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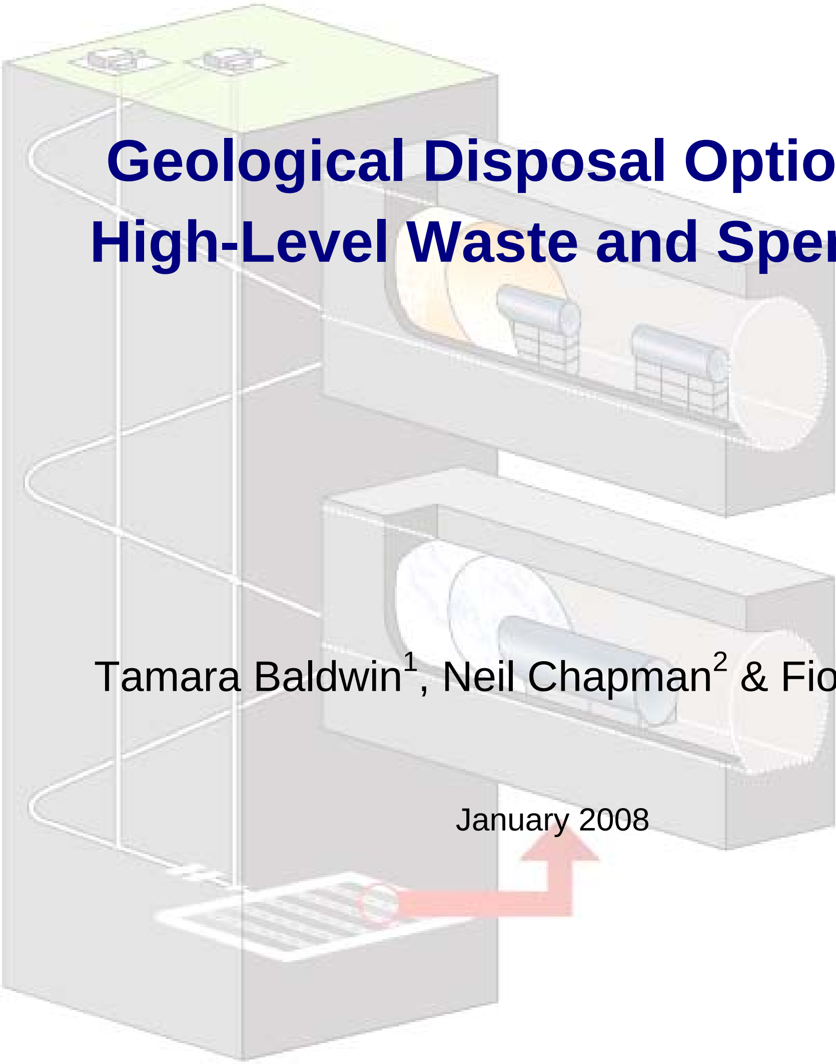

Geological Disposal Options for High-Level Waste and Spent Fuel

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Report for the UK Nuclear Decommissioning Authority

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Preface

This report describes work carried out in 2007 for the Nuclear Decommissioning Authority (NDA). The objective of the report is to provide information on a range of high-level radioactive waste (HLW) and spent nuclear fuel (SF) geological disposal concepts, in order to illustrate how geological disposal of HLW and SF might be implemented in the UK.

The work is intended to form an information source for the NDA and other stakeholders in the early stages of a future repository siting and options evaluation programme.

This information is intended for use in two principal ways:

- To compile basic data for the NDA and other stakeholders to use in comparing geological disposal options in more detail, once the geological and other constraints are better understood as the repository siting process gets underway in 2008.
- To provide illustrations for a wide range of stakeholders of the types of repository that may be feasible in different circumstances, for example, so that potential volunteer communities can gain a clearer idea of the types of facility that may be developed in their area.

The authors of the report are Tamara Baldwin (Galson Sciences, UK), Neil Chapman (Chapman & Co Consulting, Switzerland) and Fiona Neall (Neall Consulting, UK). Matt Simcoe (Wardell Armstrong, UK) prepared the example Concept illustrations.

The project was directed by Neil Chapman and the NDA project officer was John Mathieson, supported by Matt White.

Initial results of the project and the evaluation work were reviewed by a team of 21 further experts from the NDA and its consultants, the Environment Agency, the Scottish Environmental Protection Agency, DBE Technology (Germany), ONDRAF/NIRAS (Belgium), IRSN (France), ANDRA (France) and SKB (Sweden), at a workshop held in Oxford in August 2007. The results of that review have been incorporated in this final project report.

This document provides a summary of the geological disposal Concepts that could be feasible for UK conditions. A NDA companion report, currently in preparation, will provide detailed information, in the form of matrices, on the Concepts with respect to the type of geological environment in which it might be located and with respect to a wide range of safety, environmental, technical, societal and economic Evaluation Factors.

Report History

Version 1.0, the first internal draft compilation, was reviewed and edited internally by the project team to produce Version 1.1, which was approved by the Project Manager and submitted to the Nuclear Decommissioning Authority on 20th October 2007.

Review comments were received from the NDA on 13th December. In addressing these, two appendices containing the Concept datasheets and the Concept matrices, were removed. These appendices will be published in a companion report to this document, which describes a workshop at which the Concept datasheets and matrices were discussed (NDA, in preparation). A revised Version 1.2 was submitted to the NDA on 18th December 2007 and, following further comments, this final version was produced on 10th January 2008.

Executive Summary

The UK is in the process of considering how to dispose of the high-level radioactive waste (HLW) and whether to dispose or reprocess spent nuclear fuel (SF) arising from the generation of nuclear electricity. These materials, the most highly radioactive and longest-lived produced by nuclear power stations, were included in the inventory of 'legacy' wastes and materials addressed by the Government's advisory committee, the Committee on Radioactive Waste Management (CoRWM), which reported in 2006. CoRWM recommended that geological disposal – careful engineered emplacement of long-lived radioactive waste in a geological disposal facility in stable rock formations hundreds of metres below the ground – was the most appropriate solution for the long-term management of HLW and SF, should SF be declared a waste.

In this study, we have explored the engineering possibilities for geological disposal of HLW and SF in the UK. The range of geological environments – rock formations and their surrounding geological setting – that could be suitable for hosting a geological disposal facility for HLW and SF is wide in the UK. Whilst some countries have limited options for locating suitable, stable rock formations, the UK has many possibilities. Also, a wide range of engineering solutions is available – some of these solutions may be suitable for several geological environments and some may be more suitable to specific environments. This, in turn, means that there will be options for the way that geological disposal could be implemented at any specific site. The Nuclear Decommissioning Authority (NDA), which is charged with disposing of these wastes, needs to consider all the possibilities because it is not yet clear which environments or locations will emerge from a future siting programme – in principle, with a voluntary approach to hosting a geological repository, any location might need to be considered.

For more than 30 years, most countries with nuclear power have been researching appropriate geological disposal solutions. As a consequence, there are many conceptual designs available for different rock formations and geological situations, some of which are highly advanced – and one of which is in the first stage of implementation in Finland. This wealth of information has been evaluated and used to develop a set of twelve generic 'Concepts' for the design of a geological repository. This set is considered to represent a comprehensive range encompassing the principal conceptual solutions available internationally that might realistically be considered for implementation in the UK.

For each Concept a detailed description has been provided of how it is designed, where it originated, which programmes are working on it, how mature it is, what alternative variants have been considered, how it would be built and operated, what its environmental impacts are likely to be and what studies have been carried out on how it provides both short-term and long-term safety. Where there are particularly well-developed examples of a generic Concept in a national programme, additional information has been provided on how that country proposes to implement disposal and of the work that they have carried out to develop and test the approach.

This report looks at how each Concept would relate to a set of geological environments – how appropriate it would be in a specific set of geological conditions. These geological environments have not been established in any geographical sense

or related to specific rock formations in the UK. Instead, this report has grouped what are generally considered to be appropriate physical and chemical properties of environments that favour waste isolation. These groups are based on the thermal, chemical, hydrogeological and mechanical properties of the host rock and its environment. There are groups that reflect stronger and less strong rocks, environments with very low groundwater flow and those where there would be no flow at all around the waste packages (diffusion-dominated environments), and so on. Once potential sites emerge in the future programme they can be mapped onto one or more of the five geological environments used in this study.

In order to relate the Concepts to the five environments we have used a set of sixteen evaluation factors that can be used to see how well a Concept is matched to geological conditions across a range of considerations that include safety, environmental impact, ease of engineering and operation, flexibility, cost and others. The results of an expert assessment of this matching were presented as a set of matrices with comments on each Concept against each evaluation factor in each geological environment. The initial set of expert commentaries was reviewed at a large workshop that involved 21 further experts, including several from other European waste management organisations and regulators, and the commentaries were updated to produce the final set, which are presented in the workshop report.

Based on these evaluations, we present a range of conclusions with respect to possible SF and HLW repository design Concepts for the UK, chief amongst which are the following:

- A range of generic repository Concepts is available that can provide safe and secure geological disposal options to suit any suitable UK geological environment. It is not appropriate at this stage of the siting programme to select a preferred Concept. Some of the Concepts are unsuitable for some geological environments. All of the geological environments could host more than one of the Concepts, which means there will always be a choice of how to implement disposal. It would be beneficial to maintain a flexible approach to design to allow optimisation of elements of several appropriate Concepts to actual site conditions. The Concept(s) that eventually form the focus for the NDA programme once potential sites emerge can be based upon those presented here. However, it is important to appreciate that the developed and optimised design that will finally be built may look considerably different in detail when adapted to site conditions and programme drivers.

- The data provided here and the commentaries on the relevance and appropriateness of each Concept in different geological environments with respect to different evaluation factors can all be used as input to future decision-making in the early stages of siting and design work. Such exercises can be carried out by NDA and/or other stakeholders.

- A trend in several national programmes is to consider the use of ‘supercontainers’ that include several components of the planned engineered barrier system in a single package that can be pre-fabricated in a surface facility before being transported underground for disposal. This facilitates quality control on barrier components that can be critical for the safety case in some Concepts.

- The Concepts offer variable capabilities with respect to inspectability, retrievability and safeguardability of the wastes. Views on how important these matters are will need to be taken into account and weighted in taking decisions on appropriate Concepts for a site.

- Similarly, the Concepts have different non-nuclear environmental impacts. Although such impacts are considered to be very small and commensurate with many small-scale industrial activities, the repository is likely to be an operational presence in a community for many decades and the impacts need to be considered carefully by stakeholders in deciding how to optimise a Concept to a site.

- All of the excavated (tunnel or cavern) repository Concepts could include other radioactive materials that either exist already and might be considered for geological disposal (e.g. plutonium) or could arise in a future nuclear power programme (e.g. SF from a new generation of nuclear power plants). The very deep borehole Concept could include plutonium, if it was decided to dispose of this material.

- All of the Concepts (with the exception of very deep boreholes) could be co-located with disposal vaults for intermediate waste and long-lived low-level waste, utilising the same geological environment.

- Even before a future siting programme allows focussing on a group of Concepts, there are generically important areas where relatively small investments in further work would be valuable now. These include: optimising waste packaging (overpack) solutions for different Concepts; consideration of the minimum feasible open period of cavern repositories for HLW and SF based on thermal-decay data and the consequent possibilities and performance implications of completing by using cement-based backfill; scoping long-term safety analyses of cavern and very deep borehole Concepts; comparative cost evaluations of Concepts. Relatively straightforward studies would permit closer comparisons of Concepts from an equivalent level of knowledge.

Contents

1 Introduction

1.1 Background to UK Studies on HLW and SF Disposal

The UK began research into the geological disposal of high-level radioactive waste (HLW) shortly after the publication of the Royal Commission on Environmental Pollution report on nuclear power in 1976 (the Flowers Report, 1976), recommending this solution and proposing that a R&D programme got under way. Similar programmes began in several European countries in the late 1970s. At this time, the intention was to reprocess all UK spent fuel and no consideration was given to disposing of it directly. An extensive programme of field and laboratory studies began, but the need to carry out field-based research in a range of geological environments precipitated considerable local opposition to the essential drilling programmes and the government of the day cancelled the R&D programme in 1981. In this period, although there was work on defining and studying potentially useful UK rock formations, there was no project that aimed at locating a specific repository site.

Following cancellation of the HLW R&D programme, the UK position for the next twenty years was that there was no urgent requirement to dispose of HLW, which needed to cool for around 50 years before it could be emplaced in a repository, and that a watching brief would be maintained on R&D developments in other countries. Over this period, considerable advances were made in a number of countries and several geological disposal Concepts for both HLW and SF moved from a simple conceptual level to well-researched engineering solutions, underpinned by extensive testing and safety analyses.

In 2001, following a number of failed projects to locate repositories for lower activity wastes in the intervening 20 years, Government began a concerted project to address the legacy of UK wastes from the historic development of nuclear energy. It initiated the current Managing Radioactive Waste Safely (MRWS) process, formed an advisory committee, the Committee on Radioactive Waste Management (CoRWM), on how to move forward with management of the wastes and, in 2005, established the Nuclear Decommissioning Authority (NDA). In 2003, in support of the second stage of MRWS and to provide information to a range of stakeholders, including CoRWM, Nirex developed a reference Concept for geological disposal of HLW and SF, based on the Swedish KBS-3V Concept (one of the most thoroughly researched and developed European Concepts, discussed in detail later in this report). Studies of waste packaging, transport and repository post-closure safety were made to illustrate that a route, well-tested in another EU country, was potentially available for managing the UK's HLW and spent nuclear fuel (SF) wastes safely if it was transferred to a UK-specific geological environment. In October 2006 the government accepted CoRWM's recommendations for geological disposal for higher activity wastes (published in July 2006) and made the NDA responsible for implementing this policy. Consequently, the NDA became responsible for managing all of the UK's radioactive wastes and, in April 2007, Nirex's skills and knowledge base was integrated into the NDA.

Following the CoRWM report (CoRWM 2006), it was apparent that the recommended approach to finding a repository site (involving a volunteering mechanism) could lead to the consideration of several different geological environments. For a relatively small land area, the UK possesses an unusually diverse range of geological environments, many of which could prove suitable for geological disposal. As a consequence, it became important to look at a much broader range of repository concepts than the reference model, which are designed in different ways to address and take advantage of the varying properties of this wide range of rock formations and geological environments.

1.2 The Concept of Geological Disposal

Geological disposal – the careful, engineered emplacement of wastes in underground repositories at depths of several hundreds of metres – is widely accepted as the safe, secure and environmentally appropriate solution for the long-lived radioactive residues that arise from generating electricity by nuclear power. Internationally, it is the favoured solution in most countries that have decided their long-term strategy. The European Union countries generate about 35% of their electricity using nuclear power and have been researching geological disposal for more than 30 years. Several European countries have now located suitable sites or rock formations for their repositories and Finland is the first to have begun underground excavations that will lead to repository construction. The advanced status of geological repository research, development and demonstration (RD&D) work is evident from the title of a recent summary report of the European Commission: ‘Geological Disposal of Radioactive Wastes Produced by Nuclear Power – from Concept to Implementation’ (EC, 2004).

All of this experience, including both EU and worldwide repository programmes, is available to the UK. This report looks at how repository Concepts developed in other countries can be used to help the UK to begin to design disposal systems that would be appropriate to the site or sites eventually identified to host them. Since the UK has such a wide range of geological environments, the range of Concepts considered is large and draws on information from many countries.

The safety of geological disposal is derived from the so-called ‘multi-barrier system’ that is both engineered into a repository and also makes use of the isolating properties of the deep geological environment where the repository is located. In the multi-barrier system (see Figure 1.1), the solid waste material, the waste containers, the engineered components of the repository and the surrounding geological environment work in concert to isolate the radioactive and toxic components. In a typical multi-barrier design, either a thick-walled or a highly corrosion-resistant metal container will be placed around the waste. This could be protected in turn by a shell, or ‘buffer’ of compacted clay or cement, which isolates the container from the surrounding rock and from water in the rock. As discussed below, there are different ways in which these materials interact to provide the necessary isolation and containment in different geological conditions. Knowledge of likely geological conditions and how they might vary with time thus affects the choice of materials and design. The host rock formation in which the repository is built provides a further barrier and the overall geological environment back to the surface (which could involve several different rock formations) constitutes the outer shell of the multi-barrier system.

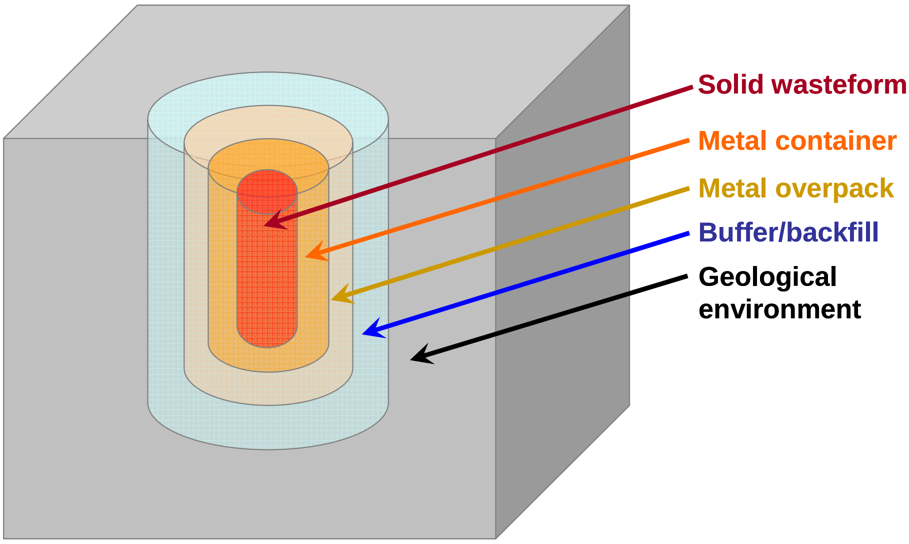

Figure 1.1: Schematic representation of the multi-barrier concept for HLW. Each nested barrier works in concert with the others to isolate and contain the radionuclides in the waste. As time passes, the system evolves and responds to environmental change and chemical interactions occur, the multi-barrier system provides continued passive isolation of the waste. The multi-barrier concept for SF does not normally include the metal container.

Once a repository is closed, conditions at depth around the waste and the engineered barriers will slowly return to those of the natural, undisturbed environment. The deep system is stable over very long periods of time and natural hydrochemical processes are slow. The engineered barriers around the waste will provide a very long period of containment, depending on the environment and the materials used, during which much of the radioactivity of the waste will decay (see below). Eventually, it is expected that the engineered barriers will degrade by interaction with groundwaters and porewaters present in the rock. This may take many thousands or tens of thousands of years and, in some environments, or for some disposal concepts, even longer stability is to be expected. Once water contacts the waste, some radionuclides will dissolve. The partially degraded engineered barriers will continue to hinder the mobilisation of these small amounts of radioactivity for hundreds of thousands of years. Any radionuclides that migrate into the groundwater system around the repository will be in tiny amounts and will be dispersed during slow movement through the geological environment. The objective of geological disposal is to ensure that, even in the distant future (many thousands of years hence) the presence of any such radioactivity in the groundwater system does not cause unacceptable health risks to future generations.

Table 1.1 provides examples of the different materials that are typically being used or considered for the engineered barriers of geological repositories and indicates the roles that they are expected to play in providing isolation and containment. In the different Concepts discussed in this report and in different national programmes, various terms are used to describe components that may seem similar but which may have slightly different functions in a particular design or safety concept. For example, waste containers, canisters, overpacks, packages or casks can sometimes appear to be used interchangeably. Table 1.1 endeavours to clarify different usages in documents describing HLW and SF repositories.

Table 1.1: The materials and functions of engineered barriers in geological repositories for HLW and SF.

Component	Typical Materials	Function
Solid waste form	In this study, we consider only vitrified HLW (solid borosilicate glass containing radionuclides in its chemical matrix) and spent fuel, which comprises pellets of uranium oxide fuel in alloy tubes (see Section 1.3).	The radionuclides in both HLW and SF are bound within the chemical or crystalline matrix of the solid material and the main function of the waste form is to reduce the rate at which they can be leached out into pore-waters in the barrier materials and groundwaters in the rock, once these contact the waste surface. Both glass and uranium oxide (a ceramic) are highly leach resistant. Some radionuclides in SF are present outside the crystalline matrix and their mobilisation cannot be prevented by the leach-resistance of the fuel: they are released immediately water contacts the fuel.
Waste container	HLW is manufactured when molten glass is poured into a thin-walled stainless steel container that is then welded closed. SF elements are generally not placed in a separate, closed container, but are held in steel or iron inserts or channels in the overpack (see below), which is itself sealed.	The function of the inner HLW container is simply operational, to facilitate handling of the vitrified waste. Although it is expected to have a limited lifetime after disposal it is not usually regarded as having any significant long-term barrier function. The inserts or structures into which SF elements are placed within the overpack are again for operational purposes: to provide a stable engineered structure that ensures geometric separation of each element and good heat transfer. In some Concepts the presence of large amounts of iron close to the SF can favourably affect the chemical environment and reduce the mobility of radionuclides.
Overpack (often referred to as 'canister', which is the terminology used by NDA)	A range of materials is proposed. Two Conceptual alternatives are considered for different disposal environments: overpacks with limited requisite lifetime after repository closure – these are typically thick-walled steel canisters – and overpacks with anticipated long containment times (tens to hundreds of thousands of years) which are typically corrosion-resistant metals such as copper, titanium or complex alloys. Overpacked waste containers make up the 'waste package' that is to be disposed of. Each overpack could contain several HLW containers or SF elements and is welded closed. The packages thus produced are sometimes called canisters, sometimes casks or sometimes just 'containers'. They can be massive items, weighing up to 100 tonnes in some Concepts.	Corrosion resistant overpacks, as their name implies, are expected to prevent water from contacting the waste for long periods of time. In some Concepts, containment might be expected for hundreds of thousands of years, during which time much of the radioactivity in the wastes will have decayed considerably. Nevertheless, long-lived radionuclides will eventually be mobilised from them, but one function of this type of overpack is to spread the releases over long times (individual containers breaking down over many thousands or tens of thousands of years instead of over a few hundreds of years), thus effectively diluting the amount of radioactivity entering the rock around the repository. Corrosion resistant overpacks are generally envisaged for geological environments where the groundwater pathway from repository to biosphere is more dynamic, with higher fluxes in the repository host rock. Short-lived iron or steel containers are deployed in geological environments that already provide an immense degree of long-term isolation. The short-lived overpacks are then intended to provide containment during the operational period and early years after disposal when activity is declining rapidly (see Section 1.3). Some geological environments offer such a high level of containment that no overpack at all is used for HLW and only a simple steel overpack is used for SF, to facilitate handling.

Component	Typical Materials	Function
Buffer	The space between the overpack (waste packages) and the repository host rock, be it a borehole, tunnel or cavern, is filled with a material that is usually called the buffer (because it buffers the package from the rock) or, when the volume is large and the material is not specially engineered, the backfill. Note that 'backfill' is also used to describe the material that is used to fill the repository access and work areas when it is closed, although it may be a modified composition to that used close to the waste packages. Natural buffer and backfill materials are often used. The majority of Concepts use clay; often bentonite because it expands and seals when it absorbs water and has an extremely low permeability to water. In some Concepts, the bentonite is prepared as a highly compacted, engineered material with higher swelling capacity. Clay can be mixed with crushed host rock to provide large volume backfill for some cavern disposal Concepts. Disposal in salt formations uses crushed salt as a backfill. Cement-based buffer is proposed for some Concepts. This is again a low permeability material.	The buffer is primarily designed to protect the waste packages and their overpack from physical and chemical processes in the rock. Whilst the buffer must be able to transfer heat to the rock from the waste, it must also help to prevent strain in the rock (e.g. movement along fractures during seismic events) from damaging the packages and prevent water flow around the packages. Typically, buffer materials only allow chemical species to reach the overpack (or radionuclides to escape from a degraded package) by chemical diffusion, which is an extremely slow process. In some Concepts, the buffer also inhibits the activity or movement of bacteria that could enhance corrosion of the canister. In the majority of Concepts, the buffer is emplaced at the same time as the waste package, but some Concepts call for much later backfilling around waste packages. The buffer is thus a critical safety component of most repository Concepts and, consequently, knowledge of its long-term behaviour and how it interacts with the overpack is important. The choice of a buffer or backfill material will depend on the flow and chemical properties of the geological environment being considered, the rock mechanical behaviour of the openings in which the waste packages are placed and the volume of openings being filled, together with the time at which the waste and buffer/backfill are emplaced.

1.3 Wastes Considered for Geological Disposal

The UK has a range of radioactive wastes that could be destined for geological disposal. Although complicated in detail, they fall into four main groups shown in Table 1.2. This report is concerned only with HLW and SF, but comments have been made on the implications for repository design if the other wastes or materials were to be co-located with them in the same disposal system but in another part of the repository (probably using a different engineering design).

1.3.1 Properties of SF and HLW

As noted in Table 1.2, both SF and HLW are initially extremely radioactive when they are produced. They also emit considerable heat from the radioactive decay of short-lived isotopes and are highly radiotoxic. Figure 1.2 shows the decline in total radiotoxicity of typical representatives of the two waste types as a function of time after the waste is produced – in the case of SF, this means the time elapsed after it has come out of the nuclear reactor and in the case of HLW the time after it was produced. A plot of heat output would look very similar to that of declining radioactivity. Also shown on Figure 1.2 is the radiotoxicity of an amount of uranium ore equivalent to that used to manufacture the fuel. The radiotoxicity of the wastes is scaled to this value.

Table 1.2: The wastes and materials that might go into a geological repository. Quantities are taken from CoRWM (2005). This report is only concerned with the first two groups (highlighted blue), but comments are made on some of the potential implications of disposing of the other two categories in the same location.

Waste type	Where it comes from and what it is	How much is there?
Spent fuel	Used fuel from nuclear power reactors at the end of its useful life. Fuel from older UK Magnox reactors is uranium metal, but it will probably all be reprocessed (see HLW, below). Fuel from the AGR reactors and from the Sizewell B PWR reactor is made from uranium oxide. If designated as a waste, it could be disposed of in unmodified form in a geological repository. Spent fuel, fresh from a reactor, is the most radioactive waste to be dealt with.	At the end of the planned lifetimes of these reactors there will be about: • 1,200 tonnes of Sizewell B PWR fuel. • 3,500 tonnes of AGR fuel. • small quantities of specialised 'cluster' fuel from research and prototype reactors.
High-level waste (HLW)	The concentrated, highly radioactive residues from reprocessing spent fuel to extract re-useable uranium and plutonium. HLW comes out of the reprocessing plant as a concentrated acidic liquor. This is evaporated to dryness and mixed with the chemical constituents of glass, then melted and cast into milk-churn sized blocks of 'vitrified waste' in stainless steel containers. This solid waste is highly stable, but intensely radioactive when it is produced.	1,290 cubic metres in its steel casting containers – it would all fit in a typical gymnasium hall.
Intermediate-level waste (ILW)	A wide variety of materials such as scrap metals and filters from reprocessing and operating nuclear plants. It is mostly mixed with cement and solidified in stainless steel drums and casks and much is already stored in this form. It ranges in activity levels but is generally much less radioactive than HLW.	Approximately 353,000 cubic metres – much more than HLW: perhaps the equivalent of several tower blocks in volume.
Uranium	Depleted, natural and low-enriched uranium from the manufacture and reprocessing of reactor fuel, if these materials are designated as wastes.	Approximately 75,000 cubic metres
Plutonium	Plutonium has been separated from spent fuel during reprocessing because it is a valuable source of energy. It can be mixed with uranium and used as reactor fuel. It is not very radioactive, but is highly toxic if ingested. Because it is also a material from which nuclear weapons are made, if it is decided that it is waste and to be disposed of, special precautions will be needed to provide 'safeguards' against it being illicitly retrieved. If UK plutonium stocks are disposed of, it is likely that they will be vitrified, like HLW, put into a ceramic material or made into low-specification mixed-oxide (MOX) fuel pellets intended only for disposal, not for use in a power reactor.	Approximately 102 tonnes.

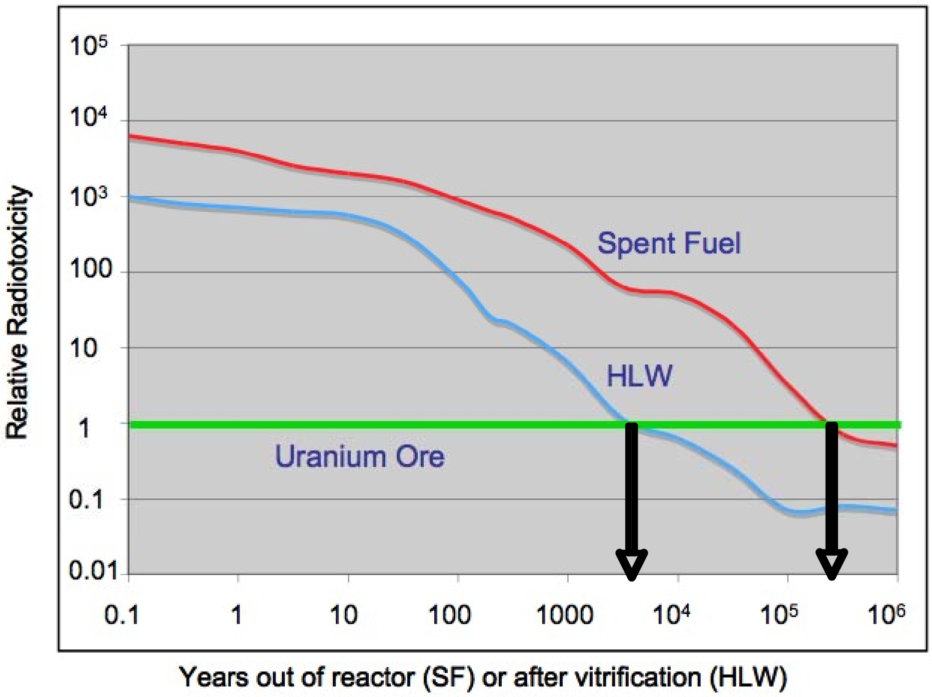

Figure 1.2: The decline in radiotoxicity as a result of radioactive decay in typical HLW and SF, as a function of time after waste production and time out-of-reactor, respectively. Radiotoxicity is scaled to that of uranium ore (see text), which has a nominal value of one. From data presented in Hedin, 1997 and NUMO, 2004.

Several important aspects of SF and HLW characteristics can be seen from Figure 1.2. First, SF is more radiotoxic (radioactive, heat emitting) than the HLW that would be produced from reprocessing it. This is initially because SF is frequently stored for many years before it is reprocessed, so the shorter-lived fission products have decayed substantially and their concentration in HLW is much lower than in fresh ‘ex-reactor’ SF. In addition, some volatile fission products from SF (such as iodine) cannot be incorporated in HLW, so do not contribute to its properties. Also, because uranium and plutonium have been removed from HLW (the aim of reprocessing), they do not contribute to its longer-term toxicity or radioactivity (having very long half lives) in the same way that they dominate the long-term behaviour of SF[1].

Second, the radiotoxicity of SF can be seen to decline by a factor of about 10,000 to the same level as that of the original uranium ore from which it was produced after roughly 100,000 years. This ‘back-to-nature’ crossover occurs much earlier for HLW, at about 3,500 years. Third, it can be seen that the radiotoxicity/radioactivity of both SF and HLW, good yardsticks for the hazard potential of the wastes if they were not to be isolated from people, decline by around a hundred-fold over a period of a thousand or so years. In fact, many uranium ore bodies (including many of those being exploited) are relatively close to the Earth’s surface compared to a deep geological repository and constitute a greater potential hazard than would the wastes

[1] Consequently, the manufacture of HLW creates by-products, including low-level waste, intermediate-level waste, plutonium and uranium (some of which may be a resource), and consideration of long-term management strategies would need to consider the fate and potential impacts of all materials created.

in an ancient repository. Of course, the eventual acceptability of a repository will be judged by detailed assessment of its performance with respect to regulatory radiological protection standards, as well as by simple comparisons such as these. A fuller discussion of these comparisons is provided by McKinley and Chapman (in press).

Although most of the radionuclides in spent fuel are locked into the crystalline matrix of the uranium dioxide of which it is formed, some are found to have migrated to crystal boundaries or even outside the pellets and into the alloy tubing of the fuel elements. When SF is contacted by water and the alloy tubes corrode, these highly mobile radionuclides are mobilised quickly into the pore-waters in the surrounding engineered barriers. In contrast, HLW has no such ‘instant release fraction’ (IRF) of radionuclides, although there are heterogeneities in HLW (e.g. cracks and constituents with different solubilities). The IRF is important to take into account when selecting designs and materials for the engineered barriers for SF and could affect the viability of some of the Concepts, as discussed later.

1.3.2 How Waste Properties Affect Repository Design Considerations

We can use the discussion above to make some broad, generic observations that provide pointers to help focus repository design considerations:

- The most critical period for isolating the wastes is the first hundreds of years, when their hazard potential is greatest but declining swiftly.
- After a few thousand years, HLW is no more radiotoxic than a rich uranium ore-body and would be expected still to be well-isolated and contained in a deep geological repository.
- Similarly, after about a hundred thousand years, SF is no more radiotoxic than a rich uranium ore-body.

The last two points suggest that, in terms of comparisons with natural radioactivity to which people are exposed globally, a geological repository has done most of its ‘isolation work’ after a few thousands of years (for HLW) to around a hundred thousand years (for SF) – although note the previous caveat that performance has to be judged quantitatively against regulatory radiological protections standards. Nevertheless, owing to the stable, undynamic and protected nature of deep geological environments, passive isolation and containment of the wastes will continue for much longer periods into the future. However, because regulations for the safety of disposal facilities are typically set at exposure levels that are more than an order of magnitude lower than even average exposures to natural radiation, safety evaluations generally look out to around one million years into the future and at mechanisms that could give rise to very small exposures on such timescales.

What do these observations mean for the design and safety function of engineered barriers in a geological repository? First, it is clear that designs and materials that can completely contain both HLW and SF within the engineered barriers of a repository for around 1,000 years would contribute immensely to overall confidence in the safety of a repository system. Combined with a desire to provide a high level of containment over the early period of elevated temperatures in a repository, this is an objective aimed at by most repository designers. Second, it is possible to envisage both designs and materials that would provide totally engineered containment for HLW (within the engineered barrier system) until after its ~3,500 year natural crossover time. However, it is difficult to envisage either designs or materials that could reliably do the same for SF, owing to the much longer time involved. Third, our knowledge of the longevity of engineered materials and systems (including HLW and SF) indicates that, once engineered containment has begun to degrade, mechanisms exist for leaching small amounts of radioactivity from the wastes and into the rocks and groundwaters of the natural barrier system.

