4-5
5	1-3
6	1
7	1
8	1-3
9	2-4

6.2.9 Issue 9 - Impact of resaturation

The degree to which the host rock will become desaturated during operations, and the degree to which it may be altered (see Issue 7, Section 4.4.7), is likely to depend on the length of the operational period. Following closure, the repository will resaturate. The timescale for resaturation varies significantly between environments, with predictions ranging from a few years to many thousands or tens of thousands of years depending on the host rock and repository design. While resaturation is occurring radionuclides cannot leave the repository by advection.

In broad terms, the resaturation time will be proportional to the groundwater flow rate in the host rock. Repositories in more transmissive host rocks (Environments 1, 2, 3, 5, 8c) might be expected to resaturate more quickly than those in low-permeability rocks (Environments 4, 6, 7). Heterogeneity in resaturation may be significant because it can lead to non-uniform properties within the engineered barriers. This is more likely to occur in host rocks where flow is dominantly in discrete features (Environments 1, 2 and 3).

In vaults where there is significant potential for gas generation, there may be a complex coupling between resaturation and gas generation. Water from resaturation participates in the gas generation process but a build-up of gas pressure within the vault may inhibit resaturation. Understanding the rate of resaturation is particularly important for predicting the evolution of compacted bentonite buffers. The thermal conductivity of bentonite increases with saturation. If the buffer resaturates more slowly than allowed for by the design, it may not be able to conduct heat away from the waste canister sufficiently well and may become ‘baked’. This overheating reduces its swelling pressure, tends to promote crack formation and can lead to a redistribution of mass, especially silica, within the buffer. All of these processes may impair the function of the buffer.

Relatively rapid resaturation may be necessary to ensure the correct functioning of the EBS, because the EBS is likely to be optimised for the expected long-term conditions (saturated and reducing). This has potential implications for strategies that plan to keep the vaults open for a significant length of time following waste emplacement. In this case, it would be necessary to design an EBS that can function under two different sets of environmental conditions. Such a strategy is likely to add cost and uncertainty.

On a larger scale, understanding the dependence of material properties, in particular thermal conductivity, on saturation is important in determining repository layout for heat-generating wastes. It is quite likely that the thermal peak will occur before the end of resaturation.

Most models assume uniform resaturation but this is unlikely to be the case in practice. For example, resaturation experiments carried out by SKB have shown a large variation between adjacent deposition holes. The implications of this heterogeneity for the long-term safety case are unclear.

Table 6.3 Influences of Environments 1, 2, 3, 4 and 5 on the technical issues.

<table>
<tr><th rowspan="2">Technical issues</th><th colspan="5">Environments</th></tr>
<tr><th>1
Hard fractured rock to surface</th><th>2
Hard fractured rock overlain by relatively high-permeability sedimentary rocks</th><th>3
Hard fractured rock overlain by sedimentary rocks containing at least one low-permeability unit</th><th>4
Bedded evaporite host rock</th><th>5
Siliceous sedimentary host rock</th></tr>
<tr><td></td><td colspan="5">General comments on geological environments</td></tr>
<tr><td></td><td>The EBS has a critical physical barrier function as the geosphere cannot be relied on as a physical barrier.</td><td>Chemical functions of the EBS may be as important for safety as physical functions.</td><td>The geosphere is a significant barrier so a lower-integrity EBS may be adequate.

The low-permeability cover sequence is likely to restrict deep groundwater flow.</td><td>Chemical functions of the environment are at least as important as physical functions.

Metal corrosion, concrete degradation enhanced.</td><td>Chemical functions of the EBS may be as important for safety as physical functions.</td></tr>
<tr><td>1 (For HLW/SF) Influence of different waste form types on the design of the EBS

Limited knowledge about decay effects on EBS materials – but possibly minor significance.

Limited knowledge about microbes (may be significant for some waste materials).

Behaviour of any Pu/U waste forms must be determined.</td><td colspan="2">EBS design must ensure sufficiently low waste dissolution rates (which is general to all environments but more significant for fractured rock environments with relatively high groundwater fluxes), taking into account:
• instant release fraction (IRF) of wastes;
• matrix dissolution under realistic repository conditions (notably pH, redox, gas partial pressures, groundwater salinity);
• characteristics of UK fuels, glass and ceramic waste forms and long-term degradation rates. Effect of alkaline fluids if interaction occurs between cemented ILW and glass.

Longer-lived waste packages/overpacks are needed for fractured rock systems if there is significant groundwater flow and therefore knowledge of corrosion is important; corrosion will depend on the water chemistry.

Geometry of EBS may depend on the spatial distributions of fractures in the host rocks.</td><td>As for Environments 1 and 2 except that the geosphere is a more significant barrier so that a lower-integrity EBS may be adequate.

The low-permeability cover sequence is likely to restrict deep groundwater flow.</td><td>The plastic characteristics mean that cavities must be supported, which may influence the geometry of the EBS and materials that can be used.

This host rock will provide such good containment that a conventional EBS is not needed.

Most engineering materials are incompatible with this environment.</td><td>Potentially reasons similar to those for Environments 1, 2 and 3 (if fractures and/or high-permeability horizons are significant) or similar to those for Environments 6 and 7 (if the host rock contains a significant content of clay).</td></tr>
</table>

Technical issues	Environments				
	1 **Hard fractured rock to surface**	**2** **Hard fractured rock overlain by relatively high-permeability sedimentary rocks**	**3** **Hard fractured rock overlain by sedimentary rocks containing at least one low-permeability unit**	**4** **Bedded evaporite host rock**	**5** **Siliceous sedimentary host rock**
	Geometry will also depend on the thermal properties of wastes, as this will determine the minimum waste package spacing.				
1 (For ILW) Influence of different waste form types on the design of the EBS	In fractured rocks, venting of canisters can allow gas to escape, but this also results in a potential for relatively rapid release of Cl-36 and I-129. The EBS needs to limit the release rates of mobile species such as Cl-36 and I-129 and those of actinides and others in the very long term. Cementitious EBS will react with CO_2, but it has yet to be demonstrated that this process will sufficiently limit ^{14}C releases under repository conditions.			Very low water availability will probably limit gas generation and this lithology can withstand high gas pressures. However, seals need to be designed to withstand any pressurisation that does occur.	Potentially reasons similar to those for Environments 1, 2 and 3 (if fractures and/or high-permeability horizons are significant) or similar to those for Environments 6 and 7 (if the host rock contains a significant content of clay).
2 Interactions between engineered components	Heterogeneous supply of water to the EBS, caused by the heterogeneous hydraulic characteristics of fractured host rock, may cause heterogeneous water-mediated interactions between components of the EBS. The host rock would have thermal conductivities lower than those of host rocks in Environments 4 and 8 and higher than those in Environments 6 and 7. In a HLW/SF repository, this would affect the temperatures attained and hence reactions.			Rock salt will deform plastically, influencing the stresses on different EBS components. High porewater salinities may develop within the EBS due to the influence of halite in the host rock. Relatively high thermal conductivity (the highest among the host rocks considered) would minimise peak temperatures in a HLW/SF repository.	Heterogeneous supply of water to the EBS, caused by heterogeneously distributed conductive fractures and/or local lithological heterogeneities, may cause heterogeneous water-mediated interactions between components of the EBS. Thermal conductivity would be similar to that of the host rocks in Environments 1, 2 and 3, with similar implications for peak temperatures.
3 EBS/host rock interactions	Host rock porosity and permeability are heterogeneously distributed, leading to heterogeneous mechanical interactions between EBS and host rocks (such as spalling of rocks from excavated surfaces, extrusion of expanding bentonite into fractures).			Rock salt will deform plastically, influencing the mechanical interactions	Potentially reasons similar to those for Environments 1, 2 and 3 (if fractures and/or high-

Technical issues	Environments 1 Hard fractured rock to surface	2 Hard fractured rock overlain by relatively high-permeability sedimentary rocks	3 Hard fractured rock overlain by sedimentary rocks containing at least one low-permeability unit	4 Bedded evaporite host rock	5 Siliceous sedimentary host rock
	Grouts (cements, superplasticisers, Na silicate liquids) may be needed to seal fractures, possibly influencing interactions between the EBS and the host rocks. Volume changes in EBS materials (especially swelling of bentonite components) would stress the host rock and help to seal the EDZ. Interactions between the EDZ and host rock could be affected by the development of a significant EDZ (this would be a site-specific issue). The host rock would have thermal conductivities lower than those of host rocks in Environments 4 and 8 and higher than those in Environments 6 and 7. In a HLW/SF repository, this would affect the temperatures attained and hence reactions involving porewater and host rocks.			between the EBS and host rock. Relatively high thermal conductivity (the highest among the host rocks considered) would minimise peak temperatures in a HLW/SF repository.	permeability horizons are significant) or similar to those for Environments 6 and 7 (if the host rock contains a significant content of clay). Thermal conductivity would be similar to that of the host rocks in Environments 1, 2 and 3, with similar implications for peak temperatures.
4 Impact of groundwater/ porewater on EBS materials (including impact of saline water)	The flux of groundwater to the EBS is heterogeneous, reflecting the heterogeneous distribution of conductive fractures. Local erosion of bentonite barriers may occur where conductive fractures are juxtaposed against bentonite. The chemistry and salinity of the groundwater will influence the nature of chemical reactions that occur.			There will be very little groundwater present.	The flux of groundwater to the EBS could be heterogeneous, if there are heterogeneously distributed conductive fractures and/or local lithological heterogeneities.
5 Duration for which EBS materials may maintain their functions (durability)	The EBS has a critical physical barrier function as the geosphere cannot be relied on as a physical barrier.	Whether or not this issue is affected by the characteristics of the environment will depend upon the disposal concept.	The low-permeability cover sequence will probably limit groundwater flows, thereby acting to preserve the EBS.	Some barriers (particularly cement, bentonite) are incompatible with this environment owing to the chemical reactivity of the salt and/or the need to ensure the engineered barriers have sufficient physical strength to resist convergence.	Whether or not this issue is affected by the characteristics of the environment will depend upon the disposal concept.

Technical issues	Environments				
	1 Hard fractured rock to surface	**2 Hard fractured rock overlain by relatively high-permeability sedimentary rocks**	**3 Hard fractured rock overlain by sedimentary rocks containing at least one low-permeability unit**	**4 Bedded evaporite host rock**	**5 Siliceous sedimentary host rock**
6 Gas/groundwater (or porewater) interactions	Gas may be transported relatively rapidly through fractures in the host rock, influencing the contact area between gas and groundwater.		The rate of gas generation may be relatively low owing to the low-permeability cover limiting groundwater fluxes. This low-permeability cover may also trap any gas that does escape from the EBS.	There will be very little groundwater present.	Gas may be transported relatively rapidly through fractures in the rock. Heterogeneity in permeability may influence the contact area between gas and groundwater. A potential exists for some enhanced dissolution of carbonate mineral cements if CO_2 in the gas dissolves in groundwater (though this effect will probably be minor).
		Potential exists for dissolution of gas in groundwater in relatively permeable units overlying the host rock.			
			Gas will be retarded or trapped by low-permeability units, and migration will be directed along higher-permeability units, influencing the contact area between gas and groundwater.		
7 Characterising the site adequately	Heterogeneity of groundwater flow caused by fracture networks in host rocks needs to be characterised.			Mechanical heterogeneities need to be determined.	Potentially reasons similar to those for Environments 1, 2 and 3 (if fractures and/or high-permeability horizons are significant) or similar to those for Environments 6 and 7 (if the host rock contains a significant content of clay).
		Differing mechanical and hydrogeological characteristics of host rocks and overlying rocks.			

Technical issues	Environments 1 Hard fractured rock to surface	 2 Hard fractured rock overlain by relatively high-permeability sedimentary rocks	 3 Hard fractured rock overlain by sedimentary rocks containing at least one low-permeability unit	 4 Bedded evaporite host rock	 5 Siliceous sedimentary host rock
		Presence of overlying sedimentary cover will make it more difficult to characterise the host rock than in Environment 1.			
8 Demonstrating long-term stability	Relatively difficult to demonstrate long-term stability, because groundwater flow in fractured rocks may respond to environmental changes relatively quickly and these rocks preserve relatively little evidence for their THMC history.		Easier to demonstrate long-term stability than in Environments 1, 2 and 4, because low-permeability units resist changes and are likely to preserve evidence for their history. Harder to demonstrate long-term stability than in Environments 6 and 7.	Relatively difficult to demonstrate long-term stability, because these rocks preserve little evidence for their THMC history.	Easier to demonstrate long-term stability than in Environments 1, 2 and 4, because low-permeability units resist changes and are likely to preserve evidence for their history. Harder to demonstrate long-term stability than in Environments 6 and 7
9 Impact of resaturation	Heterogeneous hydrogeological characteristics of fractured host rocks lead to heterogeneous inflow of groundwater.			Resaturation will be very slow.	If there are heterogeneously distributed conductive fractures and/or local lithological heterogeneities, there may be heterogeneous inflow of groundwaters.

Table 6.4 Influences of Environments 6, 7, 8 and 9 on the technical issues.

Technical Issues	Environments			
	6 Mudstone host rock	**7 Plastic clay host rock**	**8 Carbonate host rock**	**9 Non-evaporitic host rock with hypersaline groundwater**
	General comments on geological environments			
	Chemical functions of the environment are at least as important as physical functions.		Low-permeability variant: The geosphere is a significant barrier so a lower -integrity EBS may be adequate. Massive variant: any low-permeability cover rocks are likely to restrict deep groundwater flow . Otherwise, chemical functions may be as important as physical functions.	Information limited. Metal corrosion, concrete degradation enhanced.
1 (For HLW/SF) Influence of different waste form types on the design of the EBS	Cavities must be supported, which may influence the geometry of the EBS and EBS materials that can be used. The rocks tend to be bedded formations. Their thickness and dip will influence layout. .		Low-permeability variant: similar to those for Environments 6 and 7. Massive variant: similar to Environment 2 if high-permeability cover; similar to Environment 3 if low-permeability cover.	Hypersaline groundwater will be relatively reactive and will restrict the choice of materials that may be used in the EBS. Metal corrosion will be promoted and bentonite will degrade; the latter may be incompatible with this environment.
1 (For ILW) Influence of different waste form types on the design of the EBS	Cavities must be supported, which may influence the geometry of the EBS and EBS materials that can be used. For wastes that produce significant gas, the EBS would need to be designed to maintain its functions at high gas pressures owing to gas being unable to escape. However, low groundwater flow rates may limit the rate of gas generation.		Low-permeability variant: EBS would need to be designed to maintain its functions at high gas pressures owing to gas being unable to escape. However, low groundwater flow rates may limit the rate of gas generation. Massive variant: Venting of canisters can allow gas to escape, but this also results in a potential for relatively rapid release of ^{36}Cl and ^{129}I. EBS needs to limit the release rates of mobile species such as ^{36}Cl and ^{129}I and actinides and otbers in the long term	Hypersaline groundwater will be relatively reactive and will restrict the choice of materials that may be used in the EBS. Metal corrosion will be promoted and cement will degrade; the latter may be incompatible with this environment.

<table>
<thead>
<tr><th rowspan="2">Technical Issues</th><th colspan="4">Environments</th></tr>
<tr><th>6
Mudstone host rock</th><th>7
Plastic clay host rock</th><th>8
Carbonate host rock</th><th>9
Non-evaporitic host rock with hypersaline groundwater</th></tr>
</thead>
<tbody>
<tr><td></td><td></td><td></td><td>Cementitious EBS will react with CO_2, but it has yet to be demonstrated that this process would sufficiently limit ^{14}C releases under repository conditions.</td><td></td></tr>
<tr><td rowspan="3">2 Interactions between engineered components</td><td>Some plastic deformation may occur, influencing the stresses on different EBS components.</td><td>Plastic deformation will occur, influencing the stresses on different EBS components.</td><td>Relatively high thermal conductivity may result in relatively low temperatures in a HLW/SF repository.

Massive variant: Heterogeneous supply of water to the EBS, caused by the heterogeneous hydraulic characteristics of fractured host rock, may cause heterogeneous water-mediated interactions between EBS components.</td><td rowspan="3">Interactions between engineered components will be influenced by chemistry of water present; hypersaline groundwater will be relatively reactive and promote corrosion/degradation of engineered materials. Some materials (notably cement and bentonite) may be incompatible with this environment..</td></tr>
<tr><td colspan="2">Relatively low thermal conductivity may result in relatively high temperatures in a HLW/SF repository.</td><td></td></tr>
<tr><td colspan="3">Interactions between the EBS components will be influenced by the chemistry of the water present; relatively high concentrations of organic compounds may occur in the groundwater and the rock, which may form complexes with certain radionuclides. In Environment 8 there will be high concentrations of CO_3, which may also form complexes with some radionuclides and react with cement, thereby influencing interactions. Other potentially important inflowing constituents are chloride, sulphur, and thiosulphate.</td></tr>
<tr><td>3 EBS/host rock interactions</td><td colspan="2">Relatively low thermal conductivity may result in relatively high temperatures in a HLW/SF repository.</td><td>Low-permeability and Massive variants: Relatively high thermal conductivity may result in relatively low temperatures in a HLW/SF repository.

Carbonate from the host rock will react with cementitious components.