The design of a repository system that provides adequate levels of containment and meets safety standards is thus clearly a matter of balancing the properties of the type of waste, the performance of the engineered barriers and the properties of the host rock and geological environment in which the repository is located. Because the latter can be very variable, especially in terms of controlling the amount and composition of groundwater that can pass through the repository system, the relative isolation capacity of the engineered barriers can also vary to match.

In perhaps the simplest example, environments with higher fluxes of water (or fluxes or chemical compositions that are likely to vary with future changes in climate) would tend to equate with more robust engineered barriers and waste container materials with longer lifetimes. At the other end of the spectrum, environments with essentially zero flux of water and very high resilience to future climate change would require shorter-lived containers and simpler (but nonetheless reliable) engineered barriers. These choices were reflected in the barrier functions discussed in Table 1.1.

In the descriptions of the Concepts presented in this report, the ways in which these balances of materials and design choices, requisite performance periods for different system components and properties of appropriate geological disposal environments, have been made in many different countries will be seen frequently.

1.4 Scope and Objectives of this Report

The aim of this document is to provide information on a comprehensive range of potential geological disposal Concepts that could be feasible for the disposal of the UK’s vitrified high-level waste (HLW) and spent fuel (SF).

This information is intended for use in two principal ways:

- To compile basic data for the NDA and other stakeholders to use in comparing geological disposal options in more detail, once the geological and other constraints are better understood as the siting process gets underway in 2008.
- To provide illustrations for a wide range of stakeholders of the types of repository that may be feasible in different circumstances, for example, so that potential volunteer communities can gain a clearer idea of the types of facility that may be developed in their area.

The information to fill these two roles has been gathered from numerous international studies that have been carried out over many years, all of which have considered feasible geological disposal solutions for national waste management programmes. Some of these studies have progressed only so far as outline Concepts, while others are underpinned by decades of research and development and form the basis of mature national programmes.

Some of the international studies are only for HLW or only for SF, whilst others consider disposal of both in the same repository. As discussed in Section 1.1, the properties of HLW and SF are different, so it may be that an appropriate design for the UK's wastes could combine features of more than one Concept.

During the next few years, as possible sites begin to emerge, the UK geological disposal programme will need to retain flexibility to consider how best to engineer a repository to the actual geological and geographical conditions at these sites. Having a good understanding of which Concepts are available and how much is known about them will assist this process and allow it to progress in an optimal fashion without forcing any specific design forward at an inappropriately early stage.

The Concepts are described generically in this document, but with examples of how other countries are considering implementing them. Where there are well-developed Concepts from national programmes, some with decades of development and evaluation, these have been included as specific examples of the generic Concepts. In addition, these examples have been selected to illustrate, as far as possible, each major set of generic Concepts that are described.

This document provides a summary of the geological disposal Concepts that could be feasible for UK conditions. A companion report (NDA, in preparation) provides detailed information on the Concepts with respect to the type of geological environment in which they might be located and with respect to a wide range of safety, environmental, technical, societal and economic Evaluation Factors.

The companion report has been produced separately because it represents *Work in Progress*. It describes the Concepts discussed here and presents matrices that provide commentaries on the Concepts. The matrices were produced as part of this study and were reviewed at a workshop that brought together NDA staff, regulators, representatives of waste management organisations and regulators from other countries, and consultants.

An extremely important matter for readers to appreciate is that it is inevitable that the basic, generic Concepts described in this report will go through several stages of adaptation and tailoring to site-specific factors, engineering requirements and stakeholder preferences. A repository development programme, from siting through to implementation, is expected to last decades. The design that will eventually emerge for licensing and implementation will thus certainly look different in detail to the generic Concepts illustrated here.

In the concluding discussion (Section 8) this report looks at how the information presented here might be used in subsequent stages of design development, optimisation and decision-making.

2 Inventory of UK Wastes Considered

The 1,290 m^3 of vitrified HLW calculated for the CoRWM inventory to arise by 2015 in the UK (CoRWM 2006) is the basis of the inventory considered in this study. Spent nuclear fuel is currently not declared as a waste for disposal but, since it may become so in the future, it is also considered for disposal in the various repository Concepts studied here. From the CoRWM inventory of radioactive materials the amounts of SF considered are 3,500 tHM from AGRs, arising until 2023 when the last AGRs are shut down, and 1,200 tHM from the Sizewell B PWR, which arises at a rate of 30 tHM per year between 1995 and 2035 inclusive. Other materials included in the CoRWM inventory, such as the low- and intermediate-level wastes, are not considered in this study.

The masses and volumes of waste are of less interest in this study, however, than the number of waste packages to be disposed of in a repository. For the vitrified HLW, the numbers of waste canisters is already fixed by the form in which the borosilicate glass is fabricated, that is, in stainless steel flasks holding 150 L of glass. The 1,290 m^3 of packaged HLW is equivalent to 6,582 of these flasks. However, in most Concepts, it is expected that the HLW flasks will be encapsulated within a more robust canister or overpack for disposal and these could contain more than one HLW flask, thus reducing the total number of HLW packages to be handled. Figure 2.1 shows the example of two HLW flasks packed in one canister. If the thermal output of the HLW containers allowed, this could be increased to three to bring the dimensions of the canister into line with the longer spent fuel canisters shown.

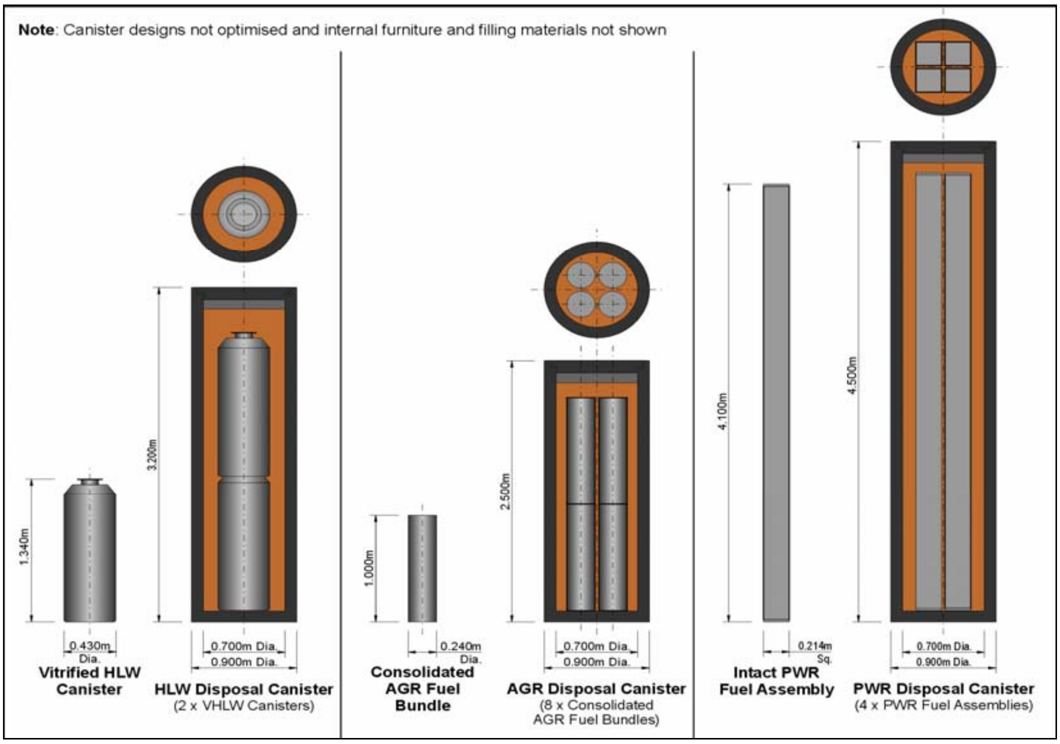

Figure 2.1: The generic packaging model for spent fuel and HLW used by Nirex to provide information for CoRWM (Nirex 2005a).

The packaging of the spent fuel is more variable in that fuel assemblies can be placed whole into the disposal container or, to increase container filling efficiency, they can be dismantled and the fuel elements consolidated. The CoRWM inventory assumed that spent fuel was packaged in containers based on the Swedish KBS-3V Concept, that is, in a copper canister with a cast iron insert, as shown in Figure 2.1. For the PWR spent fuel, the containers hold four intact fuel assemblies (2.12 tHM; Nirex 2005a) giving a canister 4.5 m long and 0.9 m in diameter. The AGR fuel elements are shorter and the assemblies are dismantled to give consolidated fuel bundles, each containing pins from 3 complete fuel elements, which can be emplaced in groups of four stacked in a canister. Figure 2.1 shows two stacks (1.03 tHM; Nirex 2005a) to give a canister 2.5 m tall with a diameter of 0.9 m. However, the lower burn-up of AGR fuel (typically 24 MWd/kgU compared to a typical value of 33 MWd/kgU for the PWR fuel; Nirex 2003) may allow an additional layer, increasing the canister length to about 3.5 m, or even two additional layers for a 4.5 m canister.

Table 2.1: HLW and SF volumes and packaging options. The highlighted (blue) packaging options correspond to those shown in Figure 2.1 and represent the reference waste packaging numbers used in this study. The other packaging options illustrate the potential advantages to be had in terms of reduced waste package numbers and the near uniform package size that could be achieved if the waste thermal output allows.

	Waste volume (m^3)	Waste package contents	No. of waste packages	Approximate package dimensions - length x diameter (m)
HLW	1,290 [1]	Single flask	6,582	1.0 x 0.9
		Two flasks	3,291	3.2 x 0.9
		Three flasks	2,194	4.5 x 0.9
SF				
PWR	2,740 [2]	4 intact fuel assemblies	654	4.5 x 0.9
AGR	5,410 [2]	2 x 4 fuel bundles	3,391	2.5 x 0.9
		3 x 4 fuel bundles	2,261	3.5 x 0.9
		4 x 4 fuel bundles	1,696	4.5 x 0.9

[1] *No packaging besides the fabrication flask is included in this volume for HLW.*
[2] *Volume includes packaging in copper-cast iron canisters.*

Table 2.1 shows the reference values used in this study for the volumes of wastes and numbers of waste packages, based on the CoRWM inventory packaging assumptions (waste package numbers from Chapman & McCombie 2006). This table also includes alternative options to illustrate some of the possibilities for optimising waste packaging for a particular repository or site. The reference packaging options discussed in this report are highlighted on the table and assume:

- 3,291 HLW containers, each containing two flasks within a single overpack;
- 654 PWR spent fuel containers, each containing four fuel assemblies;
- 3,391 AGR spent fuel containers, each containing eight fuel bundles.

This gives a total of 7,336 waste packages. A minimum (number of waste packages) packaging option is also discussed in this report; this assumes the HLW is packaged with three flasks to one overpack and that the AGR spent fuel is packaged with approximately 2 tHM per canister (4 x 4 fuel bundles as in Table 2.1). This minimum packaging option gives a total number of waste packages of 4,544. These two package numbers are used as working assumptions for this report and differ slightly from the estimated numbers used by the NDA in related studies. However, the precise numbers are not significant in the context of this report, but the slightly different numbers of packages seen in different studies and the discussions above indicate the acknowledged need for further studies on optimising HLW and SF packaging.

2.1 The Timescale of a Repository Programme

Section 2 notes that all the wastes considered in this report will have been produced by 2035 – indeed the HLW will all have been produced by 2015. The timescale of a repository development programme needs to account for the time and rate of waste arising, the time for which waste needs to cool before it can be disposed of and the time required for each step in siting, licensing and construction. The timescales have an impact on some of the Concepts that we discuss and, in particular, on cost and spend profiles and on repository open times, which distinguish some generic Concept groups from others.

Typically, repository site selection, site investigation, design, assessment, licensing and initial stage construction programmes are currently expected to take about 20 years if the process progresses without delay. Most Concepts (though not all) require waste to be cooled for around 40 to 50 years prior to disposal. The HLW inventory contains radionuclides from reprocessing already ‘old’ fuel – some up to almost 50 years out of the reactor.

Many of the Concepts have similar operational schemes for waste delivery and emplacement underground, with typical estimated rates of disposal of 1 to 3 packages per day – perhaps 200 to 600 packages per year. This depends on a number of factors, including capacity of encapsulation plant, design of the repository access and handling operation and numbers of loading machines, and indicates a rough operational period of between about 10 to 30 years if the waste is ready for disposal. If a repository were available by 2020 to 2030, emplacement might thus be completed by 2030 to 2060 if all the waste is sufficiently cooled.

The time profile will vary between Concepts and will need to be matched to the thermal characteristics of the waste: for example, assuming a nominal 50 years cooling before emplacement in a repository, the last PWR fuel to come from Sizewell may not be ‘disposable’ in some repository designs until some time after 2075. Other designs, however, (those using cooled casks) could take SF after only a few years cooling.

It should be noted that both the waste inventory (from CoRWM) and the timescales discussed above may differ from assumptions used in the NDA Lifetime Plan (LTP). However, the details of the schedule and inventory are not significant to the conclusions of this report, since the objective here is to describe general Concepts that could be used to implement geological disposal of HLW and SF in the UK.

3 Geological Environments

A group of Geological Environments was defined against which to evaluate the repository options. Because the feasibility of a repository Concept and its associated inventory depends on the physical and chemical properties of the deep environment, the environments have been based around these properties. As a consequence, the environments are not defined in terms of particular UK host rock formations or geological structures but are useful in providing a general structure under which the Concepts can be discussed. Also, as is shown below, the host rock environments can be mapped to representative UK geological environments.

Important aspects of repository Concept feasibility depend upon the thermal, hydrogeological, chemical and mechanical ('THCM') properties of the geological environment and waste characteristics. These properties determine whether it would be possible to construct and operate a repository of a specific design safely and effectively. Some examples of their importance are shown in Table 3.1, below.

Table 3.1: Table of geological environment properties and example factors that depend on them.

Geological Environment Property	Some factors that depend on this property
Thermal (such as the ability to conduct heat)	Spacing of waste containers and consequent size of the repository
Hydrogeological (such as the flux of water through the host rock)	Isolation capability of the geological environment and degradation behaviour of engineered materials
Chemical (such as groundwater salinity)	Stability of both natural and engineered materials in the repository, such as clays and metals
Mechanical (such as the strength of the rock)	Capability to construct large openings, the types of support system and maintenance that will be required and the ability to retrieve waste

The description of the Geological Environments has been couched in terms of the last three of these properties (CHM). Thermal properties are important, and these are discussed when repository options are considered, but are of less practical use in categorising geological environments. The set of Geological Environments selected here does not use quantitative definitions but is qualitative, as it is important to understand that the range of repository Concepts that are considered in this report could be feasible within relatively broad 'property bounds' within some of the groups and this will not be estimable until other site conditions (depths, geological structure and characteristics, topography, geographical location) are defined. The Geological Environments identified for the purposes of this project are shown in Table 3.2 (where the descriptions apply at repository depth only; the overlying geology could be variable).

Of course, the extent to which a site will perform in isolating wastes depends on both the CHM properties and the other geological and geographical conditions mentioned above, including the overlying geology, and can only be evaluated quantitatively by assessing their combined effect on the evolution of the repository in a 'total system safety assessment'. This will include factors such as how any releases of radionuclides in the distant future are dispersed and diluted as they move through the overlying geological formations, how gas produced in the repository is dissipated safely without affecting the performance of the system and how the biosphere (and its inevitable evolution over future centuries owing to environmental change) will affect the way in which radionuclides could affect future generations. As part of a programme of work to develop a generic Disposal System Safety Case (DSSC), covering a broad range of wastes and materials, the NDA is looking in an integrated way at the key safety functions of representative UK geological environments.

Table 3.2: Table of the Geological Environments used in this study (the descriptions apply at repository depth only; the overlying geology could be variable).

No.	Environment Description
G1	Stronger rocks with very low flow of likely saline waters
G2	Stronger rocks with higher water flow; probably relatively fresh water
G3	Weaker rocks with no effective flow and relatively saline waters in pores (transport is dominated by diffusion with no advective flow)
G4	Weaker rocks with very low water flow and relatively saline waters in pores (there is some advective flow)
G5	Evaporite formations: plastic, with no water flow and little accessible water (brine) content

As noted above, it is possible to give some practical examples of the types of formation found in the UK that would lie within the Geological Environments selected here with regard to host rock geology, and these are indicated in Table 3.3 below.

Table 3.3: Example UK geological environments related to those used in the current study.

Host Rock	Overlying Rock Formation	Relevant Geological Environment in this Study
Crystalline Rock	Low Permeability Sedimentary Rock Formations	G1 or G2
Crystalline Rock	High Permeability Sedimentary Rock Formations	G1 or G2
Crystalline Rock	Crystalline Rock to Surface	G2
Indurated Low Permeability Sedimentary Rock Formation	Low Permeability Sedimentary Rock Formations	G3 or G4
Indurated Low Permeability Sedimentary Rock Formation	High Permeability Sedimentary Rock Formations	G3 or G4
Plastic Low Permeability Sedimentary Rock Formation	Sedimentary Rock Formations (permeability unspecified)	G3
Evaporites - Salt Dome & Bedded Salt	Sedimentary Rock Formations (permeability unspecified)	G5
Carbonate	Sedimentary Rock Formations (permeability unspecified)	G2

4 Geological Disposal Concepts Considered

The set of twelve deep geological **disposal Concepts** examined in this study were derived from a list of seven key features that were considered to differentiate between disposal Concepts. For each of these key features, such as emplacement in short boreholes from a disposal tunnel, **variants** were identified that give rise to specific repository Concepts; for example, vertical and horizontal boreholes are considered as separate repository Concepts. The list of key features and their variants is given in Table 4.1, with the identification number of the twelve discrete repository Concepts examined. The Concepts considered are suitable for either HLW or SF, or (generally) for both.

In compiling this set of Concepts, the aim was to provide a wide variety of Concepts applicable to the geological environments found in the UK, based on international precedents. The only important geological disposal Concept for solid HLW and SF that has not been considered is the Concept developed for Yucca Mountain in Nevada, USA, since desert environments and rock formations that are not saturated with groundwater at repository depth do not occur in the UK. The Concepts discussed in this report are thus comprehensive of Concepts relevant to the UK that have been considered previously elsewhere.

It should be noted that some variants could be common to several Concepts. For example, the use of a long-lived or short-lived overpack/canister is examined as a variant of an '*in-tunnel (axial)*' disposal Concept. However, use of long-lived or short-lived overpack/canisters could also be a variant of several other disposal Concepts such as '*in-tunnel (borehole)*' and '*in-tunnel (axial) with supercontainer*' and their variants. It was considered that evaluation of closely related variants in this way would duplicate a good deal of material, with no obvious benefit to the study.

Table 4.1: Key features and variants leading to the disposal Concepts selected for this study.

Key Feature	Variants	Concept No.
In-tunnel (borehole)	Vertical borehole	**1**
	Horizontal borehole	**2**
In-tunnel (axial)	Short-lived canister	**3**
	Long-lived canister	**4**
In-tunnel (axial) with supercontainer	Small working annulus	**5**
	Small annulus + concrete buffer	**6**
	Large working annulus	**7**
Caverns with cooling, delayed backfilling	Steel MPC + bentonite backfill	**8**
	Steel or concrete/DUCRETE container + cement backfill	**9**
Mined deep borehole matrix		**10**
Hydraulic cage	Around a cavern repository	**11**
Very deep boreholes		**12**

5 Evaluation Methodology

5.1 Outline of the Approach Used

The stepped approach used in this project can be described as follows:

1. The first step has been to consider the wide range of geological environments present in the UK that could have potential for hosting a repository. These have been considered only at the general level of typical hydrogeological, chemical and mechanical properties of a repository host rock formation that affect the feasibility of a repository design. As discussed in Section 3, this led to consideration of five generic Geological Environments.

2. Next, the broad groups of geological disposal Concepts that are available were considered, including groups such as ‘tunnel and borehole’ repositories and cavern repositories. The aim was to be as comprehensive as possible in identifying disposal Concepts that have some likelihood of being feasible somewhere in the UK, as discussed in Section 4.

3. From these broad groups, a set of 12 generic Geological Disposal Concepts was developed that comprises the main variants that may offer specific advantages under given circumstances.

4. Each of the 12 generic Geological Disposal Concepts is described in a data sheet, showing how and for what environment or host rock the Concept was developed, what its advantages and shortcomings are with respect to implementation and safety, what it could look like in UK conditions and how much work has been carried out on it worldwide. Summary datasheets are presented in this report, and the full datasheets in the companion report. Some of this information is based on the experience and judgement of the authors. Where there are well-developed examples from other national programmes, these have been used for additional data sheets to illustrate specific Concepts and designs (see Appendix A). The summary descriptions of each generic Concept, together with illustrations of what they could look like in practice, are presented in Section 6.

5. Each of the 12 Concepts was then considered in relation to the five broad Geological Environments (Section 3). Specific information was elicited by using a set of Evaluation Factors (described in Section 7.1). Thus, for each Concept, a matrix was produced that provides text describing the qualities of each Concept against the Evaluation Factors in the Geological Environments. These matrices show how a Concept performs against all the Evaluation Factors in the range of Environments. The comments recorded in the matrices were made by expert judgement based on the material to hand. They were reviewed at a workshop with a much wider group of experts (including several from other European programmes) and updated based on the discussions and the opinions provided. The matrices have been published in the companion report, which also a summary of the workshop.

6. Matrices were also produced for each of the Evaluation Factors in which all the Concepts are assessed against the Geological Environments. These matrices allow comparison of performance of all the Concepts against one another for each Evaluation Factor over the range of Environments. These Evaluation Factor matrices use the same text as the Concept matrices. They are also published in the companion report.

5.2 Constraints and Assumptions

In carrying out this evaluation, a number of assumptions have been made or constraints set as to what to include and what to leave outside the study. These are outlined below.

1. This evaluation concerns how a geological repository design might be developed to contain the CoRWM inventory of existing or committed HLW and SF. Where appropriate, different containment options for HLW and for SF have been studied.
2. It is possible that other wastes and/or radioactive materials in the CoRWM inventory assigned for geological disposal could be disposed of at the same location. The implications of doing this have been considered separately from the main study. Section 8 discusses the implications of ‘co-location’ of plutonium, depleted uranium and long-lived low- and intermediate- level radioactive waste (LILW-LL). The co-location implications of some of the minor CoRWM waste streams for geological disposal (referred to as ‘cluster’ fuels) have also been looked at, briefly.
3. In the same manner as the CoRWM inventory, the implications for the repository options of including additional wastes from new nuclear power stations that may be operated over coming decades are commented upon separately in the discussion in Section 8.
4. It was assumed that all of the Concepts could be developed so as to provide levels of safety that are acceptable to the regulatory authorities. Consequently, their safety performance from international studies over many years and other precedents is used instead to comment on the degree of confidence in safety for each Concept, as well as to show what uncertainties exist and where they lie (expressed in terms of how straightforward it may be to make a safety case).
5. There has been no attempt to rank the Concepts. It would be premature to do so without a clearer idea of real siting possibilities. It has been recorded on the matrices where there are important aspects with respect to an Evaluation Factor for a Concept and some of these points are included in the summary data sheets in Section 6. This should give the reader a first-order feeling for feasibility or for issues that will likely form a focus if a particular Concept is eventually selected for more detailed evaluation. It is anticipated that in due course, once site conditions are available, the information provided here could be used as the basis to carry out a formal comparison exercise that weights attributes and ranks options so as to provide a narrowing down for specific circumstances. This is discussed further in Section 8.

5.3 The Data Sheets

The role of the data sheets for the Concepts is to collate and summarise the information available internationally. The data sheets were used as the main input for developing the commentaries in the matrices.

5.3.1 Structure of the Data Sheets

The information is grouped into eight main categories with a number of sub-categories:

1. Main characteristics of the Concept
    - Origin
    - Current and recent studies worldwide
    - Maturity of the Concept
    - Wastes for which it is suitable
    - Constraints on repository depth or host formation
2. Long-term safety Concept
    - How the multi-barrier Concept is implemented
    - Engineered Barrier System (EBS) design and materials
    - Safety functions of the barriers
    - Safety functions of other components
    - Performance assessment / safety assessment studies published
    - Significant changes since the Concept was first envisaged
    - Detailed variants worth recording
3. Development and operation
    - The requirements on the site
    - Demands on the site characterisation procedure
    - Excavation / construction processes
    - Implications for the requirement / location of an encapsulation facility
    - Operation / emplacement procedures
    - Key aspects of QA focus
4. Programme management
    - Key stages and main decision points
    - Retrieval options
    - Pre-closure monitoring requirements
    - Post-closure monitoring options
5. Environmental impacts
    - Spoil volumes / storage
    - Resources and availability
    - Transport of materials
    - Nature of surface facilities required
    - Any special noise or visual issues
6. Hypothetical scenarios for the UK

7. Key uncertainties and outstanding R&D
8. References

The Concepts discussed in this report are generic models, as the specific design of a repository will be tailored to the host rock, geological environment, waste type etc. Thus, the detailed design of, say, Concept 1 for deployment in a sedimentary formation, will be rather different from that in a crystalline host rock or an evaporite. The information in the data sheets tries to encompass these variations rather than focus on a specific design. However, it is clear that some Concepts have only been considered for implementation in one host rock whereas others have been applied more widely. Moreover, some Concepts are still at the 'desk studies' stage while others have moved to full-scale demonstration tests. Thus the amount and quality of information available for the Concepts is very mixed.

5.3.2 Identification of the Safety Functions for Each System Component

Most components of the repository system are introduced in order to fulfil a specific role in providing long-term safety – a safety function. These were outlined in general terms in Table 1.1. In some cases, the safety function of a component can be stated simply, and possibly even quantitatively; for example, for a short-lived canister where complete containment of the radionuclides for a period of around 1000 years is required. For other components, the safety functions may be more complex and difficult to define, requiring modelling studies to test whether the function is fulfilled.

Understanding of the safety functions, and the conditions under which they can be fulfilled, changes through the development of a Concept. At the desk study stage, the safety functions are idealised and the actual component properties required to fulfil them are not known. For example, for the short-lived canister, the specifications of a canister which will ensure a 1,000 year lifetime depend on knowledge of such factors as overburden (depth) and rock mechanical stresses, corrosion rate, groundwater geochemistry, and bentonite swelling pressure, all of which may be unknown. In contrast, at the near-implementation stage, the properties of components can be precisely specified in order to fulfil defined functions. However, since this level of understanding is site- and design-specific, the identification of safety functions on the data sheets is restricted to a more generic description of what might be termed 'expected safety functions'. There is no indication of the relative importance of the components or of the natural and engineered barriers in providing long-term safety as, again, this is site- and design-specific.

5.3.3 Issues that are Common to All or Most Concepts

There are several over-arching issues that are common to most or all of the Concepts. Rather than duplicating general information on each data sheet, a short generic discussion is given here for each of these issues and the comments on the data sheet are restricted to differences and exceptions.

Site characterisation

For any site, there is a minimum programme of exploration and characterisation that must be carried out in order to confirm the nature and extent of the target host formation(s) and the properties of the surrounding geological environment. A site characterisation programme will normally start from large-scale, regional information, such as overall geological structure and stability of the area (e.g. rate of uplift), gathered from existing data sources (e.g., national geological surveys and mining records) and a programme of surface-based, remote techniques such as seismic and geophysical methods. At least one deep borehole (to repository depth and beyond) may also be required for calibration of geophysical data, especially where the target formations are covered by unrelated sequences as with, for example, crystalline basement under sedimentary cover.

Within this regional framework, more detailed data will be collected for site-specific understanding. The requirements in this stage are likely to depend on the geological environment and the host rock targets. For example, seeking to identify suitably thick and laterally extensive clay host rocks in a sequence of near horizontal sediments is likely to be considerably different from characterisation of a fractured crystalline terrain where the properties of the faults and fractures are more important in controlling both mechanical and hydraulic properties of the repository near field. However, a drilling programme for additional boreholes to various depths, depending on the site requirements, is likely to be carried out in most geological environments to allow additional geophysical testing as well as monitoring of groundwater composition and movement (see “Monitoring” below). Obtaining sub-surface samples of host rock and fracture zones from cored intervals also often provides information beyond that which can be obtained from surface exposure of the same rocks. Hydraulic testing of boreholes is common in a fractured environment for determination of the properties of fractures and connectivity. This will supply essential data for modelling of the local and repository-scale groundwater flow which is important in the assessment of the long-term evolution and performance of the repository system.

Once a site is deemed acceptable on the basis of surface-derived and borehole data, additional data gathering during the excavation of underground facilities is usually carried out in order to confirm the site properties and refine repository design and layout, as well as to monitor the impacts of the excavation. The initial constructions would include underground investigations to confirm site characteristics. For example, this is the intention with the ONKALO facility currently being constructed in Finland at the Olkiluoto site; after an approximately 10 year programme of characterisation and other studies, it is intended that the ONKALO will become the access to, and some working areas of, the main spent fuel repository.

The degree of detail needed in characterisation information, for example, whether at the level of disposal panels, disposal tunnels or individual canister disposal locations, will depend on the repository Concept, the specific design (e.g. the degree of rock support) and the properties of the host rock itself. As this will be very variable, the Concept data sheets note where requirements are likely to be either particularly straightforward or particularly onerous. This is further expanded in the matrices where the differences arising from deployment of a Concept in various geological environments are highlighted.

Monitoring

Monitoring can be divided into two phases with different objectives:

- **Pre-closure** monitoring includes all the monitoring activities that are undertaken from initiation of site characterisation at a specific site until the repository is backfilled and closed. In the first instance, the objective is to confirm the conditions necessary for the safety of workers and the public as well as protection of the environment (IAEA 2006) but many of these activities also have the additional objective of establishing the baseline conditions at the site and recording the impacts caused by site characterisation activities, excavation of the underground characterisation facility and, later, the repository. For example, Posiva considered all the processes that could potentially impact on the long-term safety of the Olkiluoto repository (Miller *et al.* 2002) and, from these, planned a comprehensive monitoring programme at the site (Posiva 2003). This programme will be carried out over the duration of the ONKALO activities and continued, probably in modified form, during the repository construction and operation (Posiva 2006). It is likely that other repository projects will need to establish similar monitoring programmes, although the specific parameters investigated will be tailored to the geological environment and the requirements of the Concept.
- **Post-closure** monitoring of the site will probably also have to be carried out during a period of institutional control of the site after repository closure. This monitoring will continue some pre-closure activities to provide assurance for post-closure safety of the repository (see, for example: IAEA 2001). In this case, the objective is observation of the changes to the site, particularly hydrogeological changes, after underground openings have been filled and groundwater can resaturate the repository volume, to confirm that the host rock and site properties conform to those used in the assessment of long-term safety. Direct post-closure monitoring of the waste itself, for example by placing instruments within the buffer, is contrary to the principle of passive safety, whereby the repository will provide long-term safe containment of the waste without continual monitoring or other interventions, and it is not clear how the waste could be monitored (nor, indeed, what would be monitored) without breaching the isolation otherwise provided by the EBS and the near-field host rock (IAEA 2001, 2006). However, research is ongoing into remote monitoring methods that could be applied post-closure, should this be a requirement of future generations. A way of providing extended waste monitoring was proposed in Switzerland (EKRA 2000). A pilot repository could be constructed (including waste emplacement and sealing) at the site prior to excavation of the main repository and monitored during the main operational phase, which could be several decades long. A pilot repository does not constitute post-closure monitoring and would not confirm the long-term performance of the EBS and host rock, but may provide data to increase confidence in understanding the behaviour of the system.

From the above description, it should be evident that, for most Concepts, pre-closure monitoring is likely to depend more on the repository site and geological environment than on the Concept itself; very deep borehole disposal is probably an exception. However, with respect to the sort of pilot facility monitoring suggested in the EKRA proposal, the options available are likely to vary considerably with the Concept: for example, cavern Concepts are intended to have a long period when monitoring of the waste is possible before backfilling of caverns. Some other Concepts could, in principle, offer options for pre-closure monitoring waste if required, although there are undoubtedly technical issues to be resolved with, for example, leaving open the disposal tunnels above disposal boreholes once the waste is emplaced. These options are discussed on individual Concept data sheets.

Retrieval

Retrievability is taken as the removal of one or more waste packages some time after emplacement in the repository, for whatever reason. The time element indicates that it is not simply a case of reversing emplacement due to an unforeseen problem with, for example, emplaced buffer material not meeting the quality assurance criteria.

The issue of retrieval may be considered to fall into two aspects: the philosophical arguments about retrievability (ethics, desirability etc.), which will not be considered here, and the practical, technical matters concerning retrievability in a disposal Concept.

The position of national radioactive waste disposal programmes with respect to retrievability is varied (McCombie and Zuidema 2001): the earliest formal position taken on retrievability was in the USA where a 50 year period of retrievability was required in regulations as a guarantee that recovery options were possible should some unforeseen problem occur during the operational period of the repository. Recently, the US Department of Energy, Office of Civilian Radioactive Waste Management (DOE OCRWM) has altered the reference design of the proposed Yucca Mountain repository to make direct control of wastes and easy retrievability feasible for at least three hundred years. In Sweden, SKB amended its strategy to include a 25 year demonstration disposal phase and specific studies were performed to provide evidence that wastes could be retrieved after this period if this choice were made. Some other countries also directly addressed the technical feasibility of retrieving emplaced wastes: for example, in France, the Andra Concepts for disposal of HLW in both clay and granite are designed to allow retrieval for a period of some hundreds of years (Andra 2005a, b) and UK Nirex conducted laboratory experiments into the removal of soft grouts from around ILW containers that would be emplaced in a repository. In Japan, the requirement for retrieval of HLW from a deep repository has not yet been clarified, while in Germany, special provisions for retrieval are not foreseen. In the UK also, CoRWM has recommended moving to closure of the repository as soon as is feasible.

The generic Concepts described on the data sheets do not assume that retrieval of the waste is a prerequisite of the Concept so that retrieval of wastes may be more or less difficult depending on the specific design, implementation, host rock properties and, of course, the time after emplacement that retrieval is carried out. The exceptions to this are the cavern Concepts (during the open period) for which easy retrievability is a key driver of the Concept. Some comments are given on the data sheets in regard of ease of retrieval of single, specific or multiple waste packages and further comments, with respect to the different geological environments, are given on the matrices for each Concept.

Encapsulation and surface facilities

In all the Concepts considered (apart from deep boreholes), the waste is encapsulated in some type of container whether a steel overpack, a copper-iron canister, a large multi-purpose container or a steel-concrete supercontainer. Since these containers are not suitable for transport and would require additional shielding and protection to meet regulations for transport on public road/rail systems. Therefore, most Concepts envisage the construction of an encapsulation facility as a major part of the surface infrastructure at the repository site, although some national waste management organisations are considering the construction of encapsulation facilities next to interim waste stores.

Other surface facilities common to most Concepts could include:

- access and ventilation shaft buildings and ramp portal;
- waste transport reception area (although this could also be part of the encapsulation facility) and transport coordination centre;
- facilities required for the excavation and construction activities including material stores, power supply and utilities (drainage, ventilation) support, waste water handling, spoil management area, rock crushing and concrete preparation plant;
- security / gatehouse;
- support buildings, such as administration offices, underground personnel locker rooms, equipment stores, visitor centre and vehicle workshops.

The exact composition and disposition of these facilities will obviously vary somewhat according to the Concept and surface site – or indeed, the sites, as a ventilation or construction shaft at the extremity of the underground facility may require a second surface site if the primary site is not required to include the whole repository footprint. However, as the data sheets and matrices do not consider the nature of the site surface, the comments relating to surface facilities are limited to noting where requirements are, in some way, significantly different from the usually expected facilities, as listed above.

Proven and New Technologies

To date, disposal Concepts have been designed using materials which are well known and have well understood properties, for example, steel, copper, bentonite, concrete. Similarly, Concepts tend to be constructable using currently available technology. Thus, considerable weight is given to the "tried and tested" in both materials and technology for implementation.

While this may be considered a pragmatic approach, the possibility of technological advances in either materials or methods which could improve a Concept with respect to operational safety, long-term safety, ease of making the safety case or ease of implementation (with its likely cost implications) or any other aspect cannot be ignored. Indeed, some programmes (Sweden, Finland) have an explicit undertaking (or regulatory requirement) to use "best available technology", although this is a difficult objective to define.

In some areas, best available technology may be relatively straightforward to introduce. For example, with respect to excavation, once a new technology that offers advantages over the old has been shown to meet regulations for safe working and enough experience has been gained in conventional engineering or mining applications to build the confidence for application in a repository project (bearing in mind the high level of public scrutiny this will enjoy), there is no barrier to its deployment. This is rather in contrast to, say, the use of a new ceramic material for the canister. In this case, the behaviour over long periods of time must be understood – in the first instance, to ensure that it could meet expectations with respect to canister lifetime of 1,000 years or more, but also that there were no detrimental interactions with other components of the EBS in the longer term. For a new material, especially one for which there are no appropriate natural or archaeological analogues, establishing long-term stability could be very difficult. Laboratory and *in situ* tests both have limitations of time and applicability and much would rely on scientific understanding of the nature of the material. In this case, best available technology may still be the older materials such as steel and copper since the uncertainty in the long-term is reduced.

For these reasons, proposed use of new materials has so far been limited to peripheral materials such as low pH cement for grout and shotcrete applications, which will undoubtedly be needed in many repository projects.

Consequently, new or developed technology is called upon in the Concepts considered only where no currently available technology is appropriate or sufficient for the purpose. Mainly, this applies to emplacement procedures and quality assurance methods where there are still open questions even for quite well developed Concepts. No Concept calls on new materials, although the DUCRETE considered as an alternative for the concrete disposal containers in the cavern Concept (Concept 9) may perhaps be said to be still under development.

Repository footprint

The size of a repository footprint has two different implications:

- A Concept with a large footprint may be considered inappropriate for a host rock if that host rock is likely to be too laterally restricted to accommodate it. Conversely, a very small footprint suggests that the thermal load on the host rock could be high, unless the waste has undergone significant decay or the Concept is highly ventilated, which could make it less suitable for some clay-rich host rocks if the design were such that it would cause significant drying-out of the host formation. The footprint is thus a factor in choosing a Concept for a site.

- The underground footprint could be related to the surface land area which must be controlled in some way. In Japan, it seems likely that the implementing organisation will need to own or control all the land above the repository footprint. In a densely populated country, there are obviously financial repercussions from such a requirement. In the UK, the situation is not yet clear, but it could be that NDA is required, for example, to control the mineral rights over the whole footprint area. As the surface facilities for some

Concepts could be considerably smaller than the underground footprint, the requirement to own or control the area of the latter may cause these Concepts to be considered potentially less favourable.

In considering the hypothetical scenarios for implementation of a Concept for UK waste, a very simple estimate has been made of the possible repository footprint (at disposal depth) for the waste inventory used in this study. It is essential to note that the purpose of this estimate is to allow basic comparisons to be made between Concepts for the same inventory in the same or similar Geological Environments. The comparisons are likely to focus on the second issue, above, although the data sheets and matrices also contain some comments about the requirements that different Concepts make on a site in terms of laterally (or vertically) extensive host rock formations.

The estimates should be regarded only as indicative, since they rely principally on simple geometrical information based on the closeness with which stable openings for caverns, tunnels and boreholes can be excavated. There is also some consideration of the thermal impact of the various wastes but, as noted in Section 2, the inventory will include wastes with a wide range of thermal properties, thus this may be considered to add more ‘fuzziness’ to the estimate. Without any site in mind, it is difficult to give a realistic assessment of the features of the site that will need to be accommodated by the layout. Moreover, the factors involved in fitting a Concept to a site are more subtle than just assigning the space for a number of waste packages. Many of the most important factors influencing layout and the overall repository footprint, such as orientation of principal stresses, important for stable tunnel excavation, and the hydraulic gradient, which influences the direction water moves through and around the repository, have been ignored in the estimates, since no site information is considered.

A summary of footprint estimates for all Concepts, and the assumptions in their derivation, is given in Table 5.1. Additional explanation of these estimates is also given in section 6 (‘Hypothetical scenarios for the UK’) of the full Concept datasheets (Appendix A).

Table 5.1: Estimated Repository footprint areas for the twelve Concepts in relevant Geological Environments. The assumptions on which these estimates are based are summarised in the Table but additional information is given in Section 6 of the full concept datasheets (Appendix A).

Concept	Geological Environment	Estimated footprint		Assumptions
		Packaging option	Area (km^2)	
1	G1, G2, ?G3, G4, G5	Reference	1.2 - 3.5	Based on minimum and realistic area per waste package from H12[(1)] for HLW (45 m^2 and 250 m^2) and KBS-3V[(2)] for spent fuel (250 m^2 and 650 m^2).
		Minimum	1.2 – 3.0	Area/WP of 250 - 650m^2 for all waste packages, assuming the larger HLW and AGR packages have similar thermal output to the PWR packages.
2	G3, G4, ?G1, G2, G5	Reference	2.5 – 3.0	Assuming 2 SF waste packages or 4 HLW canisters (each containing 2 HLW flasks) per deposition hole requires 2800 'cells'; equivalent to about 50 - 60% of the Andra repository which has a footprint of 5 km^2.
		Minimum	2.5 – 3.0	Two waste packages of any type per deposition hole, assuming the larger HLW and AGR packages have similar thermal output to the PWR packages, is equivalent to about 50 - 60% of the Andra repository which has a footprint of 5 km^2.
3	G1, G2, G5	Reference	1.3 – 2.0	Based on area/waste package of 150/180/240 m^2 for HLW/AGR/PWR wastes + 50% to account for unused tunnel length, infrastructure & fault avoidance.
		Minimum	1.1 – 1.6	Area/WP of 240 m^2 for all waste packages + 50% % to account for unused tunnel length, infrastructure & fault avoidance.
	G3, G4	Reference	1.2 – 1.6	Based on area/waste package of 140/170/230 m^2 for HLW/AGR/PWR wastes + 30% to account for infrastructure and also for unused tunnel length & fault avoidance which are assumed to be less than in stronger rocks.
		Minimum	1.1 – 1.4	Area/WP of 230 m^2 for all waste packages + 30% to account for infrastructure and also for unused tunnel length & fault avoidance which are assumed to be less than in stronger rocks.
4	G1, G2	Reference	1.3 – 2.0	Based on area/waste package of 150/180/240 m^2 for HLW/AGR/PWR wastes + 50% to account for unused tunnel length, infrastructure & fault avoidance.
		Minimum	1.1 – 1.6	Area/WP of 240 m^2 for all waste packages + 50% % to account for unused tunnel length, infrastructure & fault avoidance.
	G4	Reference	1.2 – 1.6	Based on area/waste package of 140/170/230 m^2 for HLW/AGR/PWR wastes + 30% to account for infrastructure and also for unused tunnel length & fault avoidance which are assumed to be less than in stronger rocks.
		Minimum	1.1 – 1.4	Area/WP of 230 m^2 for all waste packages + 30% to account for infrastructure and also for unused tunnel length & fault avoidance which are assumed to be less than in stronger rocks.

Concept	Geological Environment	Estimated footprint		Assumptions
5	G1, G2, G3, G4	Reference	1.4 – 2.0	Based on area per supercontainer of 275/200/150m^2 for PWR/AGR/HLW, respectively + 40% to account for unused tunnel length, infrastructure & fault avoidance.
		Minimum	1.3 – 1.6	Area per supercontainer of 275m^2 for all waste packages + 25% to account for unused tunnel length, infrastructure & fault avoidance; fewer waste packages means less tunnel length and few tunnels, thus less lost area.
6	G3, G4	Reference	1.4 – 2.0	Based on 0.1 km^2 per 1000 HLW supercontainers, 0.25 km^2 and 0.3 km^2 per 1000 AGR and PWR SF supercontainers + 40% for unused tunnel length, infrastructure & fault avoidance.
		Minimum	1.4 – 1.8	Based on 0.3 km^2 per 1000 supercontainer for all waste packages + 30% for unused tunnel length, infrastructure & fault avoidance; fewer waste packages means less tunnel length and few tunnels, thus less lost area.
7	G1, G2, G3, G4	Reference	1.4 – 2.0	Based on 0.1 km^2 per 1000 HLW supercontainers, 0.25 km^2 and 0.3 km^2 per 1000 AGR and PWR SF supercontainers, respectively + 40% for unused tunnel length, infrastructure & fault avoidance.
		Minimum	1.4 – 1.8	Based on 0.3 km^2 per 1000 supercontainers for all waste types + 30% for unused tunnel length, infrastructure & fault avoidance; fewer waste packages means less tunnel length and few tunnels, thus less lost area.
8	G1, G2 ?G5	Re-packaged	0.1 – 0.2	722 multipurpose containers requiring 5 caverns each 200 x 15 x 10m, possibly + 1 ‘spare’ cavern as buffer store. Minimum and maximum tunnel spacing of 50 and 100 m. Additional area for infrastructure, shafts and ramp of 0.05 km^2.
	G3, G4		0.2 – 0.4	722 multipurpose containers requiring 10 caverns each 200 x 10 x 10m, possibly + 1 ‘spare’ cavern. Narrower caverns reflect weaker rock. Minimum and maximum tunnel spacing of 50 and 100 m. Additional area for infrastructure, shafts and ramp of 0.05 km^2.
9	G1, G2	Re-packaged	0.1 – 0.2	722 multipurpose containers or DUCRETE-disposal casks requiring 5 caverns each 200 x 15 x 10m, possibly + 1 ‘spare’ cavern as buffer store. Minimum and maximum tunnel spacing of 50 and 100 m. Additional area for infrastructure, shafts and ramp of 0.05 km^2.
			0.1 – 0.3	722 concrete disposal casks requiring 6 caverns each 200 x 20 x 10m, possibly + 1 cavern as buffer store. The CDCs are larger, and assumed to have poorer thermal conductivity, than the steel MPCs, thus require more space per container. Minimum and maximum tunnel spacing of 50 and 100 m. Additional area for infrastructure, shafts and ramp of 0.05 km^2.
10	G1, G2, G5, ?G3, G4	Reference	0.3 – 0.4	Up to 12 caverns, each ~ 200 m long, 6 m high and 6 m wide for ~200 ca. 300m-long boreholes. Caverns and boreholes are spaced to allow an area of 1000 - 2000 m^2 per borehole for heat dissipation (not all boreholes require the

Concept	Geological Environment	Estimated footprint		Assumptions
				larger spacing – only where the PWR SF is concentrated. If it is mixed with older HLW, the lower limit applies). 50% extra area is allowed for infrastructure and access tunnels.
		Minimum	0.2 – 0.3	Six to nine caverns, each up to 200 m long, 6 m high and 6 m wide for up to 100 ca. 300m-long boreholes. Caverns and boreholes are spaced to allow a area of 1000 to 2000 m^2 per borehole for heat dissipation. 50% extra area allowed for infrastructure and access tunnels.
11	G2, ?G4	Re-packaged	0.2 – 0.3	722 multipurpose containers requiring 10 caverns each 110 x 20 x 12m, possibly + 1 'spare' cavern as buffer store. The larger cavern, compared to Concepts 8 & 9, is to allow for a 1m-thick hydraulic layer around the disposal vault. Caverns are spaced at a minimum of 100m (centre-centre) apart. Additional area for infrastructure, shafts and ramp of 0.05 km^2.
12	G1, G2	HLW only	< 0.1 at surface	5 – 10 deep boreholes each with a disposal interval of 1000 - 2000m drilled from a surface pad of about 250 x 250 m. If some or all boreholes are deviated, the area affected at disposal depth will be larger than the surface footprint but is difficult to assess in any meaningful way.

(1) JNC 2000.

(2) SKB 2006.

6 Overview of Concepts

In this section we provide summaries of each of the twelve Concepts considered in the report, in the form of a data sheet and a diagram. The data sheets provide a high-level summary of each Concept, including:

- a description of the main characteristics of the Concept, i.e. the materials used in the engineered barrier system;
- the main reasons that the Concepts have been developed, and the function of each component within the system;
- important aspects that will need to be taken into account in considering the appropriateness of Concepts during the forthcoming siting programme.

The data sheets represent shortened versions of detailed data sheets presented in the companion report.

The diagrams present a schematic illustration of the Concepts. The diagrams illustrate the overall geometry of the repository system and include a blow-up section showing more detail of the engineered barrier system. Note that the diagrams, in particular the blow-up sections, are not drawn to scale.

Concept 1	In-tunnel (vertical borehole) with long-lived or short-lived canister
Main characteristics of the Concept	
Waste is emplaced in short (typically 6-8 m), medium to large diameter (e.g. 0.6 to 1.5 m) boreholes drilled in the floor of disposal tunnels. The waste is emplaced in a metal canister (or "overpack" in the case of HLW containers). Where long-lived containment within the canister/overpack is required, a corrosion-resistant copper canister with an iron insert is commonly used. Alternatively, a short-lived (some hundreds to a few thousands of years) steel canister can be used in environments where the safety case places less emphasis on long-term canister integrity. The annulus around the waste package is usually filled with a buffer material to isolate and protect the canister, typically highly compacted bentonite, but other materials could be used, for example, crushed salt in a salt host rock, as described for Concept 4.	
Main drivers for the Concept	
The Concept was originally developed for disposal of spent nuclear fuel in stable crystalline basement rocks in Sweden in the KBS study in the late 1970s and early 1980s. The vertical deposition boreholes were developed in response to uncertainty about the extent and properties of the EDZ (excavation damaged and disturbed zone) around the deposition tunnel. It was unknown whether the EDZ could provide a long, interconnected, high porosity and permeability zone in which water flux would be high and which could provide fast advective pathways to water-conducting fracture zones, thus circumventing part of the geosphere barrier. The boreholes were intended to isolate each waste package and place them in less disturbed rock beyond the tunnel EDZ so that radionuclide releases would be slowed by transport through undisturbed rock before reaching the tunnel EDZ or other geosphere pathways (note however, that this places significant requirements on the quality of the rock at each borehole site). The use of a copper (or titanium) canister to provide a very long period of containment was driven by the realisation that the instant release fraction (IRF) of radionuclides not held within the UO_2 matrix (or the Zircaloy cladding) of the spent fuel could be released as a pulse. This may not be greatly attenuated by the geosphere, due to the chemical properties of these radionuclides (e.g. very high solubility and low sorption) and the hydrogeological properties of the geological environment. The IRF could thus give rise to unacceptably high releases to the biosphere unless the waste were contained for long enough to allow radioactive decay of radionuclides such as ^{14}C. Moreover, the longevity of the canisters means that failures are likely to be spread over a long period of time and to be distributed throughout the repository area, thus being dispersed and diluted in time and space. In geological environments where a high degree of containment is provided by the host rock and geosphere, short-lived steel canisters are also considered suitable.	
Important Aspects of the Concept	
The Concept is flexible with respect to disposal of both spent fuel and HLW and to implementation in a wide range of host rocks. The Concept is mature for implementation in crystalline rocks and has a substantial knowledge base – amongst the best of any Concept worldwide – from 30 years of focussed research, development and demonstration by many national programmes, most notably those undertaken by SKB (Sweden) and Posiva (Finland). Where corrosion-resistant materials are used, the engineered barrier provides long containment and significant decay of radionuclides. This reduces the emphasis on the host rock and geosphere properties, as long as the natural barrier can be relied upon to isolate and protect the EBS in the long-term. The Concept results in a relatively large excavated volume per waste package, and a proportionately larger repository than some axial emplacement, because of the size of the disposal tunnels required to handle the waste packages (especially long PWR spent fuel elements). The emplacement of compacted bentonite buffer to the density specifications and geometrical tolerances required is difficult in wet host rocks and additional development and demonstration of procedures for emplacing the waste and the EBS is required. The acceptable conditions for a disposal borehole (e.g. fracturing, inflow rate) are critical for long-term safety performance but operational criteria have not yet been fully established and will be site-specific.	

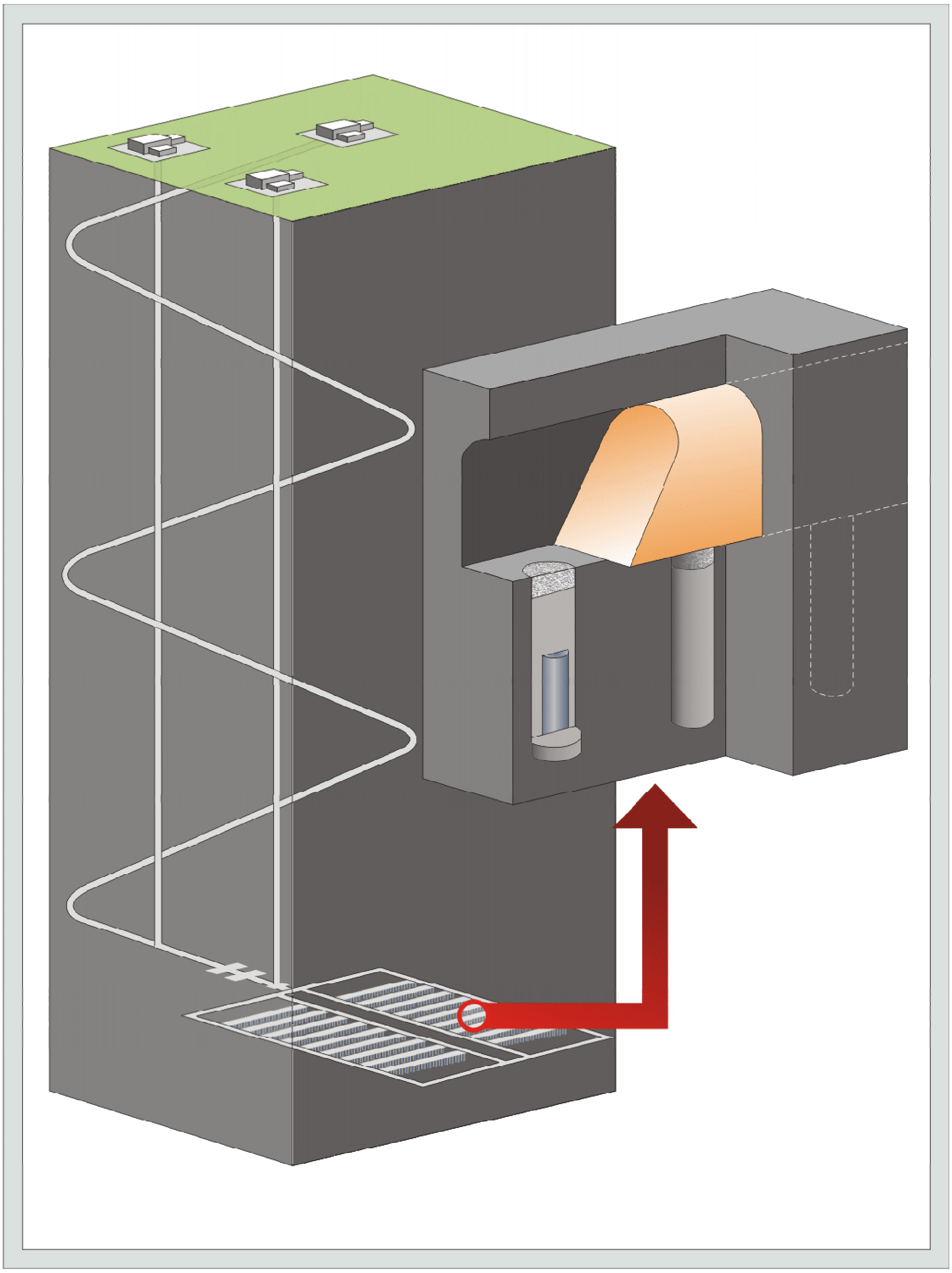

Figure 6.1: Schematic illustration of Concept 1, in-tunnel (vertical borehole) with long- or short-lived canister. In this illustration, 'panels' of disposal tunnels are shown incomplete and the extent of the repository and additional ventilation shaft(s) is not indicated. In all the Concepts, construction (in some panels) and waste emplacement (in others) could be carried out in parallel. This is an operational and strategic decision. The remaining Concept illustrations for tunnel and cavern repositories show only a small, nominal disposal area.

Concept 2	In-tunnel (horizontal borehole) with long-lived or short-lived canister
Main Characteristics of the Concept	
One or more waste packages are emplaced in short, horizontal or near-horizontal, large diameter (~0.7-1.5 m) boreholes drilled in the walls, usually on both sides, of the disposal tunnels. The waste is emplaced in a metal canister (or "overpack" in the case of HLW containers). Where long-lived containment within the canister/overpack is required, a corrosion-resistant material is used, for example a copper canister with an iron insert. Alternatively, a short-lived (some hundreds to a few thousands of years) steel canister can be used in environments where the safety case places less emphasis on long-term canister integrity. A liner may be used to support the boreholes and a buffer (e.g. bentonite) may be included to fill the space around and between the waste packages.	
Main drivers for the Concept	
The original Concept was developed by SCK·CEN (Belgium) and Andra (France) for disposal of mainly vitrified HLW in clay host rocks. A similar Concept has been developed in the Netherlands for disposal in salt. For use in crystalline, fractured rocks, the Concept would be closely related to Concept 1. The Concept has usually only been considered for deposition holes which contain one to a small number of waste packages, that is, holes up to a few tens of metres in length, because of rock mechanical considerations in weaker rocks which limit the borehole length unless a very substantial liner is used. Also, with longer holes, small changes to borehole diameter are more likely (both from excavation and later deformation) and could disrupt emplacement operations of waste packages that are only slightly smaller than the hole and are simply pushed into place. Andra note that the use of horizontal boreholes, up to a few tens of metres in length, makes better use of the laterally (rather than vertically) extensive argillaceous formations present in their proposed repository siting area, which outweighs the extra difficulties of handling packages in horizontal rather than vertical deposition holes. Andra also prefers to use metal-lined deposition holes with no buffer material as this provides adequate containment in the host rocks identified whilst reducing hole size, use of concrete and the volume of clay disturbed by the excavation. The use of a substantial borehole liner also allows retrieval of waste emplacement for a significant period after emplacement, which is a requirement of the Andra disposal programme.	
Important Aspects of the Concept	
Implemented as envisaged by Andra, that is, in argillaceous rocks, which provide a good natural barrier, and without the use of backfill, the Concept is relatively simple, practical and efficient in terms of potential emplacement rate, excavated volume per waste package and the repository footprint. The Concept is flexible in principle with respect to disposal of both HLW and SF, although outstanding uncertainties regarding the thermal impact of SF on the argillaceous host rock and steel liner (especially if reversibility is required) need to be addressed. Should waste retrieval be required, this Concept may offer advantages over axial tunnel emplacement Concepts, which require completion of the whole disposal tunnel up to sealing, and also vertical emplacement options. The Concept is not very mature either for crystalline or sedimentary host rocks, despite its relatively long history, with demonstration testing particularly lacking. However, for crystalline host rocks, much of the extensive knowledge base of the KBS-3 Concept would be relevant and, for argillaceous rocks, studies from other programmes (e.g. France, Belgium, Switzerland) would provide significant information. Although the Concept is, in principle, flexible with respect to different host rocks, significant development work would be required, for example, for stronger, fractured rocks where buffer emplacement is required. In this case, problems of emplacing bentonite in wet host rocks, similar to those for Concept 1, may be expected. For fractured rocks particularly, the acceptable conditions in the emplacement boreholes (e.g. inflow rate, fracture size and density) could be important for long-term safety performance and will require very detailed site characterisation information.	

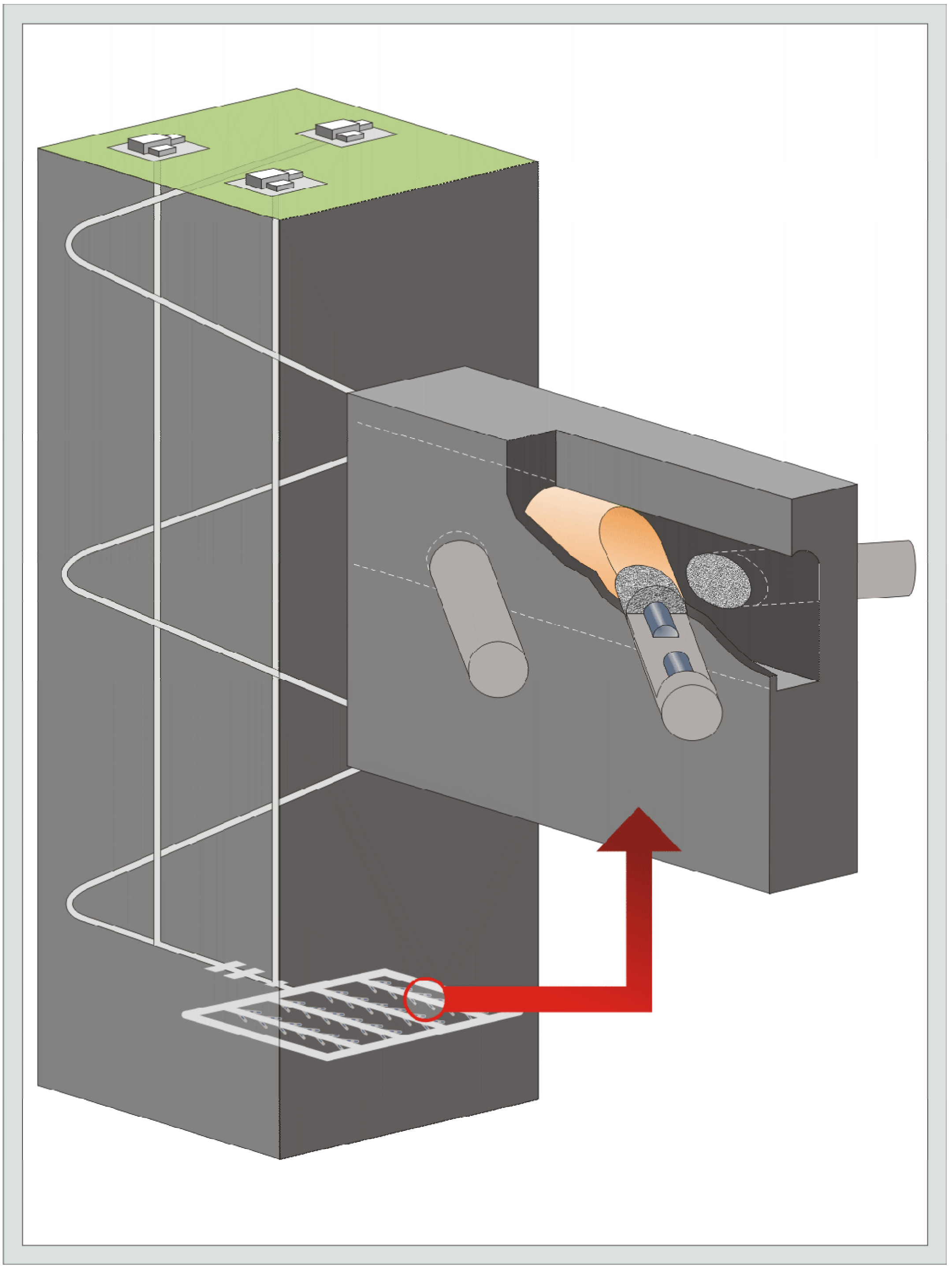

Figure 6.2: Schematic illustration of Concept 2, in-tunnel (horizontal borehole) with long- or short-lived canister.

Concept 3	In-tunnel (axial) with short-lived canister and buffer
Main Characteristics of the Concept	
Waste, encapsulated in steel overpacks, which provide complete containment for some hundreds or thousands of years, is emplaced axially along disposal tunnels surrounded by a thick buffer layer of bentonite that completely fills the tunnel with no further backfill. Waste packages are also separated by sections of buffer. The disposal tunnels are closed immediately after completion of waste emplacement with very substantial seals to resist the bentonite swelling pressure.	
Main drivers for the Concept	
The Concept was developed by Nagra for HLW disposal for Project Gewähr 1985, the legally required demonstration of HLW disposal feasibility in Switzerland, for crystalline basement rocks in Northern Switzerland, and also by Ondraf/Niras in SAFIR 2 for disposal in the plastic Boom clay in Belgium. In Switzerland, based on extensive experience with tunnel excavations, it was expected that the EDZ would be minor if tunnel boring machine (TBM) technology could be used to excavate the circular cross-section disposal tunnels in crystalline rock. Waste packages could be well isolated along the axis of the tunnel with the use of a thick bentonite buffer, avoiding the influence of a tunnel EDZ in this way, rather than by using vertical boreholes (Concept 1). Axial deposition in circular tunnels was also seen as an efficient disposal method as the excavation volume per waste package is minimised due to the relatively small tunnel diameter and no individual disposal boreholes are required. Similarly, in the Boom clay, the properties of the host rock suggested that an EDZ developing around the disposal tunnels during excavation would close due to creep after tunnel sealing and would not remain a significant issue for long-term safety. The Concept has also been adopted by Nagra for spent fuel/HLW co-disposal in a clay host rock (the Opalinus clay in Northern Switzerland). The relatively large tunnel diameter (3.7 m in Swiss crystalline rocks; 2.5 m in Opalinus clay; 2.0 m in Boom clay) allows for a thick bentonite buffer around the waste packages (up to 1 m in diameter). In the Concept as envisaged for crystalline host rock, the buffer has an initial role to protect the waste canister/overpack but, since this was assumed to provide containment for only about 1,000 years, the main long-term role was as a barrier to transport of radionuclides into the geosphere. The SAFIR 2 Concept in the plastic Boom clay used a steel tube in the centre of the buffer to facilitate emplacement of the waste packages. This Concept has been abandoned by the Belgian programme, however, because there were concerns relating to the corrosion of the canister and also with respect to the practical implementation, particularly regarding thermal expansion of the central steel tube. This Concept is also under consideration by DBE, Germany, for disposal of spent fuel in a salt dome formation at Gorleben; in this case crushed salt is envisaged as the backfill around the canisters.	
Important Aspects of the Concept	
The Concept is flexible with respect to disposal of both spent fuel and HLW and to implementation in a wide range of host rocks, although relatively dry host rocks are favoured. The Concept results in a small excavated volume per waste package, and a proportionately small repository, because the disposal tunnels are used for emplacement of the waste axially and there is no need to invert/rotate the waste packages into boreholes, nor for additional excavation of boreholes. The Concept is mature for implementation in both crystalline and sedimentary rocks (including evaporites) and has a very substantial knowledge base from 30 years of focussed research, development and demonstration by several national programmes, including those in Switzerland (Nagra), Japan (NUMO), Spain (Enresa), Belgium (Ondraf/Niras) and Germany (DBE Technology). The short containment period provided by the steel canister means that all waste packages are likely (and must be assumed) to fail over a relatively limited period of time. This places emphasis on performance of the geosphere, especially for spent fuel and the IRF, as the natural barrier must be relied upon to attenuate the radionuclide releases. The emplacement of compacted bentonite buffer to the density specifications required is difficult in a wet host rock. Bentonite granules may provide a suitable medium in relatively dry environments but may not produce a sufficiently dense material in wet, fractured rocks. Acceptable conditions for a disposal position (e.g. fracturing, inflow rate) are likely to be very important for long-term safety performance; acceptance criteria are probably site-specific and will require a highly detailed site characterisation programme, especially in fractured host rocks.	

Concept 4	In-tunnel (axial) with long-lived canister and buffer

Main Characteristics of the Concept

Waste, encapsulated in a copper (or titanium) corrosion-resistant canister, which provides a long period of complete containment, is emplaced axially along disposal tunnels surrounded by a thick buffer layer of bentonite that completely fills the tunnel, with no further backfill. Waste packages are also separated by sections of buffer. The disposal tunnels are closed immediately after completion of waste emplacement with substantial seals to resist the bentonite swelling pressure.

Main drivers for the Concept

The Concept similar in essentials to Concept 3, but uses a long-lived copper or titanium canister, with an iron insert for mechanical strength, in place of the short-lived steel overpack.

The Concept has so far only been developed by Ontario Power Generation (OPG) in Canada, for disposal of spent fuel in the crystalline rocks of the Canadian Shield. The use of the long-lived canisters confers advantages over steel canisters with respect to the instant release fraction (IRF) of the spent fuel, as the longer containment time allows significant decay of some safety-relevant IRF nuclides (e.g. ^{14}C), as well as spreading canister failures, and thus releases, over a very long time period.

The OPG design also differs from Concept 3 in having two spent fuel waste packages side-by-side at each disposal position to accommodate the very strong stress anisotropy found in parts of the Canadian Shield which requires the excavation of oval cross-section tunnels for stability of the openings. This design supersedes an earlier Canadian (AECL) design using short vertical boreholes in the floor of disposal room as the stress anisotropy gave problems with borehole stability.

In the OPG design, the buffer has several component parts, using bentonite and bentonite/sand mixtures with different initial densities. The high density bentonite around the waste package is emplaced as a single unit, surrounding both waste packages, on to a bentonite-sand base. This simplifies and speeds the operation by avoiding the use of many complex shaped blocks, as well as providing additional shielding during the emplacement operation.

Important Aspects of the Concept

The Concept is flexible with respect to disposal of both spent fuel and HLW and to implementation in a wide range of host rocks, especially in the circular cross-section tunnel version similar to Concept 1.