Volume changes in EBS materials (especially swelling of any bentonite</td><td>Highly saline water will react more readily with EBS components (steel, cement, bentonite and so on) than lower salinity water.</td></tr>
</tbody>
</table>

Technical Issues	Environments 6 Mudstone host rock	 7 Plastic clay host rock	 8 Carbonate host rock	 9 Non-evaporitic host rock with hypersaline groundwater
			components) would stress the host rock and help to seal the EDZ. Interactions between the EDZ and host rock could be affected by the development of a significant EDZ (this would be a site-specific issue). Massive variant: Host rock porosity and permeability are heterogeneously distributed, leading to heterogeneous mechanical interactions between EBS and host rocks (such as spalling of rocks from excavated surfaces, extrusion of expanding bentonite into fractures). Grouts (cements, superplasticisers, Na silicate liquids) may be needed to seal fractures, possibly influencing interactions between the EBS and the host rocks.	
	Some plastic deformation may occur, influencing the stresses on different EBS components. There will be some convergence of the host rock. Clays in the host rocks will react with cementitious components.	Plastic deformation will occur, influencing the stresses on different EBS components. There will be some convergence of the host rock.		
4 Impact of groundwater /porewater on EBS materials (including impact of saline water)	Resaturation will be slow. The impact of porewater is likely to be relatively uniform, but if rare relatively conductive fractures occur it	Resaturation will be slow. The impact of porewater is likely to be relatively uniform.	Low-permeability variant: The impact of porewater is likely to be relatively uniform. Massive variant: The flux of groundwater to the EBS is heterogeneous, reflecting the	Hypersaline groundwater will be relatively reactive and promote corrosion/degradation of engineered barrier materials. Some materials (notably cement and bentonite) may be

Technical Issues	Environments 6 Mudstone host rock	7 Plastic clay host rock	8 Carbonate host rock	9 Non-evaporitic host rock with hypersaline groundwater
	may be higher than in plastic host rocks (Environments 4 and 7).		heterogeneous distribution of conductive fractures.	incompatible with this environment.
5 Duration for which EBS materials may maintain their functions (durability)	Whether or not this issue is affected by the characteristics of the environment will depend upon the disposal concept. Gas generation is likely to be restricted by water availability.		Low-permeability variant: Similar to Environments 6 and 7. Massive variant: If the cover rocks are high-permeability, whether or not this issue will be important will depend on the disposal concept. If the cover rocks are low-permeability, the cover sequence will probably limit groundwater flows, thereby acting to preserve the EBS.	Some barriers (particularly cement, bentonite) are incompatible with this environment owing to the chemical reactivity of the salt and/or the need to ensure the engineered barriers have sufficient physical strength to resist convergence.
6 Gas/groundwater (or porewater) interactions	There will be limited opportunity for gas to react with porewaters owing to the low permeability of the rock and high gas entry pressures.		Low-permeability and massive variants: The host rock is reactive with respect to CO_2 dissolved in groundwater. Low-permeability variant and massive variant with low-permeability cover: Gas generation may be restricted by limited flow of water. Massive variant with low-permeability cover: This cover may also trap any gas that does escape from the EBS. Massive variant with high-permeability cover: Gas may be transported relatively rapidly through fractures in the host rock, influencing the contact area between gas and groundwater.	The solubility of gas will generally decrease compared to environments where lower-salinity water occurs.
7 Characterising the site	These environments are relatively uniform chemically and hydrogeologically.		Low-permeability variant: This environment is relatively uniform	High salinities result in high groundwater densities; gradients

Technical Issues	Environments 6 Mudstone host rock	 7 Plastic clay host rock	 8 Carbonate host rock	 9 Non-evaporitic host rock with hypersaline groundwater
adequately			chemically and hydrogeologically. Massive variant: Heterogeneity of groundwater flow, caused by fracture networks in host rocks, needs to be characterised.	need characterising. Brines will generally be more corrosive towards equipment.
8 Demonstrating long-term stability	Relatively easy to demonstrate long-term stability owing to slow rates of response to environmental change and likelihood that evidence for environmental changes will be preserved.		Relatively easy to demonstrate long-term stability, but slightly more difficult than for Environments 6 and 7 owing to relatively high chemical reactivity and possibly slightly less resistance to environmental changes.	If the hydrogeological setting implies little density-driven flow, the dense characteristics of the groundwater imply near-stagnant conditions and can be used as an argument to support long-term stability.
9 Impact of resaturation	Resaturation is likely to be slow, but if rare relatively conductive fractures occur may be higher than in plastic host rocks (Environments 4 and 7).	Resaturation will be very slow.	Low-permeability variant and possibly massive variant with low-permeability cover rocks: Resaturation is likely to be very slow, but may be higher than in plastic host rocks (Environments 4 and7) if rare conductive fractures occur. Massive variant with high-permeability cover: Heterogeneous hydrogeological characteristics of host rocks lead to heterogeneous inflow of groundwater.	The increased density of brine compared to fresh water will increase the head gradient towards excavations, compared to the case where lower-salinity water is present.

Table 6.5 Summary of major knowledge limitations on the technical issues.

Technical Issues	Knowledge limitation
1 Influence of different waste form types on the design of the EBS	• For HLW/SF, the effects of decay on EBS components are not well known. • The influence of micro-organisms is uncertain for all kinds of waste. • The behaviour of Pu/U waste forms is uncertain. • The implications of C-14-bearing methane evolution for EBS design in the case of ILW is uncertain.
2 Interactions between engineered components	• Kinetic and thermodynamic data limit the capability to predict cement/bentonite interactions. • The significance of certain cement additives (such as . superplasticisers) is uncertain. • Coupling between the mechanical and chemical processes affecting engineered components is difficult to predict and poorly known. • Processes controlling erosion of clay barriers are inadequately known.
3 EBS/host rock interactions	• The impact of grouts used to seal fractures on interactions between the EBS and host rock is poorly known. • Kinetic and thermodynamic data limit the capability to predict cement-clay interactions. • The impact of hypersaline water on EBS/host rock interactions is difficult to predict. • Coupling between rock convergence (collapse of excavations) and chemical interactions is difficult to predict and inadequately known. • The effect of EBS/host rock interactions on the characteristics of the EDZ is relatively poorly known.
4 Impact of groundwater /porewater on EBS materials (including impact of saline water)	• Fundamental technical limitations to predictability exist if porewater/groundwater very saline (above seawater equivalent salinity).
5 Duration for which EBS materials may	• Fundamental technical limitations to predictability..

Technical Issues	Knowledge limitation
maintain their functions (durability)	• There is some uncertainty in how activities in the operational phase may affect the post-closure duration for which engineered barriers may maintain their functions. • The significance for durability of locally high salinities developed by evaporation during the pre-closure phase (or during the early post-closure phase if there is no backfilling) is uncertain (this is likely to be a particular limitation for HLW/SF).
6 Gas/groundwater (or porewater) interactions	• Couplings between gas generation, groundwater flow, accessibility of water to wastes and barrier materials and convergence behaviour of the rock make it difficult to demonstrate that treatments of gas/water interactions in PA models are appropriately conservative. • The influence of groundwater chemistry on gas solubility is poorly known for the more saline groundwaters that might be encountered in a repository in England or Wales. • It is unclear whether existing models of two-phase flow in fractured rocks at the repository and larger scales adequately capture the key gas-migration processes (that is, it is unclear whether up-scaling can be performed adequately). • The extent to which EDZs may act as pathways for gas migration and hence influence the accessibility of groundwater/porewater to migration gas is uncertain.
7 Characterising the site adequately	• Whilst there is considerable expertise in the UK, since 1997 little work has been carried out to develop a deep geological repository in England or Wales. Consequently, experts need to be organized into teams that can undertake integrated site characterisation. • Knowledge obtained from surface-based investigations (including geophysical surveys, and borehole drilling and testing) alone may be inadequate to develop a convincing safety case.
8 Demonstrating long-term stability	• Lacking and/or limited preservation in the rocks and groundwater/porewater of evidence for past environmental variations.

Technical Issues	Knowledge limitation
9 Impact of resaturation	• Predicting resaturation rates at scales smaller than the entire repository is difficult. • Impacts of groundwater density (in combination with other effects, such as mixing between groundwater, development of gas pressures in the repository and so on) on resaturation rate are difficult to predict. • Temporal evolution of the EDZ, particularly during the pre-closure stage, is difficult to predict and has an uncertain impact on resaturation.

7 Conclusions

This study has reviewed the technical issues that may be associated with the development of a deep geological repository for higher activity wastes in England and/or Wales. The study has focussed on the post-closure phase and only considered construction and operational issues where these clearly impact on the ability to achieve a satisfactory post-closure safety case.

The aims were to:

- select a set of geological environments to represent the range of plausible repository host environments in England and Wales, and highlight a range of technical issues;
- identify the environment-specific broad technical issues that would need to be considered in order to evaluate a safety case in each environment.

In England and Wales the geology, hydrogeology and geochemical characteristics of groundwater and rocks are very varied. Nine different generic environments, some with subdivisions, were required to capture this variability in properties and to illustrate the potential impacts of issues associated with a deep geological environment. The classification of these environments is not unique and other classifications would have been possible.

Technical issues that might affect the development of a deep repository in these environments are equally varied. Some of the issues highlighted in this project are essentially statements of principle that need to be taken into consideration during site selection, concept selection and the development of a repository. Nine broad technical issues were identified about which it was possible to identify the current state of knowledge and then assess the impact of the issue in the UK.

At the highest level the geological environments can be divided into two groups:

- a group in which the geosphere can be expected to provide a significant barrier to radionuclide migration that can be relied upon as a key feature of the safety case;
- a group in which the geosphere may provide some containment, but where the long-term performance of the EBS will play a major role in safety.

The first group of environments are those in which it can be shown that there is an extensive low-permeability barrier between the wastes and the biosphere. The barrier may be the host rock (such as salt or a low-permeability clay) or it may be one of the units in the overlying sequence. These environments all tend to have low flow rates at repository depths, which tend to minimise interactions between EBS components and between the EBS and the host rock.

The second group of environments are those where there is no significant low-permeability unit between the wastes and the biosphere to provide geosphere containment. Groundwater flow rates at repository depths tend to be higher than in the first group. A result is that there may be more significant interactions between groundwaters and EBS components, between the different EBS components, and between the EBS and the host rock.

Many of the technical issues that were identified involved the various materials that make up the EBS system. In essence they covered the:

- interactions between the different EBS components;
- interactions between the EBS and groundwater/porewater;
- interactions between the EBS and the host rock;
- way in which the EBS will evolve with time.

In general, these issues are of greatest significance for those environments in which the safety case depends heavily on the long-term performance of the EBS. In these environments the processes implicit in these issues will be most significant, because the various interactions increase in magnitude with increasing groundwater flux. Saline groundwater may also increase the importance of an issue associated with the evolution of the EBS.

The lack of more detailed geosphere-specific issues does not imply that the geosphere is in some way less important than the EBS, but rather that geosphere-specific issues that would impact upon a safety case are implicit in the:

- descriptions of the geological environments;
- discussions of how issues related to the design of a repository (including its EBS) will be affected by the characteristics of the host environment.

A key overall conclusion is that the design of a repository should be matched to the characteristics of its host geological environment so as to:

- make a safety case;
- produce an optimal solution that is not unnecessarily expensive and/or technically difficult to implement.

Most of the issues associated with the performance of EBS materials under repository conditions are reasonably well understood under certain conditions. There remain, however, uncertainties relating to:

- the extrapolation of experimental studies to in situ conditions;
- the extrapolation of data gathered by other programmes to conditions in England and/or Wales;
- applying repository concepts that have already been proposed to environments different to those in which they have been tested;
- applying repository concepts that have been proposed elsewhere, but not yet been thoroughly evaluated.

UK-specific expertise relates mostly to the behaviour of EBS materials for a cementitious repository at Sellafield. This experience may not always be readily transferrable to other locations and disposal concepts. In particular, in the UK knowledge of the performance of materials commonly proposed for the EBS of HLW/SF repositories is limited compared to other countries with more mature HLW/SF disposal programmes.

Issues associated with repository-derived gas have received a great deal more prominence in the UK programme in recent years. Issues associated with gas may be important in all of the environments, though their impacts may vary between environments. In general, the issues relate to the potential for overpressurisation of the system in the first group of environments and to the potential for rapid release of free gas to the biosphere in the second group.

Any environment selected to host the deep repository will need to be investigated thoroughly. Site investigation will pose difficulties for all of the environments, not least because current experience of planning and executing this type of investigation in the UK is limited. Within the UK there is relatively little recent practical experience of underground investigations, such as would be gained in a URL. However, the current NDA programme does not appear to include a URL, instead envisaging that surface-based investigations would be followed directly by repository construction.

One of the objectives of the site investigations will be to demonstrate that any chosen site is sufficiently stable (in mechanical, hydrogeological and geochemical terms). Experience suggests that provided the site investigations collect appropriate data, it should be possible to address this issue readily.

Key points that emerged early in the analysis and which were repeatedly reinforced:

- the need to match the EBS design to the geological environment and waste form type, recognizing that a ‘one size fits all’ EBS may be inappropriate;
- the highly coupled nature of the repository system.

The overall conclusion of this study is that the UK programme potentially faces a wide range of technical issues. This arises partly but not wholly from the current lack of a site and the great variety of potentially suitable geological environments in England and Wales. The nature of the UK waste inventory is also significant. Work has been carried out to address the majority of the technical issues within the UK or within other disposal programmes. However, additional work may be required to apply the results of work in other countries to UK conditions, especially if the final UK repository site has different characteristics to the Sellafield site investigated by Nirex during the 1990s.

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Glossary and list of abbreviations

AECL	Atomic Energy of Canada Limited
ANDRA	Agence Nationale Pour la Gestion des Déchets Radioactifs, the French national radioactive waste management agency
CoRWM	Committee on Radioactive Waste Management
ADZ	Alkaline disturbed zone
AGR	Advanced gas-cooled reactor
BFS	Blast furnace slag
BfS	Bundesamt für Strahlenschutz , the German Federal Office for Radiation Protection
BVG	Borrowdale Volcanic Group, the sequence of predominantly volcaniclastic rocks which during the 1980s and 1990s was proposed to host a repository for ILW and some LLW near Sellafield (the project was cancelled in 1997).
CARE	Cavern retrievable disposal concept
CDC	Concrete disposal casks
CoRWM	Committee on Radioactive Waste Management
Defra	Department for Environment, Food and Rural Affairs
DGR	Deep geological repository
DU	Depleted uranium
DUCRETE	Depleted uranium concrete
EA	Environment Agency
EDZ	Excavation damaged zone
EBS	Engineered barrier system
Enresa	Empresa Nacional de Residuos Radioactivos SA, the Spanish radioactive waste management organisation
GFZ	Deutsches GeoForschungsZentrum, German Research Centre for Geosciences
GRA	Guidance on Requirements for Authorisation
HLW	High-level (radioactive) waste
IAEA	International Atomic Energy Agency
ILW	Intermediate-level (radioactive) waste
IGSC	NEA’s Integration Group for the Safety Case
IRF	Instant release fraction
JAEA	Japan Atomic Energy Agency

JNC	Japan Nuclear Cycle Development Institute
LLWR	Low Level Waste Repository, which is located near Drigg in Cumbria
MPC	Multi-purpose transport/storage/disposal containers
Nagra	Nationale Genossenschaft für die Lagerung Radioaktiver Abfäller, the Swiss organisation charged with preparing and implementing a sustainable waste management solution for radioactive waste
NDA	Nuclear Decommissioning Authority
NEA	Nuclear Energy Agency (of the OECD)
NII	Nuclear Installations Inspectorate
NORM	Naturally occurring radioactive materials
NRVB	Nirex Reference Vault Backfill, a cementitious backfill for use in a deep geological repository for ILW and some LLW, developed in the UK by Nirex
NUMO	Nuclear Waste Management Organisation of Japan
NWAT	Nuclear Waste Assessment Team
OECD	Organisation for Economic Cooperation and Development
ONDRAF/NIRAS	Organisme National des Déchets Radioactifs et des Matières Fissiles Enrichies/De Nationale Instelling voor Radioactief Afval en Veriiikte Splijtstoffen, the Belgian agency for radioactive waste and enriched fissile materials
OPG	Ontario Power Generation
OPC	Ordinary Portland cement
PA	Performance Assessment
PFA	Pulverised fly ash
PGRC	Phased Geological Repository Concept developed by Nirex and the NDA RWMD
Posiva	The Finnish radioactive waste management organisation
PWR	Pressurised water reactor
QA	Quality assurance
QC	Quality control
RSA 93	Radioactive Substances Act 1993
RWMD	Radioactive Waste Management Directorate (of the NDA). This body has taken over work previously carried out by UK Nirex Ltd.
Safety case	A synthesis of evidence, analyses and arguments to quantify and substantiate that a repository will be safe after closure and beyond the time when active control of the facility can be relied upon (NEA, 2008)

SCK/CEN	Studiecentrum voor Kernenergie/Centre d'Etude de l'Energie Nucléaire, the Belgian nuclear research centre
SEPA	Scottish Environment Protection Agency
SF	Spent fuel
SFR	Swedish Final Repository for radioactive operational waste
SKB	Svensk Kärnbränslehantering AB, the Swedish nuclear fuel and waste management company
SKI	Statens Kärnkraftinspektion, the Swedish nuclear power inspectorate
THMC	Thermal-hydrological-mechanical-chemical coupled processes
Transmissivity	A measure of how much water can be transmitted through a rock formation or structure (such as a fault or fracture) under the influence of a specified driving potential (head) gradient.
TRU	Transuranic wastes, which are distinguished in some countries as wastes that contains radionuclides with atomic numbers greater than that of uranium. There is no universal definition of TRU waste, but it broadly approximates to the IAEA definition of long-lived low- and intermediate-level waste (IAEA, 2003).
URL	Underground rock or research laboratory
US DoE	United States Department of Energy
WIPP	Waste Isolation Pilot Plant

8 Appendix A: Expert workshop participants

Name	Affiliation	Particular expertise/ experience	First workshop participant ?	Second workshop participant ?
Paul Abraitis	EA/NWAT	Geochemistry, wasteform design and evaluation	Yes	Yes
David Arcos	Amphos	Geochemistry	No	Yes
Andy Baker	ABConsult	Geology and geochemistry, safety assessment	Yes	Yes
Fred Barker	NuLeaf	***Participated as an observer***	No	Yes
Ian Barraclough	EA/NWAT	Safety assessment	Yes	Yes
Adrian Bath	Intellisci	Geochemistry	Yes	No
David Bennett	Terrasalus	Geochemistry	No	Yes
Sue Brett	NuLeaf	***Participated as an observer***	Yes	No
David Copplestone	EA Science	Chemistry	No	Yes
Susan Duerden	EA/NWAT	Radioactive waste management	Yes	Yes
David Evans	BGS	Geology, gas storage	No	Yes
Alan Herbert	ESI Ltd	Hydrogeology, contaminant migration	Yes	Yes
Bill Lee	CoWRM	***Participated as an observer*** Materials science	Yes	No
Francis Livens	CoWRM	***Participated as an observer*** Radiochemistry	Yes	Yes
Rob Macgregor	EA	Radioactive waste management	No	Yes
Rae MacKay	University of Birmingham	Hydrogeolgy	Yes	No
Tim McEwen	McEwen Consulting	Geology	Yes	Yes
Richard McLeod	SEPA	***Participated as an observer*** Hydrogeology Radioactive waste management	Yes	No
Richard Metcalfe	Quintessa	Geochemistry	Yes	Yes
Simon Norris	NDA RWMD	Safety assessment	Yes	Yes
Uisdean Michie	Independent consultant	Geology	Yes	Yes
Neil Milestone	Sheffield University	Cement chemistry	No	Yes
Peter Robinson	Quintessa	Hydrogeology, Safety assessment	Yes	Yes
Richard Shaw	BGS	Geology	Yes	Yes
Gavin Thomson	EA/NWAT	Radioactive waste management	Yes	Yes
Mike Thorne	Mike Thorne and Associates	Wastes and waste forms	Yes	No
Sarah Watson	Quintessa	Hydrogeology Safety assessment	Yes	No
Roger Yearsley	EA	Radioactive waste management	Yes	Yes

9 Appendix B: First expert workshop notes

Introduction

The first expert workshop was held on 30 January 2008 with the aims of:

- reviewing initial lists of geological environments, engineered barriers and waste types developed by the Quintessa project team;
- identifying some of the key issues to be considered during the second phase of the project, to complement Quintessa's work on identifying issues.

This appendix provides a factual record of this first expert workshop, and takes into account reviews of an earlier version of the record that were received from workshop participants. Also included are modified geological environment descriptions. These descriptions were developed by Quintessa's team to take into account feedback received from the workshop's participants, both during and after the workshop. However, the purpose of this appendix is to enable the reader to understand more readily the reasoning behind the conclusions presented in the main report. The conclusions presented in the appendix are interim and the reader is referred to the main document to see the final results of the project.

The outputs from the workshop were important inputs (among others) into the process of identifying technical issues.

This appendix is divided into the following sections:

- introductory briefing given to workshop participants;
- notes from Working Group 1, which considered waste characteristics and interactions between wastes and the EBS;
- notes from Working Group 2, which considered EBS components and interactions between EBS components and the geosphere;
- notes from Working Group 3, which identified the attributes of geological environments and the priority issues for consideration in each one, whilst noting cases where these might be expected to be more or less relevant to particular types of waste;
- details of the geological environments that were considered.

The output from Working Group 3 differed from those planned. This working group was initially asked to consider geological environments and the interactions between wastes and the geosphere. However, members of the group did not consider it possible to analyse in detail the relationships of the geological environments to the various waste forms without reference to the variety of EBS designs that could be employed. Consequently, it was decided to modify the approach to the one described here.

Record of workshop

Background

The Environment Agency's objectives for the project are to:

- understand the key technical issues that would need to be addressed in a safety case for a deep repository in different geological environments, and how they might be addressed;
- understand the current international status of work on those issues;
- provide a basis for planning and prioritising future scrutiny work, research and resources, in preparation for assessing future safety cases.

The project should identify the key issues that could challenge the ability to produce an acceptable long-term safety case, particularly those specific to an environment or concept. It should identify the relative importance of the key issues and build confidence that all important issues have been considered. The first workshop should reinforce this confidence.

Important ground rules for the project are that:

- The project must not prejudge the outcome of site selection.
- The geological environments considered should exist in England and Wales and be potentially suitable for a geological repository.
- The project should not consider geological environments specific to Scotland or Northern Ireland, where the Environment Agency has no remit.
- It is important to focus on issues that are relevant to the post-closure safety case, but nevertheless to mention major issues that could affect how (or whether) it would be possible to reach the point where a safety case can be developed (for example, to consider whether excavations would be sufficiently stable to allow construction and operation of a repository).

Workshop briefing

Quintessa provided a brief summary of the work carried out prior to the workshop, which was also described in briefing material supplied to the workshop participants before the meeting, and outlined the work programme for the three working groups. The workshop was part of the first stage of the project and was designed to identify key issues and produce tables showing influences between wastes, engineered barriers and geological environments. The outputs from the first workshop were not end products in themselves. Details would be considered in the next phase of the project.

A significant part of the workshop was devoted to discussions within three working groups. The working group discussions were divided into two sessions. At the start of the discussions the groups were provided with a set of headings that would be used to define rows/columns of interaction matrices. These headings described different components of the disposal system and its surrounding environment (characteristics of the wastes, the EBS or the geological environments). In the first session each group reviewed the headings proposed for one technical area and proposed modifications, clarifications, enhancements and so on. These modified headings were then used to construct interaction matrices, which the groups used during the second working session to define the issues that might be associated with the interactions between different aspects of the disposal system.

The discussion groups focused on 'big issues' considered high priority, characteristic of each geological environment and relevant to geological repositories. The aim was not to describe issues in detail, or consider alternative possible waste management/ disposal options (such as long-term storage, deep borehole disposal). Care was taken not to make judgements with respect to geological environments or to site selection. Both favourable and potentially adverse characteristics/interactions were identified.

Working groups

The working groups and their responsibilities were as follows:

- Group 1:
    - Membership: Sarah Watson (chair/reporter), Richard McLeod, Roger Yearsley, Paul Abraitis, Bill Lee, Mike Thorne.
    - Session 1 - Review waste types/characteristics.
    - Session 2 - Identify interactions between wastes and the EBS.
- Group 2:
    - Membership: Adrian Bath (chair/reporter), Gavin Thomson, Sue Brett, Susan Duerden, Francis Livens, Rae Mackay, Peter Robinson.
    - Session 1 - Review EBS components.
    - Session 2 - Identify interactions between EBS components and the geosphere.
- Group 3:
    - Membership: Tim McEwen (chair/reporter), Simon Norris, Rob Macgregor, Ian Barraclough, Richard Shaw, Uisdean Michie, Andy Baker.
    - Session 1 - Review geological environments.
    - Session 2 - Identify interactions between wastes and the geosphere (but see comment above).

Participants had the following affiliations, or were selected for the following reasons:

- The Quintessa team were involved in identifying environments and the initial issues to be considered (Tim McEwen, Adrian Bath, Richard Metcalfe, Sarah Watson) (in addition, Peter Robinson, also from Quintessa, attended as he is involved in a related NWAT-funded project).
- Five 'external' participants were chosen with their expertise covering the main technical areas of interest (Uisdean Michie - general geological issues related to radioactive waste; Mike Thorne - waste forms and engineered barriers; Andy Baker - general safety case development; Ray Mackay - hydrogeology; Richard Shaw - UK Geology).
- Two observers were nominated by CoWRM - Bill Lee and Francis Livens.

- One observer was nominated by Cumbria County Council/NuLeaf - Sue Brett.
- One observer was from SEPA - Richard McLeod.
- One participant was from NDA - Simon Norris.
- Other attendees were selected by NWAT/the Environment Agency - Rob Macgregor, Ian Barraclough, Gavin Thomson, Susan Duerden, Roger Yearsley, Paul Abraitis.

Richard Metcalfe circulated between the groups to ensure that they remained focussed at the correct level of detail and did not stray into areas being considered by one of the other groups.

At the end of the first working session, each group chair/reporter provided a brief verbal report of the headings that would be used in the second session and the logic behind selecting them.

During the second session, the precise method of working varied between the different groups. However, at the start of the meeting Quintessa's team suggested that the following general approach should be followed during this session:

- For the interaction matrix it was assigned to consider, each group was asked to state generally whether/how the item represented by each row title influences the item represented by the column headings, considered collectively.
- For the interaction matrix it was assigned to consider, each group was asked to state generally whether/how the item represented by each column heading influences the items represented by the row titles, considered collectively.
- For each cell in the interaction matrix it was assigned to consider, each group was asked to indicate the likely importance for repository performance of mutual influences between the items represented by row titles and column headings.
- As permitted by time available, the groups were asked to provide explanations of the influences (prioritized according to strength and so on) and hence identify the issues that may have a bearing on the development of key safety arguments.

After the second working session, each group chair/reporter provided a brief verbal summary of the key issues identified by their group. After the workshop, each group chair/reporter produced a more detailed written summary of the points raised during the break-out sessions. These written summaries are included in the following sections of this workshop record. The different formats of these sections reflect the different methods of working adopted by the different groups.

Notes from Working Group 1- waste characteristics and interactions between wastes and the EBS

Introduction

This section summarises the outputs from Working Group 1, which considered the different waste types that might be emplaced in a repository in the first session, and identified the interactions between waste types and engineered materials in the second session.

Waste types and wasteforms

The major change that Group 1 made to the initial list of waste types and wasteforms provided in the briefing notes was to consider the wastes primarily in terms of the way in which they are conditioned (cement, ceramic and so on) rather than in terms of the raw waste stream. The wasteform/conditioning is likely to be the primary control on wasteform degradation processes and hence the rate of inventory release. It is also the factor that is most likely to affect the engineered structures within the repository.

It was decided that the following wasteform types should be considered:

- cemented wasteforms (dominantly ILW and LLW);
- ceramic wasteforms (including pellets of UO_2);
- vitrified wasteforms;
- small volume wasteforms that are in some way different, such as Synrock and some of the GE Healthcare wastes (although were Synrock to be used for HLW it would not be a small volume waste form; also, the current UK approach is to vitrify the HLW);
- ‘new’ wasteforms currently under development – polymers, bitumens etc;
- single (large) items, probably from decommissioning, that might be disposed of without specific packaging/conditioning.

It was also noted that there are some significant waste streams for which there is currently no defined wasteform. The most significant of these waste streams is probably graphite, which will originate from the reactor cores of the AGR and Magnox reactor stations. This graphite contains a significant inventory of C-14 which might potentially be released as a gas (as well as other activation products). In recent Nirex work, C-14 transported in the gaseous phase has been shown to have the potential to challenge the safety case for the generic system considered by Nirex/NDA (see Nirex Report N/122).

It may also be necessary to distinguish between wastes that have already been packaged and those that have not yet been conditioned/packaged. In the former case, the facility will need to be designed to accommodate the existing packages. It may be possible, or necessary, to rework a limited number of packages. For wastes that have not yet been packaged, it may be possible/appropriate to design the wasteform/ packaging to take account of both experience gained to date and the EBS design. There is a presumption against conditioning some wastes, such as NORM, until a disposal route has been identified.

The basic waste types defined prior to the workshop were expanded and/or clarified as follows:

- HLW arising from reprocessing activities. These wastes are immobilised through vitrification. The total packaged volume will be 1,290 m^3, with total activity of 3.8 x 10^7 TBq. There will definitely be a significant volume of vitrified waste (it exists/is being produced now) and there is the potential for ceramic waste forms (such as Synrock) to be manufactured in the future, although the likelihood of this appears to be small.
- ILW. These wastes are generally grouted into 500-litre vented stainless steel drums, 3-m^3 drums and 3-m^3 concrete and steel boxes. The limited usefulness of 4-m boxes was noted. Other encapsulants are being considered for particular waste streams. The total conditioned waste volume could be up to 353,000 m^3, with a total activity of 2.4 x 10^6 TBq. The diverse wastes arise from a variety of sources:
    - reprocessing;
    - reactive metals (U and Magnox, Al, Zn);
    - routine operations at power stations and on nuclear sites;
    - ion exchange resins and so on – bitumen, polymer, cement;
    - decommissioning wastes that are dominated by short-lived radionuclides, both concrete and steel-dominated wastes will arise and these will be distinctive both in volume and time of arising;
    - graphite from reactor cores – which is likely to be contaminated (it may also be necessary to distinguish graphite from AGR fuel elements from bulk core graphite) and has a large volume;
    - sludges from liquid effluent treatment – cemented.

To date, ILW has generally been conditioned in a matrix comprising OPC modified with filler, typically comprising BFS or PFA. Small quantities of waste have been encapsulated in polymeric resins. Further use of polymeric encapsulants and alternative cements is being considered for certain problematic waste streams, along with high-temperature processes that may yield non-cementitious waste products (such as glass or slag-like residues).

Broadly, the ILW can be divided into:

- cemented wastes:
    - cemented wastes with high organics loadings;

    - cemented reactive metals and, perhaps more importantly, Magnox swarf;
    - totally encapsulated wastes (cemented sludges etc);
    - partially immobilised cemented wastes;
- polymer-encapsulated wastes.

Additional kinds of waste material and potential waste materials that were discussed:

- LLW that is not suitable for surface disposal at the LLWR, which has a packaged volume of 37,200 m^3 but a total inventory below 1 x 10^5 TBq and the following properties:
    - cementitious packages;
    - larger (and heavier) than average waste packages (such as 4-m box);
- ILW (operational wastes) that have decayed during storage to the extent that they are LLW by the time of emplacement;
- Magnox fuel that may possibly undergo direct disposal if it is not, or for some reason cannot, be reprocessed and is declared as waste (a possible example being material in Sellafield ponds where the Magnox cladding has dissolved), although it is currently not clear how this would be conditioned;
- SF from both AGR and PWR, which would have a total packaged volume of 8 150 m^3, and a total activity of 3.3 x 10^7 TBq, should it be declared as waste in future (although it is not currently declared as waste, SF has been considered by NDA in their recent work);
- submarine spent fuel, which has much greater fissile enrichment compared with 'normal' reactor fuel;
- NORM that does not meet the acceptance criteria for the LLWR, which is dominated by low-activity radium scales from the oil and gas industry and which can be divided into:
    - oilfield NORMs, which are Ra-rich barium/strontium sulphates and carbonates (if these wastes cannot go to sea they will likely be routed to landfills or possibly the LLWR);
    - gas field NORMs, which are dominated by unsupported Pb and Po and are generally not destined for deep disposal;
- stockpiled plutonium from reprocessing activities. If declared as waste, this is likely to be conditioned to either a ceramic or a glass wasteform. The total packaged volume will be 3,270 m^3, total activity of 4 x 10^6 TBq. For security reasons, this plutonium might be combined with HLW;
- stockpiled uranium from reprocessing;
- natural and depleted uranium, which is currently dominated by stored uranium hexafluoride that would probably be converted to oxide for disposal, if declared a waste.

Outline inventories of these wastes are given in Nirex report N/085 (Nirex, 2003).

The members of Group 1 raised several additional issues relating to these wastes.

There could be quite a large inventory of natural and depleted uranium. One possibility is that the depleted uranium oxide might be added to any future cement-based backfill (such as in DUCRETE). Depleted uranium makes good radiation shielding and could be used for this purpose in relation to other highly active waste forms.

Disposal of NORM wastes currently takes place to the marine environment, but this kind of disposal might not be continued in the future (this is currently under discussion between SEPA and Scotoil).

In addition to the originally specified list of wastes and potential wastes, Group 1 thought consideration should also be given to the potential disposal of spent MOX fuel that might arise from any programme of 'new nuclear build'. New build would, however, generally use fresh uranium fuel, not MOX. Therefore, it might be more appropriate to note the views of Group 1 but to decouple the issue of wastes arising from new build and wastes arising from burning MOX in current or future generation reactors.

It may be useful to consider the distinction between entire fuel elements and bundles of fuel pins. It was pointed out that it would also be possible to dismantle the pins and dispose of the fuel pellets. However, this would be a difficult operation, as there would be the potential for release of part of the gap inventory.

There is a potential option to convert to a SF wasteform that immobilises the IRF (initial release fraction).

It is necessary to make the distinction between steel-clad and Zircaloy-clad fuels.

It is further noted that organic complexants may potentially have an adverse impact on the solubility (increased solubility) and sorption (reduced sorption) properties of some key radionuclides (notably actinides).

The discussion outlined above led to the following list of waste types that might need to be considered by a future deep geological repository programme:

- HLW vitrified;
- HLW ceramic;
- cemented high organic ILW;
- cemented reactive metal ILW;
- totally encapsulated cemented ILW;
- partially immobilised cemented ILW;
- polymer-encapsulated ILW;
- reactor decommissioning concrete, which would have a cemented wasteform;
- reactor decommissioning steel, which would have a cemented wasteform;
- cemented LLW;
- spent fuel (elements, pin bundles, IRF immobilised), including steel-clad and zircaloy-clad fuels;
- glass and ceramics from Pu stockpile;
- enriched uranium – UO_2 ceramic;

- natural and depleted U – cemented or ceramic – or possibly as bulk metal shielding;
- spent MOX – which may possibly be the same as SF?
- graphite for which there is currently no wasteform;
- uranium metal.

The general term ‘cement’ as used here refers to ‘cement systems’ containing OPC and filler materials. There is a range of alternative cements, which can vary greatly in their chemistry (and hence reactivity with both waste and other repository components) and durability. The cement type might vary with waste stream, meaning that some of the groupings given above would need to be further subdivided in the design phase.

The large number of different wasteforms means that the backfill/buffer might need to be customised to the wasteform. A ‘one size fits all’ approach to the design of the near field is unlikely to provide an optimised solution.

The potential for interaction between different wastes and the different wasteforms was noted.

This list of wasteforms was condensed to provide the following table column entries for use in the interaction matrices in the second discussion session:

- cemented LLW and NORM;
- graphite (note that this is a relatively large volume waste stream for which the wasteform has not yet been determined);
- HLW glass;
- ceramic wasteform SF plus ceramic U + Pu and disposal MOX;
- cemented high organics ILW;
- cemented reactive metals;
- cemented generic ILW;
- polymer-encapsulated wastes;
- cemented reactor decommissioning wastes;
- miscellaneous wastes including unpackaged items, carbides exotic fuels.

Table for consideration by Group 1: Waste types versus engineered components

This first table includes comments on the EBS components by Group 1 and is applicable to all waste types. The group considered that their general comments on the waste types had been captured by the discussions during the first session.

Waste types versus EBS	Cemented LLW and NORM	Graphite (treatment unknown)	HLW glass	SF plus HLW ceramic plus U and Pu immobilised as ceramic	Cemented ILW with high organics loading	Cemented reactive wastes (Magnox, U, Al, Zn)	Cemented ILW – generic	Polymer-encapsulated wastes	Cemented reactor decommissioning wastes (concrete and steel-dominated	Miscellaneous, carbides, exotics and so on
System geometry (depth, access, footprint, caverns, tunnels)	May be controlled by heat load, rock strength, local plume interaction (such as the need to separate cements and bentonite buffers), criticality. Engineering controls on emplacement related to package sizes and remote handling. Inescapable link to flow rates/host rock permeability.									
Waste package only (without buffer/backfill)	The host rock for this EBS solution must by definition be very low flow, so few interactions would occur between the various components. Could remove many of the interface issues if this type of design could be adopted.									
High integrity waste package/overpack	High integrity probably needs to be defined in terms of the likely package lifetime relative to the half-life of the waste. Carbon steel overpacks could deliver high integrity containment if sufficiently thick to ensure that sacrificial generalised corrosion results in a long lifetime. Vents in packages breach the integrity. Therefore a vented package cannot be included here, no matter what the other materials are in the package.									
Lower integrity waste package/overpack	Handling containers only and from above all vented packages.									
Physical buffer and microbial barrier	Prevents water flow and hence gas generation and protects wasteform from 'wrong chemistry'. Physical degradation, settling may be an issue.									
Backfills	Interesting interface with buffer. When is it a conditioning material and when is it simply present as structure/protection?									
Chemical containment and conditioning	Degradation of container and wasteform. Influence on radionuclide mobility.									
Linings (including plugs and seals)	Primary purpose is the preservation of packages both prior to and post-closure. Important in terms of knowing what is present at the start of any post-closure analysis.									
Excavation support	May be important to package integrity. Lifetime needs to be considered in retrievability context. Super-plasticisers required in shotcretes and so on even if not in other components. Will need to consider their impact on radionuclide mobility.									
Operational infrastructure	Lifetime needs to be considered in retrievability context. Material remaining from construction (such as components of TBMs (tunnel boring machine)) are the source of additional chemical components not usually included in the repository system 'inventory'.									
Other	EDZs and construction techniques to control EDZ (TBM versus conventional blasting). Constructability issues. Abandonment of equipment such as tunnelling machines in situ.									