The Concept can result in a smaller excavated volume per waste package than Concept 1, and a proportionately smaller repository, because the disposal tunnels are used for emplacement of the waste axially and there is no need to invert/rotate the waste packages into boreholes, nor for additional excavation of boreholes.

The long containment times provided by the engineered barrier, with the use of copper or titanium canisters, allows significant decay of radionuclides, especially important for the spent fuel IRF, and spreads the releases over a very long period of time. This reduces the emphasis on the host rock and geosphere, as long as the natural barrier can be relied upon to isolate and protect the EBS in the long-term.

Axial emplacement of waste using a long-lived canister is not a Concept preferred in any major nuclear country, although it combines elements of two of the most highly-developed disposal Concepts (Concept 1 and Concept 3), and the substantial knowledge base developed for these Concepts is relevant and could be applied during implementation of Concept 4.

The emplacement of compacted bentonite buffer to the density specifications required is difficult in a wet host rock. The OPG procedure as specified is likely to be practical as specified only in dry host rocks. Use of bentonite granules may also provide a suitable method in relatively dry environments but may not produce a sufficiently dense material in wet, fractured rocks.

Acceptable conditions for a disposal position (e.g. fracturing, inflow rate) are likely to be important for long-term safety performance requiring a highly detailed site characterisation programme, especially in fractured host rocks. This may be less important for the thick, compound buffer of the OPG Concept than for a circular tunnel with the more usual 0.3 – 0.7 m thick buffer, similar to Concept 1.

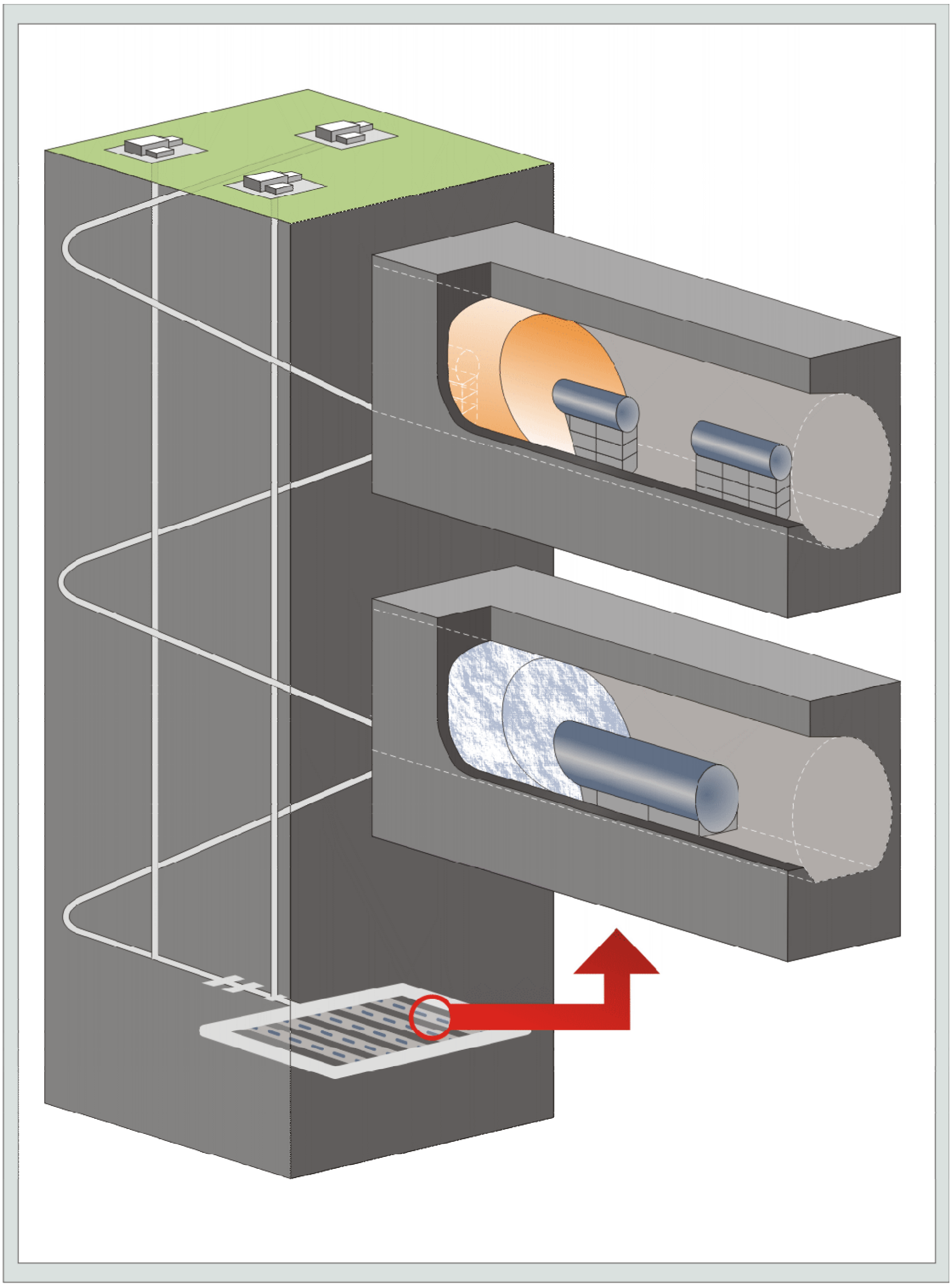

Figure 6.3: Schematic illustration of Concepts 3 and 4, in-tunnel (axial) with long- and short-lived canister and buffer (the lower figure illustrates disposal in salt, with a salt backfill).

Concept 5	In-tunnel (axial) with supercontainer (small annulus)
Main Characteristics of the Concept	
Waste is emplaced axially in circular tunnels in the form of a supercontainer in which the waste, overpack or canister and buffer are pre-assembled at a surface facility into an enclosed, perforated steel handling shell. The tunnel is as small as possible to minimise the void space around the supercontainer, which must be filled by swelling of the buffer as no additional backfill or buffer material is used. Bentonite buffer sections are used to isolate one or more supercontainers.	
Main drivers for the Concept	
SKB (Sweden) and Posiva (Finland) decided to assess a horizontal version of the KBS-3 Concept, known as KBS-3H, to avoid potential problems with spalling around vertical deposition boreholes. In addition, axial emplacement of the waste packages made it possible to take advantage of a reduced EDZ around the disposal tunnel by using a small diameter, TBM-excavated tunnel. Placing of the bentonite buffer in the form of pre-formed bentonite blocks in high humidity conditions was, however, problematic due to premature swelling of the bentonite causing cracking and disintegration. This led to the development of the supercontainer in which the buffer and waste package are emplaced as a single unit inside a perforated handling shell. To avoid the necessity for additional backfill, the tunnels are as small as is feasible; the supercontainers are emplaced using water cushion equipment which requires only a very small (few centimetres) effective clearance to lift and transport the supercontainer into position. Bentonite in the supercontainer will swell and extrude out of the handling shell once saturation begins. However, as the amount of bentonite is only just sufficient to fill the 5 cm annulus to the required density, it is important that no bentonite is displaced. Thus each supercontainer is isolated in the tunnel by a bentonite-only section (distance block). The distance blocks also serve to space out the waste packages to ensure the thermal limits on the bentonite are not exceeded.	
Important Aspects of the Concept	
The Concept is flexible with respect to disposal of both spent fuel and HLW. It is also flexible, in principle, with respect to implementation in a range of host rocks, although any tendency to friability in the host rock that could introduce loose material into the annulus would preclude weaker rocks (see below). The Concept can result in a small excavated volume per waste package – and a proportionately small repository – because the disposal tunnels are used for emplacement of the waste axially and there is no need for the space required to invert/rotate the waste packages into boreholes, nor for additional excavation of boreholes. The Concept is relatively mature for implementation in crystalline rocks (e.g. Sweden and Finland) as it builds to a large extent on the very substantial knowledge base developed for Concept 1, including site-specific information of SKB and Posiva. Acceptable conditions for a disposal position (particularly water inflow rate) are critical for avoidance of bentonite erosion from the supercontainer and the immediate annulus. Besides the requirement for detailed characterisation of disposal tunnels, this may also limit suitability of this Concept in wet, fractured host rocks if significant lengths of disposal tunnels are unusable. Uncertainty about the long-term effect of interaction between bentonite and the corrosion products of the handling shell means that the effective thickness of the buffer may be reduced from the nominal emplaced thickness. Thus the necessity to avoid the detrimental effects of interaction with a concrete tunnel liner could preclude implementation in many weaker rocks. The very small annulus around the supercontainers means that recovery/reversal of emplacement of a supercontainer using the water cushion equipment (which must slide under the supercontainer) may be awkward, especially after the bentonite has begun to extrude in wetter sections of the tunnel. Thus the difficulties of reversal or retrieval may be greater than for in-hole Concepts.	

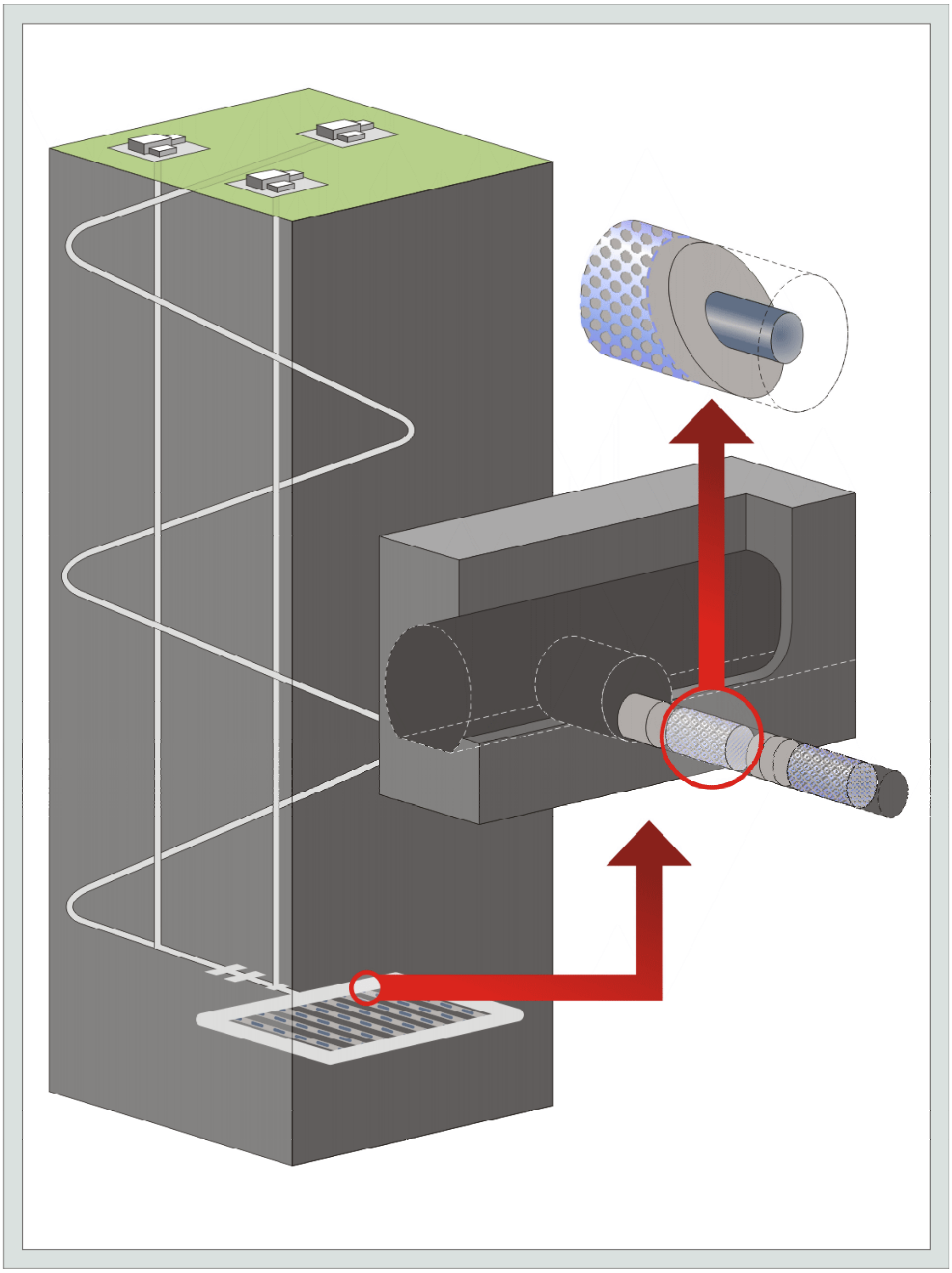

Figure 6.4: Schematic illustration of Concept 5, in-tunnel (axial) with supercontainer (small annulus).

Concept 6	In-tunnel (axial) with supercontainer (concrete buffer)
Main Characteristics of the Concept	
Waste is emplaced axially in circular tunnels, probably lined for support, in the form of a supercontainer in which the waste, canister or overpack and buffer are pre-assembled at a surface facility into an enclosed steel handling shell. The buffer material is ordinary Portland cement (OPC)-based concrete. The tunnel diameter may be significantly larger than the supercontainer, which sits on a small pedestal at its disposal position. Where a large annulus is used, additional cement-based backfill is used to fill around and between the supercontainers. The tunnels may be some hundreds of metres long to take advantage of a laterally extensive formation.	
Main drivers for the Concept	
The Concept was developed by Ondraf/Niras for the plastic Boom clay (Belgium) to address potential problems which were identified with the earlier SAFIR 2 Concept in which HLW flasks in thin steel overpacks were slid into position along a steel tube positioned axially in a bentonite-filled disposal tunnel (Concept 3). The SAFIR 2 design was replaced primarily because of uncertainty regarding EBS performance. In particular, it was considered possible that certain types of corrosion, such as localised corrosion or stress corrosion cracking, might threaten the integrity of the overpack during the thermal phase. There were also questions with respect to the practical implementation, particularly regarding thermal expansion of the central steel tube. Expansion, coupled with the swelling pressure exerted by the clay buffer, would cause the steel to be highly stressed, possibly leading to plastic deformation. Scoping calculations showed that the maximum permissible tube length would be less than 20 m. Other uncertainties related to the difficulty of transport and emplacement of an unshielded overpack, and quality assurance of the engineered barriers. By using a supercontainer the waste is shielded throughout the emplacement procedures, which are simplified (although the supercontainer is larger and heavier to handle), and there are no detrimental interactions between the buffer, backfill and the concrete tunnel liners. The OPC-based concrete buffer (and backfill used) is designed to provide alkaline, passivating conditions around the steel overpack, enhancing longevity by reducing corrosion. After failure of the overpack, it will continue to provide a favourable chemical environment as well as a diffusion/transport barrier.	
Important Aspects of the Concept	
The Concept is flexible with respect to disposal of both SF and HLW. The Concept can result in a small excavated volume per waste package, and a proportionately small repository, because the disposal tunnels are used for emplacement of the waste axially and there is no need for the space required to invert/rotate the waste packages into boreholes, nor for additional excavation of boreholes. The use of the supercontainer increases safety during the emplacement operations by making the procedures simpler and more robust (e.g. fewer components to emplace) and also by use of a self-shielded waste package. The Concept is based on approximately five years of research and development and it builds to a large extent on the substantial knowledge base developed for the SAFIR 2 Concept and investigations in the Boom Clay. Detailed development is still on-going by Ondraf/Niras and practical demonstration of many aspects, for example, backfilling with cement-based mortar, has not yet been undertaken. The long-term performance of the OPC-based buffer material in terms of a transport/diffusion barrier is uncertain, especially in an environment where cracking could occur due to rock stresses. The Concept is also most appropriate for host rocks where the interaction between the highly alkaline pore fluids from the concrete and the surrounding rock will be limited to the vicinity of the near field and not significantly affect the geosphere. The large, heavy supercontainers place particular demands on the transport and handling systems, as well as on access tunnels.	

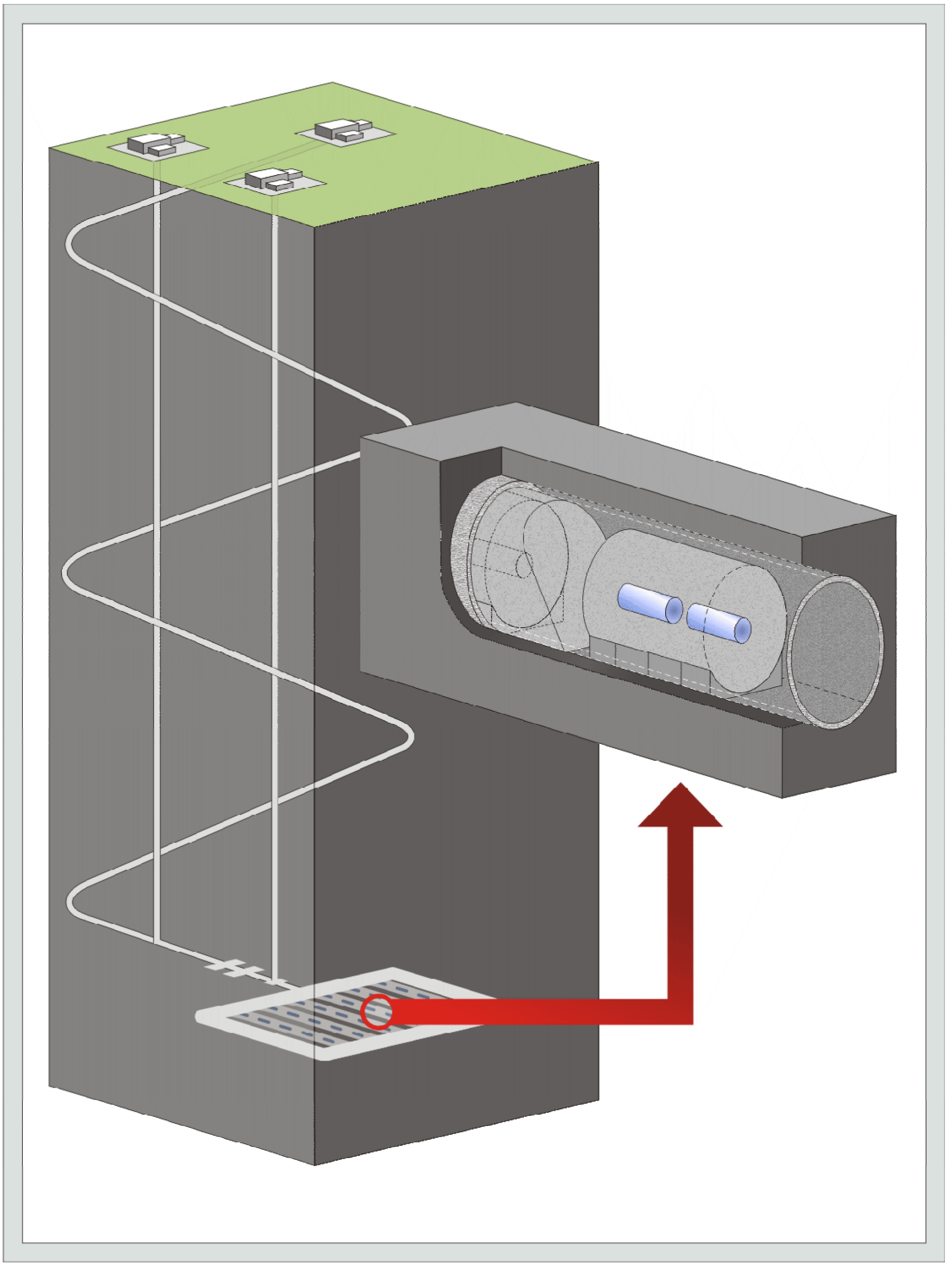

Figure 6.5: Schematic illustration of Concept 6, in-tunnel (axial) with supercontainer (concrete buffer).

Concept 7	In-tunnel (axial) with supercontainer (large annulus)
Main Characteristics of the Concept	
Supercontainers, comprising waste, overpack and compacted bentonite buffer assembled in a robust steel handling shell, are emplaced horizontally along the disposal tunnels on short pedestals which facilitate handling but do not necessarily place the supercontainer in the centre of the tunnel. The tunnels are larger than the supercontainer diameter by ~1 m or more to allow easier emplacement, and recovery if required. Depending on the heat output of the waste, the supercontainers can be placed end-to-end or spaced out along the tunnels, which may be some hundreds of metres long. The annulus around the supercontainer and any spaces between them are filled with a non-compacting backfill such as a mixture of crushed rock and bentonite.	
Main drivers for the Concept	
Difficulties were encountered with use of bentonite during the FEBEX experiment at the Grimsel Test Site (GTS) in Switzerland, which involved the construction of a full-size EBS section of compacted bentonite with an axially placed waste package (substituted by a heater, in the experiment) in a specially excavated tunnel (essentially Concept 3). Construction of the bentonite buffer in the form of pre-formed compacted bentonite blocks, as described for the Project Gewähr / Kristallin-I studies, in high humidity conditions was problematic due to premature swelling of the bentonite causing cracking and disintegration of pre-formed blocks. As a result, a modified Concept including a prefabricated EBS module (also called a supercontainer) was considered as part of a study of alternative disposal Concepts for HLW by NUMO (Japan) for generic sites in recognition that candidate repository sites may be considerably less dry than the GTS. However, unlike the layout envisaged in Concept 5, it was seen to be fundamentally more robust from an operational safety perspective to have a larger working annulus around the supercontainer so that, in the event of an operational incident, recovery or reversal of the emplacement process would be relatively straightforward. The properties of the backfill are undefined and there have been varied suggestions, for example, that it should be 100% bentonite, although less dense than the buffer, but extending the diffusion barrier, or higher permeability material to act as a hydraulic cage around the supercontainer and reduce the potential effects of localised water inflow (this may then also require intermediate tunnel seal sections).	
Important Aspects of the Concept	
The use of the totally sealed supercontainer means that Concept is flexible with respect to implementation in a range of host rocks, as a liner could be used as a temporary (operations phase) hydraulic barrier in wet, fractured rock or for support in weaker rocks. When using a liner, the backfill would be expected to buffer any chemical interactions (e.g. from concrete) to prevent alteration of the bentonite once the supercontainer handling shell corrodes. As the supercontainer is fabricated under controlled conditions (in a hot cell), the density of the bentonite could be greater than normally considered (e.g. greater than 2.0 tonnes/m^3), providing high swelling pressure on saturation to reduce any small unfilled voids in the backfill. The Concept can result in a small excavated volume per waste package, and a proportionately small repository, because the disposal tunnels are used for emplacement of the waste axially and there is no need for the space required to invert/rotate the waste packages into boreholes, nor for additional excavation of boreholes. The Concept is only at the desk study stage, thus there is significant development required in all areas including technology, long-term safety functions of components and safety assessment. The Concept is nominally similar to Concept 5 with the addition of backfill. However, the functions of the backfill in the concept are as yet undefined and there are options to tailor the backfill properties to fulfil functions beyond that of a simple hydraulic barrier (e.g. chemical buffering between the bentonite and a concrete tunnel liner). Uncertainty about the long-term effect of interaction between bentonite and the corrosion products of the handling shell means that the effective thickness of the buffer may be reduced from the nominal emplaced thickness.	

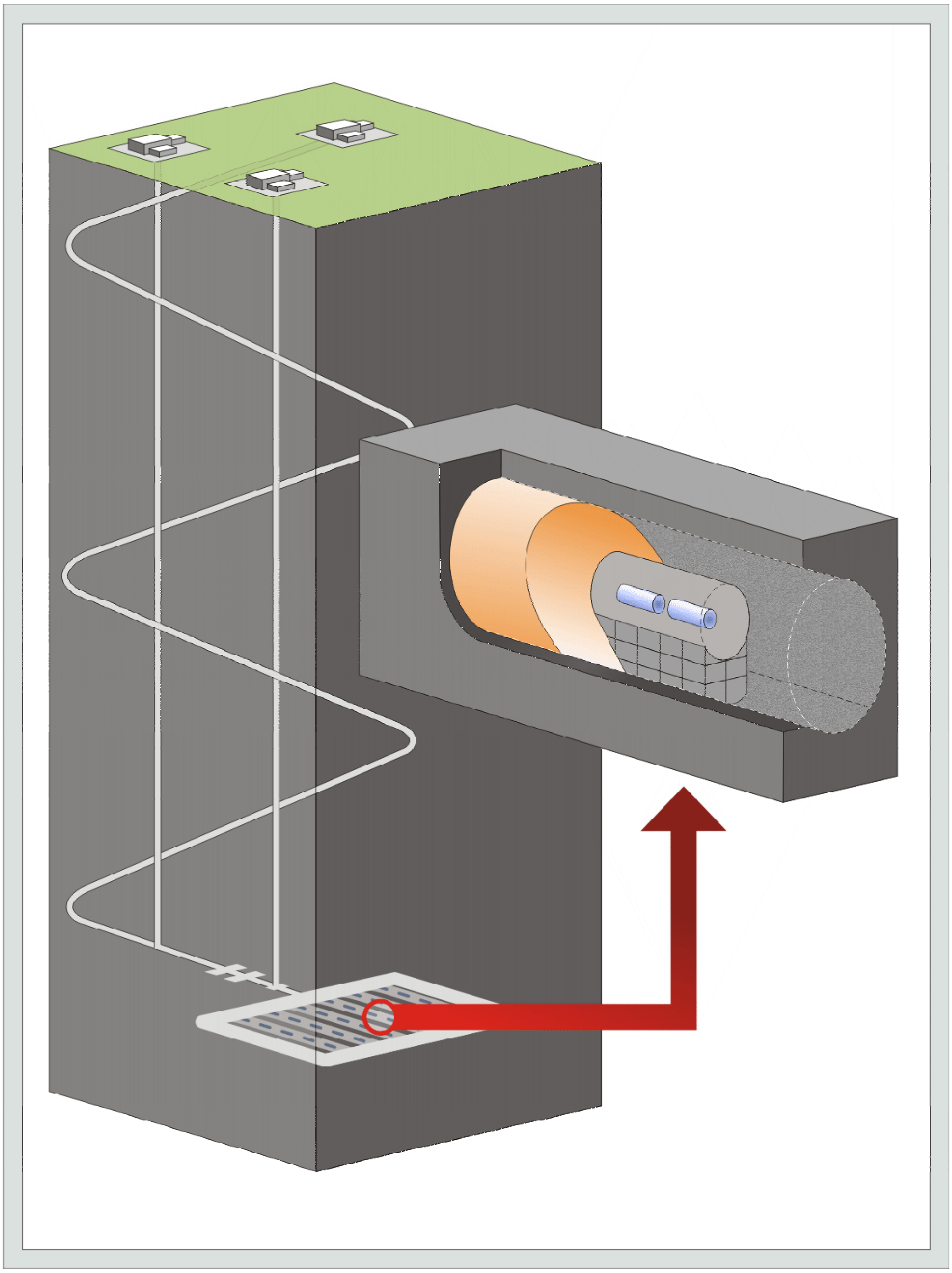

Figure 6.6: Schematic illustration of Concept 7, in-tunnel (axial) with supercontainer (large annulus).

Concept 8	Caverns with steel MPC (bentonite backfill)
Main Characteristics of the Concept	
Large, steel multi-purpose transport/storage/disposal containers (MPCs), which can hold up to around 20 HLW flasks or multiple fuel assemblies, are emplaced upright in large ventilated caverns for a period up to 300 years to allow cooling and inspection. The period before backfilling (i.e. until the MPCs are cool enough to backfill without detriment to the bentonite) will depend on the type, amount and age of the waste in the MPCs, but could vary from less than 100 years for old HLW (heat generation of 400W per HLW flask or less) to more than 200 years for SF or MPCs containing 20 young HLW flasks (>1000 W per HLW flask). After the open period, bentonite backfill materials are emplaced around the containers, cavern seals are emplaced and access tunnels are backfilled for final closure of the repository.	
Main drivers for the Concept	
The general Concept of cavern disposal has been considered feasible for many years but not developed in any detail until recently. The most current development work is in Japan (where the Concept is referred to as the Cavern Retrievable Concept – CARE) driven by (a) concerns that conventional repository Concepts were not appropriate if waste retrieval was required for a significant period and (b) the requirement for the implementing organisation to purchase all the land above the repository footprint, which favours smaller footprint Concepts. The cooling of the wastes for a period of up to 300 years means that one of the factors influencing repository layout – namely the thermal output of the waste – is much diminished and the Concept provides a very compact repository footprint even for the large Japanese inventory (the reference inventory for the first repository is 40,000 HLW flasks). The Concept is included in the NUMO alternatives for HLW disposal in Japan.	
Important Aspects of the Concept	
The Concept is flexible with respect to disposal of both SF and HLW. It is also flexible, in principle, with respect to implementation in a range of host rocks since cavern liners would be used for operational safety grounds in most, if not all, host rocks. The Concept can result in a very small repository footprint because of the packaging of waste into a relatively small number of large containers and the delay to backfilling, which allows the wastes to cool. There is, however, a trade-off between size of footprint and the required storage period as dense packing of the waste using minimum numbers of MPCs means that longer delay to backfilling will be required. Conversely, spreading the waste in more MPCs and over more caverns reduces the maximum temperature in the backfill allowing earlier closure. The Concept allows straightforward retrieval of waste during the open period, as well as inspectability, but with associated security issues. The Concept has only been the subject of limited desk studies to date. Although much of the technology already exists (e.g. transport casks, surface interim stores), many aspects of the long-term safety of the Concept are still uncertain, including the requirements for the backfill and the technology developments for its deployment. The Concept is not flexible with respect to early closure if this is earlier than the originally planned cooling period. If earlier closure was required, alternative backfill materials would need to be investigated, with the concomitant reconsideration of the safety case. The Concept is vulnerable to incomplete closure or loss of institutional control during the long open period.	

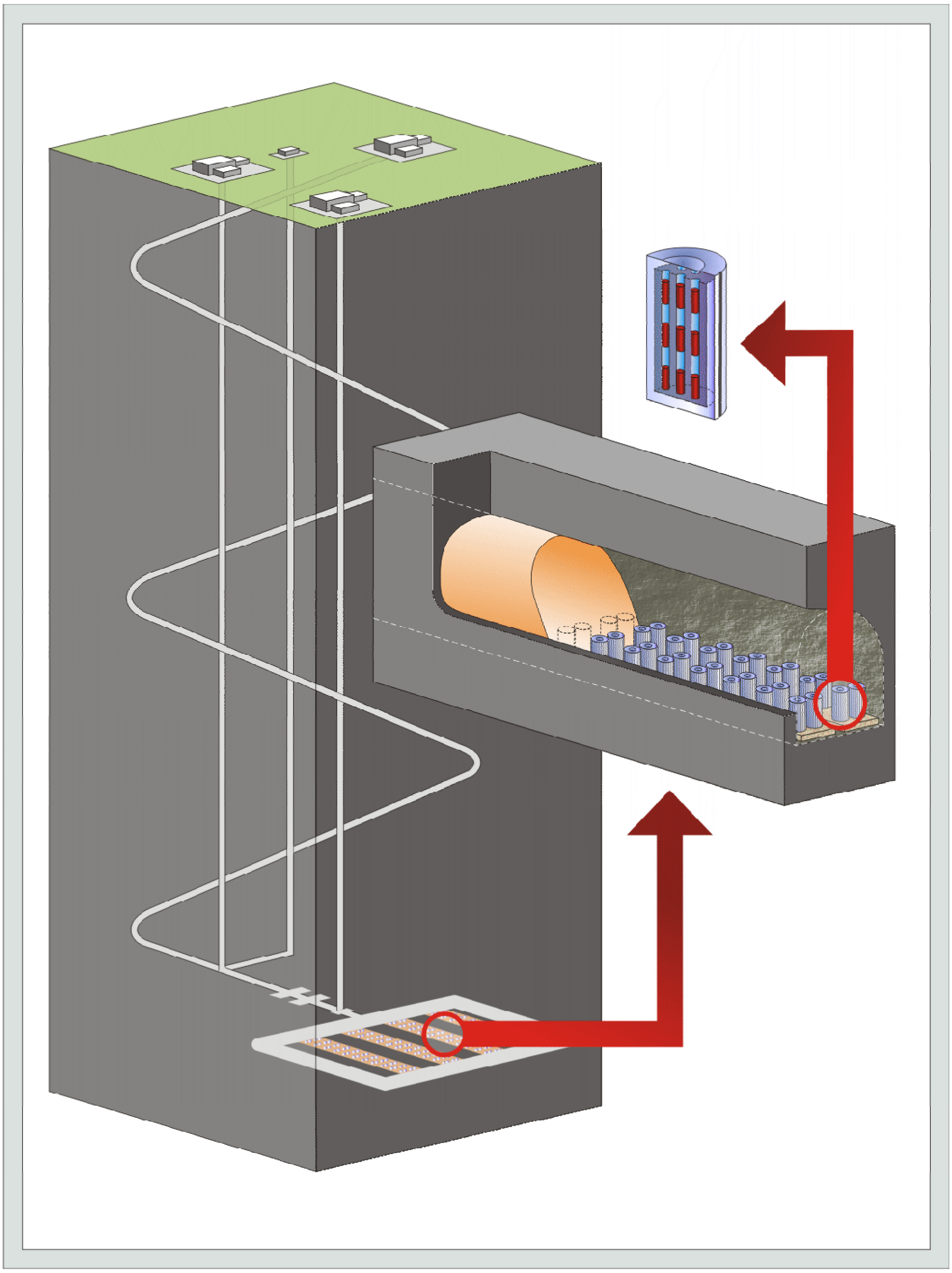

Figure 6.7: Schematic illustration of Concept 8, caverns with steel MPC (bentonite backfill). Note that there is scale change on the blow-up diagram: the caverns are of the order of 10-20 m wide and high, compared to the previous tunnel Concepts, where the tunnels were only a few metres in diameter.