General Comments

- Different types of EBS will be needed for different types of wastes within the same repository.
- Interfaces are a big theme both in the wasteform and in the interactions between the various engineering components.
- Volumes of wastes influence the nature of the engineering that can be placed/take place around them.
- Geological environments with thick beds or massive units will tend to make optimisation of EBS and layout easier than environments with thinly bedded units.

This table lists the potential issues/interactions/comment that were identified by Group 1.

Waste types versus EBS	Cemented LLW and NORM	Graphite (treatment unknown)	HLW glass	SF plus HLW ceramic plus U and Pu immobilised as ceramic	Cemented ILW with high organics loading	Cemented reactive wastes (Magnox, U, Al, Zn)	Cemented ILW – generic	Polymer-encapsulated wastes	Cemented reactor decommissioning wastes (concrete and steel-dominated	Miscellaneous, carbides, exotics and so on
System geometry (depth, access, footprint, caverns, tunnels)	Handling large LLW packages underground Only separate from cemented ILW if good reason to do so but doesn't need to be 'deep' on safety grounds. May not be optimal to separate because of additional effort required to characterise another host rock even if accessed from same shaft, and so on,	Large volume Candidate for a separate repository? Nothing that intrinsically requires it to be spread out (heat, criticality).	Heat and environmental controls during operations. Heat loading dictates spacing. Long-lived radionuclides require long containment (travel times) and so implies disposal at significant depth.	Heat loading dictates spacing. Long-lived radionuclides require long containment (travel times) and so implies disposal at significant depth.	Relatively small volume but gas generating. Gas generation may require engineering for gas release. Need to think carefully about location to prevent unwanted interactions with other waste types (including HLW and SF) – need to optimise emplacement.	Quite large volumes. Need to think about location to optimise emplacement. Interactions with other wastes HLW and SF. Gas generation may require engineering for gas release (but much of the gas release could occur early - within a few decades, so could be an operating and monitoring issue).	Quite large packaged volumes containing relatively large volumes of less reactive metals. Need to think about location to optimise emplacement. Interactions with other wastes HLW and SF. Gas generation may require engineering for gas release.	Currently small volume but could grow as new packaging proposals are developed. EBS/environment might push packaging in this direction. Need to think carefully about location – need to optimise emplacement.	Quite large packaged volumes with relatively large volumes of less reactive metals. Need to think about location to optimise emplacement. Interactions with other wastes HLW and SF. Gas generation may engineering for gas release. Could be an issue with large or awkward packages defining tunnel etc dimensions.	
Waste package only (without buffer/backfill)			Corrosion resistance of exotic materials is not well known at high temperatures so may be an issue if relying on this alone to provide containment.	Corrosion resistance of exotic materials is not well known at high temperatures so may be an issue if relying on this alone to provide containment.						
High integrity waste package/overpack			Copper Ti etc availability	Copper Ti etc availability			Availability of manufactured boxes at required rates may be a practical issue.			
Lower integrity waste package/overpack										
Physical buffer and microbial barrier			Buffer selection will be controlled by local heat generation. Bentonite availability may be an issue. Need to carry out testing with bentonite to be used in disposal so need to make this	Buffer may be needed for IRF. Need to ensure saturation on right timescale to ensure conductivity and stop overheating of buffer. Bentonite availability may be an issue. Need to	Possible low k cement buffer. May need to separate these from bentonite buffers around HLW/SF.	Possible low k cement buffer. May need to separate these from bentonite buffers around HLW/SF, Waste form expansion likely to be an issue for buffer integrity.	Possible low k cement buffer. May need to separate these from bentonite buffers around HLW/SF.			

Waste types versus EBS	Cemented LLW and NORM	Graphite (treatment unknown)	HLW glass	SF plus HLW ceramic plus U and Pu immobilised as ceramic	Cemented ILW with high organics loading	Cemented reactive wastes (Magnox, U, Al, Zn)	Cemented ILW – generic	Polymer-encapsulated wastes	Cemented reactor decommissioning wastes (concrete and steel-dominated	Miscellaneous, carbides, exotics and so on
			decision early or run larger programme to keep options open.	carry out testing with bentonite used in disposal so need to make decision early or run larger study to keep options open.						
Backfills					Backfill may need to be gas permeable.					
Chemical containment and conditioning			Rely on wasteform not chemical conditioning. Conditions rate at which wasteform degrades.	Rely on wasteform not chemical conditioning. Conditions rate at which wasteform degrades.						
Linings (including plugs and seals)										
Excavation support										
Operational infrastructure	Large heavy packages if 4-m box used.		Heat removal is a problem. Large heavy packages.	Heat removal is a problem. Large heavy packages.		Package integrity issues if they get wet.	More opportunity for standardised containers.		Could be an issue with large or awkward packages.	

Important note/issues

The group found that the diversity of issues and potential interactions between wastes and EBS meant that it was difficult to assign a single importance rating to a cell. The group therefore considered issues first, but did not have time to grade them later. The strategy was to identify the most important issues and/or those highly specific to a waste type first. Thus, entries on the table should reflect a) the most important issues and/or b) issues likely to be apparent to a specialist group but not to the more general project team. A blank cell does not mean that there are no potential issues associated with the interaction; it simply indicates that a) the important issues are captured by the general list given below, b) the issues are of lower importance/more general or c) the group ran out of time before they were able to complete the entries.

General issues not specific to a particular waste/EBS combination

- Co-disposal defined as common access/surface facility. Could be different levels of a repository or different zones within a repository constructed on a single level.
- Corrosion resistance and durability of repository materials are not well understood, especially when different materials may be interacting with each other. Interfaces between different materials are key.
- Geometry of interfaces is important for corrosion.
- Out of package criticality controlled by local geometry and geochemistry.
- Gas generated from steel is different from the organic-sourced gas. Gas generation from the wastes may be a major issue.
- Super-plasticisers will be required in construction. Little is known about how they affect radionuclide transport. The new generation may be less problematic than those considered a decade ago.
- Need to consider interactions between chemical containment systems in different parts of facility. This is important for co-disposal of cement-based wasteforms and HLW, and possibly other co-disposals.
- Local repository environment is assumed to rapidly become oxygen-poor to anoxic soon after closure and resaturation. This is important for waste form dissolution and solubility and transport of radionuclides.
- Engineering skills required for construction and operation may not be currently available in the UK.
- May need investment in infrastructure to supply the required boxes and so on. It may prove difficult to fabricate overpack boxes to required QA at required rate.
- If build in evaporite and backfill with evaporite, then the interfaces between the host rock and the backfill disappear.
- Thermal degradation, radiolysis, degradation (water) are key issues for polymer wasteforms, about which very little is currently known.
- The resaturation of the waste will take place over very different lengths of time, depending on the geological environment.

Notes from Working Group 2 - EBS and interactions between EBS components and the geosphere

Group 2 followed the suggested procedure outlined above and produced three tables, providing general comments on the table column and row headers and then identifying interactions and grading them in terms of their likely strength/importance. These tables are given in the following pages.

A key conclusion/observation of the group was that it will be necessary to design the EBS to work with the particular geological/hydrogeological environment and then optimise the design to local conditions found at the site. It is also clear that there is considerable variation in the significance of some issues between the different environments. This suggests much more design and characterisation work may be required in some environments to develop a safety case.

This first table, in a similar manner to the first table for Group 1, provides general comments which are relevant to all the geological/hydrogeological environments. The subsequent table then makes comments specific to each environment.

Geological environment **EBS component**	**Hard fractured rock to surface** **(Environment 1)**	**Hard fractured host rock with permeable cover (advective transport in cover)** **(Environment 2)**	**Hard fractured host rock with low-permeability cover (diffusive transport in cover)** **(Environment 3)**	**Bedded evaporite host rock** **(Environment 4)**	**Siliceous sedimentary host rock** **(Environment 5)**	**Mudstone host rock** **(Environment 6a)**	**Plastic clay host rock** **(Environment 7)**	**Low-permeability carbonate host rock** **(Environment 8a)**	**Non-evaporitic host rock with hypersaline groundwater** **(Environment 9)**
System geometry (depth, access, footprint, tunnels)	Rock stress effects on excavation, stability of groundwater to climatic impacts, rock strength and transmissivity versus depth, geothermal gradient (low significance), topography of area, waste container sizes, rock strength limit on tunnel size, depth, permeability of cover, waste volumes, possibility for multi-layer repository, intactness of rock and usable fraction of volume, sedimentary architecture and dip, avoidance of major geological structures such as faults. Main issues for system geometry are keeping access open for operational period (50-100 years, possibly longer if a longer waste retrieval phase is required), ventilation, mitigating high stress if present, achieving adequate volume of good rock and thermal separation of HLW/SF, avoiding major geological structures, vertical versus horizontal deposition for HLW/SF canisters.								
Waste package only (no buffer/backfill)	Waste containers in overpacks such as Japanese CARE in Ti and Belgian HLW steel in concrete, rock strength to maintain open tunnel/cavern, stress not too high, fracturing, response to thermal regime of HLW/SF, tunnel may be lined, tunnel bored close to diameter of overpack (Belgian concept), cavern storage for CARE, retrievability or remediation may be facilitated by cavern storage, design of floor and canister/overpack support. Main issues for the zero buffer/backfill EBS are corrosion of container, mechanical damage or irretrievability due to rock fall, releases directly into near field rock due to, for example, defective canisters, rapid groundwater movement and RN transport along open tunnels.								
High integrity waste package/overpack	Waste (HLW/SF) in Cu or Ti canisters with very long lifetimes, low water flux and chemical conditions adjacent to container controlled by buffer, total containment until canister breached by corrosion except in case of defective canisters or shearing by seismic displacement. Use of these containers only possible for volumes of HLW/SF (there is no equivalent long-life container for ILW). Main issues are rate of corrosion in relation to water composition in buffer, performance of buffer (see below) in limiting water ingress, accelerated corrosion due to oxygenated water ingress or high sulphide or other corrosion agents, respect distances between canisters and displaceable geological structures in case of seismic movement, erosion of buffer.								
Lower integrity waste package/overpack	Waste in steel canisters (HLW/SF) or drums (ILW), low water flux and chemical conditions adjacent to containers controlled by buffer or backfill, backfill may have high pH to lower corrosion rate, limited duration of total containment after which containers fail due to corrosion. Containers may hold HLW/SF and/or ILW. Main issues are rate of corrosion in ambient chemical conditions, loss of high-pH conditioning, defective containers, mechanical damage during emplacement, erosion of buffer/backfill.								
Buffer as physical, chemical and microbial barrier	Buffer of very low-permeability diffusive material that restricts water ingress and would also be a solute transport barrier; pore sizes inhibit microbial viability (also potentially possible to emplace aseptic buffer to ensure clean buffer adjacent to waste canister); usually compacted bentonite or similar clay. Main issues are loss of swelling pressure due to very saline water, flocculation by fresh water, physical erosion by water flow through adjacent fracture in rock, alteration/dissolution by high pH leachate from cement materials in grout, backfill or concrete, cation exchange and minor mineral reactions with pore water, alteration of clay by Fe from steel canister, also consistency of emplacement to avoid defects in seal, transmission of gases, resaturation.								
Backfills in deposition tunnels and access tunnels	Low-permeability material to fill tunnels and caverns after emplacement; purposes are to prevent extrusion of buffer from deposition holes/tunnels, to restrict groundwater movement through tunnels, to support rock and prevent fracturing, to act as additional barrier to RN movement out of repository; usually mix of bentonite or other clay with crushed rock spoil or other gravel. Main issues are maintaining expansion to fill voids (clay/rock), flocculation of clays, effect of salinity or other chemical alteration, physical erosion by water, effective emplacement, transmission of gases, resaturation.								
Chemical containment and conditioning	Low-permeability material that has chemical and physical properties that restrict movement of radionuclides out of repository by effects on solubility and sorption, also may condition chemical environment to lower corrosion rate of containers; usually cement grout or other high-pH mixture, could also be other mineral mixtures having required properties and normal pH; also concrete boxes for grouted ILW containers. Main issues are alteration/dissolution of buffer clay and rock by high pH leachate, erosion of cement, leaching of alkalinity and lowering of pH, release of sorbing colloids, effectiveness under containers, quality control of emplacement, for example preventing voids, non-retrievability unless soft cement, transmission of gases.								
Linings, plugs and seals for deposition holes/tunnels	Steel or concrete linings in deposition holes/tunnels that preserve geometry and facilitate emplacement of containers and buffer (if used), also temporary linings inside pre-cast buffer that maintains inside geometry to allow canister insertion; short duration; cement or bentonite plugs or seals for closing tunnels and shafts to prevent fast paths for water flow. Main issues are corrosion of steel, cracking of concrete, corrosion of rebars in concrete, void between lining and rock provides fast water pathway, effectiveness of keying plugs/seals into the host rock, possibility of bypass flow around seals, long-term degradation of seals, for example high-pH alteration of bentonite, effect on gas migration pathways, durability of plugs/seals to future climate change such as glaciation, permafrost								
Excavation support for galleries and access tunnels	Grouting, steel sets, shotcrete, concrete linings, rock bolts to maintain open and safe conditions for duration of operation, 50-100 years. Main issues are longevity for operational period (50-100 years?), corrosion of steel, deterioration of shotcrete and concrete including rebar corrosion, water inflow to rock bolt holes, effectiveness and durability of grouting, high-pH alteration and precipitation in fractures due to grouting, organics contamination by superplasticisers, removal of support materials before closure, effects of remaining materials on long-term flow paths and water composition.								
Operational infrastructure	Steel tracks, pipes, cabling, pumps, hoists, spills of oils and other liquids including human excreta, construction water leakage into rock, plastics, particulates including exhaust carbon and ventilation air, various machinery, emplacement devices, TBM machines (if TBM tunnelling for example for deposition tunnels) , damaged containers, rejected deposition holes, ventilation piping and so on. Main issues are how much will be left in situ at closure and how much removed, effects in short-term and long-term of for example organic liquids, solids, steels and so on.								
Other aspects of engineering design and operation	Handling rock spoil at surface or designing re-use of spoil as backfill, likelihood of success in achieving adequate characterisation of important features of site, safety and success rate of drill and blast or other excavation methods (such as TBM).								

Geological environment EBS component	Hard fractured rock to surface (Environment 1)	Hard fractured host rock with permeable cover (advective transport in cover) (Environment 2)	Hard fractured host rock with low-permeability cover (diffusive transport in cover) (Environment 3)	Bedded evaporite host rock (Environment 4)	Siliceous sedimentary host rock (Environment 5)	Mudstone host rock (Environment 6a)	Plastic clay host rock (Environment 7)	Low-permeability carbonate host rock (Environment 8a)	Non-evaporitic host rock with hypersaline groundwater (Environment 9)
System geometry (depth, access, footprint, tunnels) **Waste package only (no buffer/backfill)** **High integrity waste package/overpack** **Lower integrity waste package/overpack** **Buffer as physical, chemical and microbial barrier** **Backfills in deposition tunnels and access tunnels** **Chemical containment and conditioning** **Linings, plugs and seals for deposition holes/tunnels** **Excavation support for galleries and access tunnels** **Operational infrastructure** **Other aspects of engineering design and operation**	Large volume of potential host rock, faulted/fractured at a variety of length scales, strong rock when unfractured or when fracture density low, potential for high stresses e.g. in tectonic lens, large span vaults would be stable depending on strength & stress, low/moderate salinity increasing with depth, hydrochemical heterogeneity, possibly low stability/buffering of redox & pH, generally low permeability rock mass between fracture zones, dual porosity with matrix diffusion, low porosity, advective solute transport, easy gas migration in fractures, low/high hydraulic gradients depending on topography	Host rock: as for Environment 1 although the volume of suitable rock may be smaller. Cover sequence: May comprise a variety of different materials with different engineering properties. Transport through the cover sequence will be dominated by advection, most probably porous, but fractures may potentially be important in certain units. Water chemistry similar to or of fresher composition than for host rock.	Host rock: as for Environment 1 although the volume of suitable rock may be smaller and the hydraulic gradients are likely to be lower. Possibly higher stability of redox than Environment 2, high SO_4 and HS likely, Cover sequence: diffusion is likely to dominate in many of the formations in the cover sequence. gas trapping possible in cover sequence under low K sediments	Massive bedded formation (probably halite or anhydrite, not very thick host beds, basinal faulting, soft weak to fairly strong rock, creep major feature, low stress, large caverns may or may not be stable for operational period, in other cases support needed for small excavations, high salinity (brine), high SO_4, Mg, K, etc, reducing but not buffered, possible organics, pH unbuffered, homogeneous chemistry, no free flow of water except in major features and minor seeps, brine inclusions in matrix	Possibility of structurally complex host rock, major basinal faulting, fracturing, heterogeneous rock types and strengths depending on architecture, diagenesis/cementation, grain size, etc, bedding plane fractures, stress variable, large span unsupported vaults possible in some rocks not in others, groundwater inflows likely to be major, water composition variable low to moderate up to brine in deep basin centre, reducing, moderate pH, potential high pCO_2 and high alkalinity due to lack of silicate dissolution, moderate permeability, high/moderate porosity, porous medium flow plus fracture advective flow, possibly low stability to glaciation & permafrost and other climate effects	Possibility of structurally complex host rock, major basinal faulting, small scale jointing and fracturing, heterogeneous bedded rock types and strengths depending on architecture, diagenesis/cementation, bedding/cleavage/partings may be dipping, bedding plane fractures, stress variable, large span unsupported vaults possible in some rocks not in others, groundwater inflows could be major but sparse, water salinity moderate, reducing, moderate to higher pH, potential high pCO2 and high alkalinity, very low matrix permeability, low porosity, diffusive solute transport through matrix plus, potentially long resaturation times occasional fracture advective flow, possibly low stability to glaciation & permafrost and other climate effects	Usually flat bedding, beds of limited thickness, soft plastic weak rock, moderate creep, self-healing so no open fractures except where siltier beds or carbonate cementing permit, very low permeability, solute transport entirely by diffusion, potentially very long resaturation times, moderate to high porosity, reactive organics and sulphide minerals in host rock, salinity low to moderate (~seawater value), reducing and moderate to higher pH, well buffered, high pCO_2 and alkalinity, microbial activity may be high, no pathways for gas migration, relatively permeable 'aquifer' formations above and below provide solute pathways if clay barrier not effective, high stability to climate change unless erosion cuts down to top of clay	Massive non-karstic carbonates including deep non-aquifer chalk, fracturing significant and water flow dominantly by advection with possibility of high flows in major faults/fracture zones, porosity may be high (e.g. in chalk) so matrix diffusion probably effective, may contain substantial fraction of clays, low to moderate strength, low stress, water composition fresh to saline (~seawater), reducing but not well buffered, moderate to higher pH, high pCO_2 and alkalinity, geochemically homogeneous, moderate stability to climate change, gas migration dependent on fracture permeability and diffusion into matrix	Likely to be a basinal relatively low permeability indurated siltstone or sandstone with siliceous cementation of matrix, evaporites in basinal sequence are source of high salinity, moderate to high rock strength, fractured with possible high inflows, reducing, high salinity causes stratification and compartmentalisation of water masses and very slow ('stagnant') water flow