Concept 9	Caverns with steel MPC or concrete/DUCRETE CDC (cement backfill)
Main Characteristics of the Concept	
Large, steel multi-purpose transport/storage/disposal containers (MPCs) or concrete disposal casks (CDCs), which can hold up to approximately 20 HLW flasks or multiple fuel assemblies, are emplaced upright in large ventilated caverns for a period up to 300 years to allow cooling and inspection. The period before backfilling (i.e. when the MPCs/CDCs are cool enough to backfill without detriment to the bentonite) will depend on the type, amount and age of the waste in the MPCs, but could vary from less than 100 years for old HLW (heat generation of 400W per HLW flask or less) to more than 200 years for SF or MPCs containing 20 young HLW flasks (>1000 W per HLW flask). After the open period, cement-based backfill is emplaced around the containers, cavern seals are emplaced and access tunnels are backfilled for final closure of the repository.	
Main drivers for the Concept	
The general Concept of cavern disposal has been considered feasible for many years but not developed in any detail until recently. The most current development work is in Japan (see Concept 7) driven by a) concerns that conventional repository Concepts were not appropriate if waste retrieval was required for a significant period; b) the requirement for NUMO to purchase all the land above the repository footprint, which favours smaller footprint Concepts. Cooling of the wastes for a period of up to 300 years means that one of the factors influencing repository layout – namely the thermal output of the waste – is much diminished and the Concept provides a very compact repository footprint. The original Concept assumed that the backfill material would be based on bentonite. However, it was also recognised that emplacement of bentonite-based backfill would be time consuming as the expected long-term safety performance is dependent on the barrier properties and, thus, on homogeneity and density of the emplaced material. Consequently, for use when rapid closure was desirable, cement-based alternatives have been considered as possibilities, although no studies have been carried out to examine the implications for long-term safety. A variant on this Concept is the use of concrete disposal casks (CDCs), possibly incorporating depleted uranium (if declared a waste). DU-containing concrete (“DUCRETE”) fulfils the double role of providing additional radiation shielding compared to conventional concrete (or a smaller, thinner walled CDC) and disposing of unwanted DU and may introduce an additional benefit into the EBS by influencing SF solubility (although this depends on the form of the DU in the concrete).	
Important Aspects of the Concept	
The Concept is flexible in principle with respect to implementation in a range of host rocks since cavern liners will be used for operational safety grounds in most, if not all, host rocks. The Concept can result in a small repository footprint because of the packaging of waste into few large containers and the delay to backfilling allowing wastes to cool. There is however a trade-off between the size of footprint and the required open period: dense packing of the waste means that backfilling would have to be delayed for longer. Conversely, spreading waste over more caverns reduces the maximum temperature in the backfill allowing earlier closure. The Concept allows straightforward retrieval of waste during the open period, as well as inspectability, but with associated security issues. The Concept has only been the subject of limited desk studies to date. Although much of the technology already exists (e.g. transport casks, surface interim stores), many aspects of the long-term safety of the Concept are still uncertain including the implications of a cement-based backfill. The Concept is not flexible with respect to early closure, although deployment of cement-based backfill could allow rapid closure. The Concept is vulnerable to incomplete closure or loss of institutional control during the long open period.	

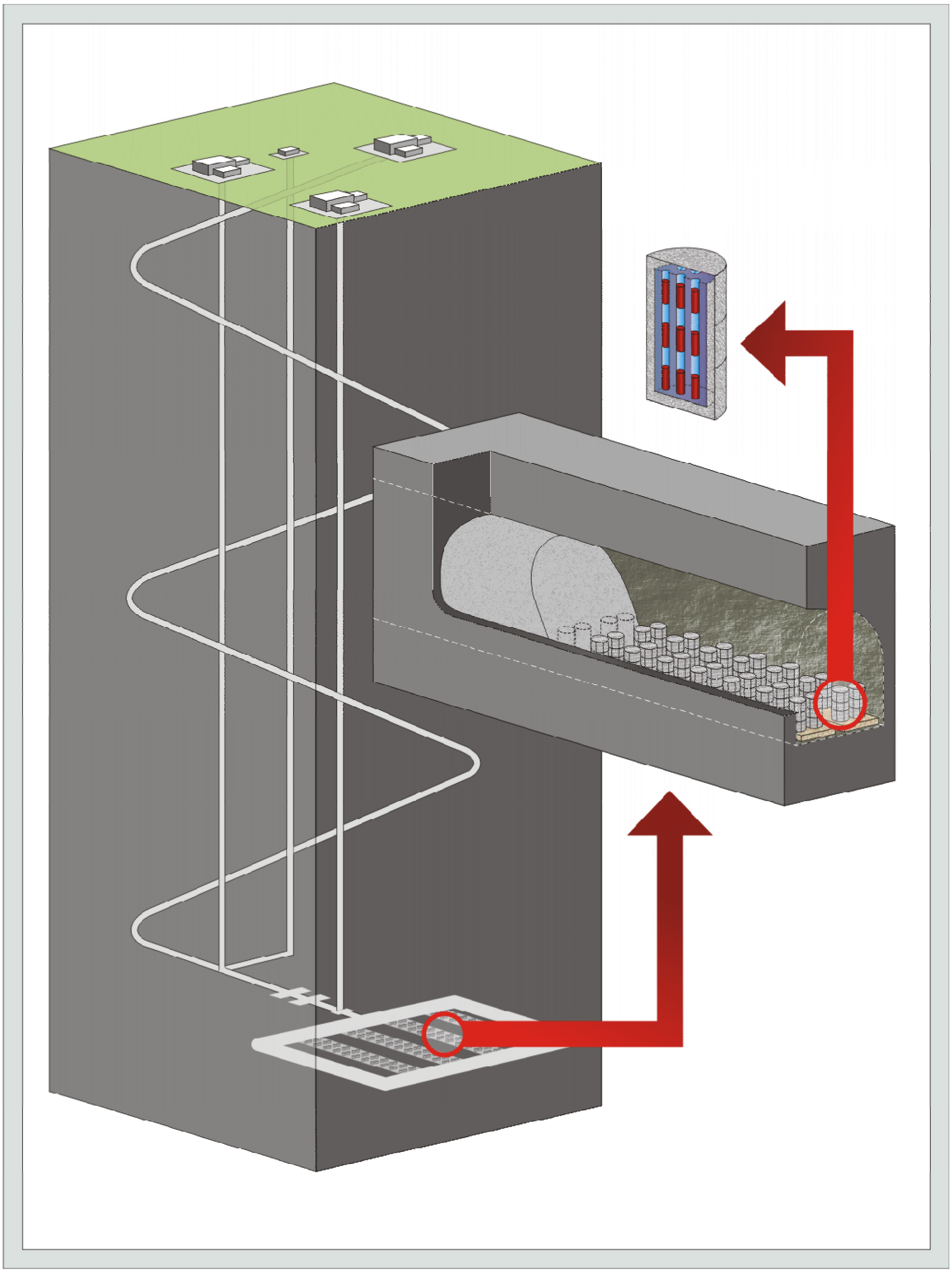

Figure 6.8: Schematic illustration of Concept 9, caverns with steel MPC or concrete/DUCRETE CDC (cement backfill). As with the previous illustration, note that there is scale change on the blow-up diagram: the caverns are of the order of 10-20 m wide and high, compared to the previous tunnel Concepts, where the tunnels were only a few metres in diameter.

Concept 10	Mined deep borehole matrix

Main Characteristics of the Concept

Waste packages are emplaced in stacks in long (~200 m or more) vertical boreholes which are bored from deep underground either directly from a disposal tunnel or between an upper operational cavern and a lower cavern, which is used for excavation of the boreholes only and backfilled and sealed before emplacement begins. In the latter case, raised boring allows excavation of large diameter holes (1.5-2 m) over several hundreds of metres.

The waste packages may be prefabricated EBS modules (supercontainers) containing waste, overpack and buffer in a handling shell or waste in an overpack/canister around which buffer material may be emplaced.

Main drivers for the Concept

The Concept arose in studies of alternative repository designs for both hard rock and salt. AECL (Canada) and NUMO (Japan) both considered disposal of waste packages in moderately deep bore holes without conventional surface excavation operations as a potential option for hard rock. The German reference Concept for disposal in salt domes considered a matrix of 300 m deep boreholes and this was subsequently developed in detail up to 1999 as one of the two design options for the Gorleben repository.

The attraction of the Concept is the use of the vertical extent of a host rock and (from the Japanese perspective) the small repository footprint while reducing the surface operations, compared to conventional deep borehole Concepts (see Concept 12) – although, even in the AECL study, the boreholes were only some hundreds of metres long, not kilometres. Also, compared to deep boreholes, the technology for construction and operation of the mined borehole Concept is already standard.

The original AECL study concluded that although the Concept was feasible in principle, there were large uncertainties in respect of emplacing the buffer around the waste packages. As a result, the NUMO studies considered the use of supercontainers to simplify emplacement of the EBS.

The DBE Technology Concept for salt (Gorleben) remains a favoured option and differs significantly from the hard rock Concepts as it involves neither buffer nor overpack.

Important Aspects of the Concept

The Concept is flexible with respect to disposal of both spent fuel and HLW. It is also flexible with respect to implementation in a range of host rocks although, in weaker rocks, limitations on size of openings at depth may limit the practical depth for the lower cavern and thus borehole length. This may be less of a constraint if boreholes are drilled directly from the upper cavern, although this is likely to require a larger cavern.

The Concept can result in a small repository footprint, due to the vertical extent of the repository, and also a relatively small excavated volume per waste package, which reduces if longer boreholes can be used and fewer disposal caverns are required.

The Concept is immature and there are considerable uncertainties over the long-term safety performance, especially in fractured hard rocks, given the practical difficulty of emplacing backfill/buffer to the sort of quality/properties normally considered acceptable.

The relatively close packing of the waste in 3D suggests that thermal convection within the borehole matrix during a possibly extended thermal period could be an issue. The implications on local groundwater flow and geochemistry have not yet been investigated.

A major technology requirement is likely to be the development of weight-bearing interim seals which prevent the weight of upper waste packages crushing the lower ones and potentially contaminating the borehole fluids while the borehole is still open (it is assumed that neither waste packages nor supercontainers would be emplaced into a dry borehole and that dense bentonite mud would be used partly for borehole support and partly to control the descent of the waste packages, especially in the case of equipment failure).

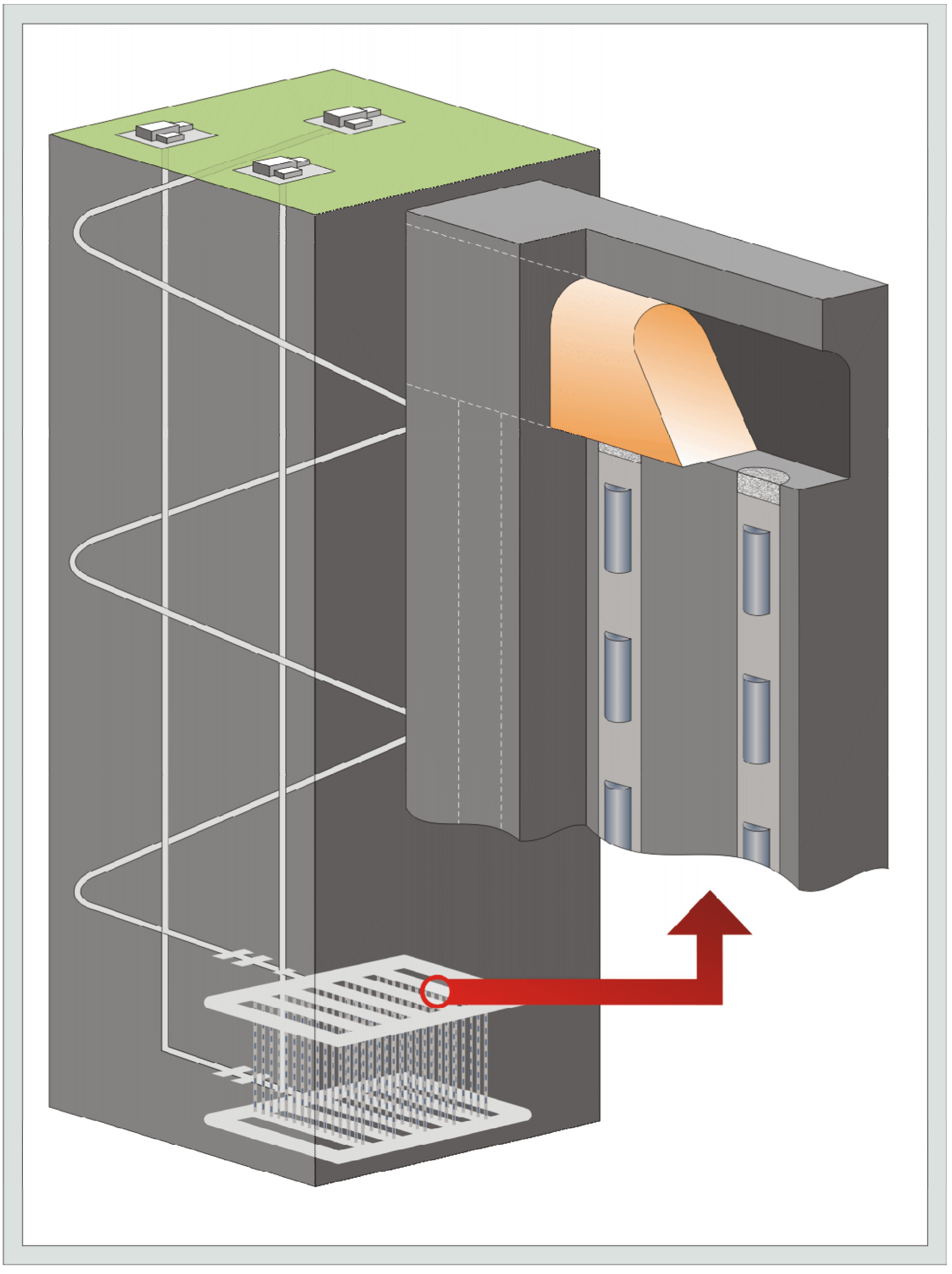

Figure 6.9: Schematic illustration of Concept 10, mined deep borehole matrix.

Concept 11	Hydraulic cage (around a cavern repository)
Main Characteristics of the Concept	
The concept of a hydraulic cage around a disposal volume (vault, cavern or whole repository) commonly refers to the use of a zone of material that has a high permeability compared to the average host rock and to the repository volume or the EBS. This zone acts to channel the water away from the disposal volume. The zone may be a simple trench excavated around a cavern and backfilled with high porosity material such as coarse gravel and cobbles or coarsely crushed and graded rock. A more complex option for a larger repository volume is the excavation of a screen of outlying boreholes that intersect the flow field and divert water away from the repository.	
Main drivers for the Concept	
The use of a hydraulic cage in a repository Concept for SF or HLW was first formalised in the WP Cave Concept by SKB (Sweden), which employed a low permeability bentonite zone, but the general Concept of engineering a high permeability zone which intercepts and diverts water, creating reduced advective flow behind it has mainly been considered for ILW repositories (e.g. in Sweden and Japan). The original WP Cave brought the hydraulic cage Concept together with an unusual repository EBS, but hydraulic cages have been more widely considered as a way of modifying the geological barrier properties around any reasonably compact repository. For sites with higher groundwater fluxes, the reduction of flux through the repository volume by using a hydraulic cage could make a more robust safety case. Although the usual objective is to modify water flux for long-term safety, it could also be possible to use a hydraulic cage to improve conditions during the operational phase. Thus, use of a hydraulic cage in conjunction with the CARE Concept (Concept 8) using ventilation tunnels adjacent to the caverns to create the hydraulic barrier has been suggested in Japan. Here, we describe the use of a hydraulic cage around the CARE concept (Concept 8) caverns. The Concept has not been specifically proposed by any waste management organisation for HLW or SF (although SKB have proposed a hydraulic cage around ILW vaults in the SFL3-5 concept) and is presented as an illustration of how hydraulic cages could be integrated with other Concepts.	
Important Aspects of the Concept	
A hydraulic cage around a compact repository Concept could improve the ease of making a safety case at sites with higher water flows, although this clearly depends on the type of site, host rock and the repository Concept envisaged. The use of a hydraulic cage might be restricted to Concepts with a small repository footprint as engineering a hydraulic cage around an extensive repository could be impractical. A hydraulic cage around a cavern repository (Concept 8) could mitigate some of the consequences of maintaining drained, ventilated openings deep underground on the local groundwater flow by diverting groundwater away from the caverns. The theory of the hydraulic cage is well established but large-scale, practical implementation that would function over the very long timescales of interest is uncertain and currently no programmes are actively pursuing this option for HLW or SF. When engineered around caverns, the excavated openings must be some metres larger than the caverns require, to allow for construction of the cage. Thus, for 15 m-wide CARE-type caverns, the excavated opening would need to be around 20 m. This is feasible in good, hard rock at depths up to 700 m or more. However, in weaker rocks requiring massive tunnel liners for support, the depth of deployment will be restricted and it may be necessary to restrict cavern size, making less efficient use of cavern space.	

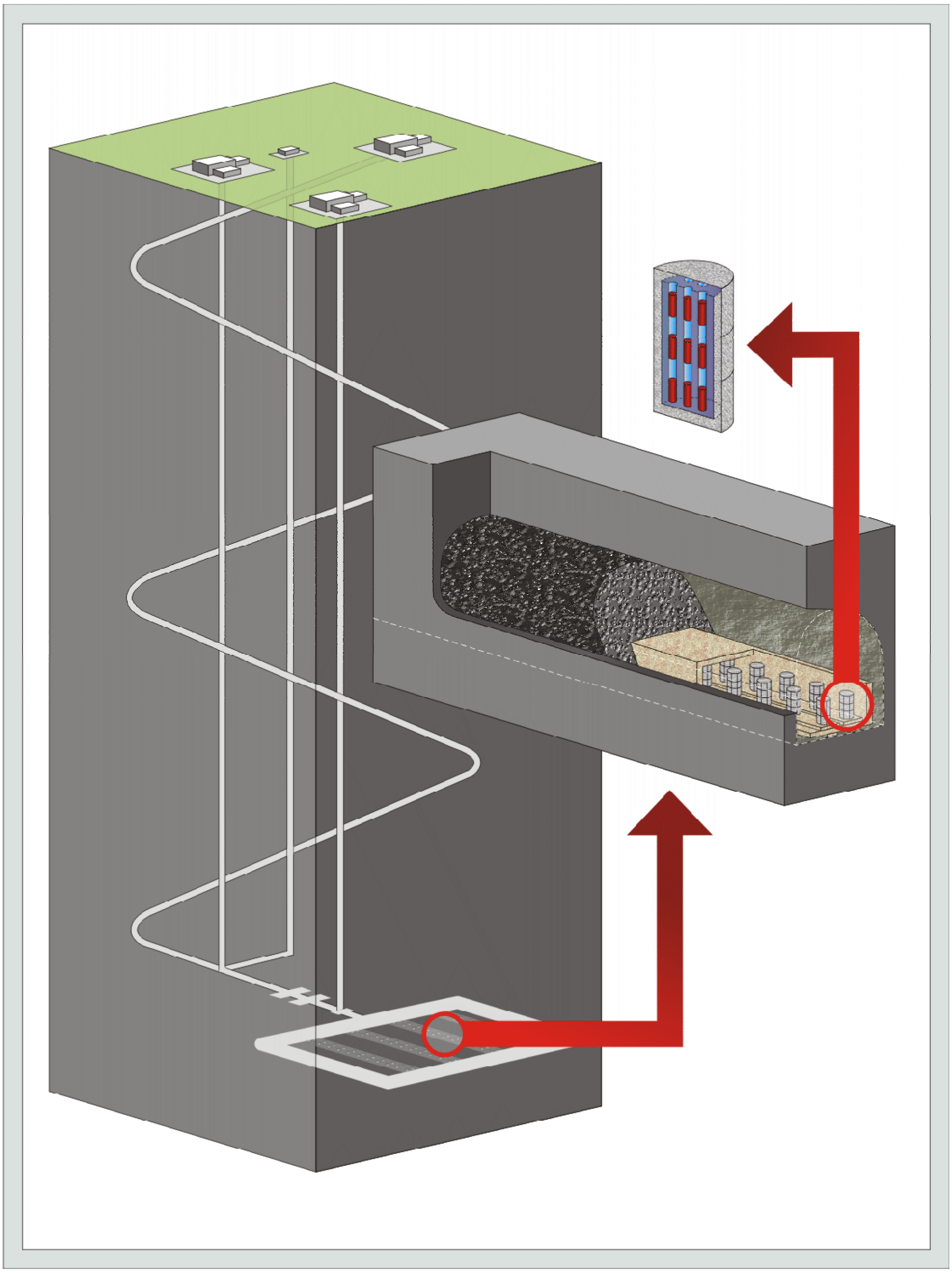

Figure 6.10: Schematic illustration of Concept 11, hydraulic cage (around a cavern repository). As with the other cavern concepts, note that there is scale change on the blow-up diagram: the caverns are of the order of 10-20 m wide and high, compared to the previous tunnel Concepts, where the tunnels were only a few metres in diameter. Note that this cavern concept includes a concrete inner vault (brown) that is backfilled with cement (grey).

Concept 12	Very Deep Boreholes
Main Characteristics of the Concept	
Simple metallic waste packages with no overpack are emplaced in the lower region (the bottom 1000 – 2000 m) of a borehole drilled from the surface to a depth of about 3 to 5 km. The borehole is fully lined with metal casing from the surface and should be of sufficient diameter to leave a generous annulus to ensure ease of emplacement. Various options are considered for backfilling the disposal zone of the borehole. The long, upper section of the borehole is sealed. If required, the uppermost part of each borehole could be destroyed, to ensure that wastes are practically irrecoverable. Each disposal borehole is drilled either singly and vertically, from its own drilling pad, or as part of a group from a central location of limited area (probably a few hectares, depending on the amount of waste), using directional drilling technology to deviate the lower sections by a few degrees to ensure the disposal zones in each hole are some tens of metres or more apart.	
Main drivers for the Concept	
The very deep hole Concept dates from the earliest days of geological disposal studies. Many variants have been considered, for depths down to 10 km, including Concepts that involve using the heat from SF or HLW to melt the rock at great depth and seal-in the waste. Most attention has been on disposal of cooled waste, however. Evaluations have been carried out in Sweden, and Nirex reviewed the history of the Concept in detail. The origin lies in the idea of using great depth to provide very high levels of isolation in what is considered to be a geologically remote and stable environment. Other attractions of very deep boreholes are the relatively limited requirements of site investigations compared to, for example, the detailed fracture characterisation required for some conventional repository Concepts, the practical irrecoverability of the wastes once emplaced, the small surface facilities and structures required and the potential for disposal campaigns carried out as needed, without the necessity to keep open an underground facility. Although there are several very deep scientific boreholes (deepest over 12 km) around the world that show that deep borehole drilling capability per se exists, there have been no practical tests to link large-diameter hole drilling technology with waste disposal technology, no detailed studies of waste handling and operational and post-closure safety, and no integrated disposal Concept has been developed. The Concept has been proposed for SF, HLW and fissile materials, such as separated Pu. There may be operational issues with SF disposal (due to the instant release fraction of the SF) that make this Concept poorly suited to this material. The Concept appears most suited to relatively small volumes of HLW and especially appropriate for fissile materials.	
Important Aspects of the Concept	
The key issue with this Concept is the lack to date of any detailed design or performance assessment study. The Concept is flexible with respect to implementation in a range of host rocks since the key issue is the hydrogeological environment at depth, in particular the lack of active groundwater movement, rather than the properties of the specific rocks at that depth. The Concept can be implemented in disposal ‘campaigns’ with no activities required in interim periods and the surface area required for the excavation (and emplacement) operations may be very small. The Concept provides very secure disposal of waste with effectively little chance of recovering waste without major technological investment. There are uncertainties about the operational procedures for this Concept as most evaluations have focused on the feasibility of borehole excavation and less on the operational safety and practicality: for example, the need to support or isolate waste packages so that the lower ones are not crushed, potentially contaminating the borehole fluid during emplacement operations. The safety case centres on the isolation provided by the deep geosphere but no detailed, comprehensive safety assessment has yet been performed. The size of the waste package for practical implementation in the near future (that is, without major development of ~1 m diameter boreholes) means that, although suitable for HLW, very little SF, for example, only one PWR fuel assembly, could be contained in one waste package. Thus, the Concept would be inefficient for SF disposal, as well as potentially poorly suited for the operational safety reasons mentioned above.	

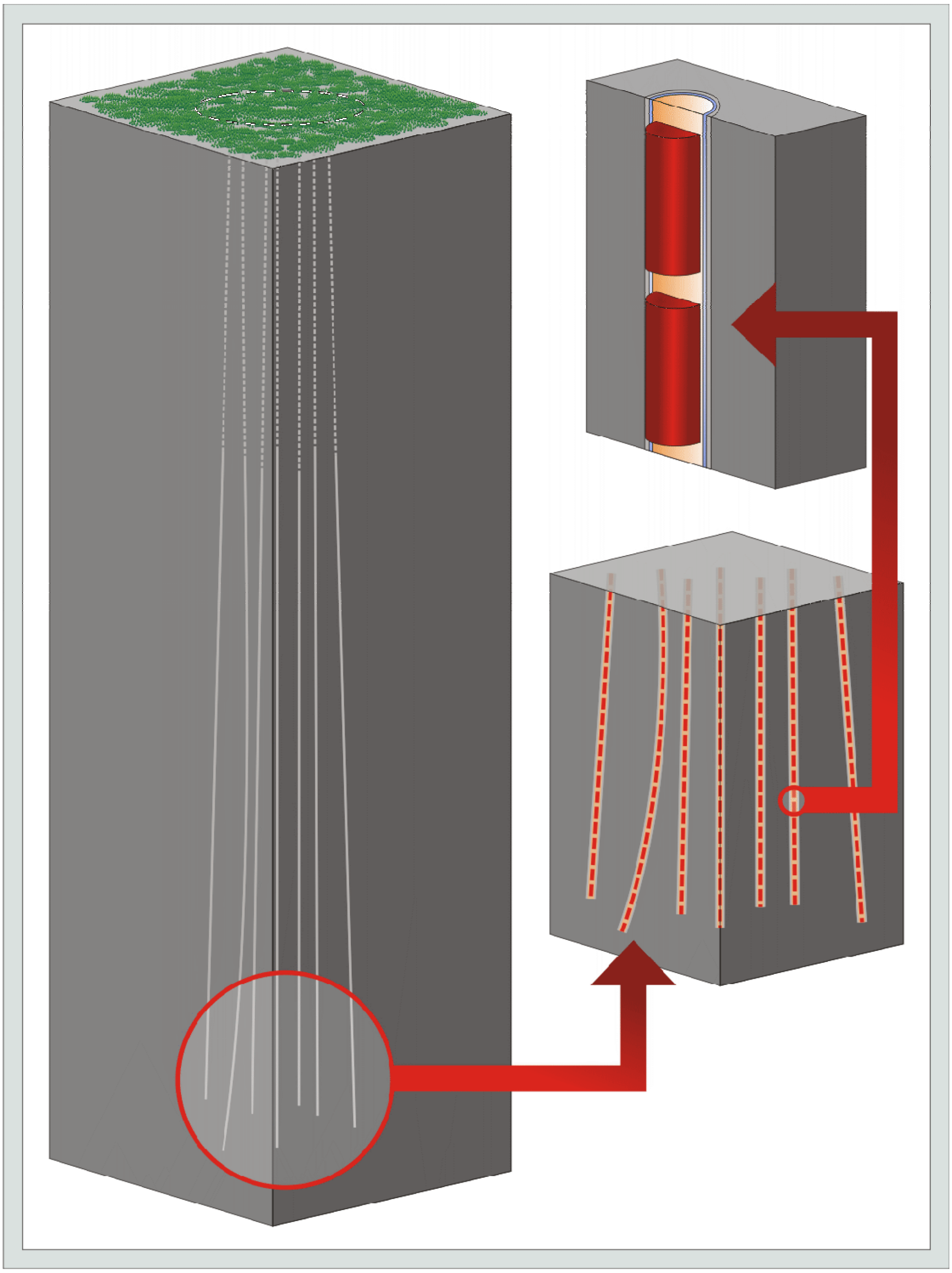

Figure 6.11: Schematic illustration of Concept 12, very deep boreholes. The scale on the main image is vastly different to the previous example concept illustrations; with depth in the range of 3 to 5 km, rather than around 500 m (the green surface represents a forest). The black circle indicates the area over which borehole operations will be carried out.

7 Evaluation Factors & Matrices

7.1 The Evaluation Factors

As outlined in the introduction to this report, the purpose of this study is to provide information on a broad range of geological disposal concepts for HLW and SF. In order to structure discussion of this information, a set of Evaluation Factors has been developed. The Evaluation Factors are a set of engineering, safety, environmental, socio-economic and cost attributes around which specific qualities of a Concept can be discussed. A similar set of factors, and some of the discussion presented, could be developed and applied in a weighted form to aid future decision-making when specific Concepts are being considered with respect to specific sites.

The Evaluation Factors were developed by drawing on expert input and reviewing evaluation criteria used in other national and international assessment studies. These included Finland’s Assessment of Alternative Disposal Concepts (Posiva 1996), the Swedish studies Project on Alternative Systems Study (PASS, SKB 1992) and Project JADE: Long-Term Function and Safety (SKB 2001), the EA/SEPA Guidance on the Environment Agencies' Assessment of BPEO Studies (EA 2004), the UKAEA Assessment and Identification of BPEO (UKAEA 2004) and the CoRWM Value Tree (CoRWM 2006).

A long list of many possible Evaluation Factors was created at the start of this study, using the references listed above, and the input of the project team and NDA staff was then used to reduce this to a list focused on key elements of repository concepts. These factors were continuously reviewed and adjusted throughout the project.

Table 7.1 lists the 16 Evaluation Factors, arranged under an initial set of broad headings that, at lower level, are broken down into the more specific factors. Each Evaluation Factor is discussed in more detail below and its meaning and use in this study defined.

Evaluation Factors for the impact of a given Concept on flora and fauna (for example, preservation of species and habitat conservation), were excluded from this study as, without a selected disposal site, too little information is known to enable any Concept-distinguishing comments to be made. This was also true of the impact on wider communities, which does not distinguish between Concepts at this stage in the process. Additionally, no factor has been selected that looks at the surface facilities each Concept may require; this is because each Concept will look very different in its final optimised form, which will account for the site topography, geology and wishes of the local community. As such, very little meaningful comment on these Evaluation Factors is possible at this stage.

It was originally intended to include a criterion on Concept energy use and carbon footprint. However, with such high-level generic Concepts and without specific designs it was found that such information was not readily available in time for this project. However, this information will be useful later and more readily calculable when Concepts are translated into detailed, site-specific designs.

Table 7.1: Evaluation Factors used in this study, with each sub-factor listed by its headline group.

Headline Factors	Sub-factors	No.
Technical & Engineering Feasibility	Flexibility	**1**
	Ease and implications of retrievability	**2**
	Maturity of technology / R&D requirements	**3**
	Timescale for implementation, construction, operation and closure	**4**
	Ease of repository construction and waste emplacement	**5**
Safety	Risk to the public	**6**
	Operational safety	**7**
	Ease of making a post-closure safety case	**8**
Impact on the Environment	Non-radioactive waste arisings, radiological and chemical pollution	**9**
	Resource and security of supply	**10**
	Land use area and density	**11**
	Nuisance	**12**
Socio-Economic Impact	Socio-economic impacts on the local community	**13**
	Burden to future generations	**14**
Waste Security and Safeguards	Safeguards capability and security	**15**
Cost	Total lifetime cost and spend profile	**16**

1. **Flexibility:** is the ability of the Concept to cope with various volumes of waste, multiple waste types, different staging points and endpoints. This also considers the flexibility of the Concept with respect to subsequent management decisions, which may require earlier closure than originally planned, or a storage period before closure.

2. **Ease and implications of retrievability:** looks at whether and how waste retrievability could be implemented in the Concept, any implications to the Concept safety functions of implementing such retrievability and the possibility for allowing phased disposal and/or open (storage) periods in the repository.

3. **Maturity of technology/R&D requirements:** reflects how well developed the Concept is, if it has been well studied over many years and by many organisations, and if there are any significant outstanding R&D issues that have yet to be resolved.

4. **Timescale for implementation, construction, operation and closure:** any issues to be resolved and development and demonstration yet to be carried out are noted, where these may impact on the period of time before a Concept could be implemented. This factor also notes whether the ease of waste emplacement would allow an increased emplacement rate or earlier closure than planned, if such were required.

5. **Ease of repository construction and waste emplacement:** the use of standard or unusual construction equipment and methods is discussed, as are the implications of these. Different construction and emplacement requirements for different geological environments are also noted.

6. **Risk to the public:** considers the radiological and non-radiological (e.g. transport) risks to the public during construction and operation of the repository, that is, pre-repository closure risks. Post-closure public safety is not considered here as every Concept is assumed to meet all required safety regulations, otherwise it would not be developed. At the high level of analysis presented here, it is not meaningful to include a discussion of the risk to the public for each Concept in each Geological Environment (see Section 7.1.1).

7. **Operational safety:** considers the radiological and non-radiological risks, and duration of such, to the workers at the repository, including the construction, waste emplacement and closure phases.

8. **Ease of making a post-closure safety case:** considers if there are any factors which may make elaboration of the safety case by the implementers problematic or, conversely, inspire greater confidence in it (including, for example, issues such as the effect on the safety case of phasing/holding a repository open for an extended period and the potential for, and impacts of, inadvertent intrusion by people in the distant future).

9. **Non-radioactive waste arisings, radiological and chemical pollution:** discusses the non-radioactive waste arisings, such as the spoil volumes likely to be incurred, and any radiological and chemical pollution, including air and water quality.

10. **Resource and security of supply:** notes the use of materials with significant volumes, such as steel, concrete or bentonite, and their current and future security of supply (for example, steel is currently relatively inexpensive, readily available and may also be recycled, but these statements may not be true over the long timescales involved with geological disposal).

11. **Land use area and density:** looks at the likely land use/footprint size required by the Concept - this covers the estimated entire repository footprint to the largest extent both above and underground because the legal position is currently uncertain as to whether the land for the full repository will need to be purchased, or just that required for the surface facilities. Land use density is also discussed, where the surface facilities may be concentrated in one location, or spread over a larger area.

12. **Nuisance:** includes any particular noise, transport, or visual impact that may be associated with the Concept, such as rock crushing machines, large rock spoil heaps left on site for a long time or significant materials transport requirements. The degree to which the community is affected by the site visual impact, noise and transport will be determined, to a large extent, by the proximity of the site.

13. **Socio-economic impacts on the local community:** comments on the impact that a Concept may have on the local community such as through increased employment and the timescale over which this increased employment might materialise. However, at the high level of analysis in this study, it was found to have little meaning to attempt a discussion of the socio-economic impact of each Concept in each Geological Environment (see Section 7.1.2).

14. **Burden to future generations:** includes long-term repository management pre-closure and monitoring requirements, future financial obligations, the effect of extended open storage periods and any ongoing requirements to protect the repository and the person from the effects of human intrusion. Comments are also made on the potential attractiveness of materials used in the repository, such as copper or titanium, that future society may wish to mine.

15. **Safeguards capability and security:** notes if the Concept impacts on nuclear waste safeguards capability, such as through a decreased ability to account for or contain the waste, or waste security, through the ease in which nuclear materials may be accessed. Section 8 discusses safeguards further.