Overall strength and potential significance of issues arising from the interaction of EBS components with the geological/hydrogeological environment (Categories of likely significance: 3 = STRONG, 2 = MODERATE, 1 = WEAK)

Geological Environment / **EBS Component**	Hard fractured rock to surface (Environments 1a & 1b)	Hard fractured host rock with permeable cover (advective transport in cover) (Environment 2)	Hard fractured host rock with low-permeability cover (diffusive transport in cover) (Environment 3)	Bedded evaporite host rock (Environment 4)	Siliceous sedimentary host rock (Environment 5)	Mudstone host rock (Environment 6a)	Plastic clay host rock (Environment 7)	Low-permeability carbonate host rock (Environment 8a)	Non-evaporitic host rock with hypersaline groundwater (Environment 9)
System geometry (depth, access, footprint, tunnels)	3: Rock stress, depth compromise between stress and low transmissivity, avoid major structures, a large footprint may be required to locate sufficient "good" rock or a multi-layer repository, keeping excavations open for an extended period may be difficult.			3: Dependent on sedimentary architecture and heterogeneity, variable strength of rock affects size of caverns/tunnels, avoid major structures, circular cross-section tunnel only in plastic clay rock, some environments may be limited in extent compared to required footprint?					3: Deep and remote so long access tunnel, sedimentary architecture. Disturbance to stable system may be a problem.
Waste package only (no buffer/backfill)	NOT FEASIBLE: inadequate geosphere performance			1: Barrier provided by impermeable host rock.	3: High degree of package and overpack engineering, gallery/tunnel construction for retrieval, long travel times essential.		1: Closure over canisters, corrosion.	3: Long travel times, engineering, tunnel construction.	3: Very long travel times, corrosion, no reliable buffer.
High integrity waste package/overpack	3: Corrosion by HS or O_2, high salinity, high dependence on buffer, probability of defective canisters, seismic shearing.		1: Stable groundwater system.	1: With halite/other evaporite backfill.	2: Corrosion by HS or O_2, high salinity, high dependence on buffer, probability of defective canisters, seismic shearing.		1: Closure over canisters, corrosion.	1: Travel times, engineering.	3: Very long travel times, corrosion, no reliable buffer.
Lower integrity waste package/overpack	3 (NOT FEASIBLE?): totally dependent on buffer/backfill retention, short travel time in geosphere.		3: Longer travel time in geosphere.	1:Ggas release from ILW is an issue.	3: Totally dependent on buffer/backfill retention and adequate travel time and retention in geosphere.		2: Corrosion, closure over canisters, irregular closure.	3: Long travel times, engineering, tunnel construction.	3: Very long travel times, corrosion, no reliable buffer.
Buffer as physical, chemical and microbial barrier	2: Less stable groundwater, buffer erosion.	1: Loss of swelling due to salinity, colloid generation, long-term alteration, emplacement.		Not applicable	2: Stability of groundwater, loss of swelling due to salinity, erosion & colloid generation, long-term alteration.		1: Clay buffer not required unless to bar organics.	1: Swelling pressure, colloids, alteration, erosion.	3 (NOT FEASIBLE): Is there a compatible buffer?
Backfills in deposition tunnels and access tunnels	2: Less stable groundwater.	1: Cover provides more long-term stability of groundwater .		1: Salt backfill only.	2: Erosion and colloid generation.		1: Backfill not required unless to bar organics.	1: Erosion and colloid generation.	2: Void fill function only.
Chemical containment and conditioning	3: Degradation, loss of high pH, corrosion, sorption.	2: Degradation by groundwater, leaching of alkalinity and high pH, container corrosion, poor retention.		Not applicable	2: Degradation by groundwater, leaching of alkalinity and high pH, container corrosion, poor retention.		Not applicable	2: Degradation, leaching, carbonation.	Not applicable
Linings, plugs & seals for deposition holes/tunnels	3: Rock stress and fracturing, insertion and preservation of linings for efficient emplacement of containers, seal emplacement important in fractured environment and also in Environment 3 to re-instate the diffusive barrier in the access shaft/drifts.			Not applicable	3: Rock stress and fracturing, insertion and preservation of linings for efficient emplacement of containers, seal emplacement important in permeable horizons and zones.		3: Important to ensure seals effectively re-instate the natural barrier?	3: Rock stress, fracturing and joints.	3: Fracturing, insertion.
Excavation support for galleries and access tunnels	1: Strong rock, large caverns and tunnels possible, risks of rock falls in fracture zones, rock bolting, grouting of major structures to control water inflows.			3: High creep rate in halite, may need support.	3: Variable rock quality, fracturing.	1: Fracturing, cleavage.	3: High rate of closure, circular tunnel.	1: Fracturing, block joints.	3: Very high corrosion rate of steel support.
Operational infrastructure	1: Excavation methods (drill & blast or TBM).			2: Corrosion, salt dust in ventilation, exclude water.			2: Short time for retrieval		3: Corrosion in brine, salt clogging of pumps and so on.
Other aspects of engineering design and operation	1: Radon hazard and ventilation, rock spoil and sulphide oxidation (acid rock drainage).			2: Gas hazard.		1: Rock spoil, pyrite oxidation.			2: Hydrocarbon risk.

In addition, and potentially relevant for all environments, is the issue of the resaturation of the EBS and waste (where appropriate) and the near-field of the host rock. The physical process of resaturation is accompanied by potential physical and chemical changes to the EBS and the repository near-field, and could take very considerable times where the host rock has a low permeability. It is also linked in a potentially complex manner with gas production.

Notes from Working Group 3 - geological environments and interactions between wastes and the geosphere

Geological environments

The group discussed and agreed the following changes to the list of geological environments provided by Quintessa. The revised environments are described in a subsequent section.

- It would be better to refer to the environments as geological/ hydrogeological environments, rather than merely geological environments, as their definitions made use of both geological (evaporite, mudstone and so on) and hydrogeological (or implied hydrogeological and/or transport) terms (such as permeable, porous, fractured, advection, diffusion).
- It was considered inappropriate to subdivide the 'hard fractured rock' environment (Environment 1) into low relief and high relief, as the varying relief would not have a fundamental impact on the processes and issues of interest. Different relief could have an impact on the repository design (such as access route to the repository – horizontal access or shafts), but the potential impact on long-term safety would not be significant; nor would it necessarily influence the type of wastes that could be disposed of, if it is assumed that access could be appropriately backfilled. Environments 1a and 1b were therefore combined into a single environment, Environment 1.
- The descriptors used for Environments 2 and 3 should refer to the implied dominant transport processes in the cover sequence: dominantly advective transport in the cover sequence in Environment 2 and predominantly diffusive transport in the low-permeability unit assumed to be present in the cover sequence in Environment 3. The most appropriate way of referring to these types of environments would be to emphasise the important differences between them.
- Environment 5, that was referred to as 'strong, low-permeability, siliceous host rock' should be referred to as 'siliceous sedimentary host rock' (the host rock is a siltstone or a sandstone), to distinguish it from the 'low-permeability carbonate host rock' (Environment 8).
- The term 'low relief' should be removed from the descriptor for Environment 6 for the reasons noted above.
- The 'plastic clay host rock' environment, Environment 7, should be reinstated. Although potentially suitable plastic clay host rocks are probably not present onshore in England and Wales, they are likely to exist offshore and be close enough for land-based access to be feasible. It would be better to include such an environment at this stage, for the sake

of completeness, as such rocks have implications for EBS design, waste retrievability and so on and the key processes may differ from those in some other environments.

- Environment 8 would best be referred to as ‘low-permeability carbonate host rock’, a description relevant to both Environments 8a and 8c.
- In line with the merging of Environments 1a and 1b, it is recommended that the ‘high relief sedimentary host rock’ should be removed from the initially proposed set of table column headings, for the reason set out above.
- It is recommended that there should be a new environment termed a ‘*non-evaporitic host rock with hypersaline groundwater’*. This environment would include locations at depth where the host rock was not an evaporite, but where the groundwater was of very high salinity. This salinity could be assumed to be indicative of relatively stable hydrogeological, and by inference relatively stable hydrogeochemical, conditions.

These suggested changes were incorporated into a revised version of the interaction matrices for Groups 2 and 3. The revised environments are listed below (in which the references to (a) and (b) refer to the original descriptions of the environments). They are also described in more detail in the following section.

- Environment 1 – hard fractured rock to surface (Environments 1a and 1b combined into a single environment);
- Environment 2 – fractured hard rock overlain by relatively high-permeability sedimentary rocks in which advective transport dominates;
- Environment 3 – fractured hard rock overlain by sedimentary rocks containing at least one significant low-permeability unit in which diffusion dominates solute transport;
- Environment 4 – bedded evaporite host rock;
- Environment 5 – siliceous sedimentary host rock (Environments 5a and 5b are not considered separately);
- Environment 6 – mudstone host rock;
- Environment 6a – mudstone host rock which is dominantly flat-lying and undeformed;
- Environment 7 – plastic clay host rock;
- Environment 8 – carbonate host rock;
- Environment 8a – low-permeability carbonate host rock in which solute transport is likely to be dominated by diffusion;
- Environment 8c – a relatively massive limestone host rock, overlain by a mixed sedimentary sequence that is likely to contain both high- and low-permeability formations (but with at least one significant low-permeability formation to protect the host rock from processes such as karstification);
- Environment 9 – non-evaporitic host rock with hypersaline groundwater.

Interactions between wastes and the geosphere

The group did not consider it possible to analyse in detail the relationships of the geological environments to the various wasteforms, without reference to the variety of EBS designs that could be employed. They therefore decided to concentrate on identifying the attributes of each environment, and the priority issues for further consideration, whilst noting cases where these might be expected to be relevant to particular types of waste or EBS. These attributes and issues are described in note form below.

Environment 1 – Hard fractured rock to surface (Environments 1a and 1b combined into a single environment)

- Potentially there could be rapid connectivity of groundwater, via the fracture network, from the repository to the surface, with consequent:
  - implications for EBS design, since the wasteform and the EBS will be required to provide the main barrier to radionuclide transport;
  - requirements to understand transport processes in fracture networks and to demonstrate and model rock matrix diffusion convincingly;
  - possible problems in characterisation compared to some environments (the environment may in any case be geologically complex, although complexity may or may not have adverse implications for safety case).
- It could be difficult to make a safety case for large volumes of ILW, as the large volumes would probably make containment within a low-permeability buffer impractical, in contrast to HLW/SF smaller volumes so that:
  - there are already advanced disposal concepts for SF/HLW disposal in this type of environment (such as KBS-3, Nagra, NUMO), which may be adaptable to environments in England and/or Wales;
  - it could well be possible to make an adequate safety case for HLW/SF and some other relatively low-volume waste types.
- There are potential problems with gas since there may be *relatively* high release rates of gas from the environs of a repository due to the possibly *relatively* high permeability (above 10^{8-9} m/s) and subsequent rapid gas transport to the surface, leading to:
  - problems with wastes that produce relatively large gas volumes, such as organic-rich wastes and wastes with large volumes of reactive metals, which would require special treatment and/or special EBS designs;
  - interactions of gas with flowing groundwater;
  - potential difficulties in modelling gas transport in fractures.
- It is likely to be relatively difficult to argue convincingly that the geosphere will provide a major role in containing activity in the long term, so when developing a safety case more reliance is likely to be placed on the EBS. An important function of the geosphere is to ensure that the EBS acts as intended over long periods of time. Travel times to the surface of radionuclides released from a repository would tend not to be long and retardation mechanisms may have only a limited effect. Consequently, the geosphere barrier may not be as effective as in some other environments.

- There is a need to understand interactions between the host rock and any high-pH plume from cementitious waste, and possibly from cementitious components of the EBS.
- Geophysical signatures produced by repositories and the concomitant effect of human intrusion (intruding to investigate an obvious non-natural feature) could be significant.

Environment 2 – Hard fractured rock overlain by relatively high-permeability sedimentary rocks in which advective transport dominates

- The same issues as those described for Environment 1 apply to Environment 2, as the host rock has essentially the same characteristics. However, the effect of the releases from a repository in Environment 2 would be ameliorated by dilution and dispersion in the cover sequence. These processes could be very significant. For Environments 2 (and 3) the safety case may not depend so much on the fractured host rock as it would in Environment 1, and so requirements for understanding could be less.
- The thickness and properties of the sedimentary cover would be significant, as the potential for delay of the radionuclide release, dilution of the release and spreading of this release in time and space would depend on their thickness, properties, internal structures, and so on.
- There are implications for the type of site investigation and research and development programmes required (many of these comments are applicable to any of the environments):
    - It is generally undesirable to investigate rocks using boreholes alone. Where the host rocks are not exposed at the surface, there will be great uncertainties in the 3D variations in host rock characteristics. This problem also exists to a lesser extent where the host rock is exposed at the surface, because the properties of the rock near the surface and at depth may differ for many reasons (though probably least so for hard fractured rocks). For example, near-surface weathering processes will cause the characteristics of a rock to change.
    - There are fewer uncertainties if the host rock can be examined in 3D, either because it is exposed at the surface or can be seen in existing underground openings, such as road and rail tunnels (the Opalinus Clay is visible in numerous road and rail tunnels in the Swiss Alps and in the Mt Terri URL, and is exposed just to the north in Germany). If such information is not available elsewhere, data from a URL is essential in order to decide whether or not a site is suitable to host a repository (such a URL can be at the selected site and/or elsewhere).
    - Current UK policy would appear to require a site to be selected for potential disposal before any underground construction can be carried out. In some ways this is similar to the current situation in Sweden, but in that country there is information from an existing research-based URL constructed in the same type of geological/hydrogeological environment as is proposed for the repository.
- The gas pathway, and its comparison with the groundwater pathway, is an issue. From the perspective of developing a safety case, there is a

considerable difference between the gas not reaching the surface, due to its dissolution in groundwater, and it reaching the surface.

- There is a need to understand interactions between the host rock and any high-pH plume from any cementitious waste and possibly from any cementitious components of an EBS.
- Geophysical signatures are produced by repositories and may influence the likelihood of human intrusion (in future humans might intrude to investigate an obvious non-natural feature).

Environment 3 – Hard fractured rock overlain by sedimentary rocks containing at least one significant low-permeability unit in which diffusion dominates solute transport

- There is the potential for considerable delay in groundwater and gas-mediated transport of radionuclides, due to the presence of the low-permeability barrier in the cover sequence. Diffusion processes will dominate so there is scope for building confidence using geochemical data.
- A good understanding of this low-permeability barrier would be essential to demonstrate that it did indeed act in the manner hoped for and assumed in the safety case. The following issues concerning the performance of the barrier were noted as important:
    - The barrier may not need to be very thick to have the necessary effect (in contrast to Environment 6 where the host rock itself has this lithology) and perhaps as little as a few tens of metres may be sufficient for a single barrier in a sedimentary cover.
    - There may be more than one such barrier and the combined effect of two or more barriers could prove sufficient. This has implications for the potential to separate the different waste types – see below.
    - The barrier must not be faulted out or effectively bypassed in some other structural (geological) manner. It needs to be sufficiently continuous for it to be considered as behaving as a continuous barrier. This *effective continuity* is applicable to the other bullet points.
    - The barrier may need to be continuous over a very large area, as the size of the groundwater flow regime may be considerable (many hundreds of square kilometres at Bure, France).
    - The barrier must have a low permeability over all its subcrop, with no large lithological changes that might allow for the formation of preferential pathways through it.
    - There is a need to demonstrate that the barrier acts in this manner under all future climate states and consequent changes in the hydrogeological regime with regard to recharge and discharge locations, and so on.
    - The characteristics of the barrier have important implications for the design and operation of site investigation programme. The combined use of hydrogeochemical/ palaeohydrogeological investigation techniques is likely to be paramount.
- Depending on the specific site characteristics, there is the potential for the vertical separation of wastes which could be advantageous for co-location

of wastes that need to be prevented from chemically interacting with one another. Possibly, some wastes could be emplaced in the hard fractured basement rocks, whilst others could be located in the sedimentary sequence, noting that:

  - Such separation is dependent on the thickness, properties and relative location(s) of the low-permeability components of the sedimentary sequence.
  - It may be possible to locate some wastes within the higher permeability parts of the cover sequence (where these are isolated by two or more low-permeability barriers).

- The low-permeability barrier may provide a trap for gas, thereby increasing the likelihood of gas dissolution in the groundwater.
- Need to understand interactions between host rock and high-pH plume from the cementitious waste and possibly components of the EBS.
- Geophysical signatures produced by repositories – and the concomitant effect of human intrusion (intruding to investigate an obvious non-natural feature).

Environment 4 – Bedded evaporite host rock

The following points and questions requiring specific study were identified.

- Although very little free water is available for interaction with the wastes, brine lenses can be present and can be corrosive. The lack of free water means that the overall consequence from the groundwater pathway is likely, therefore, to be very low.
- The generation of a pulse of groundwater around the repository is possible, due to the effect of the convergence of evaporites caused by construction and then closure of the repository (see German safety cases for Gorleben). It is therefore important to understand halite deformation (as this is the most likely host rock).
- Evaporites are a resource and the importance of human intrusion affecting evaporites is highlighted in the GRA (Guidance on Requirements for Authorisation). Following the approach set out in the GRA might lead to the conclusion that such environments are unacceptable because of the high radiation doses that would result from their exploitation. However, different approaches and arguments are possible, as shown by the selection of evaporites as host rocks in other countries. Although potential exploitation may be a negative factor, in many other respects evaporites can provide a strong safety case. Although the same environment could be used for CO_2 sequestration, the consequences would not be as high radiologically compared to a resource that is extracted (and, therefore, there is considered to be less of a potential problem in this respect).
- Important to understand gas production from ILW and its transport.
- Would radiolysis of the host rock be an issue for HLW/SF?
- Could place different waste types in separate evaporite horizons – possibly separated by considerable vertical distances (see comment above).