16. **Total lifetime cost and spend profile:** allows comment on the cost incurred for a geological repository for the different implementation phases (development, construction, operation, closure): without better data (which are scarce internationally) and a more detailed analysis than has been carried out in this study, it is only possible to make general comments on relative costs, which are discussed in Section 7.1.3.

7.1.1 Risk to the Public

Although an important factor in developing and implementing any Concept for the disposal of HLW and SF, it was found that the Evaluation Factor “risk to the public” did not distinguish between any of the concepts at the current high level of analysis. All radioactive waste management options must meet the same safety requirements and are subject to the same regulations. It may be possible, at a later stage, to distinguish between detailed designs by looking at the ease with which those regulations will be met, but at this high level very little meaningful comment could be made.

The exception to this was for Concept 12, mined deep boreholes. It was noted that emplacement operations would take place at the surface rather than deep underground and are likely to involve packages without overpacks (although in secure, shielded, possibly mobile structures). In principle, there could be greater risks associated with accidents or perturbations during emplacement than with mined repositories.

7.1.2 Socio-Economic Impacts on the Local Community

It was found that the socio-economic impact of a given Concept on a local community could not be meaningfully discussed in the matrices in this high-level study. Each Concept has yet to be developed into an actual design, employment estimates range from a few tens to a few hundred employees at different stages of the repository lifetime, the exact costs and materials requirements are unknown, the size of the surface facilities is yet to be optimised (and can not be without a selected site), and the environment and nature of the local community is unknown.

Some generic statements can be made: for example, there is the potential for increased employment within the community, in addition to employees brought into the area, and there will be an increase in trade for indirect services and ancillary businesses. Obviously, the size of the local community near the selected site will affect the degree to which it is impacted. For example, a small village could be more affected than a large town. Any potential community involvement and compensation packages should also benefit the community.

It is noted that the proposed framework for implementing geological disposal in the UK (Defra, 2007) recognises that *"Any communities that [are] ultimately chosen to host a geological disposal facility will be keen to exploit ... benefits, and will expect Government and the NDA to ensure that the project contributes to their further development and well-being"*. The potential benefits identified in the proposed framework could include:

- Skilled employment for hundreds of people over many decades.
- Major investments in local transport facilities.
- Spin-off industry benefits; infrastructure benefits; indirect benefits to local educational or academic resources.
- Benefits from visitor centres.
- Positive impacts on local hotel and service industries.
- A benefits package that contributes to the sustainable development of the affected area.

The key issue for this study is to determine whether any of the generic Concepts are likely to offer greater socio-economic impacts than other Concepts: for example, the following observations can be made:

- The cavern-based Concepts (Concepts 8, 9 and 11) require maintenance and preservation of disposal technology skills over much greater periods than the other Concepts, which could provide opportunities for long term employment.

- The deep borehole Concept (Concept 12) provides less employment opportunities than other Concepts by virtue of the smaller requirement on mining, civil, mechanical and electrical engineering skills.

7.1.3 Total Lifetime Cost and Spend Profile

Analysis of repository programme costs at the high level of the current study is not possible without considerable uncertainty. Cost studies have been carried out in many national programmes but few are fully published, the information is patchy and it is generally difficult to translate the basic assumptions, cost rates and means of itemising costs to another Concept, country or programme strategy. In fact, costs and spend are highly sensitive to many factors and a programme management strategy can be devised to control spend in different ways. The principle sensitivities and uncertainties are related to timing (when to start siting, construction, encapsulation, disposal, closure etc – all of which are, to varying extents, decisions that are flexible), site-specific conditions (which can require programme and design modifications), waste inventory (whether additional wastes are included for disposal), the licensing process (not decided), benefits to communities and factors such as retrievability policy and numerous other programme risks.

Nonetheless, some generic observations can be made regarding the relative cost attributes of tunnel, cavern and very deep borehole repositories, according to different categories of expenditure:

- Repository Siting and Site Investigation: this is likely to be similar for all tunnel and cavern repositories but could vary significantly with geological environment and depth. For very deep boreholes, where there is no experience in designing and running a siting programme, the relative costs are currently unknown.

- R&D: in principle, Concepts that have been extensively studied for 30 years or so should require limited additional R&D to transpose to the UK situation. The amount of R&D that would be required for less-developed concepts is likely to be variable – for example, cavern concepts using MPCs, although not studied in detail as disposal systems and raising specific issues of their own, are based on the use of components with well-understood technologies. On the other hand, technologies such as hydraulic cages and very deep boreholes will certainly raise new R&D issues whose costs are currently difficult to estimate.

- Encapsulation and Transport: tunnel Concepts all require the construction and operation (over a prolonged period) of an encapsulation plant, either at the current interim storage sites or at the repository. Encapsulation is a substantial cost element in the Scandinavian and Swiss programmes. Cavern concepts using MPCs could purchase these components as required (in distinct disposal campaigns if appropriate), but the large dimensions of these items could impact on the requirements and costs for the transport infrastructure.

- Construction and Operation: The cost of construction could vary as a result of more difficult ground conditions, or due to additional requirements on the repository. For example, cavern repositories will have higher cost impacts associated with requirements to keep the caverns open for extended periods and these costs could extend hundreds of years into the future. In principle, deep boreholes could be much cheaper to construct than repositories but the operating costs have not been evaluated so far.

- Closure: all tunnel repositories are likely to have broadly similar costs for closure, but this item is dependent on decisions on open period and retrievability requirements. Cavern repositories could prove very costly to close owing to the volumes of materials that may be required (although the potential to replace bentonite with cement could affect this significantly). The cost of closure for very deep boreholes is likely to be significantly smaller than for 'conventional' repositories.

7.2 The Matrices

The matrices allow the twelve Concepts to be related to each of the five broad Geological Environment groupings and to the thirteen Evaluation Factors[2], with comments on how well each option relates to each environment and factor. This means it is possible to see information on the performance of geological disposal Concepts under a wide range of circumstances.

The matrices were produced in two versions. The first version relates, for each of the 12 Concepts, every Evaluation Factor to every Geological Environment, resulting in a total of 12 matrices (see Figure 7.1). The second relates the five Geological Environments to the 12 Concepts, for each of the 13 Evaluation Factors, producing 13 matrices in total (see Figure 7.2).

The matrix comments help to draw out the most relevant points for consideration, from the UK viewpoint, for that combination of Concept, Evaluation Factor, and Geological Environment. The majority of boxes include at least one comment. However, some areas of the matrices are greyed-out to indicate that that combination of Concept and Geological Environment is considered to be unsuitable for implementation, e.g. implementation of Concept 5, which relies on a weaker host rock, such as clay, to provide a radionuclide diffusion barrier, would not be implemented in a strong rock, such as a fractured granite, because it does not provide a diffusion barrier and therefore does not perform the required safety function. The boxes may also be greyed-out if it is possible to implement the Concept in that Geological Environment, but it is highly unlikely that such would be done because it would represent significant and unnecessary over-engineering, such as emplacement of a bentonite-based buffer in a salt host environment. The explanations for these decisions are indicated on the relevant Concept matrices.

The discussion (Section 8) draws out the conclusions that can be made from the matrices and each matrix is included in the companion report (NDA, in preparation).

[2] There are 16 Evaluation Factors in total but, as discussed in Section 7.1, Evaluation Factors 6 (risk to the public), 13 (socio-economic impact) and 16 (cost), did not allow any distinguishing comments to be made in the matrices at this high level and so were excluded from the matrices (presented in the companion report).

1		In-tunnel (vertical borehole) with long- or short-lived canister		
		Geological Environment		
		G1	G2	G3
Evaluation factor		Stronger rocks with very low flow, of likely saline waters	Stronger rocks with higher water flow, probably relatively fresh water	Weaker rocks with no effective flow and relatively saline water in pores
1	Flexibility	Very flexible for all waste package sizes. Flexible with respect to staged operations in disposal areas (i.e. a group of disposal tunnels linked together by a perimeter access tunnel).	Very flexible for all waste package sizes. Flexible with respect to staged operations in disposal areas (i.e. a group of disposal tunnels linked together by a perimeter access tunnel) although individual disposal tunnels should be completed as soon as possible to reduce problems with premature swelling of borehole bentonite, which is likely to be a significant problem in wetter conditions. If it is required to keep disposal tunnels open for periods greater than a few months, a method of sealing the boreholes to prevent bentonite extrusion would be required.	It may be awkward to emplace longer packages owing to smaller practical tunnel diameters in weaker rocks at depth. Flexible with respect to staged operations in disposal areas (i.e. a group of disposal tunnels linked together by a perimeter access tunnel). Access and disposal tunnels will need to be lined for support.
2	Ease and implications of retrievability	It is possible to retrieve a specific single canister before backfilling of the disposal tunnel and with more difficulty afterwards. The concept requires buffer emplacement as the waste is emplaced but disposal tunnels can, in principle, be left open if measures are taken to cap the filled boreholes.	It is possible to retrieve a specific single canister before backfilling of the disposal tunnel and with more difficulty afterwards. The concept requires buffer emplacement as the waste is emplaced; disposal tunnels can, in principle, be left open but early bentonite swelling due to water inflow in the disposal holes requires strong and immediate measures to cap the filled boreholes.	It is possible to retrieve a specific single canister before backfilling of the disposal tunnel and with more difficulty afterwards. The concept requires buffer emplacement as the waste is emplaced but disposal tunnels can, in principle, be left open due to lack of groundwater inflow. Additional (standard) tunnel supports in weaker rock will be required for extended open periods, which may affect waste package retrieval.

Figure 7.1: Excerpt of the matrix for Concept 1 produced for every Evaluation Factor and every Geological Environment.

EF 5		Ease of repository construction and waste emplacement		
		Geological Environment		
		G1	G2	G3
Concept		Stronger rocks with very low flow, of likely saline waters	Stronger rocks with higher water flow, probably relatively fresh water	Weaker rocks with no effective flow and relatively saline water in pores
1	In-tunnel (vertical borehole) with long- or short-lived canister	Excavation is likely to be straightforward unless the local stress pattern is unfavourable (e.g. strong stress anisotropy). Optimal conditions for emplacement of this EBS would favour these very low/no water flow conditions. Strong rocks and homogeneous local stress increase stability of all openings, including deposition boreholes, particularly around the opening in the tunnel floor which is vulnerable to rock stress-related damage.	Excavation of repository structure, boreholes and tunnels is likely to be straightforward unless the local stress pattern is unfavourable (e.g. strong stress anisotropy). Potentially more problematic to identify suitable locations for EBS emplacement due to higher water inflow (consequent changes to layout as excavation proceeds). Grouting campaigns (which may have implications for grout/bentonite interactions) or implementation of temporary borehole drainage systems may be needed.	Access and disposal tunnels will need liners for support but various options such as temporary (shotcrete, removed before backfilling as Posiva plans for the Olkiluoto repository) or removable (steel) systems could be investigated to avoid long-term interactions between bentonite backfill and the liner material.
2	In-tunnel (horizontal borehole) with long- or short-lived canister	Excavation likely to be straightforward, although horizontal drilling of large diameter deposition holes is more challenging than for Concept 1. Optimal conditions for emplacement of this EBS would favour these very low/no water flow conditions. Strong rocks increase stability of all openings, including deposition boreholes, particularly around the opening in the tunnel wall, which is vulnerable to rock stress-related damage.	Excavation of repository structure, boreholes and tunnels likely to be straightforward (noting caveat about constructing large diameter horizontal holes). Potentially more problematic to identify suitable locations for EBS emplacement due to higher water inflow (consequent changes to layout as excavation proceeds). Grouting campaigns (which may have implications for grout/bentonite interactions) or implementation of temporary borehole drainage systems may be needed.	Access and disposal tunnels will need liners for support, possibly massive if tunnels are large diameter. Various options such as temporary (shotcrete, removed before backfilling, as Posiva plans for the Olkiluoto repository) or removable (steel) systems could be investigated to avoid long-term interactions between bentonite backfill and the liner material. Ease of construction of long, lined horizontal deposition holes very dependent on rock strength.

Figure 7.2: Excerpt of the matrix for Evaluation Factor 5 produced for every Concept and every Geological Environment.

8 Discussion

Geological environments across the UK are highly varied and include almost all the environments being evaluated in other countries for their geological disposal programmes (with the exception of unsaturated environments and onshore salt domes). In each of these environments there are significantly different choices for the way in which a safe repository could be implemented, and there will be options for how geological disposal is implemented at any candidate disposal site. It is thus not surprising that there is a broad range of generic Concepts that could be deployed in the UK.

The key aspects of each Concept, in each of the five Geological Environments are tabulated in Table 8.1 at the end of this section – we do not attempt to summarise them further here. Readers can also make their own observations based on the commentaries in the matrices included in the companion report (NDA, in preparation). The information in the data sheets and the matrices provides a basis on which the NDA or other stakeholders can undertake an initial identification of preferred Concepts (e.g. informed by multi-attribute decision analysis techniques), when this is required (e.g. when candidate sites have been identified).

The project restricted itself to evaluation of Concepts suitable for HLW and SF. Intrinsically, all of the Concepts considered here could also be suitable for disposal of other radioactive materials too. This is because the Concepts are all designed to isolate and contain long-lived radionuclides. The implications for any of the Concepts will be mainly in terms of the size of the repository that could be required, which in turn depends on the way in which additional wastes might be conditioned and packaged for disposal. Impacts on size have knock-on effects of costs, duration of operations, materials and land-use, and consequent environmental impacts. Below, we comment on some specific considerations for particular materials that may be declared waste:

- **Plutonium**: This could be converted to a form suitable for disposal by blending it into 'low-specification MOX' fuel pellets (equivalent in most disposal-relevant respects to unburned UO_2) or incorporated into a ceramic or glass waste form. Sufficient dilution is required to ensure that there are no criticality problems after disposal. The waste packages could be identical to those for SF or HLW and could be disposed of together with them. Deep borehole disposal provides a practically irretrievable solution for plutonium disposal. Conversely, cavern concepts would allow access to plutonium to be maintained for the longest period. Depending on the conditioning route adopted, the CoRWM inventory of plutonium (102 tonnes) would require between several hundred and a few thousand waste packages to be disposed of. Clearly, this could add significantly to the footprint of those repository Concepts for which we have considered an inventory of ~7,000 SF and HLW packages in this study.

- **Depleted uranium (DU):** DU could be utilised as a construction material for some Concepts (to make DUCRETE casks, for example). This would not result in any size or other operational or environmental impacts beyond those for use of conventional steel or concrete casks. Otherwise, DU would most likely be disposed in a simply conditioned form (e.g., in a cement matrix) in drums and containers that would be disposed in a similar fashion to ILW.

- **Highly-enriched uranium & 'cluster fuels':** Small amounts of these materials might be routed for disposal. No detailed studies have yet been made on how they might be conditioned for disposal but it is probable that similar styles of overpack would be suitable for these as used in many of the Concepts. It is currently assumed that highly-enriched uranium (HEU) would be downblended with DU before disposal, should these materials be declared wastes. There is no reason to believe that the Concepts considered in this report would need significant modification to host cluster fuels – the issue would again be with repository size if there were to be significant amounts of this material.

- **New-build wastes:** The disposal of waste from new-build reactors could be undertaken using the Concepts identified in this study. For a 10 GW(e) NPP programme running for 60 years, the number of additional SF packages could be equivalent to the inventory already considered here, thus doubling the size of the repository (Chapman and McCombie 2006). Since new NPPs would likely operate until at least 2070 (even assuming no further nuclear energy programme mid-century), the repository would either have to operate in campaigns or be kept open for longer – or all wastes might be stored until late in the century before disposal of any of them is implemented – or it may be considered appropriate to develop a second repository. These considerations are far into the future and there will be different drivers for decisions at that time.

- **Co-location with an ILW repository:** The NDA has a parallel programme to develop disposal solutions for the large volumes (~353,000 m^3) of ILW. The likely range of concepts for large-volume wastes involves the construction of large openings, thus favouring environments with appropriately strong rocks and low flow conditions. The size of an ILW repository will be commensurate with that of a HLW and SF repository, although access works can be shared between the two parts. Several national programmes envisage co-location in this manner, although most have much smaller amounts of ILW than the UK and the ILW region of the repository is only a small annex to the SF or HLW repository. Apart from the strategic advantages, there are many technical attractions of co-location: both repositories require broadly equivalent levels of geological isolation and their safety cases include many common aspects and can be considered together, similar cavern construction techniques can be used for all waste types with some Concepts, there may be useful operational overlaps in terms of waste arising times, and costs can be reduced.

Consideration of inclusion of some of these waste types makes sense even at this stage of the NDA programme. Others (especially new-build wastes) are much more strategic decisions and it is inevitable that any plans made today will be modified by future generations. Nevertheless, it would be prudent to consider the possibility of additional materials being included when selecting both site and Concept so as not to foreclose any options unnecessarily.

Even without considering additional wastes, further work will certainly be required to optimise the packaging of the wastes considered here. We have made simple assumptions about how this can be done so as to illustrate how Concepts can be developed. However, there is certainly scope for optimising packaging in terms of the numbers of HLW containers that are placed in an overpack and the number of fuel elements (or consolidated fuel elements) that are placed in overpacks of different dimensions. The potential gains in terms of repository size and operational savings varies from Concept to Concept. An additional point to consider in this context is the increasing interest in using supercontainers that incorporate buffer material into the waste package. This recognises the substantially increased ability to achieve high levels of quality control on critical parts of the engineered barrier system by manufacturing it under factory conditions in a surface facility.

The issue of providing nuclear safeguards for fissionable materials was found to discriminate little between the majority of the Concepts, with one or two notable exceptions. As a matter of principle, SF must be subject to nuclear safeguards as it contains significant amounts of plutonium (and other materials would also be included in safeguards provisions if disposed of: plutonium, HEU and low-enriched uranium). Safeguards requirements are basically that the origin, status and location of every SF element should be known at all times (and be able to be confirmed) and that it should be in a secure location from which it cannot be removed illicitly and unobserved by international safeguards monitors. If the transport to and disposition of SF in the repository are strictly controlled, and if the deposition locations within the repository are inaccessible and are known not to have been interfered with before final backfilling and closure of the repository, then these safeguards requirements will be largely fulfilled. However, an international safeguards regime may also require that the repository site and environs remain under remote (e.g. satellite) surveillance after closure to ensure that the SF is not illicitly recovered. In principle, there is no limit to the period that such surveillance has to be in place. In the first centuries after production, SF is highly radioactive owing to the shorter-lived radionuclides such as ^{90}Sr and ^{137}Cs and would thus be very difficult to recover. The radiological hazard diminishes with the passage of time.

Most of the Concepts provide similar levels of ‘safeguardability’, as SF is emplaced and then sealed into disposal holes and tunnels in the rock immediately, thus making it effectively inaccessible for easy diversion for the remainder of the repository operational period. The exceptions are the cavern/cask Concepts, where the waste packages are intentionally kept in an inspectable state for up to hundreds of years before sealing into the repository. Whilst this may provide some comfort to those who consider that safeguards require the material to be observable at all times, it also permits recovery and diversion should the safeguards control system break down and thus has a relatively lower level of security. At the other end of the spectrum, very deep boreholes provide the strongest of safeguards against illicit recovery, but in this study we argue that they are unlikely to be suitable for SF disposal in other respects. Nevertheless, should either plutonium or HEU be declared waste, very deep boreholes have obvious safeguards attractions.

There are few clear distinctions in the Concepts between the way that HLW and SF would be managed and emplaced. Those that are notable are:

- The cavern/cask Concepts could allow HLW to be managed separately, as the thermal period will be a little shorter and the thermal load will be a little less. In addition, the existence of some old, well-cooled HLW means that the period up to backfilling the caverns could be reduced, compared to SF.

- The relatively lower hazard potential of HLW after a few thousand years (compared to SF) suggests that simpler engineered barrier systems might be appropriate in some Concepts, for example with the use of a cement buffer rather than bentonite. This has not been explored in the current study as there is little extant information on which to base our evaluation and deeper study is warranted.

- Disposal in boreholes in evaporite formations (as envisaged as a design alternative in Germany) would allow HLW to be emplaced with no overpack, making the operation less expensive. SF would require an overpack, even though relatively simple.

- The very deep borehole concept seems conceptually more suited to HLW disposal, rather than SF disposal. With both wastes to be managed, however, it seems unlikely that it would be worth pursuing two disposal Concepts separately (unless very deep boreholes were also indicated for disposal of fissile material: Pu or HEU). The very deep borehole concept is one of the least mature concepts considered in this study.

This study has considered only generic Concepts, with detailed examples for some, where national programmes are advanced. As pointed out at the start of this report, once more is known about siting possibilities, the NDA will need to focus in on a subset of more appropriate Concepts and develop one or more for site-specific conditions, possibly in collaboration with local communities. Both the interim and final Concepts will be developments of the basic ideas presented here and may differ considerably in detail as they are progressively optimised to suit programme requirements (waste inventory, acceptable spend profile, community requests etc.) as well as site conditions. Design changes will occur through the site investigation stage of a programme and as underground investigation proceeds. The design of seals and closure arrangements will likely be modified periodically right up to final decommissioning of a repository.

Some design Concept topics are already readily identifiable as issues for stakeholder focus/discussions. These include all matters to do with the design and location of surface facilities, the manner in which construction and operation are carried out, the type of workforce required at different stages, the way in which operational monitoring will be performed and (especially for Concepts with long open periods) the way in which inspections are carried out and decisions taken to close the repository.

Table 8.1: Important aspects of each of the Concepts that will need to be taken into account in considering the appropriateness of siting in the five Geological Environments. Where a combination is unlikely to be appropriate, the box is coloured grey. *(Note that this table is designed to print onto A3.)*

Concept		Important aspects of concepts for siting in the different geological environments				
		Geological Environment				
		G1	G2	G3	G4	G5
		Stronger rocks with very low flow, of likely saline waters	Stronger rocks with higher water flow, probably relatively fresh water	Weaker rocks with no effective flow and relatively saline water in pores	Weaker rocks with very low water flow and relatively saline waters in pores	Evaporite formations; plastic, with no water flow and little accessible water (brine) content
1	In-tunnel (vertical borehole) with long-lived or short-lived canister	The long containment times provided by the engineered barrier, with the use of Cu canisters, allows significant decay of radionuclides and reduces the IRF in spent fuel. This reduces the emphasis on the host rock and geosphere transport properties, which are difficult to ascertain to a high degree of certainty. The concept is flexible with respect to disposal of both spent fuel and HLW. The concept is very well developed for implementation in fractured crystalline rocks and has a substantial knowledge base established over 35 years of focussed research, development and demonstration (RD&D). The concept results in a large repository footprint (unless 2 or more repository levels are used), which has implications for the extent of the host rock. The acceptable conditions for a disposal borehole (e.g. fracturing, inflow rate) are critical for long-term safety performance but are difficult to determine since over-conservatism will increase costs and may reduce the feasibility of the site (too many unusable boreholes). The handling of highly compacted, pre-formed bentonite buffer is difficult in humid conditions underground.	The long containment times provided by the engineered barrier, with the use of Cu canisters, allows significant decay of radionuclides and reduces the IRF in spent fuel. This reduces the emphasis on the host rock and geosphere transport properties, which are difficult to ascertain to a high degree of certainty. The concept is flexible with respect to disposal of both spent fuel and HLW. The concept is well developed for implementation in fractured crystalline rocks and has a substantial knowledge base built up over 35 years of focussed RD&D. In host rocks with significant water flow in fractures the behaviour of bentonite requires special attention in both emplacement and long-term performance (erosion). The concept results in a large repository footprint (unless 2 or more repository levels are used), which has implications for the extent of the host rock. The acceptable conditions for a borehole are critical for long-term safety performance but are difficult to determine since over-conservatism will increase costs and may reduce the feasibility of the site (too many unusable boreholes).	With excellent host rock properties, less is required from the EBS performance for long-term safety and the short containment period of the steel canister is acceptable as the host rock will attenuate radionuclide releases. The concept is flexible with respect to disposal of both spent fuel and HLW, although greater spacing of spent fuel may be required to ensure temperature limits are not exceeded for bentonite or host rock. The concept could be used to take advantage of relatively thin but laterally extensive sedimentary formations. The stability of the disposal boreholes is a particular issue in weaker rocks and a liner may be required to support the openings.	With good host rock properties, less is required from the EBS performance for long-term safety and the short containment period of the steel canister may be acceptable if the host rock can be relied upon to attenuate radionuclide releases. The concept is flexible with respect to disposal of both spent fuel and HLW, although greater spacing of spent fuel may be required to ensure temperature limits are not exceeded for bentonite or host rock. The concept could be used to take advantage of relatively thin but laterally extensive sedimentary formations. The stability of the disposal boreholes is a particular issue in weaker rocks and a liner may be required to support the openings.	With the excellent host rock isolation properties, the steel canister will probably provide a long containment period due to the near absence of water in the host rock. The concept is flexible with respect to disposal of both spent fuel and HLW.
2	In-tunnel (horizontal borehole) with long-lived or short-lived canister	The concept is flexible in principle with respect to disposal of both HLW and SF. The concept is not well developed for crystalline host rocks, despite its relatively long history, with demonstration testing particularly lacking. However, much of the extensive knowledge base of the KBS-3 concept would be relevant. For fractured rocks, the acceptable conditions in the boreholes (e.g. inflow rate, fracture size and density) will be important for long-term safety performance and will require particular attention during site characterisation. The emplacement of buffer in small diameter, horizontal disposal holes is not demonstrated but a high density buffer is probably a key component of the EBS.	The concept is flexible in principle with respect to disposal of both HLW and SF. The concept is not well developed for crystalline host rocks, despite its relatively long history, with demonstration testing particularly lacking. However, much of the extensive knowledge base of the KBS-3 concept would be relevant. For fractured rocks, the acceptable conditions in the boreholes (e.g. inflow rate, fracture size and density) will be important for long-term safety performance and will require particular attention during site characterisation. The emplacement of buffer in small diameter, horizontal disposal holes is not demonstrated but a high density buffer is probably a key component of the EBS.	In clay rocks, which provide a good natural barrier, and without the use of backfill, the concept is relatively simple, practical and efficient. The concept may offer advantages over axial tunnel emplacement concepts and also vertical emplacement options if retrieval is required. The concept is flexible in principle with respect to disposal of both HLW and spent fuel, although the heat output of spent fuel may need less dense waste emplacement. The concept is not well developed, despite its relatively long history, with demonstration testing particularly lacking.	In clay rocks, which provide a good natural barrier, and without the use of backfill, the concept is relatively simple, practical and efficient. The concept may offer advantages over axial tunnel emplacement concepts and also vertical emplacement options if retrieval is required. The concept is flexible in principle with respect to disposal of both HLW and spent fuel, although the heat output of spent fuel may need less dense waste emplacement. The concept is not well developed, despite its relatively long history, with demonstration testing particularly lacking.	In evaporites, which provide a good natural barrier, and without the use of backfill, the concept is relatively simple, practical and efficient. The concept is flexible with respect to disposal of both HLW and SF. The concept is not well developed, with demonstration testing particularly lacking, but the knowledge base from other concepts in evaporites will be relevant to a great extent.
3	In-tunnel (axial) with short-lived canister and buffer	The concept is well developed and has a substantial knowledge base from 30 years of focused RD&D. The concept is flexible with respect to disposal of both spent fuel and HLW; The potential for a thick (>1m) bentonite buffer reduces the vulnerability to bentonite erosion compared to thin (0.3m) buffer concepts. The short containment period provided by the steel canister places emphasis on performance of the geosphere, especially for spent fuel and the IRF, as the natural barrier must be relied upon to attenuate the radionuclide releases. Acceptance criteria for a disposal position (e.g. fracturing, inflow rate) are likely to be important for long-term safety performance and will require particular attention during the site characterisation programme. The emplacement of the compacted bentonite buffer to the density required is difficult in a humid underground environment.	The concept is well developed and has a substantial knowledge base from 30 years of focused RD&D. The concept is flexible with respect to disposal of both spent fuel and HLW. The potential for a thick (>1m) bentonite buffer reduces the vulnerability to bentonite erosion compared to thin (0.3m) buffer concepts. Acceptance criteria for a disposal position (e.g. fracturing, inflow rate) are likely to be important for long-term safety performance and will require particular attention during the site characterisation programme. The short containment period provided by the steel canister places emphasis on performance of the geosphere, especially for spent fuel and the IRF, as the natural barrier must be relied upon to attenuate the radionuclide releases. The emplacement of the compacted bentonite buffer to the density required is difficult in a humid underground environment.	The concept causes minimum disturbance to the host rock in the disposal panels due to the excavation of only relatively small (2 - 3m) disposal tunnels - this could be advantageous in thin host rock formations. The concept is well developed and has a substantial knowledge base. The short containment period provided by the steel canister is not a problem as the good host rock can be relied upon to attenuate the radionuclide releases. The concept is flexible with respect to disposal of both spent fuel and HLW. In tight clay rocks, gas generation from the steel canister corrosion may cause uncertainties that need to be addressed in the safety assessment.	The concept causes minimum disturbance to the host rock in the disposal panels due to the excavation of only relatively small (2 - 3m) disposal tunnels - this could be advantageous in thin host rock formations. The concept is well developed and has a substantial knowledge base. The short containment period provided by the steel canister is not a problem as the good host rock can be relied upon to attenuate the radionuclide releases. The concept is flexible with respect to disposal of both spent fuel and HLW. In tight clay rocks, gas generation from the steel canister corrosion may cause uncertainties that need to be addressed in the safety assessment.	The concept is well developed for an evaporite host rock. The containment period provided by the steel canister is likely to be very long due to the near absence of water in the host rock. The concept is flexible with respect to disposal of both spent fuel and HLW. The use of salt as the buffer material results in a cost-effective alternative to bentonite for this environment. Development work has focussed on use in dome salts (halite) and the applicability to bedded evaporites in the UK would need to be established
4	In-tunnel (axial) with long-lived canister and buffer	The long containment times provided by the Cu canisters, allows significant decay of radionuclides, especially important for the spent fuel IRF, reducing the emphasis on the host rock and geosphere transport properties. The concept is flexible with respect to disposal of both spent fuel and HLW. The concept results in a small excavated volume per waste package which can mean a moderately small repository footprint. The concept is not well developed, although the large overlap with Concept 3, and the copper canister of Concept 1, means that the substantial knowledge base developed for these concepts is largely relevant. The emplacement of compacted bentonite buffer to the density specifications required is difficult in a humid underground environment. Acceptable conditions for a disposal position (e.g. fracturing, inflow rate) are likely to be important for long-term safety performance and will require particular attention during the site characterisation programme.	The long containment times provided by the Cu canisters, allows significant decay of radionuclides, especially important for the spent fuel IRF, reducing the emphasis on the host rock and geosphere transport properties. The concept is flexible with respect to disposal of both spent fuel and HLW. The concept results in a small excavated volume per waste package which can mean a moderately small repository footprint. The concept is not well developed, although the large overlap with Concept 3, and the copper canister of Concept 1, means that the substantial knowledge base developed for these concepts is largely relevant. The emplacement of compacted bentonite buffer to the density specifications required is difficult in a humid underground environment. Acceptable conditions for a disposal position (e.g. fracturing, inflow rate) are likely to be important for long-term safety performance and will require particular attention during the site characterisation programme.	In geological environments with such strong natural containment properties (no flow, diffusion only) a long-lived container provides no additional advantage over a shorter-lived container of Concept 3. In addition, some clay-rich host rocks in this group may contain significant amounts of pyrite, which would be unfavourable for copper containers.	The long containment times provided by the Cu canisters, allows significant decay of radionuclides, especially important for the spent fuel IRF, reducing the emphasis on the host rock and geosphere transport properties. The concept results in a small excavated volume per waste package which can mean a moderately small repository footprint. The concept is flexible with respect to disposal of both spent fuel and HLW, although thermal issues with young SF, especially, will need to be taken into account. The implications of using a tunnel liner in weaker rock have to be evaluated for both the bentonite and the host rock. The emplacement of compacted bentonite buffer to the density specifications required is difficult in a humid or wet underground environment. The concept is not well developed, although the large overlap with Concept 3, and the copper canister of Concept 1, means that the substantial knowledge base developed for these concepts could be relevant.	In salt formations, with no flow and strong natural containment properties a long-lived container provides no additional advantage over a shorter-lived container of Concept 3.
5	In-tunnel (axial) with supercontainer (small annulus)	The concept is relatively well studied and developed for implementation in crystalline rocks, including demonstration of the emplacement technology. The concept can result in a small excavated volume per waste package, and a proportionately small repository. The concept is flexible with respect to disposal of both spent fuel and HLW. Acceptance criteria for a disposal position (particularly water inflow rate) are critical for avoidance of bentonite erosion from the supercontainer and the immediate annulus. This issue and will require particular attention during the site characterisation programme. Uncertainty about the long-term effect of interaction between bentonite and the corrosion products of the handling shell. The concept requires smooth, straight tunnels for emplacement: variations in rock	The concept is relatively well studied and developed for implementation in crystalline rocks, including demonstration of the emplacement technology. The concept can result in a small excavated volume per waste package, and a proportionately small repository. The concept is flexible with respect to disposal of both spent fuel and HLW. Acceptance criteria for a disposal position (particularly water inflow rate) are critical for avoidance of bentonite erosion from the supercontainer and the immediate annulus. This issue will require and will require particular attention during the site characterisation programme. Uncertainty about the long-term effect of interaction between bentonite and the corrosion products of the handling shell. The concept requires smooth, straight tunnels for emplacement: variations in rock	The excellent properties of the host rock would make many aspects of this concept redundant, especially the use of supercontainer and distance blocks, which were developed for an environment with significant groundwater movement. The concept can result in a small excavated volume per waste package, and a proportionately small repository. The concept is flexible with respect to disposal of both spent fuel and HLW (although thermal load could be an issue requiring greater spacing of the SF). The concept has not been considered for implementation in sedimentary rocks. The concept requires smooth, straight, clean tunnels for emplacement, rock friability could require special attention, especially for the water cushion;	The good properties of the host rock would make many aspects of this concept redundant, especially the use of supercontainer and distance blocks, which were developed for an environment with significant groundwater movement. The concept can result in a small excavated volume per waste package, and a proportionately small repository. The concept is flexible with respect to disposal of both spent fuel and HLW (although thermal load could be an issue requiring greater spacing of the SF). The concept has not been considered for implementation in sedimentary rock. The concept requires smooth, straight, clean tunnels for emplacement, rock friability could require special attention, especially for the water cushion;	The excellent isolation capability of the host formation means that use of a long-lived canister and the supercontainer with bentonite has no long-term safety advantage and several disadvantages (e.g. operational complexity, cost) compared to e.g., simple steel canisters backfilled with crushed salt.