- EBS system likely to be easier to develop and be considerably cheaper than for some other environments.
  - Less emphasis on the EBS in the safety case, with concomitant greater emphasis on the host rock.
  - Perhaps parts of the safety case would be more easily made convincing, as it would rely more on the natural system?
- EDZ formation still needs to be understood in this type of host rock.
- Long-term retrievability (should this be required) is a problem – may be impossible for some wastes for reasons of practicality, or at least very severe constraints on retrievability or reversibility (for example, if a system similar to that proposed in Germany for disposal in salt were to be used, in which the HLW/SF was emplaced in boreholes drilled from horizontal galleries and where salt was used as backfill).
- Need to understand interactions between host rock and high pH plume from the cementitious waste and possibly components of the EBS.
- Geophysical signatures are produced by repositories and may influence the likelihood of human intrusion (in future humans might intrude to investigate an obvious non-natural feature).

Environment 5 – Siliceous sedimentary host rock

The two variants of this environment, 5a and 5b, are not separated. The majority of the comments made about the significance of there being a low-permeability unit above the host rock are equally applicable to this environment. However, it is important to note that:

- There is greater matrix porosity than in the host rock of Environment 1, but the permeability may be similar. Both porous medium and fracture flow may be present.
- In developing a safety case, it will be necessary to reach a similar level of understanding about groundwater flow in the host rock as in the case of Environment 1.
- There is a need to understand interactions between the host rock and the high-pH plume from the cementitious waste, and possibly components of the EBS.
- Geophysical signatures are produced by repositories and may influence the likelihood of human intrusion (in future humans might intrude to investigate an obvious non-natural feature).

Environment 6a – Mudstone host rock which is dominantly flat-lying and undeformed, although indurated

- There is a requirement to demonstrate that the host rock can heal after gas flow (and the majority of wastes will generate gas to some extent) or at least that any damage does not have an undue impact.
- There is good evidence that fractures in the rock are self-healing or self-sealing. A considerable body of evidence for these phenomena has been produced by several radwaste programmes (see NEA Clay Club reports).

- Complex coupled processes need to be understood, for example the links between permeability, pore pressure distribution, EDZ formation and rock strength.
- The stability of underground openings is a significant issue. There is an obvious impact of rock strength on the potential maximum size of openings and the maximum practicable depth of the repository.
    - There are implications for designing a repository to accommodate certain waste forms and larger packages may be difficult to emplace.
    - Even with limited compressive strength, tunnels are likely to remain relatively stable to depths of 500 m or greater (there is evidence of this from Bure and Benken). Therefore at these relatively shallow depths it may not prove much more difficult geotechnically to construct a repsository than in some hard fractured rocks. There are in fact potential depth limitations due to strength/stress ratios even in crystalline rocks, for example at Forsmark in Sweden and Olkiluoto in Finland.
- It is importance to understand the EDZ and its effect on radionuclide transport and gas release.
- There is a good chance of obtaining convincing geochemical evidence of low transport rates in the host rock and in particular that there is a diffusion-controlled transport system.
- There is a need to understand interactions between mudstone host rock and any high-pH plume that would originate in cementitious waste and possibly in cementitious components of the EBS.
- There are several issues concerning the ease of characterisation:
    - There is considerable experience of characterising such rocks developed over last two decades by Andra in France and Nagra in Switzerland in particular.
    - There is much recent evidence from radioactive waste disposal programmes in other countries, notably in France and Switzerland, that convincing evidence of diffusion-controlled transport is likely to be obtained from geochemical profiles.
    - As a consequence of this relative ease of characterisation, it is likely to be easier to make a convincing safety case than for hard fractured rocks.
    - Geophysical signatures are produced by repositories and may influence the likelihood of human intrusion (in future humans might intrude to investigate an obvious non-natural feature).

Environment 7 - Plastic clay host rock

- Long-term retrievability is a problem in this environment and may be impracticable owing to the need to employ extensive engineering and maintenance measures to support excavations. Rock stability problems may be similar to those of Environment 4 and potentially greater than those for Environment 6a.

- Potentially significant geochemical changes may occur in the clay if the tunnels are left open, possibly to a greater degree than in any of the other host rocks.
- Complex THMC coupled processes will need to be understood adequately and probably will be more significant than in indurated clays/mudstones. However, possibly in the plastic clay host rock these processes may be easier to understand, as the host rock behaves in a more ideal manner.
- Full tunnel supports will be required and the maximum practicable depth at which excavations can be constructed will be constrained by geotechnical properties of clay, leading to:
    - practicable upper limits on tunnel size;
    - difficulty in constructing large vaults (possibly impossible to do so), so that a relatively high packing density of ILW/LLW waste will probably be needed and reversibility will be more difficult.
- Thermal effects on clay may be significant, for example causing excess pore pressures and leading to clay deformation and the opening up of potential transport pathways through the clay, even if only in the short term.
- It may be necessary to manage a repository in this type of host rock very differently from one constructed in stronger rock. The different approaches will be due mainly to the fact that larger openings will not remain open for long periods in plastic clay. Consequently, the waste packing density is likely to be lower in plastic clay, so the repository footprint will probably be greater. It is unlikely that construction and operation of an NDA PGRC-type repository would be practicable in this type of host rock.
- This kind of host rock is relatively straightforward to characterise:
    - Considerable experience of characterising such rocks has been gained over the last two decades by SCK/CEN, ONDRAF/NIRAS, ANDRA, and Nagra, in particular.
    - A considerable body of convincing evidence is likely to be obtained from geochemical profiles, as shown recently by radioactive waste programmes in Switzerland and France.
    - It is likely to be easier to make a convincing safety case for a repository in a plastic clay host rock than for one in hard fractured rocks.
- There is a need to understand interactions between the host rock and any high-pH plume that would originate in cementitious waste and possibly in cementitious components of the EBS.
- Geophysical signatures are produced by repositories and may influence the likelihood of human intrusion (in future humans might intrude to investigate an obvious non-natural feature).

Environment 8a – Low-permeability carbonate host rock in which solute transport is likely to be dominated by diffusion

- Low-permeability carbonate host rock may behave rather like indurated mudstone (Environment 6a).
- A host rock of this type is potentially a good sink for CO_2 evolved from ILW.

- Gas production from waste and its transport through the host rock need to be understood. Important related questions are:
  - Would fracturing of the host rock take place?
  - Would such fractures heal?
- There is some evidence from gas fields that such rocks may not conduct gas readily, since in some fields such rocks act as traps/seals.
- However, there may be little data on such rocks, in contrast to other environments, as relatively little consideration has been given to this kind of host rock by waste management organisations. An exception is OPG in Canada, which is considering the construction of a deep geological repository for ILW and some LLW in a dominantly carbonate and very low-permeability host rock.
- Certain wastes, notably those containing PVC, will tend to produce acid solutions when they degrade. Acids may also be produced by radiolysis or as a result of cellulose degradation. What would be the impact of these degradation products? It is anticipated that if the repository is appropriately designed, they would be neutralised by backfill.
- Interactions of the carbonate host rock with high pH solutions from cementitious waste and/or the repository infrastructure needs to be considered.
- Depending on the nature of the carbonate (its clay content) sorption may be relatively low.
- Geophysical signatures are produced by repositories and may influence the likelihood of human intrusion (in future humans might intrude to investigate an obvious non-natural feature).

Environment 8c - Massive carbonate host rock overlain by sedimentary sequence with a least one low-permeability unit

- The properties of the surrounding rocks are of relatively great importance for long-term safety compared to the properties of the host rock itself. Depending on the characteristics of the host rock, the surrounding rocks may be of even greater importance for safety (as in Environment 3).
- The host rock may have properties that allow a greater role for the geosphere in the safety case compared to the type of host rock found in Environments 1, 2 and 3. For example, the carbonate host rock will have a greater porosity than crystalline host rock with fewer potential problems with excess gas pressures and greater potential for retardation.
- Some rocks of this kind could be used for CO_2 storage, although this is not thought to be very likely, unless the porosity is high. In certain geological situations such rocks can be associated with economic mineral reserves, which would result in an increased potential for future human intrusion.
- Geophysical signatures are produced by repositories and may influence the likelihood of human intrusion (in future humans might intrude to investigate an obvious non-natural feature).

Environment 9 (a new environment, referred to as ‘non-evaporitic host rock with hypersaline groundwater’)

- The EBS components would be more likely to corrode in highly saline groundwater, potentially causing safety problems. These are likely to be greater than in evaporitic host rocks since the porosity and hence the water content may be considerably greater.
- Generally, the solubility of gas decreases as salinity increases, so that gas evolved from a repository would have a lower probability of being dissolved in the pore fluids and be more likely to form a separate gas phase.
- This stable groundwater environment may not remain stable when the repository is constructed and operated for a considerable period. Construction may disrupt one of the main attractive features of this environment.
- There is a need for good understanding of geochemical processes in these conditions and few data are thought to exist for situations where the salinity is high.
- There is an opportunity for a convincing safety case to be made that makes use of the likelihood of deep stable groundwater conditions.

Geological/hydrogeological Environments

Introduction

This section describes the outcome of the first phase of the selection of the geological environments. The updating takes into account the discussions that took place at the first workshop.

A meeting attended by Quintessa staff and associates (Sarah Watson, Tim McEwen and Adrian Bath) and Gavin Thomson (NWAT, present for the first two-thirds of the meeting) was held on 3 January 2008. The aim of this meeting was to define the generic environment types and to start to characterise and document them.

The meeting produced an initial list of the environments defined. A list of the geoscience indicators that could be used to characterise the environments was also developed. These outputs formed an important basis for discussion at the first expert workshop on 30 January 2008.

The sections below reflect modifications to the initial geological environments that were suggested at the 30 January 2008 workshop. Perhaps the most significant recommendation was that the environments should be referred to as geological/ hydrogeological environments, because the definitions make use of both geological descriptors (evaporite, mudrock) and hydrogeological or implied hydrogeological indicators (permeable, fractured)[4].

Approach

In practice, the approach followed at the meeting on 3 January 2008 was to ‘brainstorm’ geological environments, then check this list against the Nirex ‘old sites’ list (McInerny 1988) and the geological environments considered by overseas waste disposal agencies. Geological, seismic, hydrogeological and tectonic/structural maps of England and Wales were then reviewed to ensure that coverage was comprehensive.

Finally, a basic screening of the environments was carried out. This screening removed environments for which it was not possible to find a potentially suitable example within England and Wales and environments where all of the examples in England and Wales would definitely be excluded by the Defra criteria (Defra, 2007). In practice this involved judging the likely extent of concealed explorable (not necessarily exploitable as exploration boreholes would be sufficient to lead to human intrusion) coal or hydrocarbons. If in doubt, the environment was left in and the potential presence of explorable coal or hydrocarbons at depth was one of the ‘issues’ associated with the environment.

The initial list of environments generated was at the most general level possible while still being useful to illustrate the range of environmental characteristics in England and

[4]It was decided for conciseness to retain the term ‘geological environment’ in the main report, on the understanding that geological and hydrogeological characteristics are covered.

Wales. During the definition process, it was noted that a number of these very general environment types would need to be subdivided when they were characterised, because the initial definition was too broad to allow the issues to be explored. The results, updated to take account of comments from participants in the first expert workshop, are listed below.

When defining the geological environments, the project team found that they naturally thought first in terms of the potential repository host rock and then in terms of the overlying rocks (if any). Defining the environments in this way means that some locations where there is more than one potential host rock could be classified as more than one environment type, depending on which host rock is chosen. From the point of view of defining the issues associated with the development of a repository system, this is a more useful way of considering the various repository systems than considering multiple host rock types in a single geological environment.

Environments

This section provides a brief summary of the environments that were defined at the 3 January 2008 meeting and the subsequent modifications to the definitions following review at the first expert workshop on 30 January 2008. The major changes are:

- The environments are referred to as geological/hydrogeological environments to better reflect that fact that both geological and hydrogeological characteristics are implicit in their definitions.
- Environment 7, plastic clay host rock, which was screened from the original list decided on 30 January, has been reinstated. The reason is that these rocks exist offshore and may be close enough to the coast to be accessed from the land. Additionally, this environment may present unique issues.
- An additional environment 'non-evaporitic host rock with hypersaline groundwater' has been defined.

It is important to be clear regarding the definition of descriptive terms that are often used interchangeably and sometimes misleadingly when describing environments that are potentially suitable to host a deep repository. The terms 'basement', 'hard rock', 'crystalline rock', 'hard crystalline rock' and 'hard fractured rock' (although they each have distinct and slightly different meanings) are often used to describe the same type or broad class of rock: a fractured igneous or metamorphic rock with very low matrix porosity, within which groundwater flow is dominated by fracture flow. The unfractured rock mass is strong (in the engineering sense) but the overall rock mass strength depends on the frequency and pattern of the fracturing. The term 'basement' is usually used to describe a widespread association of igneous and/or metamorphic rocks which are unconformably overlain by unmetamorphosed or less metamorphosed sedimentary rocks. The term therefore covers many of the occurrences of fractured igneous and metamorphic rock, but it does not adequately capture those cases where such rocks are exposed at the surface. Therefore, the more general and descriptive term 'hard fractured rock' is used in this report.

The environments listed below have been numbered simply to aid referencing and identification. The list below includes all of the environments considered at the first expert workshop. Some of these have been screened from further consideration in the project. Where this is the case, the reasons for screening them are noted and their presence in this list records the fact that they were considered by the project team.

Environment 1 – Hard fractured rock to surface

In this environment, the repository is developed in a hard fractured host rock. Hard fractured rocks (but not necessarily exactly the same formation as the host rock) extend close to, or to, the ground surface. Rock within a few tens to perhaps two hundred metres of the surface is likely to be weathered and is also likely to have a higher permeability than deeper rocks. The extent of this weathering and enhanced permeability will depend on the details of rock type, topography and geological history (for example glacial history). All of these rocks are likely to be fractured on a range of length scales from regional (several kilometres) scale fault and fracture zones to small-scale fracturing, with a length scale of metres or less. There is also likely to be a thin (possibly up to a few tens of metres) surface layer of (recent) Quaternary deposits.

This environment was initially subdivided into high and low relief variants. However, it was considered at the first expert workshop that the impact of relief on long-term safety would not be significant and would probably not influence the types of wastes that could be emplaced in this environment. Relief might, however, have a significant impact on the operational phase. For example, it might be possible to access the repository via horizontal drifts in some high relief areas.

Environment 2 – Hard fractured rock overlain by relatively high-permeability sedimentary rocks in which advective transport dominates

In this environment, the repository host rock is a hard fractured rock. The host rock will be fractured on a range of length scales from regional (several kilometres) scale fault and fracture zones to small-scale fracturing, with length scales of metres or less.

The repository host rock is unconformably overlain by a sedimentary sequence with a thickness of between about 200 m and 800 m. This sedimentary sequence is dominated by rocks of moderate permeability and may contain minor aquifers. The key feature of this overlying sedimentary series is that it does not contain a significant low-permeability unit, in which diffusional processes are expected to dominate solute transport, although it may contain minor low-permeability units. Faults in the sedimentary rock are likely to be transmissive and thus not provide barriers to flow. Advection will dominate solute transport in the cover sequence.

Although it is not a requirement of this environment, examples in England and Wales generally have moderate relief and are currently located in a coastal environment.

Environment 3 – Hard fractured rock overlain by sedimentary rocks containing at least one significant low-permeability unit in which diffusion dominates solute transport

In this environment, the repository host rock is a hard fractured rock. The host rock will be fractured on a range of length scales from regional (several kilometres) scale fault and fracture zones to small scale fracturing, with length scales of metres or less.

The repository host rock is unconformably overlain by a sedimentary sequence with a thickness of between about 200 m and 800 m. This sedimentary sequence contains at least one significant low-permeability unit in which diffusional processes will be dominant in solute transport. Faults within the low-permeability unit are also expected to have low transmissivities (at least over significant parts of their areas), and thus provide barriers to flow. The sedimentary sequence may be dominated by low-permeability rocks, but may also contain aquifer units.

Although it is not a requirement of this environment, examples in England and Wales are generally located in areas of low relief. Both coastal and inland examples exist.

Environment 4 – Bedded evaporite host rock

In this environment the repository host rock is an evaporite unit, which is most likely to be halite (rock salt), but which could also be another type of evaporite, such as anhydrite (though this is less likely). In the onshore area of England and Wales the form of the evaporite unit will be a regularly-bedded unit, rather than a thickened unit of irregular form, associated with a salt dome. The evaporite host rock unit is likely to be bounded by low-permeability units (mudstones and siltstones), and a significant thickness of low-permeability units is necessary (at least somewhere in the geological succession, though not necessarily adjacent to the evaporite unit) to preserve the evaporite from dissolution by flowing groundwater. Faults are likely to have low transmissivities (at least over significant parts of their areas), and thus provide barriers to flow.

The examples of this environment in England and Wales are found in areas of low to moderate relief. There are also offshore examples that could be accessed from onshore. There were initially two variants of this environment:

- Environment 4a, with bedded evaporite host rock.
- Environment 4b, within a salt dome.

This second variant was screened out as it does not occur within the area under consideration, salt domes at suitable depths being located too far offshore

Environment 5 – Siliceous sedimentary host rock

In this environment the host rock is a strong, dominantly siliceous rock, most likely sandstone or siltstone, although there may be carbonate cement present. In the host rock, flow through the porous matrix may be the dominant flow mechanism, although there may also be a component of fracture-controlled flow. The most likely host rocks are sandstones or siltstones in which a silty lithology or diagenetic cementation results in a low permeability. The host rock is part of a sedimentary sequence that is likely to contain both high- and low-permeability sedimentary rocks.

This environment has been divided into two sub-environments on the basis of the character and tectonic history of the host rock:

- Environment 5a is overlain by a sequence that does not contain any significant low-permeability units.
- Environment 5b, the sequence that overlies the host rock contains at least one significant low-permeability unit.

The examples of this environment in England and Wales are found in areas of low to moderate relief (although there may also be areas of higher relief) and may be either inland or coastal.

Environment 6 – Mudstone host rock

The host rock in this environment is an indurated mudrock, which has low permeability and within which solute transport is likely to be diffusion-controlled.

This environment has been divided into two sub-environments on the basis of the character and tectonic history of the host rock.

- Environment 6a has a mudstone host rock that is dominantly flat-lying and undeformed (it lacks a well-developed fabric/cleavage). The overlying sequence is a dominantly low-permeability sedimentary sequence, although it is likely to contain some minor aquifers. The location may be either inland or coastal and many of the examples in England and Wales are in areas of low or very low relief.
- Environment 6b has a host rock that has been altered and that potentially has a well developed fabric/cleavage (it is a tectonised mudstone), although the degree of alteration is not necessarily sufficient for the rock to be considered metamorphosed (though metamorphosed examples exist). The overlying rock sequence is likely to be a mixed sedimentary sequence, which might possibly be unconformable on the host rock, although the stratigraphical relationships depend on the evolutionary history of the basin.

Examples of such environments exist in both inland and coastal settings in England and Wales.

Environment 7 – Plastic clay host rock

In this environment, the repository host rock is plastic (non-indurated) clay.

This environment was originally screened from consideration on the basis that are no suitable plastic clay host rocks onshore in England and Wales; all onshore occurrences are either too shallow or not extensive enough. However, the workshop participants considered that suitable rocks are likely to exist offshore and may be close enough to the shore to be accessed from the land. Given that this environment may raise some distinct issues for EBS design and retrievability, it was considered sensible to include it at this stage for completeness.

Environment 8 – Carbonate host rock

In this environment the host rock is a carbonate rock (limestone or Chalk).

This environment has been divided into three sub-environments:

- Environment 8a has a low-permeability carbonate host rock in which solute transport is likely to be dominated by diffusion. The host rock can possess a low permeability due to secondary calcite cementation of the pores in the carbonate units, and possibly some interbedded carbonate mudstones. It is likely to be overlain by a significant thickness of potentially higher-permeability carbonate or other sedimentary units and glacial deposits. Topographic relief is low and the environment is likely to be coastal.
- Environment 8b has a moderately permeable carbonate host rock. Within England and Wales, this host rock either comprises the Chalk in southern England, where it forms an important aquifer, or is subject to karstification. This sub-environment is therefore screened from further consideration.
- Environment 8c has a relatively massive limestone unit. It is overlain by a mixed sedimentary rock sequence that is likely to contain both high- and low-permeability units. By definition, there will need to be at least one significant low-permeability unit to protect the host rock from processes such as karstification. Topographic relief is likely to be low to moderate and the location is likely to be inland.

Environment 9 – Non-evaporitic host rock with hypersaline groundwater

In this environment, groundwater salinity is significantly greater than seawater salinity, but the host rock is not an evaporite. By implication there may be evaporites relatively close by to supply the salinity in the groundwater within the host rock, unless the salinity is due to long-term water-rock reactions. The high salinity might indicate relatively stable hydrogeological, and by inference, hydrogeochemical conditions.

In the original list defined by Quintessa's staff, this environment was implicitly included within the other environment definitions. However, the issues that may be associated with the presence of hypersaline groundwater at the repository location merit it (which lacks a well-developed fabric/cleavage) being distinguished as a separate environment.

Environment 10 – Small islands

Small islands were initially considered as a separate geological environment. However, it was subsequently decided that they do not generally offer sufficient long-term existence as islands to be considered as a separate environment. Furthermore, based on their geological and hydrogeological characteristics, they could be included within one of the other environments considered here. On the timescale of post-closure safety assessment, and taking into account the likely future changes in sea level, it was judged that the majority of current small islands are unlikely to remain. Therefore, the advantage of a small island possessing an independent groundwater flow system will not persist into the future in most cases. There are, however, some small islands which are likely to retain their status as islands, even during the maximum decease in sea level expected during a future glacial maximum of over 100 m.

Geoscience indicators

A preliminary list of geoscience indicators that might be used to distinguish between environments is developed in this section. The geoscience indicators do not include characteristics that are unlikely to discriminate between geological environments in England and Wales. For example, seismic hazard is assessed to be uniformly low throughout these countries, and was judged not to be a discriminating indicator, at least at this rather broad level.

The table below presents many questions which would need to be answered if a site were being taken forward for repository development. However, if choices were being made between environments, it might be necessary for the indicators to be more performance-related.

Indicator group	Indicator descriptions
Geological	• complexity of stratigraphic sequence that will require characterisation • topographic relief • likely horizontal extent and thickness of host rock unit • likely homogeneity of host rock and overlying rocks • likely frequency and magnitude of faulting and fracturing • long-term stability of environment – susceptibility to significant erosion etc • likelihood of future glaciation
Geotechnical	• rock strength • likely stress state • potential stability of underground excavations in host rock and in any cover rocks – implications for spans and geometries of vaults and construction of access shafts/drifts
Geochemical	• composition (not just 'salinity') of host rock porewater • composition (not just 'salinity') of groundwater along likely path of groundwater plume • fracture and rock matrix materials that will interact with radionuclides along likely path of groundwater plume • redox state and buffering of host rock groundwater • any unusual geochemical conditions – high sulphate, unusual pH, colloids, etc • expected geochemical heterogeneity • likely stability of geochemical conditions
Hydrogeological	• host rock permeability and mode of groundwater flow (porous- or fracture-controlled) • cover sequence permeability and mode of groundwater flow (porous- or fractured-controlled) • likely hydraulic gradients in host rock and cover rocks • expected dominant solute transport process (advection or diffusion) in host rock • expected dominant solute transport process (advection or diffusion) in cover rocks • expected length of groundwater discharge pathway and estimate of groundwater return time • stability of hydrogeological regime to climate change etc • potential for fast pathways • expected discharge location and extent for natural discharge pathway • how host rock will interact with high pH water
Gas migration	• ease with which gas can migrate through the host rock • ease with which gas can migrate through cover sequence • potential for trapping or dissolution of gas within cover sequence
Resource	• potential for presence of coal or hydrocarbons • potential for other exploitable resources • potential for exploitable aquifers in cover sequence

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10 Appendix C: Second expert workshop notes

Introduction

This appendix provides a factual record of the second expert workshop, and takes into account reviews of an earlier version of the record that were received from workshop participants. The purpose of this appendix is to enable the reader to understand the reasoning behind the conclusions presented in the main report. The conclusions presented in the appendix are interim and the reader is referred to the main document to see the final results of the project.

This note is a contribution to the second phase of the project, which aims to identify technical issues associated with deep geological repositories for radioactive waste in different geological environments and hence to review the state of knowledge about these issues. This latter review includes determining the implications of the issues and gaps in knowledge for the safety assessment of radioactive waste repositories. The principal end-users of the project's outputs will be the Nuclear Waste Assessment Team (NWAT) of the Environment Agency.

The following activities were undertaken during the first phase of the work:

- reviewing literature;
- summarising expert knowledge of Quintessa's staff;
- obtaining and recording the opinions of independent experts and Environment Agency staff.

This third component included the first expert workshop, which was held at Richard Fairclough House on 30 January 2008, documenting the discussions held there, and then obtaining feedback from participants on the documentation. Notes of this first expert workshop are given in Appendix B.

The main outputs from the first phase were descriptions of the geological environments and technical issues to be considered by a second phase of the project.

These geological environments are entitled:

1. Hard fractured rock to surface
2. Hard fractured rock overlain by relatively high-permeability sedimentary rocks in which advective transport dominates
3. Hard fractured rock overlain by sedimentary rocks containing at least one significant low-permeability unit in which diffusion dominates solute transport
4. Bedded evaporite host rock
5. Siliceous sedimentary host rock
6. Mudstone host rock
7. Plastic clay host rock
8. Carbonate host rock

9. Non-evaporitic host rock with hypersaline groundwater.

The technical issues are:

1. Interactions between different waste form types and the design of the EBS
2. Interactions between cement and clay-based systems
3. Characterising the site adequately
4. Demonstrating long-term stability
5. Gas/groundwater interactions
6. EBS/host rock interactions
7. Durability of EBS materials
8. Impact of saline water on EBS materials
9. Impact of resaturation.

At the start of this second phase, Quintessa staff carried out an initial review of the state of knowledge concerning these technical issues. The findings were then presented to independent experts and Environment Agency/NWAT staff at a second expert workshop, which was held at Richard Fairclough House on 6 May 2008.

This appendix provides a record of this second workshop. However, the appendix does not aim to reproduce verbatim the discussions, but rather to summarize what was said and then to interpret the significance of the discussions within the context of the project. To ensure that this latter process has not caused misrepresentation of participants' views, the note was circulated to participants to enable them to correct inaccuracies. The present appendix incorporates these corrections.

Aims of the second expert workshop

The overriding aim of the workshop was to provide confidence that, by the time of its completion, the project would not have missed any important technical issue. More specific aims were to:

- review sources of information about the nine technical issues that had been identified by Quintessa during the first phase of the project and identify:
  - additional information sources if significant omissions were identified;
  - any information sources in Quintessa's list that were considered to be inappropriate;
- review limitations in knowledge about the nine issues that were identified by Quintessa and determine:
  - any additional significant limitations in knowledge;
  - whether limitations in knowledge identified by Quintessa were inappropriate.

Approach to the second expert workshop

The workshop was planned to both review work undertaken by Quintessa staff following the completion of Phase 1 of the project, and to provide pointers towards additional material for consideration during the remainder of the project.

Owing to limited time, the workshop focused predominantly on identifying uncertainties and gaps in knowledge. Furthermore, participants were requested not to spend time on additional discussions of the geological environments and technical issues identified during the first phase of the project. The deliberations during the first phase of the project, including the discussions at the first workshop, were considered to be adequate for the purposes of the project. It was, however, recognized that some of the participants in the second workshop, particularly those who had not contributed previously to the project, might have reservations about the choice of environments and issues. Therefore, the participants were invited to notify the convenors of the workshop (the Quintessa staff present) of any such reservations, so that these views might be recorded and taken into account during the remainder of the project.

The meeting included a group discussion session, which involved the participants being divided into three different groups, each of which was asked to consider a different sub-group of technical issues, as follows:

- Group 1 focussed on interactions between barrier components:
  - Issue 1: Interactions between different wasteform types and the design of the EBS
  - Issue 6: EBS/host rock interactions
  - Issue 2: Interactions between cement and clay-based systems
- Group 2 focussed on geosphere issues:
  - Issue 3: Characterising the site adequately
  - Issue 4: Demonstrating long-term stability
  - Issue 5: Gas/groundwater interactions
- Group 3 focussed on durability of the EBS and its implications:
  - Issue 7: Durability of EBS materials
  - Issue 8: Impact of saline water on EBS materials
  - Issue 9: Impact of resaturation.

Following the group discussions, there was a plenary session during which the chair person of each discussion group summarized their group's discussions and presented the main conclusions. After each of these presentations, all participants in the workshop were invited to comment on the conclusions reached.

Record of discussions at the second expert workshop

Introductory Session

Gavin Thomson (Environment Agency/NWAT) presented the background to the project and summarised what the Environment Agency/NWAT was hoping to achieve. He summarised the current position concerning government policy and the role of the Environment Agency within the current programme. He then briefly described the work being carried out by the Science Group and NWAT team.

The Environment Agency's objectives for the project were to:

- Develop an understanding of the key technical issues that would need to be addressed in a safety case for a deep repository in different geological environments, and how they might be addressed in safety arguments.
- Develop an understanding of the current status of work on those issues worldwide.
- Provide a basis for planning and prioritising future scrutiny work, research and resources, and hence be prepared to review future safety cases.

Guidance on the types of issues that the project should be identifying was as follows:

- 'Key' issues are those that could challenge the feasibility of achieving an acceptable long-term safety case.
- The project should focus on issues specific to an environment or concept.
- Some indication should be given of the relative importance of key issues.
- A priority is to build confidence that all important issues have been covered.
- The second expert workshop should reinforce this confidence.

Important ground rules for the project were:

- The project must not prejudge outcomes of site selection.
- The project should consider geological environments that exist in England and Wales and that could potentially be used to host a repository.
- No consideration should be given to Scotland or Northern Ireland, where the Environment Agency has no remit.
- It is important to focus on issues relevant to the post-closure safety case, but nevertheless to mention major issues that could affect how (or whether) it would be possible to reach the point where a safety case could be developed (for example, to consider whether excavations would be sufficiently stable to allow construction and operation of a repository).

Richard Metcalfe (Quintessa) presented the aims and approach of the workshop, along with the main findings of an initial review of technical issues. The presentation gave a brief description of each issue, outlined the main research undertaken on each issue and the organisations carrying out this research, and explained the main uncertainties/gaps in knowledge for each issue.

Inputs from Discussion Group 1

The main conclusions of Discussion Group 1 are summarized in Table C1.

For Environments 4 (bedded evaporite host rock), 8 (carbonate host rock) and 9 (non-evaporitic host rock with hypersaline groundwater), the group identified a relative lack of information concerning the issue/environment in England and Wales. This lack of information reflects not only past experience in the UK, which has focussed on crystalline rocks (and to a lesser extent mudrocks), but also on past international experience. Only the WIPP programme in the US has considered bedded evaporite host rocks in detail. Similarly, only OPG's DGR Project is considering a carbonate host rock. However, each of these projects is evaluating a rather limited range of waste types: TRU waste in the case of the WIPP and LLW/ILW in the case of the DGR.

The issues considered are highly inter-related. Issue 2 (interactions between cement and clay-based systems) is a special case of Issue 1 (interactions between different wasteform types and the design of the EBS) when the EBS includes cement and clay components. Similarly, Issue 2 is a special case of Issue 6 (EBS/host rock interactions), when the EBS contains cementitious components and the host rock is a mudrock.

A general theme of the discussions was that both physical and chemical processes need to be considered, but that these are coupled.

Table C1: Summary of the main conclusions of Discussion Group 1.

Geological environments		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
		Hard fractured rock to surface	Hard fractured rock overlain by relatively high-permeability sedimentary rocks in which advective transport dominates	Hard fractured rock overlain by sedimentary rocks with at least one significant low-permeability unit in which diffusion dominates solute transport	Bedded evaporite host rock	Siliceous sedimentary host rock	Mudstone host rock	Plastic clay host rock	Carbonate host rock	Non-evaporitic host rock with hypersaline groundwater
General comments on the environments					General lack of information on this environment. Corrosion of metals. Salt concretes.				General lack of information on this environment	General lack of information on this environment
Issue	**Decription and general comments**									
1 HLW & SF	Interactions between different wasteform types and the design of the EBS. Effects of decay on EBS materials – knowledge gap but possibly of minor significance. Microbes – knowledge gap (may be significant for some waste materials).	Waste dissolution rates (general to all environments but more acute for fractured environments). - (see IRF, matrix dissolution under realistic repository conditions – partial pressures) – fuels particular to the UK. - UK glass and ceramic wasteform characteristics and long-term degradation rates – effect of alkaline fluids if interaction occurs between cemented ILW and glass. Need high integrity packages for fractured rock systems – knowledge of corrosion important – depends on water chemistry.				Corrosive components of clays affecting choice of container material – clays generally more reactive than (granites) fractured rocks.				

<table>
<tr><th colspan="2" rowspan="2">Geological environments</th><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th><th>8</th><th>9</th></tr>
<tr><th>Hard fractured rock to surface</th><th>Hard fractured rock overlain by relatively high-permeability sedimentary rocks in which advective transport dominates</th><th>Hard fractured rock overlain by sedimentary rocks with at least one significant low-permeability unit in which diffusion dominates solute transport</th><th>Bedded evaporite host rock</th><th>Siliceous sedimentary host rock</th><th>Mudstone host rock</th><th>Plastic clay host rock</th><th>Carbonate host rock</th><th>Non-evaporitic host rock with hypersaline groundwater</th></tr>
<tr><td></td><td rowspan="2">Behaviour of any Pu/U wasteforms
.</td><td colspan="3">Buffer – effect on swelling properties of groundwater sodium at low bentonite densities.

Backfill/buffer interactions.</td><td></td><td colspan="3"></td><td></td><td></td></tr>
<tr><td>1
ILW</td><td colspan="9">Gas - flow in fractured rocks, generation and migration from ILW in clay host rocks? (container vents provide a gas release pathway at the package scale).

More concerned about dissimilar metals causing galvanic corrosion than graphite.

Cementitious materials will not necessarily capture C-14.

C-14 methane ‘story’ is a knowledge gap.

Not convinced ‘miscellaneous wastes’ are significant in the big picture.</td></tr>
<tr><td>6</td><td>EBS/host rock interactions</td><td colspan="3">Need for use of grouts to seal fractures (cements superplasticisers, Na silicate liquids).
Inflow heterogeneity.

Thermal conditions, host rock and barrier conductivity and effect of heat on EBS materials.
Thermal effect of too dry conditions.

Chemistry of inflowing waters – supply of corrodants and those affecting clay alteration, also possibly causing colloid formation and bentonite erosion.

Eh control in bentonite - knowledge gap/uncertainty.

Spalling/mechanical effects, and creation/significance of EDZ a site-specific issue,</td><td>Rock convergence (salt)</td><td colspan="3">Incoming organics.

Incoming water salinities/species (such as carbonate, chloride, sulphur, thiosulphate) – corrosion of metallic barriers.

Extent of alkaline plume (depending on cement composition/blend and flow conditions) – fracture/porosity sealing?

Effects of excavation on host rock (fracturing, oxidation).

Rock convergence (plastic clay).</td><td>Incoming species (such as organics, carbonate).</td><td>Hypersalinity corrosive to many components of the engineered barrier system.</td></tr>
</table>

Geological environments		**1** Hard fractured rock to surface	**2** Hard fractured rock overlain by relatively high-permeability sedimentary rocks in which advective transport dominates	**3** Hard fractured rock overlain by sedimentary rocks with at least one significant low-permeability unit in which diffusion dominates solute transport	**4** Bedded evaporite host rock	**5** Siliceous sedimentary host rock	**6** Mudstone host rock	**7** Plastic clay host rock	**8** Carbonate host rock	**9** Non-evaporitic host rock with hypersaline groundwater
2	Interactions between cement and clay-based systems, General comment – uncertainty likely to remain on kinetic data for concrete degradation and clay interaction.	Need for use of grouts to seal fractures – effect on any clay overburden (for example for Environment 3 - probably not significant),					Mechanical effects of excavation on clays (drying, oxidation, fracturing), tunnel liners, cement backfills.			

Inputs from Discussion Group 2

Issue 3: Characterising the site adequately

It was concluded that the requirement to characterise a site adequately applied equally to all of the geological/hydrogeological environments and thus the discussion below is applicable to any environment, except where comments are made regarding a specific environment.