Concept		Important aspects of concepts for siting in the different geological environments				
		Geological Environment				
		G1	G2	G3	G4	G5
		Stronger rocks with very low flow, of likely saline waters	Stronger rocks with higher water flow, probably relatively fresh water	Weaker rocks with no effective flow and relatively saline water in pores	Weaker rocks with very low water flow and relatively saline waters in pores	Evaporite formations; plastic, with no water flow and little accessible water (brine) content
		hardness e.g. igneous banding, could require tunnel smoothing. Reversal of the emplacement could be awkward once bentonite starts to intrude beneath the supercontainer.	hardness e.g. igneous banding, could require tunnel smoothing. Reversal of the emplacement could be awkward once bentonite starts to intrude beneath the supercontainer.			
6	In-tunnel (axial) with supercontainer (concrete buffer)	The long-term performance of the cement-based buffer material in as a transport/diffusion barrier is uncertain, especially in an environment where cracking could occur due to rock stresses. Use of a cement-based buffer (and other large cement or concrete masses) is also most appropriate for host rocks where the interaction between the highly alkaline pore fluids from the cement and the surrounding rock will be limited to the vicinity of the near field and not significantly affect the geosphere. These issues suggest that the concept will not be appropriate for deployment in fractured host rocks.	The long-term performance of the cement-based buffer material in as a transport/diffusion barrier is uncertain, especially in an environment where cracking could occur due to rock stresses. Use of a cement-based buffer (and other large cement or concrete masses) is also most appropriate for host rocks where the interaction between the highly alkaline pore fluids from the cement and the surrounding rock will be limited to the vicinity of the near field and not significantly affect the geosphere. These issues suggest that the concept will not be appropriate for deployment in fractured host rocks.	The use of the supercontainer increases safety during the emplacement operations by making the procedures simpler and more robust (e.g. fewer components to emplace) and also by increasing the self-shielding of the waste package compared to the earlier SAFIR 2 concept. The concept can result in a small excavated volume per waste package, and a proportionately small repository. The concept is flexible with respect to disposal of both spent fuel and HLW. The concept is relatively undeveloped although it builds to a large extent on the substantial knowledge base developed for the SAFIR 2 concept and investigations in the Boom clay. The large, heavy supercontainers place additional demands on the transport and handling systems, as well as on access tunnel dimensions, compared to the smaller individual HLW canisters.	The use of the supercontainer increases safety during the emplacement operations by making the procedures simpler and more robust (e.g. fewer components to emplace) and also by increasing the self-shielding of the waste package compared to the earlier SAFIR 2 concept. The concept can result in a small excavated volume per waste package, and a proportionately small repository,. The concept is flexible with respect to disposal of both spent fuel and HLW. The concept is relatively undeveloped although it builds to a large extent on the substantial knowledge base developed for the SAFIR 2 concept and investigations in the Boom clay. The large, heavy supercontainers place additional demands on the transport and handling systems, as well as on access tunnel dimensions, compared to the smaller individual HLW canisters.	The excellent isolation capability of the host formation means that use of a supercontainer with the concrete buffer has no long-term safety advantage and several disadvantages (e.g. operational complexity, cost) compared to, e.g., simple steel canisters backfilled with crushed salt.
7	In-tunnel (axial) with supercontainer (large annulus)	The use of the supercontainer provides a method of simple, relatively quick waste emplacement compared to in situ buffer emplacement around waste packages and may be particularly advantageous in a humid underground environment;. Contained within the handling shell, the density of the bentonite could be greater than normally considered (e.g. >2.0 Mgm^{-3}) to ensure optimal conditions after breaching of the supercontainer. The concept can result in a small excavated volume per waste package, and a proportionately small repository. The concept is only at the desk study stage. Although the concept is nominally similar to Concept 5, the presence of the backfill introduces an additional component for which the requirements and properties are currently undefined.	The use of the totally sealed supercontainer means that concept is appropriate for implementation in wet, fractured rock and minimises bentonite handling issues. Contained within the handling shell, the density of the bentonite could be greater than normally considered (e.g. > 2.0 Mgm-3) to ensure optimal conditions after breaching of the supercontainer. The concept can result in a small excavated volume per waste package, and a proportionately small repository. The concept is only at the desk study stage. Although the concept is nominally similar to Concept 5, the presence of the backfill introduces an additional component for which the requirements and properties are currently undefined. Uncertainty about the long-term effect of interaction between bentonite and the corrosion products of the handling shell must be investigated since it affects a key safety barrier.	The supercontainer provides a simple, relatively speedy method for emplacing waste. Several options are available for the backfill material since a high performing transport barrier is provided by the geosphere in this environment. The use of the backfill that can act as a chemical buffer region between the supercontainer and the liner means that the concept is appropriate for implementation in weaker rocks that require support. The concept can result in a small excavated volume per waste package, and a proportionately small repository. The concept is only at the desk study stage. Although the concept is nominally similar to Concept 5, the presence of the backfill introduces an additional component for which the requirements and properties are currently undefined.	The supercontainer provides a simple, relatively speedy method for emplacing waste. Several options may be available for the backfill material if a high performing transport barrier is provided by the geosphere in this environment. The use of the backfill that can act as a chemical buffer region between the supercontainer and the liner means that the concept is appropriate for implementation in weaker rocks that require support. The concept can result in a small excavated volume per waste package, and a proportionately small repository. The concept is only at the desk study stage. Although the concept is nominally similar to Concept 5, the presence of the backfill introduces an additional component for which the requirements and properties are currently undefined.	The excellent isolation capability of the host formation means that use of a supercontainer with the bentonite buffer has no long-term safety advantage and several disadvantages (e.g. operational complexity, cost) compared to, e.g., simple steel canisters backfilled with crushed salt.
8	Caverns with steel MPC (bentonite backfill)	The concept can result in a very small repository footprint especially in hard rocks. The concept is flexible with respect to disposal of both spent fuel and HLW. The operation of the repository could be optimised allowing earlier closure of caverns with old HLW or mixing of old and young wastes to spread the heat load more evenly for eventual simultaneous closure of all caverns. The concept allows straightforward retrieval of waste during the open period, as well as inspectability. The implications of large amounts of concrete in the near field and host rock create uncertainty for the safety case. The concept is vulnerable to incomplete closure or loss of institutional control during the long open period, and is not flexible with respect to early closure. The concept is at an early stage of development and the subject of only desk studies to date, although much of the technology already exists (e.g. transport casks, surface interim stores), significant development of the long-term safety case is required.	The concept can result in a very small repository footprint especially in hard rocks;. The concept is flexible with respect to disposal of both spent fuel and HLW. The operation of the repository could be optimised allowing earlier closure of caverns with old HLW or mixing of old and young wastes to spread the heat load more evenly for eventual simultaneous closure of all caverns. The concept allows straightforward retrieval of waste during the open period, as well as inspectability. The effect of large amounts of concrete on the near field and geosphere creates great uncertainty for the safety case. The concept is vulnerable to incomplete closure or loss of institutional control during the long open period, and is not flexible with respect to early closure. The concept is at an early stage of development and the subject of only desk studies to date, although much of the technology already exists (e.g. transport casks, surface interim stores), significant development of the long-term safety case is required.	The concept allows straightforward retrieval of waste during the open period, as well as inspectability. The concept is flexible with respect to disposal of both spent fuel and HLW. In weaker rocks, the limitations on excavation of openings may require more, smaller caverns than in stronger rocks, which could make the concept inefficient in terms of excavation and rock support requirements as well as operational safety requirements and ventilation/drainage infrastructure for the open period. The concept is vulnerable to incomplete closure or loss of institutional control during the long open period. The concept is not flexible with respect to early closure if this is before the required minimum storage period. The concept is at an early stage of development and the subject of only desk studies to date.	The concept allows straightforward retrieval of waste during the open period, as well as inspectability. The concept is flexible with respect to disposal of both spent fuel and HLW. In weaker rocks, the limitations on excavation of openings may require more, smaller caverns than in stronger rocks, which could make the concept inefficient in terms of excavation and rock support requirements as well as operational safety requirements and ventilation/drainage infrastructure for the open period. The concept is vulnerable to incomplete closure or loss of institutional control during the long open period. The concept is not flexible with respect to early closure if this is before the required minimum storage period. The concept is at an early stage of development and the subject of only desk studies to date.	The concept can result in a very small repository footprint. The concept is flexible with respect to disposal of both spent fuel and HLW. In an evaporite host formation, the concept may be more flexible with respect to early closure, with a crushed salt backfill, than in other rocks. The concept allows straightforward retrieval of waste during the open period, as well as inspectability. The concept is vulnerable to incomplete closure or loss of institutional control during the long open period. The concept is at an early stage of development and the subject of only desk studies to date, although much of the technology already exists (e.g. transport casks, surface interim stores), further development of the long-term safety case is required.
9	Caverns with steel MPC or concrete/ DUCRETE CDC (cement backfill)	The concept can result in a very small repository footprint especially in hard rocks. The concept is flexible with respect to disposal of both spent fuel and HLW. The operation of the repository could be optimised allowing earlier closure of caverns with old HLW or mixing of old and young wastes to spread the heat load more evenly for eventual simultaneous closure of all caverns. The concept allows straightforward retrieval of waste during the open period, as well as inspectability. The effects of large amounts of concrete on the near field and host rock create some uncertainty about the performance of the geosphere. The concept is vulnerable to incomplete closure or loss of institutional control during the long open period, and is not flexible with respect to early closure. The concept is at an early stage of development and the subject of only desk studies to date.	The concept can result in a very small repository footprint especially in hard rocks;. The concept is flexible with respect to disposal of both spent fuel and HLW. The operation of the repository could be optimised allowing earlier closure of caverns with old HLW or mixing of old and young wastes to spread the heat load more evenly for eventual simultaneous closure of all caverns. The concept allows straightforward retrieval of waste during the open period, as well as inspectability. The effect of large amounts of concrete on the near field and geosphere creates great uncertainty about the performance of the geosphere. The concept is vulnerable to incomplete closure or loss of institutional control during the long open period, and is not flexible with respect to early closure. The concept is at an early stage of development and the subject of only desk studies to date.	The concept allows straightforward retrieval of waste during the open period, as well as inspectability. The concept is flexible with respect to disposal of both spent fuel and HLW. In weaker rocks, the limitations on excavation of openings may require more, smaller caverns than in stronger rocks, which could make the concept inefficient in terms of excavation and rock support requirements as well as operational safety requirements and ventilation/drainage infrastructure for the open period. The concept is vulnerable to incomplete closure or loss of institutional control during the long open period. The concept is not flexible with respect to early closure if this is before the required minimum storage period. The concept is at an early stage of development and the subject of only desk studies to date.	The concept allows straightforward retrieval of waste during the open period, as well as inspectability. The concept is flexible with respect to disposal of both spent fuel and HLW. In weaker rocks, the limitations on excavation of openings may require more, smaller caverns than in stronger rocks, which could make the concept inefficient in terms of excavation and rock support requirements as well as operational safety requirements and ventilation/drainage infrastructure for the open period. The concept is vulnerable to incomplete closure or loss of institutional control during the long open period. The concept is not flexible with respect to early closure if this is before the required minimum storage period. The concept is at an early stage of development and the subject of only desk studies to date.	The concept can result in a very small repository footprint. The concept is flexible with respect to disposal of both spent fuel and HLW. In an evaporite host formation, the concept may be more flexible with respect to early closure, with a crushed salt backfill, than in other rocks. The concept allows straightforward retrieval of waste during the open period, as well as inspectability. The concept is vulnerable to incomplete closure or loss of institutional control during the long open period. The concept is at an early stage of development and the subject of only desk studies to date, although much of the technology already exists (e.g. transport casks, surface interim stores), much development of the long-term safety case is required.
10	Mined deep borehole matrix	The concept can result in a compact repository due to the vertical extent of the boreholes - longer boreholes will tend to result in a smaller footprint, which could be used to advantage in, for example, small but favourable host rock blocks. Although the safety concept is not yet developed, the construction techniques are well proven (in many rock types and environments) and cost effective. The concept is flexible with respect to disposal of both spent fuel and HLW. In fractured host rocks, making a safety case could be difficult unless the as-emplaced EBS can be shown to meet requirements: a pre-fabricated unit (small supercontainer) and possibly long-lived canisters are favoured in these environments.	The concept can result in a compact repository due to the vertical extent of the boreholes - longer boreholes will tend to result in a smaller footprint, which could be used to advantage in, for example, small but favourable host rock blocks. Although the safety concept is not yet developed, the construction techniques are well proven (in many rock types and environments) and cost effective. The concept is flexible with respect to disposal of both spent fuel and HLW. In fractured host rocks, making a safety case could be difficult unless the as-emplaced EBS can be shown to meet requirements: a pre-fabricated unit (small supercontainer) and possibly long-lived canisters are favoured in these environments.	In clay host rocks, there are probably more options for the EBS and a pre-fabricated unit (small supercontainer) may not be required as the host rock provides a good barrier to radionuclide transport. Although the safety concept is not yet developed, the construction techniques are well proven (in many rock types and environments) and cost effective. The concept is flexible with respect to disposal of both spent fuel and HLW. In weaker rocks, limitations on size of openings at depth may limit the practical depth for the lower cavern and thus borehole length, however, the concept could still result in a relatively compact repository. Disposal of young hot wastes, especially, could give rise to thermal issues since the disposal volume is compact in 3-D, limiting	In clay host rocks, there are probably more options for the EBS and a pre-fabricated unit (small supercontainer) may not be required if the host rock provides a good barrier to radionuclide transport. Although the safety concept is not yet developed, the construction techniques are well proven (in many rock types and environments) and cost effective. The concept is flexible with respect to disposal of both spent fuel and HLW. In weaker rocks, limitations on size of openings at depth may limit the lower cavern and thus borehole length, however, the concept could still result in a relatively compact repository. Disposal of young hot wastes, especially, could give rise to thermal issues since the disposal volume is compact in 3-D, limiting	The concept can result in a compact repository due to the vertical extent of the boreholes - longer boreholes will tend to result in a smaller footprint, which could be used to advantage in a small host formation. The excellent isolation provided by the host formation reduces the necessity for buffer around the waste packages although salt could be used as backfill. The construction techniques are well proven in salt and cost effective. The concept is flexible with respect to disposal of both spent fuel and HLW. Disposal of young, hot wastes, especially, could give rise to thermal issues since the disposal volume is compact in 3-D, limiting the area for transfer of heat to the geosphere.

Concept		Important aspects of concepts for siting in the different geological environments				
		Geological Environment				
		G1	G2	G3	G4	G5
		Stronger rocks with very low flow, of likely saline waters	Stronger rocks with higher water flow, probably relatively fresh water	Weaker rocks with no effective flow and relatively saline water in pores	Weaker rocks with very low water flow and relatively saline waters in pores	Evaporite formations; plastic, with no water flow and little accessible water (brine) content
		Detailed characterisation of the fractures within the boreholes is likely to be required, although in a largely stagnant groundwater regime the requirements may be less stringent and focus on potential rock movement. Disposal of young hot wastes, especially, could give rise to thermal convection; the implications have not yet been assessed.	Detailed characterisation of the fractures within the boreholes is likely to be required, to determine both rock mechanical (for avoidance of rock movements) and hydrogeological properties that are likely to determine the long-term safety performance of the concept. Disposal of young hot wastes, especially, could give rise to thermal convection; the implications have not yet been assessed.	the area for transfer of heat to the geosphere. The role and influence of thermal convection on the near field behaviour has not been assessed.	the area for transfer of heat to the geosphere. The role and influence of thermal convection on the near field behaviour has not been assessed.	
11	Hydraulic cage (around a cavern repository)	A hydraulic cage is not required in this environment.	A hydraulic cage around a compact repository concept in a fractured hot rock could make the difference between a marginal site being acceptable or rejected. A hydraulic cage around a cavern repository (Concept 8) could mitigate some of the consequences of maintaining drained, ventilated openings deep underground on the local hydrogeology by diverting groundwater away from the caverns. The theory is well established but large-scale, practical implementation that would function over the long timescales of interest is uncertain. The possibilities for repository concepts for which a hydraulic cage would be feasible and effective are limited; with the current knowledge base, probably only a cavern-type repository would fall into this category.	A hydraulic cage is not required in this environment.	A hydraulic cage around a compact repository concept in a fractured hot rock could make the difference between a marginal site being acceptable or rejected. A hydraulic cage around a cavern repository (Concept 8) could mitigate some of the consequences of maintaining drained, ventilated openings deep underground on the local hydrogeology by diverting groundwater away from the caverns. The theory is well established but large-scale, practical implementation that would function over the long timescales of interest is uncertain. The possibilities for repository concepts for which a hydraulic cage would be feasible and effective are limited; with the current knowledge base, probably only a cavern-type repository would fall into this category. For 15m-wide CARE-type caverns, the excavated opening would need to be around 20m. In weaker rocks such opening may not be feasible or the depth of deployment will be restricted.	A hydraulic cage is not required in this environment.
12	Deep boreholes	The concept can result in a small disposal area at depth but, perhaps more importantly, the surface area required for the excavation (and emplacement) operations may be very small. The concept provides extremely secure disposal of waste with effectively little chance of recovering waste without major technological investment. The concept is flexible with respect to implementation in a range of host rocks since the key issue is the hydrogeological environment at depth, in particular the lack of active groundwater movement, however, the properties of the rocks at depth must be capable of supporting the excavation of the borehole. There are uncertainties about the operational procedures for this concept as most evaluations have focused on the feasibility of borehole excavation and much less on the operational safety and practicality. The safety case relies on the isolation provided by the deep geosphere but no detailed safety assessment has yet confirmed that this is sufficient. The size of the waste package for practical implementation means that the concept could be inefficient for SF disposal.	Stronger rocks with locally significant fluid content (e.g. in major fracture or deformation zones) may be encountered at several kilometres depth, although conditions are considered likely to be essentially stagnant and the fluids are likely to be brines. Even relatively low flows of fluids in a connected fracture network (such as found nearer the surface) are not expected. This G2 environment is thus not expected to occur at depths of 3 to 5 km.	This concept is not suitable for weaker rock environments, which would not, in any case, be likely to occur at the disposal depths envisaged. It should be noted that weaker rocks may be traversed at shallow depth in many locations, before entering the stronger host formations and borehole design will need to account for this.	This concept is not suitable for weaker rock environments, which would not, in any case, be likely to occur at the disposal depths envisaged. It should be noted that weaker rocks may be traversed at shallow depth in many locations, before entering the stronger host formations and borehole design will need to account for this.	The concept can result in a small disposal area at depth but, perhaps more importantly, the surface area required for the excavation (and emplacement) operations may be very small. The concept provides extremely secure disposal of waste with effectively little chance of recovering waste without major technological investment. The safety case relies on the isolation provided by the deep geosphere. In the case of a vertically extensive salt diapir, this is well founded but could be more complicated in, for example, deep, bedded evaporite formations. There are uncertainties about the operational procedures for this concept as most evaluations have focused on the feasibility of borehole excavation and much less on the operational safety and practicality. The size of the waste package for practical implementation means that the concept could be inefficient for SF disposal.

9 Conclusions

Listed below are some key conclusions of this study:

1. A wide range of generic repository Concepts is available that can provide safe and secure geological disposal options to suit any appropriate UK geological environment. It is not necessary yet, nor appropriate, to select a preferred Concept. Indeed, it would be beneficial to maintain a flexible approach to design to allow optimisation of elements of several appropriate Concepts to actual site conditions.

2. Some of the Concepts are unsuitable for some geological environments. All of the geological environments could host more than one of the Concepts, which means there will always be a choice of how to implement disposal.

3. The Concept(s) that eventually form the focus for the NDA programme once potential sites emerge can be based upon those presented here. However, it is important to appreciate that the developed and optimised design that will finally be built may look considerably different in detail when adapted to site conditions and programme drivers.

4. The data provided here and the commentaries on the relevance and appropriateness of each Concept in different geological environments with respect to different evaluation factors can all be used as input to future decision-making in the early stages of siting and design work. Such exercises can be carried out by the NDA and/or by other stakeholders.

5. Several of the generic Concepts have mature and well-developed representatives in other national programmes around the world and the NDA would benefit from maintaining close contact with these programmes, especially concerning design optimisation studies.

6. Because the Concepts are at different levels of development, there are some important topics where more information on certain Concepts would be valuable to allow closer comparison. For example, there are no reasonably comprehensive, scoping, long-term safety evaluations for cavern Concepts or very deep boreholes, comparable with those for some of the ‘conventional’ Concepts.

7. Further work on packaging (overpack dimensions and content) of HLW and SF for different Concepts is warranted. The models already available and those used here have not been optimised to each or any Concept.

8. Particular attention should paid to development of supercontainer designs, which appear to offer several quality control advantages, although being potentially large items to handle underground.

9. There are limited options for managing HLW separately from SF and these are restricted to a few of the Concepts only. Nevertheless, there are potential

advantages in doing this (e.g. for older, cooler HLW) and the possible options are considered worth exploring in future work.

10. The Concepts offer variable capabilities with respect to inspectability, retrievability and safeguardability of the wastes. Views on how important these matters are will need to be taken into account and weighted in taking decisions on appropriate Concepts for a site.

11. Similarly, the Concepts have different non-nuclear environmental impacts. Although such impacts are considered to be very small and commensurate with many small-scale industrial activities, the repository is likely to be an operational presence in a community for many decades and the impacts need to be considered carefully by stakeholders in deciding how to optimise a Concept to a site.

12. Information on the costs of almost all the Concepts for geological disposal is patchy and can currently only be transferred with significant uncertainties. Even at a relatively simple level of evaluation there are notable differences in spend profiles between conventional repositories, cavern repositories and very deep boreholes. Further work in this area would be useful.

13. All of the Concepts (with the exception of the very deep borehole Concept) can readily be extended to include other long-lived radioactive wastes that either exist already or could arise in a future nuclear power programme.

14. There are benefits from considering the co-location of a HLW and SF repository with an ILW repository.

15. Some simple, generically important studies might be considered, where relatively small investments in further work would be valuable now, even before a future siting programme allows focussing on a group of Concepts. These include: optimising waste packaging (overpack) solutions for different Concepts (see 7 and 8 above); the performance implications of cement-based buffer options for older, well-cooled HLW (see 9 above); consideration of the minimum feasible open period of cavern repositories for the UK age-series of HLW and SF arisings; scoping long-term safety analyses of cavern and very deep borehole Concepts (see 6 above); comparative cost evaluations (see 12 above). Relatively straightforward studies would permit closer comparisons of Concepts from an equivalent level of knowledge.

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Appendix A National Example Data Sheets

In-tunnel (vertical borehole) with long- or short-lived canister	Concept 1

KBS-3V (SKB, Sweden)

1. Main Characteristics of the Concept

After 30-40 years storage at the interim storage facility, CLAB, the spent fuel (SF) will be encapsulated in long-lived copper canisters with a cast iron insert. The canisters will then be transported to a deep repository consisting of a system of horizontal tunnels at a depth of 400–700 metres in the bedrock. The tunnels will be approximately 250 metres long and spaced at a distance of 40 metres from each other. On the floor of the tunnels, vertical deposition holes will be spaced at intervals of about 6 metres, each approximately 8 metres deep. Each deposition hole, 1.75 m in diameter, will be levelled off with a cast low pH concrete base plate, about 5-10 cm thick, and a copper plate a few millimetres thick (SKB 2006a). The copper canisters will be deposited in the deposition holes and surrounded by a buffer of highly compressed bentonite. When the deposition is finished, the tunnels and shafts will be sealed by filling with a mixture of crushed rock and bentonite.

Origin:

SKB, the Swedish waste management organisation, has been conducting investigations of the Swedish bedrock and carrying-out technological development work since the mid-1970s (SKBF/KBS 1977, 1978, 1983a,b). When selecting the disposal route three basic principles were applied (SKBF/KBS 1983b, §1.2):

- A very high level of safety is required, in both the short and the long term.
- Burdens on future generations shall be avoided.
- It shall be possible to carry out the necessary measures with the highest possible degree of national independence (thus requiring implementation within Sweden).

Different conceptual methods for waste disposal were considered and ruled out for various reasons, for example, the concept is not a final solution (continued storage), the technology is not currently available in Sweden (transmutation and launching into space), or suitable areas in Sweden are unknown or not of sufficient extent (injection into aquifers or disposal under ice sheets). The most promising concept was that of deep geological disposal, possible in Sweden's stable crystalline bedrock (salt and clay strata, as well as sedimentary rocks, do not occur to a sufficient extent to justify further investigation) (SKBF/KBS 1978ab, 1983b).

In 1983 (SKB 2003a), a method for direct disposal (no reprocessing) in Swedish crystalline bedrock, incorporating an independent multi-barrier system, was recommended. Subsequently named the KBS-3 method and accepted by the Swedish Government in 1984, this is still the selected disposal concept, the design requiring waste canisters to be emplaced vertically (KBS-3V).

The deposition boreholes were developed in response to uncertainty about the extent and properties of the engineered disturbed zone (EDZ) around the deposition tunnel, essentially whether it could provide a high porosity and permeability zone in which water flux would be high, increasing diffusion across the buffer, and providing fast advective pathways to water-conducting fracture zones, thus essentially circumventing the geosphere barrier. The boreholes were intended to isolate each waste package and place them in less disturbed rock beyond the tunnel EDZ so that releases would be slowed by diffusion through the bentonite buffer before intersecting the tunnel EDZ.

***Maturity and current status*:**

This concept is very mature with over 30 years of concept-specific R&D and large-scale demonstration tests. This includes the long-term test of buffer material, the large-scale gas injection test, the temperature buffer test and the Prototype Repository Experiment, which are being conducted at SKB's Hard Rock Laboratory (HRL) in Äspö, and tests on bentonite swelling pressure, hydraulic conductivity and resaturation, which are being conducted on behalf of SKB at Clay Technology's laboratories in Lund (Hicks 2007).

SKB is currently conducting site investigations in two volunteer communities, Östhammar (Forsmark area) and Oskarshamn (Laxemar area). Investigations began in the spring of 2002 and a preliminary safety assessment was submitted to SKI, the Swedish Nuclear Power Inspectorate, in 2006. The results from the bedrock investigations in both locations were said to be promising but more data are needed to complete the picture. A final safety assessment with complete data from both sites will be submitted to the Swedish regulators in 2009.

Although KBS-3V is the selected reference concept, SKB continues to monitor and carry out research into other concepts. Horizontal canister emplacement (KBS-3H) has been judged to require less rock excavation, thus less backfill, and is therefore possibly environmentally and economically interesting. A new test commenced in 2004 at the Äspö HRL aimed at demonstrating and evaluating horizontal emplacement of copper canisters in the rock and will last until 2007. The results of this will be presented in SKB's RD&D-Programme 2007 (research, development and demonstration). SKB is planning to submit its permit application for a deep repository in 2009 and this will be based on vertical copper canisters (KBS-3V). A possible switch to horizontal canisters (KBS-3H) will be made after the application and can then be regarded as a further development of the basic method (SKB 2004, 2006a). The horizontal variant is also being studied as part of an ongoing joint research project between SKB and Posiva. A safety assessment for this variant at the Finnish site of Olkiluoto will be presented by Posiva in mid-2007 (SKB 2006a).

Wastes:

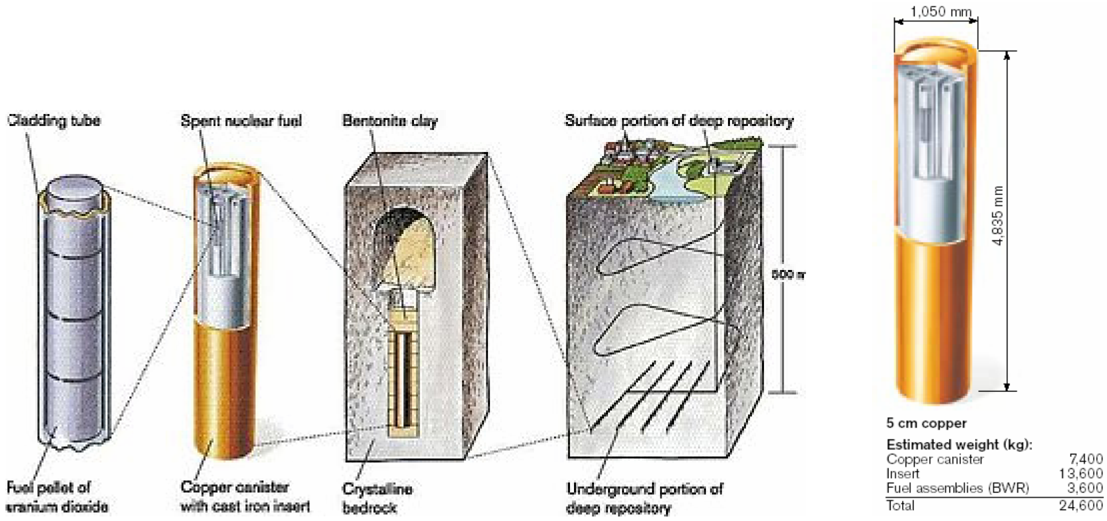
Spent nuclear fuel (SF) will be encapsulated in long-lived copper canisters. Around 9,000 tonnes of SF are forecast to arise from the Swedish nuclear power programme, corresponding to approximately 4,500 canisters. Allowing for uncertainties in the future nuclear power programme, the safety assessment SR-Can was based on a repository with 6,000 canisters, equivalent to approximately 12,000 tonnes (SKB 2006a).

Repository depth or host formation constraints:

The host formation is constrained to the Swedish stable Precambrian crystalline bedrock because salt and clay strata, as well as sedimentary rocks, do not occur to a sufficient extent (SKBF/KBS 1978ab, 1983b). The Swedish crystalline basement is characterised by the fact that it contains blocks of sound rock that are bounded by more or less pronounced fracture zones (SKBF/KBS 1983a).

The repository depth of approximately 500 m was chosen because the repository must be located deep enough so that it will not be affected in the long-term by events on the surface, such as glacial erosion, well drilling or underground construction, and for the hydraulic conductivity to be sufficiently low and chemical conditions favourable. However, the repository can not be so deep that high rock stresses jeopardise the stability of the bedrock or that the temperatures are too high. It was decided that a repository depth of 400-500 m was sufficient in good Swedish bedrock but that depths of up to 1000 m will not pose any major technical problems (SKBF/KBS 1983a). The actual repository depth will be determined in the light of site-specific conditions (SKBF/KBS 1983b).

Illustrations



KBS-3V multi-barrier concept. *(Images courtesy of SKB, Sweden.)*

2. Long-term Safety Concept

Multi-barrier concept:

The fundamental principle for KBS-3V is that the long-term safety of the repository shall not be dependent upon supervision and corrective measures after the repository has been sealed. To meet the demands on safety, the multi-barrier principle is applied, which means that the safety of the repository is not completely dependent on the functions of any one single barrier. The different barriers should complement each other via mechanisms that are as independent of each other as possible (SKBF/KBS 1983b).

In addition to the natural barrier provided by the host rock, the KBS-3V concept uses an engineered barrier system (EBS) consisting of a low solubility waste matrix (uranium dioxide with Zircaloy cladding for spent fuel), a waste package of long-lived copper canisters, a buffer of highly compacted bentonite clay, and backfill of a bentonite-crushed rock mixture.

***EBS design and materials**:*

Waste package: The waste package consists of a long-lived corrosion resistant canister. Copper is used to provide a thick corrosion resistant outer layer (50 mm thick) over a central insert of spheroidal graphite cast iron that provides the high mechanical strength necessary to withstand the rock overburden and the bentonite swelling pressure (SKBF/KBS 1983a, SKB 2006a). The copper canister, made of pure oxygen-free copper, has a length of approximately 4.8 m and a diameter of 1.05 m (SKB 2006a).
There are two versions of the canister insert, one for 12 boiling water reactor (BWR) assemblies and one for 4 pressurised water reactor (PWR) assemblies. Canisters, including the BWR and PWR assemblies, weigh 25 and 27 tonnes, respectively. The decay heat of SF disposed in one canister is limited to 1,700 W, to ensure the temperature requirements of the buffer are met (SKB 2006a).
SKB (2006a) has tested four possible fabrication methods for the copper tube: roll forming of copper plate to tube halves which are welded together, seamless tubes formed by extrusion, pierce and draw processing, and forging. All these methods produce a copper cylinder that must be machined internally and externally as well as on the end surfaces to get the desired dimensions. The current reference canister will be fabricated with a seamless tube. Lids and bottoms of copper are machined from hot forged blanks.

Welding of the lid and bottom of the copper canister is done by friction-stir welding (FSW) in the reference case, as this is the currently preferred alternative (SKB 2006a). Alternatively, electron-beam welding (EBW) could be used, but this option was not considered in the preliminary safety assessment SR-Can (SKB 2006a). Radiographic and ultrasonic techniques for non-destructive testing (NDT) of the canisters and welds are being developed and have been subject to an initial evaluation (SKB 2006a).

Buffer: The buffer consists of highly-compacted bentonite clay, which has a good bearing capacity (to hold the canister in position), good thermal conductivity and good long-term chemical stability. It has been shown that pure bentonite with a density of about $2x10^3$ kg m^{-3} has a hydraulic conductivity of 10^{-13} to 10^{-14} m s^{-1} and is thus less permeable to water than the surrounding crystalline rock (SKBF/KBS 1983a) (a typical range for granite is 10^{-7} to 10^{-9} m s^{-1} (Brassington 1988)). This means that the groundwater in the rock fractures does not flow through the filled deposition hole but around it and transport through the buffer takes places by diffusion.

The bentonite in the repository remains chemically stable for more than 1 million years if the temperature does not exceed approximately 100^{o}C, and the repository is therefore designed to keep the temperature in the bentonite below 80^{o}C (SKBF/KBS 1983a).

The bentonite buffer will be deposited as blocks below and above the canister and rings surrounding the canister, each approximately 500 mm high, 1,690 mm in diameter and 315 mm thick. One block will be placed below the canister, nine rings surround the canister and four blocks above the canister. The blocks placed immediately below and above the canister must be processed so as to fit the canister geometry properly. The annular gap between the canister side and the buffer is nominally 5 mm wide and 30 mm along the circumferential boundary between the buffer and the rock. The gaps will be left empty or filled with pellets, the latter option potentially limiting, but probably not eliminating, the effects of thermal spalling.

Although the specific type of bentonite has not been selected yet, SKB considered two different types of bentonite in SR-Can as example cases (SKB 2006a): natural Na-bentonite of Wyoming type (MX-80) and natural Ca-bentonite (Deponit Ca-N). The aim in the manufacture of bentonite blocks and rings and the subsequent deposition process is to achieve a specific final density in the water–saturated buffer of 1,950–2,050 kg m^3. The bulk density is dependent on the annular gaps between the canister and buffer and between buffer and rock, left in order to facilitate deposition (SKB 2006a).