The following comments and suggestions were made:

- It is important to try and understand the 'big picture' from the outset. This issue applies equally to any of the geological/hydrogeological environments.
- It is thus better if the geological/hydrogeological system is studied in a more general manner from the outset, rather than quickly concentrating on a small area which is believed, based perhaps on information available before the investigation starts, to show greatest promise. This approach requires that greater emphasis be given to the following types of analysis:
    - A study of the regional geological and hydrogeological setting, which implies that studies such as the regional water balance investigations are highly desirable (in contrast to concentrating on obtaining as many hydraulic conductivity data as possible early in the project).
    - This goal has implications for the area over which investigations may be required. In areas where there are only low-permeability rocks such as hard fractured rocks, investigations of this kind may be limited to geological mapping and limited hydrological/hydrogeological studies.
    - In some sedimentary environments, for example where the geology includes relatively permeable rocks (even though the host rocks themselves would be chosen to be of low permeability), investigations could be required over a very extensive area, possibly of several hundreds of square kilometres. Such investigations are likely to require deep boreholes, perhaps at considerable distances from where the repository might eventually be sited.
- We need to ask questions such as: What do we need from the site? What does the geosphere need to offer in order to demonstrate that radioactive waste could be disposed of here safely? This latter question is rather similar to the one posed in the early stages of SKB's repository programme in the report entitled 'What requirement does the KBS-3 repository make on the host rock?' (SKB report TR-00-12).
- An integrated approach to the investigations is required. For this to take place, it is highly desirable for a dedicated team to be set up well in advance of the investigation. This team would include representatives from the various components of the investigation programme, together with representatives from safety assessment and repository design/engineering. Good examples of such an approach, and the methods they employ to work collectively, are provided by several existing waste disposal

programmes. One important point here is the considerable time that is required to set up such a team and for it to function efficiently. Again, considerable evidence is available from other waste disposal programmes. This requirement for an integration team, that would continue through all phases of the investigations and be intimately involved in all aspects of the modelling, is probably the most significant recommendation that is made regarding the design and operation of the site investigation programme.

- A similar approach would need to be followed with regard to the development of a URL programme. Practical experience of working in such facilities is required well in advance of their construction, if proper use is to be made of such a facility. So far in the UK insufficient experience of URLs has been gained to make maximum use of underground investigations.
- It is beneficial to keep modelling as simple as possible, otherwise too much time is spent on model development, and complex models are likely to require data that are difficult to obtain to the density required. Considerable time constraints are likely to exist, especially in the earlier stages of the investigations, and it is better to be able to run several phases of relatively simple models, rather than only a limited number of complex ones.
- It would be beneficial to learn as much as possible from other industries (such as mining, mineral assessment, hydrocarbons industry) and from other waste disposal organisations. There is a tendency in some areas of the radioactive waste field not to make sufficient use of this information.

Issue 4: Demonstrating long-term stability

The discussions on Issue 4 produced the following consensus opinions.

The presence of geologically stable conditions at depth is an important element in demonstrating that radioactive waste can be disposed of safely. Stability, in this sense, does not imply that steady-state conditions exist; it is recognised that no natural system is likely to be in equilibrium. The geosphere is constantly evolving, although in many cases rather slowly, especially at depth. Such slow evolution is perfectly acceptable for safe geological disposal. The concept of geological stability implies, therefore, that the changes that occur in the geological system do so to an extent and at such a rate that their effects are unlikely to compromise the short- or long-term safety of the disposal system. What is perhaps of greatest important in this regard is that the effects of this evolution and its implications for repository safety are sufficiently well understood.

In the UK tectonic stability is not an important issue, as the level of seismicity is current low and is expected to remain low for many millions of years.

The stability of the hydrogeological and hydrogeochemical system is more difficult to demonstrate, but there is considerable consensus around the world that it is possible to demonstrate such stability. There have been two recent NEA workshops on stability, the first on argillaceous rocks in 2003 (NEA, 2005) and the second on crystalline rocks in 2007 (NEA, in preparation). There is also the possibility of an NEA brochure that will discuss the concept of geological stability for all geological environments in the context of the disposal of radioactive waste.

There is an important difference between the geological/hydrogeological environments in terms of the likelihood of being able to demonstrate convincingly that the system at depth evolves sufficiently slowly (is adequately stable). It is likely to be easier to demonstrate such stability in argillaceous rocks than in any other rock type. The argillaceous rock in this case does not have to be the host rock itself, but could be one or more of the low-permeability barriers in the geological succession.

The group discussed the anticipated relative ease with which it is likely to be possible to demonstrate stability, based on:

- the likelihood of being able to find evidence in the rock of a groundwater system that will convincingly demonstrate that conditions have been stable in the past (at least the last 100,000 years);
- the likelihood that all elements (THMC) of the geologically stable conditions at depth have been maintained.

The results of the discussions are summarized in Table C2 which indicates the relative level of ease on a scale of one to five, with one being the easiest and five the most difficult. These scores do not imply that environments with a score of five are definitely unstable, but rather that:

- demonstrating stability in such environments is likely to be difficult;
- such environments possess some characteristics which tend to reduce their capability to buffer the effects of external events, such as climate change.

Table C2: Ease of demonstrating geological stability for each environment.

Geological/hydrogeological environment	Ease of demonstration of stability
1	4-5
2	4-5
3	1-3
4	4-5
5	1-3
6	1
7	1
8	1-3
9	2-4

It should be noted that the **ease** of demonstrating stability is only one factor among many that needs to be considered when evaluating whether or not a site might be suitable as a repository host. The **importance** of demonstrating stability might in fact be different in different environments. Therefore, in some cases the difficulty of demonstrating stability might not matter as much as in others.

Issue 5: Gas/groundwater interactions

It was realised that the group did not contain much expertise in this area, although some general comments were made on this subject.

The main question that was asked was: Are there any generic issues specific to all of the environments or are the issues more specific to a site and to a repository design?

- It was suggested that the subject was site-specific and that it might be possible only to carry out detailed work when a site had been selected.
- It was also suggested that evidence could be obtained from other industries that dealt with the subject of gas in rocks, such as the hydrocarbons industry, CO_2 disposal and gas storage.

Inputs from Discussion Group 3

The conclusions of the third discussion group are summarized in Table C3.

It was a generally-held opinion within the group that we do not have the same level of knowledge about the behaviour of different barrier systems in different environments. Consequently, there are more uncertainties associated with some environments than with others. A related point is that there is inevitably a tendency for discussions to be biased by previous investigations. Consequently, when completing Phase 2 of the project, it is important to document the extent to which each environment has been investigated, so that these potential baises are transparent to readers.

Issue 7: Durability of EBS materials

A general point was that in positing this issue an assumption seems to have been made that durability is important. However, the durability of EBS materials may not always be important; whether or not this issue needs to be considered will depend on the nature of a particular safety case. The concepts of durability and design functions need to be linked in the review during Phase 2 of the project. To achieve a required safety target it is not usually necessary to contain all nuclides/contaminants in the wastes. Therefore, the durability of EBS materials may not necessarily be a problem.

It was felt that in the case of ILW, engineered barrier durability (Issue 7) does not really need to be considered further, since:

- for these kinds of wastes, it will always be possible to construct an engineered barrier that will be sufficiently durable to achieve its purpose;
- the geosphere will always play a role in ensuring the safety of these wastes (whether as a physical barrier or as a medium to ensure dispersion of any contaminants that would leave a repository).

If there is a requirement to ensure retrievability of the wastes, this has implications for the durability of EBS materials. The durability of the EBS during the pre-closure and post-closure phases must be considered. There are significant knowledge gaps on the impacts of a repository being kept open for a long period on the durability of the engineered materials, both in the open phase and in the subsequent post-closure phase. Thus, the implications of keeping the repository open for a protracted period, and particularly the impact on uncertainties concerning the post-closure performance of the EBS, require further consideration.

The briefing material for the workshop stated that it is '*unlikely to be possible to demonstrate sufficient durability of an EBS to assume that it will contain the very long-lived radionuclides*'. It was noted that this statement is overly negative, since there is general agreement that all but the long-lived nuclides can be contained.

The durability of the engineered barrier system could be enhanced by optimising the wastes, wasteforms and waste containers prior to disposal. However, Ian Barraclough noted that this topic is outside the scope of the project.

The impact of keeping a repository open for a prolonged period on the durability of the EBS is being considered by ANDRA in context of the French disposal concept. It is recognized that how a repository is operated will affect the post-closure durability of the barriers. The RWMD also recognizes this point.

When reviewing the general topic of EBS durability, related issues that should be considered are:

- the possibility of changes in the reasons for using particular materials over the lifetime of a project;
- development of heterogeneities in engineered barriers, for example the history/characteristics of cracking;
- knowledge gaps on the durability of cement;
- the differing durabilities of different kinds of cement (such as OPC versus low-pH cements);
- the possible uses of alternative kinds of materials, besides those commonly proposed for EBS;
- justifications for particular EBS components, for example why copper or iron is chosen;
- incompatibility of certain waste types with certain EBS systems, for example the possible incompatibility of bentonite barriers used in proximity to waste that produces large volumes of gas at a relatively high rate.

Issue 8: Impact of saline water on EBS materials

There was general agreement that the main reasons why this issue is important are:

- The rates of degradation/reaction of most EBS materials depend upon the chemistry and salinity of the water present. For example, steel will tend to corrode more rapidly if the concentration of Cl is high. Similarly high SO_4 levels may have a detrimental impact on the longevity of Cu canisters.
- In the presence of highly saline water, it is difficult to predict the future chemical evolution of the barrier materials owing to the inherent complexity of chemical reactions in highly saline systems and the relatively limited availability of reliable thermodynamic data.

However, it was pointed out that the presence of highly saline water often implies very low groundwater flow rates. Such low flow rates would generally be advantageous with respect to safety, and may outweigh any disadvantages due to the difficulties in predicting chemical reactions.

Other sub-issues which were discussed by the group are:

- Evaporation during the open phase of the repository and/or during resaturation could lead to local development of very high salinities. These locally high saline conditions might impact upon the durability of EBS components. This issue has been considered by Yucca Mountain project.
- The disposal and/or treatment of highly saline water that would be pumped during the development and operation of a repository may be a problem.
- The long-term behaviour of seals is poorly known.

Issue 9: Impact of resaturation

It was agreed that the overall, repository-scale effects of resaturation are well understood and can be reliably predicted. However, detailed effects, such as the changes in thermal conductivity of bentonite buffers as a consequence of resaturation, are difficult to model reliably. Consequently, additional work is required in this field.

If a repository was kept open for a prolonged period, as would be required if waste retrievability were incorporated into a disposal concept, there would be additional uncertainties concerning the impacts of resaturation. For example, the properties of the EDZ around the repository would change over time as a result of void spaces being kept open. This phenomenon would in turn change the characteristics of resaturation.

Table C3: Particular aspects of each issue that are important and/or uncertain in each environment, as concluded by Discussion Group 3.

Geological environments		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
		Hard fractured rock to surface	Hard fractured rock overlain by relatively high-permeability sedimentary rocks in which advective transport dominates	Hard fractured rock overlain by sedimentary rocks containing at least one significant low-permeability unit in which diffusion dominates solute transport	Bedded evaporite host rock	Siliceous sedimentary host rock	Mudstone host rock	Plastic clay host rock	Carbonate host rock	Non-evaporitic host rock with hypersaline groundwater
General comments on the environments		The EBS has a critical physical barrier function as the geosphere cannot be relied on as a physical barrier.	Chemical functions of the environment may be as important for safety as physical functions.		Chemical functions of the environment are at least as important as physical functions.					
Issue	**Decription and general comments**									
7	Durability of EBS materials	Gaps in knowledge are particularly important, because reliance is placed on EBS. Erosion of bentonite barriers possibly important (again because reliance is placed on EBS),	Durability may or may not be important, depending upon the particular concept,		Some barriers are incompatible with this environment, Fundamental technical limitations to predictability exist,	Durability may or may not be important, depending upon the particular concept,				Some barriers are incompatible with this environment. Fundamental technical limitations to predictability exist.

Table C3: Continued.

Geological environments		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
		Hard fractured rock to surface	Hard fractured rock overlain by relatively high-permeability sedimentary rocks in which advective transport dominates	Hard fractured rock overlain by sedimentary rocks containing at least one significant low-permeability unit in which diffusion dominates solute transport	Bedded evaporite host rock	Siliceous sedimentary host rock	Mudstone host rock	Plastic clay host rock	Carbonate host rock	Non-evaporitic host rock with hypersaline groundwater
General comments on the environments		The EBS has a critical physical barrier function as the geosphere cannot be relied on as a physical barrier.	Chemical functions of the environment may be as important for safety as physical functions.		Chemical functions of the environment are at least as important as physical functions.					
Issue	**Decription and general comments**									
8	Impact of saline water on EBS materials		The main potential problems are: 1) the predictability of chemical reactions under very saline conditions; 2) degradation of chemical barrier functions; and 3) degradation of physical barrier functions as a result of the chemical processes. Whether problems occur or not will be concept-specific.			The main potential problems are: 1) the predictability of chemical reactions under very saline conditions; 2) degradation of chemical barrier functions; and 3) degradation of physical barrier functions as a result of the chemical processes. Whether problems occur or not will be concept-specific.				
9	Impact of resaturation	Predicting resaturation rates (especially locally) is difficult.			Very slow resaturation.	Predicting resaturation rates (especially locally) is difficult.		Very slow resaturation.	Predicting resaturation rates (especially locally) is difficult.	

Plenary discussions

The final plenary discussions showed that inter-relationships exist between the different technical issues. The impact of each issue upon repository safety cannot be determined without considering all these inter-relationships together. It follows that just because one particular issue may impact unfavourably upon a particular repository concept within a given geological environment does not mean that the repository will be unsafe. Conversely, some technical issues could have positive implications for safety.

Most of the technical issues identified apply to all geological environments considered. However, the relative importance of the issues for repository safety in any particular environment will depend on site-specific and repository concept-specific factors. Thus, at the present generic stage of the UK's radioactive waste disposal programme, it is not possible to state precisely whether or not a particular issue will be significant for safety.

There are overlaps between some of the technical issues, which tend to result in important safety points being obscured. For example, Issue 2 'interactions between cement and clay-based systems', Issue 6 'EBS/host rock interactions' and Issue 7 'durability of EBS materials' overlap. Issue 2 concerns interactions between cementitious and clay-based components of the engineered barrier system and also between cementitious engineered components and clay-based host rocks. Just from the description given in the briefing notes for the workshop, it is not immediately apparent why interactions between cement and clay-based systems is worthy of more attention than interactions between any other components. In the absence of site- and concept-specific information, it cannot be concluded definitively that these interactions between cementitious and clay-based systems would be of special importance.

The particular classification of issues arising from Phase 1 of the project obscures the fact that it is important to evaluate interactions between engineered barrier systems in general. It is also important to state explicitly how interactions between different engineered components and/or the geosphere (Issues 2 and 6) differ from the 'durability of the EBS materials' (Issue 7). While there is a relationship between Issues 2 and 6 and Issue 7, in so far as interactions between components may impact upon durability, any consideration of an EBS system's durability must refer to the period of time for which the EBS system may perform its required function.

A related aspect is that definitions of issues need to be more precise. For example, it is necessary to emphasise that durability is defined with respect to some safety function (the length of the time for which the barrier performs its required function), but recognize that a particular barrier component may have different functions and that the durability of the barrier component with respect to each one may be different. Similarly, Issue 4 'demonstrating long-term stability' needs to be defined so that the meaning of 'stability' is clarified. In this case, 'stability' does not mean that the geological environment is unchanging, but rather that the environment changes sufficiently slowly with no undesirable consequences for safety.

The desirability of not excluding from the review possible innovative new technologies and/or approaches was also considered. It was pointed out by several participants that there is a danger of focussing too much on research that has already been done. A counter view was that the UK government has already made a policy decision to proceed with deep disposal, so that the remainder of the project must not digress into consideration of other conceivable options. However, it was also pointed out that there are great uncertainties given the generic nature of the programme that is being developed for potential implementation in England and/or Wales. It is conceivable that an actual site might be suitable for one kind of waste, but not for another. For example, the site might be favourable for SF/HLW or L/ILW, but not together.

Ian Barraclough stated that one purpose of the project is to inform the Environment Agency/NWAT of the status of technical issues, and not suggest solutions to them. From this perspective, innovative research could be seen as suggesting new solutions to the technical issues, rather than being technical issues in themselves. Thus, the content of ‘blue skies research’ is outside the scope of the project (although the need for it might not be outside the scope).

Bearing in mind these points, a conclusion was reached that there was a need to keep the review general and not to be too prescriptive.

There was considerable discussion of Environment 9 ‘non-evaporitic host rock with hypersaline groundwater’. While it was not within the scope of the second workshop to reconsider the definitions of the environments, these discussions were valuable because they highlighted how many of the issues would be affected by this environment. It was noted by Richard Metcalfe that this environment had been discussed at length during the first expert workshop and then a clear divergence in opinions had emerged on whether or not to consider this environment separately from the others. However, during the first workshop it had been decided to retain Environment 9 because otherwise it would have been necessary to subdivide all the other environments (except for Environment 4 ‘bedded evaporite host rock’) to take into account that any of them might potentially contain brines. It would not be a good use of the discussion time at this second workshop to revisit these earlier deliberations.

It was pointed out that all environments potentially pose problems for the development of a repository but that, in the absence of any site-specific and/or concept-specific information, it cannot be stated that any problems cannot be resolved. Thus, it cannot and should not be stated whether one environment might be preferable to another; it is outside the scope of the project to attempt to reach such a conclusion. At the present generic stage, all that should be done is to highlight those issues that are likely to be particularly important in any environment, without stating what might be the overall suitability of the environment.

A final point that was highlighted by all the three discussion groups is that there is much information in the literature from industries concerned with fields other than radioactive waste management. It would be appropriate for the review in the second phase of the project to at least mention relevant work being undertaken by the oil industry and, in particular, concerning CO_2 storage.

Conclusions from the second expert workshop

During the workshop, no significant omissions from the list of technical issues were identified. Similarly, no significant modifications to the geological environments produced by Phase 1 of the project were needed. There was general agreement that the selected issues and environments together provide an appropriate basis for reviews by NWAT of the present state of the radioactive waste disposal programme being developed in England and Wales.

The discussions determined the implications for repository performance of each issue in each environment. An important outcome was that, for each of the nine issues identified in the first phase of the project, many more detailed sub-issues were identified. However, the importance for safety of these different sub-issues is expected to be site- and/or disposal concept-specific. Thus, it is appropriate for the review in the second phase of the project to give only general information about the nine issues. Information about the more detailed sub-issues could then be presented as examples of the ways in which these issues would be expected to be important.

It is important to recognize that in the UK and internationally, different combinations of disposal concepts and geological environments have previously been investigated at different levels of detail. This recognition will be an important step to ensure that bias is avoided when judging the merits and/or demerits of any radioactive waste disposal project that might be proposed in future.

Most of the technical issues identified apply to all geological environments considered. However, the relative importance of the issues for repository safety in any particular environment will depend upon site-specific and repository concept-specific factors.

There are overlaps between some of the technical issues, which tend to result in important aspects being obscured. Whilst it was recognized that the range of technical issues is appropriate, it was agreed that issues should be redefined so that:

- overlaps (though not inter-relationships) between issues are minimized;
- the issues are all presented at a comparable level of detail;
- issues are defined in such a way as not to imply that unnecessarily stringent criteria must be met in order to meet safety targets (for example, by defining stability to mean that conditions evolve sufficiently slowly that there are no adverse consequences for safety, rather than to imply that conditions must be unchanging to achieve acceptable levels of safety).

References

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