Base plate: A cast concrete base plate in each deposition hole has been added to the repository design. The base plate acts as a stiff support and so the pile of bentonite blocks has a vertical centre line defined, such that the gap between the blocks and rock surface is even enough to allow the block lifting tools and other parts to pass freely (SKB 2006a).

The thickness of the cast base plate will be adapted to the roughness of the rock and will be about

5 cm at the thinnest part and 10 cm as a maximum. The base plate is to be cast of concrete with low pH cement, the recipe development of which is in progress. A copper plate, a few millimetres thick, will be placed on the concrete surface to protect the bentonite from being wetted by ground water penetrating the concrete plate. A peripheral gap is to be left between the concrete base plate and the rock wall where ground water can be collected and pumped up from the hole as long as the deposition tunnel is open (SKB 2006a).

Backfill: When SKB first proposed the KBS-3V concept, the intention was to use a bentonite-sand mixture for the backfill (SKBF/KBS 1983a). However, in the latest safety assessment, SR-Can, SKB considered two backfill materials (SKB 2006a):

- Pre-compacted blocks of a natural swelling clay (not necessarily a bentonite), such as Friedland clay. The whole tunnel would be filled with pre-compacted blocks and the gaps between the rock and the blocks filled with pellets of the same material.
- Pre-compacted blocks made of a mixture of bentonite of buffer quality and crushed rock with a weight ratio of 30/70. The gaps between the rock and the blocks would be filled with bentonite pellets and the maximum grain size for the ballast material (the crushed rock) is assumed to be 5 mm. The crushed rock from the excavation of the repository will be reused in the backfill. A clay fraction density of around

1,600 kg m^{-3}, when water saturated, is planned.

SKB (2006a) estimate that this would result in 70% to 86% of the tunnel cross-section being filled with blocks. It is assumed that 2% of the cross-section initially is void and the remaining volume is filled with pellets. This would result in a variation in average dry density for the tunnel cross-section of 1,700 kg m^{-3} to 1,850 kg m^{-3} for Friedland clay and 1,840 kg m^{-3} to 2,020 kg m^{-3} for the example 30:70 material.

***Safety functions of the barriers*:**

Waste: The first barrier is that of the SF itself. Although not designed with disposal in mind, uranium dioxide pellets, the form of the SF, have very low solubility in water and will be dissolved and dispersed at a very slow rate (SKBF/KBS 1983a).

Waste package: The long-lived copper canister provides containment of the SF for most of the period of interest. The copper shell acts as a corrosion barrier and the iron insert provides the necessary stability for the whole waste package when exposed to the different mechanical loads that it may encounter during the one million year time period of the safety assessment (SKB 2006b). A key implication of the use of long-lived containers is the effect of distributing eventual radionuclide releases in time and space as the containers fail over a very long period, perhaps 10^5 to 10^7 years. This is explicitly taken into account in safety assessments where the failure of only a small number of containers is assessed over the period of interest of about 10^6 years.

Buffer: The highly compacted bentonite clay buffer saturates and swells with groundwater, taking up to 100 years, and results in the saturated buffer containing approximately 20% water by weight. As the swelling is constrained within the borehole, a high swelling pressure, of the order of 10 MPa, is created that gives the bentonite a self-healing capacity and prevents water bearing passages from being created in the material (SKBF/KBS 1983a). During the period of containment, the bentonite buffer is to protect the canister against corrosion attack and minor rock movements:

- *Corrosion*: As the water in the buffer is virtually stagnant, corrosion products cannot travel through the buffer to the container, other than by diffusion. Transport to the canister surface is further delayed by the fact that the corrosive substances adhere to the surface of the clay mineral.
- *Rock shear*: The water-saturated clay has a plastic consistency, such that the bentonite can absorb decimetre-sized movements in the surrounding rock and protect the canister. If a crack should form in the bentonite due to such movements, it self-heals.

After canister failure, the buffer and intact parts of the canister will hinder water from entering the canister and retard any radionuclide transport, which will only take place by diffusion. Moreover, most radionuclides are further retarded by sorption.

Backfill: The backfill in the repository tunnels and shafts lends mechanical stability to the excavated spaces and restores the hydrological conditions in the area (SKBF/KBS 1983a).

Host rock: The purpose of the host rock, selected for its low flow rate, is to isolate the waste and to provide a stable chemical environment for the canister and the buffer. The host rock provides an environment where the function of the engineered barriers is preserved for very long periods of time. A strong retardation of most radioactive substances also takes place in the rock through chemical processes between the rock minerals and the radioactive substances, thus allowing further time for radioactive decay during transport through the rock (SKBF/KBS 1983a).

Safety functions of other components:

Each borehole is considered independent once filled but the overlying disposal tunnel backfill/seals must withstand the borehole buffer swelling pressure to prevent loss of density.

PA/SA studies:

Numerous including: KBS-3 (SKBF/SKB 1983a); SKB 91 (SKB 1992); SR-97 (SKB 1999);

SR-Can (SKB 2006a) – note only the main report in each assessment series is referenced.

Significant changes since first envisaged:

Between 1983 (SKBF/KBS 1983a) and 2006 (SKB 2006a) there have not really been any significant changes to the overall concept but slight changes have been made to:

- The spacing of tunnels and holes;
- The backfill has changed from a bentonite-sand mixture to bentonite and crushed rock;
- The copper canister thickness has been halved from 100 mm to 50 mm;
- Drainage is now included in the deposition holes during the emplacement period.

Detailed variants worth recording: *N/A*

3. Development and Operation

Requirements on site:

The final repository site will only be built where there is a sufficiently large rock formation with suitable geological, hydrological and geochemical properties (SKBF/KBS 1983a), such as low groundwater flow rate and the lack of any potentially desirable mineral deposits. For the two sites currently under investigation by SKB preliminary repository layouts, based on the site descriptions and 6,000 canisters, have been developed. At Forsmark, the reference layout is developed at the –400 m level whilst Laxemar is developed at –500 m. The Forsmark candidate area undergoing site investigation is approximately 6 km long and 2 km wide (SKB 2006a).

Demands on site characterisation procedure:

Criteria are being developed on which to accept or reject deposition holes. The three main areas are (SKB 2006a):

- Avoiding deposition holes intersecting with large fractures and avoiding fractures intersecting several deposition holes, without intersecting the tunnel.
- Avoiding high flow rates in fractures intersecting deposition holes (further work on fracture transmissivity needs to be carried out to determine a practically useful flow-related acceptance criterion).
- The possibility of spalling in the deposition holes during their excavation. Detached rock fragments can be removed and cavities can be filled with, for instance, pieces of bentonite or with bentonite pellets before or during installation of the bentonite buffer. For the few instances in which this would not be possible, the holes will be discarded for deposition. It is intended that further modelling of the extent of initial spalling will be carried out for the next safety assessment, SR-Site.

Excavation / construction processes:

How the repository excavation and emplacement proceeds is not specified in the latest phase of the repository layout and design work, but it is expected that this stage will last from several tens up to a hundred years, depending on the progress made and the final number of canisters to dispose of (SKB 2006a).

The final decision on the excavation technique for the deposition tunnels has not yet been made and two techniques are under consideration: drill and blast or mechanical excavation (tunnel boring machine, TBM). Only the drill and blast option was considered in the recent safety assessment SR-Can (SKB 2006a). The cross-section for a tunnel produced with the drill and blast method is a square with an arched roof, whereas the cross-section in a mechanically excavated tunnel is circular.

Implications for requirement/location for encapsulation facility:

SKB want to build the encapsulation plant adjacent to CLAB, the central interim storage facility for SF. Locating the encapsulation plant next to the storage facility offers the advantages of enabling the encapsulation plant to benefit from CLAB's experience of handling SF and enabling several of the existing process systems and plant parts in CLAB to be utilised by both facilities.

A permit to build application was submitted in 2006 under the Nuclear Activities Act and in 2008 an equivalent application under the Environmental Code will be made. It is intended that the encapsulation plant and the final repository for spent nuclear fuel will be put into operation in 2017.

The overall production requirements on the plant are (SKB 2007):

- One canister per day must be able to be sealed and inspected.
- The plant will be used for at least 60 years.
- All the types of fuel that are stored in CLAB must be able to be handled and encapsulated.

Operational / emplacement procedures:

The overall emplacement process will consist of SF canisters being moved in shielded transport casks and then transferred to a remote-controlled and radiation-shielded deposition machine. The borehole will first be lined with rings of bentonite and then the waste package will be lowered into the borehole. When all the holes in a deposition tunnel are full, the tunnel will be backfilled with a mixture of bentonite clay and crushed rock. The main access tunnel will be backfilled when all the canisters have been deposited (SKB 2007).

As buffer emplacement in a tunnel may take place several months after the drilling of the deposition holes, the holes are assumed fill with water. Thus, draining is the first step in the preparation of the holes. The bentonite must be protected from water or high humidity until the tunnel is backfilled, otherwise it may start swelling before the deposition of the canister and/or before the tunnel backfilling can apply its counterforce on the buffer. One method under consideration is to insert a drain tube in the deposition hole and to protect the whole buffer with a plastic bag that is kept sealed until the backfilling of the tunnel starts. The plastic bag and drain tube would be removed after use. In SR-Can it is assumed that the removal of these items will be successful in all cases, or that effective remedial action will be taken in the event of failure (SKB 2006a).

Rock supports, mainly rock bolts and reinforcement nets, will be left in the tunnels, as they are essential to workers' safety, whereas the other installations and structures, for example, roadbeds, will be removed before closure of the deposition tunnels. In addition, the tunnels will be cleaned with highly pressurised water (SKB 2006a).

The final handling procedures and the final design of the buffer filling vehicle and the deposition machine have not been decided.

Key aspects and components for QA focus:

Initial state aspects that SKB regard as critical to safety are (SKB 2006a):

- The residual power of the spent fuel in each canister, affecting the short-term thermal evolution of the repository and, in particular, the peak temperatures in the near-field.
- The copper canister tightness, particularly the quality of the sealing welds.
- The strength of the cast iron insert, affected by the quality of the casting process.
- The amount and composition of buffer dry mass emplaced in each deposition hole, affecting the final density of the buffer after water saturation.
- The amount and composition of backfill dry mass emplaced in each deposition tunnel, affecting the final density of the backfill after water saturation.

Of particular importance in the site selection is a low rate of groundwater flow in the near zone around the canisters (SKBF/KBS 1983b).

4. Programme Management

Key stages and time plan flexibility / main decision points:

The current timeline estimates that the investment phase (including construction) starts in 2008/9, operation should begin in 2015, and decommissioning/closure in 2054.

Retrieval options:

SKB plans to proceed in stages when the deep repository is built. Firstly, between 200 and 400 canisters (of a total of about 4,500) will be deposited in an initial phase. After the initial phase, an evaluation will be performed where, if the outcome is positive, the rest of the canisters will also be deposited. If the outcome is negative then the canisters may need to be extracted and retrieved – this would require a government permit.

The more time has passed since deposition, the more difficult it will be to remove the bentonite clay around the canisters. The most work and the highest costs will be required if the whole repository has been closed and sealed. Two experiments on canister retrieval are being conducted at the Äspö HRL (SKB 2007).

- Slurrying test – this involves slurrying the bentonite using a salt solution containing around four percent by weight calcium chloride. Full-scale field tests with partially provisional equipment were conducted in the autumn of 2002 and spring of 2003 in the Äspö HRL and showed that the method works. Slurrying is intended to be a continuous process and an important part of the tests being conducted is to determine how long it takes to slurry the roughly 22 tonnes of bentonite buffer in a deposition hole.
- Canister retrieval test - At Äspö HRL a canister with electric heaters has been lowered into a deposition hole lined with blocks and rings of bentonite clay. It is intended that the canister will remain there for between three and five years until the bentonite is saturated with water. When the bentonite has been saturated, the canister will be freed by dissolving the bentonite with a salt solution.

Pre-closure monitoring requirements:

No special requirements beyond expected site characterisation and monitoring activities.

Post-closure monitoring options:

None.

Workforce requirements: During the operational periods, the storage facility CLAB will require around 60 personnel, the encapsulation plant will require approximately 30, and the repository will require approximately 200 (SKB 2003b).

5. Environmental Impacts

Spoil volumes / storage:

Excavation of the waste disposal boreholes is likely to produce of the order 0.1 x 10^6 m^3 of spoil, assuming 6,000 canisters. There will be very significant additional spoil due to excavation of the disposal and access tunnels, ramp, shafts and underground infrastructure. Some of the spoil could be mixed with bentonite and used in the backfill.

Resources and availability:

Approximately 22 tonnes of bentonite per borehole would be required, giving a total of about 0.1 x 10^6 tonnes, assuming 6,000 canisters. Each waste canister requires 7.4 tonnes of copper and 13.6 tonnes of iron, thus using ~0.04 x 10^6 tonnes of copper and ~0.08 x 10^6 tonnes of iron in total. Significant additional bentonite would be required for backfilling and seals of the disposal and access tunnels.

Bentonite and copper would both need to be imported although it may be possible to reuse steel and iron from nuclear power plant decommissioning. These materials are available on the international markets, although this may change in the future. The price of copper is currently significant and may remain so in the future.

Transport of materials:

This depends on the amounts of materials and the site location, although SKB would be likely to transport waste and materials by road and/or boat.

Nature of surface facilities required:

These would be expected to be similar to any other mined facility.

Any special noise or visual issues:

These would be expected to be similar to any other mined facility.

6. Key Uncertainties and Outstanding R&D

Identified areas for further R&D include (SKB 2006a):

- The potential for reducing the calculated releases of Ra-226 if co-precipitation effects can be taken into account.
- With the current understanding of colloid release from the buffer severe, or total, losses of the buffer cannot be ruled out. An experimental test programme has been implemented and this may need to be extended. Further evaluations of the circumstances under which dilute glacial waters could reach repository depth are also required.
- The mass transfer resistance between the bentonite and the flowing water in the fractures in the rock is one of the key features of the KBS-3 concept. The modelling concept has been used in all safety assessments since KBS-1. It has, however, never been experimentally verified. An experimental programme to test the assumption will be undertaken.
- The conditions under which thermal spalling will occur, as well as the extent of the spalled zone. In particular SKB want to determine if counter pressures much smaller than the bentonite swelling pressure may be sufficient to suppress spalling. This could imply that filling the buffer-rock clearance with bentonite pellets at the time of deposition would be sufficient for mitigating the spalling.
- Simulations of the stress state at repository depth during a glacial cycle are needed. In particular, the site-specific prerequisites for glacio-isostatic faulting need to be evaluated.

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In-tunnel (borehole) – horizontal borehole	Concept 2

Callovo-Oxfordian Clay (Andra, France)

1. Main Characteristics of the Concept

HLW and SF are encased in unalloyed steel overpacks. Waste packages are emplaced in steel-lined horizontal or near-horizontal boreholes, drilled in the walls on both sides of the disposal tunnels. Three to 22 packages are emplaced in each disposal borehole, depending on the waste thermal output. The borehole forms a narrow annulus around the HLW whilst a wider borehole for SF enables emplacement of a bentonite buffer. The repository concept is designed for a clay host rock.

Origin:

The French Act of Parliament of 30 December 1991 set Andra the task of assessing the feasibility of deep geological disposal for high-level and long-lived intermediate-level radioactive waste (HLLL), based on a rationale of reversibility, notably through the construction of underground laboratories in clay and granite. The Act defined three areas of research aimed at finding a solution for managing radioactive waste over the very long term, complying with the two key principles of protecting nature, the environment and health, and considering future generations. These study areas were partitioning and transmutation, deep geological disposal, and waste conditioning and long-term near-surface storage (the French Atomic Energy Commission, the CEA, performs research into transmutation whilst Andra is responsible for geological disposal and long-term or temporary storage). The Act also required that, after a period not exceeding fifteen years, the Government authorities must submit a global assessment report on these research activities to Parliament, as well as a draft law (Andra 2005a). This was met with the publication of Dossier 2005.

The study of deep geological disposal aims to provide the necessary data for assessing the feasibility of such a repository, based on the multiple-barrier principle. In 1999, the French government approved the decision to create an underground research laboratory on a clay site at Bure (Meuse/Haute-Marne). It has not been possible to construct such a facility in a granite formation in France and so Andra carries out desk studies to asses the potential of French granite formations and follows research in the underground laboratories of Switzerland, Belgium and Sweden closely (Andra 2005a).

The disposal concept was developed by SCK.CEN (Belgium) and Andra (France) for use in clay formations for deposition holes which contain one to a small number of waste packages, i.e. holes up to a few tens of metres in length, because of rock mechanical considerations in weaker rocks that limit the borehole length unless a very substantial liner is used. Longer holes also mean small changes to borehole diameter are more likely, both from excavation and later deformation, which could disrupt emplacement operations. However, longer holes will be studied to enable later optimisation.

Andra prefers to use metal-lined deposition holes with no buffer material as this provides adequate containment whilst reducing hole size, use of concrete and the volume of clay disturbed by the excavation.

Maturity and current status:

Two major reports were issued by Andra in 2005. 'Dossier ARGILE 2005' discusses the current level of knowledge as regards the suitability of clay as a host medium, based on work carried out to date at Bure and in a number of other underground research laboratories, including Mol in Belgium (Boom Clay) and Mont Terri in Switzerland (Opalinus clay). 'Dossier GRANITE 2005' discusses the potential of granite, but it is based only on the existing knowledge of French granites, supplemented by experience of French involvement in underground research laboratories in Canada, Sweden and Switzerland (Grimsel).

In Dossier 2005 Andra states that on the basis of the preceding 10 years of research, the data acquired confirm that the Callovo-Oxfordian layer of the Meuse/Haute-Marne site has favourable properties for a HLLL repository, including a stable and homogeneous geological environment, low permeability, mechanical strength and characteristics compatible with reversibility requirements (Andra 2005a).

Andra has carried out in depth research of this geological disposal concept in a clay formation and regards this as their reference disposal concept. The underground research laboratory at Bure has already been fitted with close to 1,400 sensors and meters with a view to studying the feasibility of reversible radioactive waste disposal within a 130-m-thick clay formation (Andra 2007).

Wastes:

The Andra concept centres on co-disposal of B (long-lived ILW), C (vitrified HLW) and CU (MOX and UOX spent fuel) waste categories in the same facility, where different areas, or panels, of the repository are set aside for the different waste categories. There are eight B waste classifications and packaging variations, including conditioning in bitumen or concrete and emplacement in steel or concrete containers, but ILW does not form part of this study and so are not discussed further. The stainless steel packages of category C waste (vitrified HLW) are placed in unalloyed steel overpacks for disposal. There are seven different types of C waste package: C01, C02 and C03 correspond to different historic vitrification processes and C1, C2, C3, and C4 correspond to present and future vitrification. The spent fuel assemblies are placed in the cast iron inserts of unalloyed steel containers for disposal; there are four integrated UOX assemblies per CU1 package and one integrated MOX assembly in a CU2 package (Hicks & Baldwin, 2007). Each of the C and CU package types are placed in separate groups of disposal tunnels. Spent fuel is not currently considered a waste because it contains recoverable materials such as uranium and plutonium but its possible disposal is accounted for in the design studies in case such waste is no longer reprocessed in the future (Andra 2005a). Currently, all spent fuel is reprocessed at the COGEMA facility (recently renamed AREVA NC) at La Hague and the resulting HLW vitrified and stored prior to development of a deep repository.

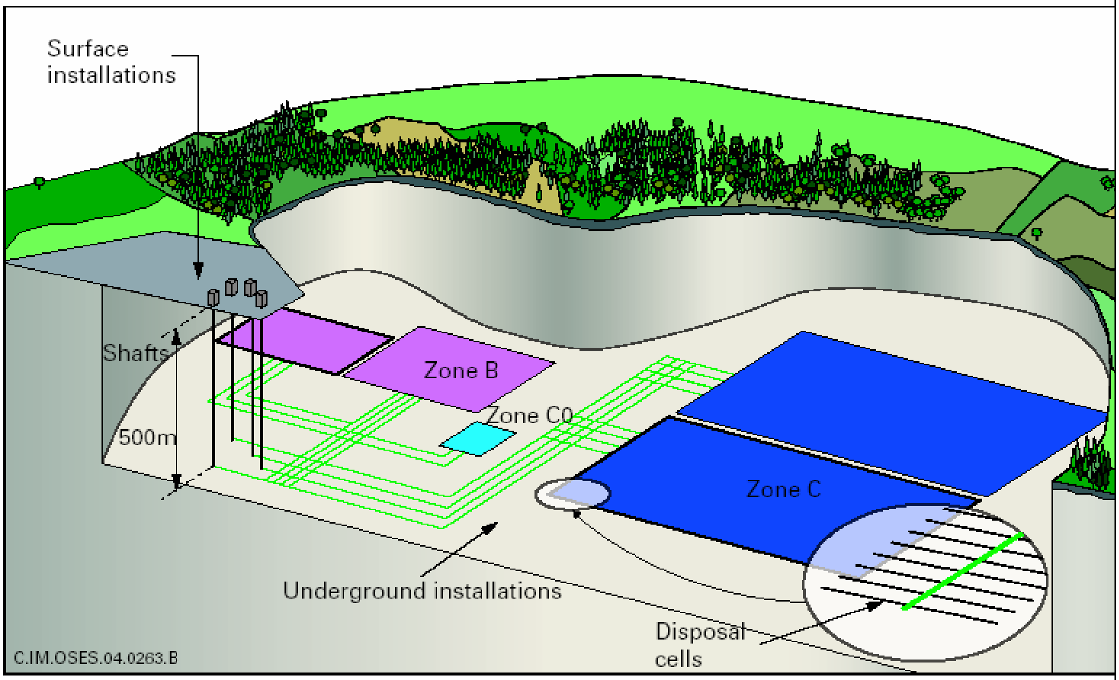
Dependent upon the reprocessing scenario assumed the volumes of waste range all the way from 6,330 m^3 HLW and no SF, if reprocessing is assumed to continue, to 2,550 m^3 HLW and 58,000 SF assemblies if reprocessing is stopped and SF is treated as a waste. This corresponds to 36,320 HLW containers for the first scenario and 14,680 HLW and 17,500 SF containers for the second (Andra, 2005b).

It is assumed that heat generating waste will be stored for roughly 60 to 70 years to allow for heat dissipation prior to emplacement in the geological repository, although this reduces to only 20 years for the older C0 waste (Londe 2007). This will help to limit thermal disturbance in the repository. However, this storage period has yet to be optimised (Andra 2005c).

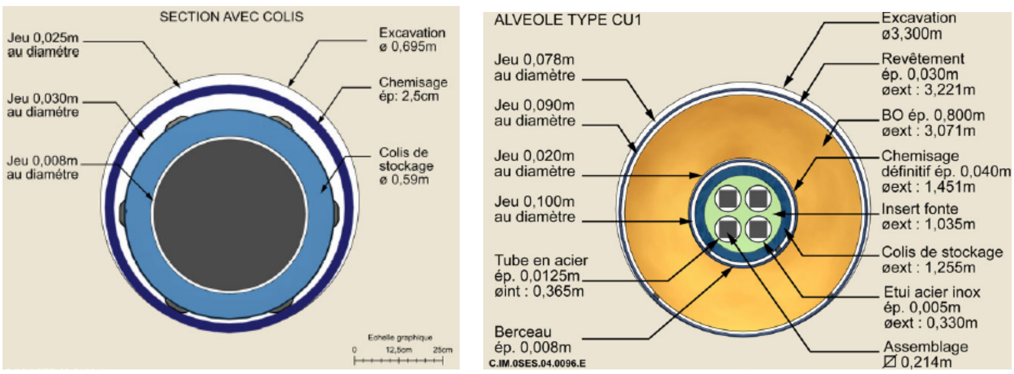
Repository depth or host formation constraints:

The stable Callovo-Oxfordian clay formation in the Meuse/Haute-Marne area of the Parisian Basin, at Bure, is being investigated as a potential repository host rock, at a depth of 490 m (Andra 2005a). The top of the Callovo-Oxfordian formation is about 400 m below the ground surface in the investigation area and the formation is at least 130 m thick. The Callovo-Oxfordian is overlain by the Oxfordian and underlain by the Dogger, which are both limestones that are over 100 m thick. The Callovo-Oxfordian is an indurated clay formation with low permeability in which radionuclides migrate slowly through diffusion only, a large number of elements are retained by the clay, it provides a stable chemical environment and offers a good mechanical resistance while remaining sufficiently deformable over the long term. Additionally, the high pore water salinity in the Callovo-Oxfordian indicates the absence of hydraulic exchanges with aquifers (Andra 2005a; Hicks & Baldwin 2007).

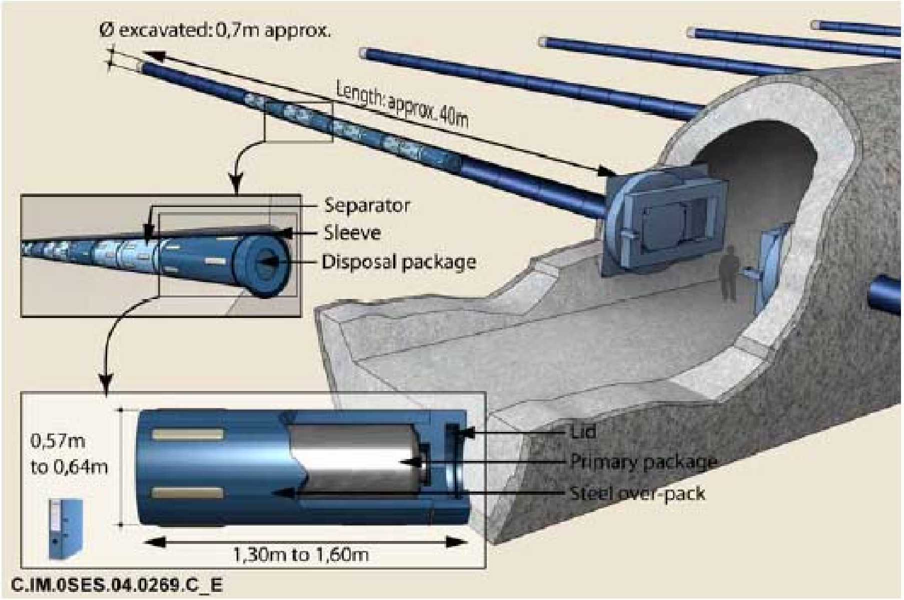
Illustrations



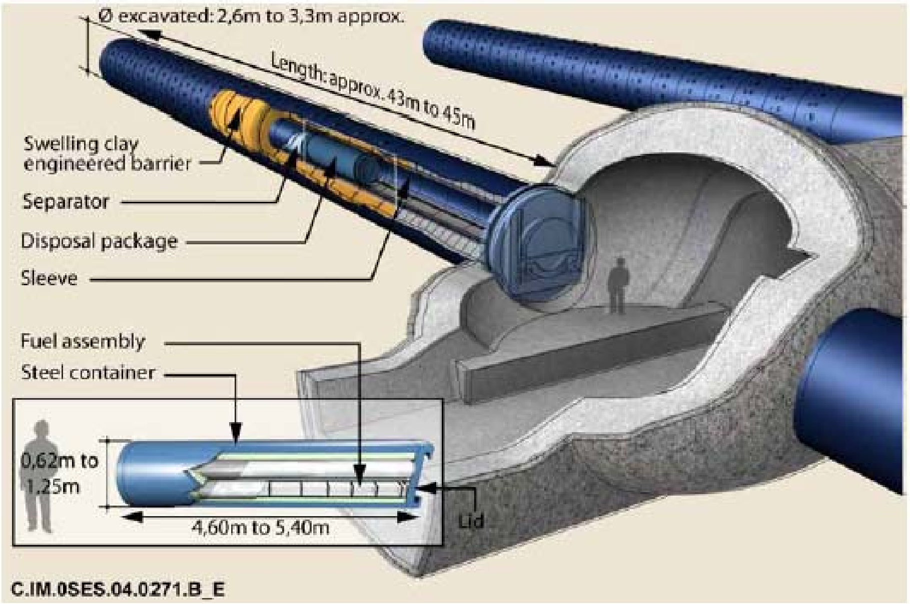
Basic diagram of a repository layout during operation. *(Images courtesy of Andra, France).*



The Andra disposal concept for C and CU wastes. *(Images courtesy of Andra, France).*



C (HLW) waste disposal tunnel. *(Images courtesy of Andra, France).*



Spent fuel disposal tunnel. *(Images courtesy of Andra, France).*

2. Long-term Safety Concept

Multi-barrier concept:

Andra defines three basic functions that the repository must fulfil (Andra 2005a):

- preventing water circulation, since water can degrade the waste packages and allow radionuclide transport,
- limiting the release of radioactive substances by the packages and immobilizing them in the repository as long as possible,
- delaying and reducing the migration of radioactive substances beyond the repository or geological layer.

The repository is located on a single level, in the middle of the geological layer and it is organised into distinct zones according to package type (B, C, CU), separated from one another and subdivided into modules. A tunnel liner is used to support the engineered structures for several centuries, and void spaces within the disposal tunnels are limited. Spacing between disposal tunnels and arrangement of the waste packages is employed to limit disturbance due to the heat output of the HLW and SF packages. The engineered structures are arranged in a dead-end fashion to limit water flow. Reversibility has been integrated into the repository design phase to privilege the use of durable materials, maintaining the technical possibility to retrieve the packages, and organising the repository operation or closure in various stages and in a modular manner.

EBS design and materials:

Overpack: Category C and CU wastes (vitrified HLW and SF) are both placed in unalloyed steel cylindrical overpacks for disposal. Unalloyed steel was chosen because this material has robust behaviour, its corrosion processes are well understood, its use is based on industrially proven technologies, and it has good welding properties and mechanical characteristics (Andra 2005d). The overpack is fitted with ceramic runners (pads), to ease emplacement, and an unalloyed steel lid welded to the casing by electron beam (Andra 2005d). The HLW packages are 1.3 to 1.6 m long, around 0.6 m in diameter, use 55 mm thick steel, weigh 1.7 to 2.0 tonnes, and each overpack will contain one such waste package (Andra 2005a,c).

There are two types of spent fuel overpacks. The first, a CU1 package managing 98% of the UOX fuel, contains four integrated UOX assemblies which are supported and spaced inside the overpacks with the use of a 40-45 mm thick cast iron insert. Such a package and its waste weigh approximately 43 tonnes, is 1.3 m in diameter, 5.4 m long and uses ~110 mm thick unalloyed steel (Andra 2005c). The second SF overpack, a CU2 package predominantly for MOX fuel, contains a single fuel assembly, weighs 8-10 tonnes and uses 120 mm thick unalloyed steel. The CU2 overpack does not make use of a cast iron insert as the mechanical strength of the package is provided by the casing, which is designed to be thicker (Andra 2005d).

Buffer: The HLW disposal boreholes will not use any buffer. However, between the perforated steel tunnel liner for SF (see below) and a second inner axial unalloyed steel lining, or sleeve, rings of bentonite will be emplaced in the SF disposal tunnels.

Tunnel liner: The disposal tunnels, also referred to as cells, will be lined with carbon steel 25 mm thick, of a similar grade to that used for the overpacks to avoid galvanic corrosion (Andra 2005d). This thickness was chosen such that 20 mm would withstand the isostatic load of 12 MPa with a safety margin of 5 mm to allow for corrosion (Andra 2005d). This steel liner will be perforated in the SF waste disposal tunnels in order to allow saturation with water.

Disposal tunnel: C waste packages (HLW) will be emplaced in an array of dead-end horizontal boreholes, either side of the access tunnels, with an excavated diameter of 0.7 m and are currently limited to 40 m in length, 30 m of which will be used for waste emplacement (Andra 2005c,d). The tunnels will be spaced 8.5-13.5 m apart and each will receive around 6 to 22 packages, dependent upon their thermal output (Andra 2005c,d). For SF each disposal tunnel will be approximately 45 m long and around 3.0 m in diameter, will be spaced on average 20 m apart and each will take 3 or 4 packages (Andra 2005a,c). The disposal tunnels are expected to remain mechanically stable for 200 to 300 years. They are laid out at right angles to the access tunnels and grouped into modules. When closed, each module (a region of the repository containing approximately 400 disposal tunnels) will be separated from the others by seals (Andra 2005d) to isolate it.

Disposal tunnel seals: Each disposal tunnel will be sealed with a steel plug ensuring radiological protection, a very low permeability bentonite (less than 10^{-11} m/s) and a retaining concrete plug (Andra 2005d).

Access tunnel: The access tunnels and shafts will be concrete lined. At closure they will be backfilled with excavated clay and sealed with a series of bentonite plugs and concrete supporting structures. The shafts will be filled with concrete at the base and sealed with 30 m of bentonite. The shafts will then be backfilled with excavated clay, with a 10-15 m bentonite insulating plug at each porous level (Andra 2005a).

Safety functions of the barriers:

Overpack: For HLW the steel overpack has been designed to prevent the inflow of water onto the waste during the thermal period, as this, in combination with high temperatures, will accelerate the dissolution of the glass matrix (Andra 2005a,c). The thickness has been designed to resist corrosion for the order of a few thousand years (Andra 2005a,c). For UOX and MOX spent fuel, a minimum leak-tight period of ten thousand years has been required (Andra 2005a,c). The cast iron insert ensures sub-criticality, improves the thermal transfer inside the package, provides the mechanical strength of the package in order to withstand external pressure and limits the residual voids in the packages (Andra 2005d).

Buffer: The aim of the SF bentonite buffer is to form, when saturated with water, a continuous, low-permeability medium around the packages that limits the transport of any dissolved radionuclides (Andra 2005c). The second inner axial steel liner will be emplaced to facilitate waste package emplacement and potential retrieval.

Liner: For HLW the liner supports the clay tunnel, enables packages to be slid into the disposal tunnel on their ceramic runners and facilitates retrieval, if necessary (Andra 2005c,d). For the SF, the external tunnel liner supports the clay tunnel and its perforated nature enables saturation of the bentonite buffer. The inner SF liner (sleeve) enables packages to be slid into the disposal tunnel on their ceramic runners and facilitates any retrieval.

Disposal tunnel: The disposal tunnels are spaced 10 m (HLW) and 20m (SF) apart to meet temperature limits (Andra 2005a).

Access tunnel: Backfilling the access tunnels limits deformations in the geological medium, offering mechanical support.

Host rock: The role of the host rock is to provide a barrier to radionuclide transport so that retardation and decay, or dispersion, of released radionuclides occurs during transport to the biosphere.

***Safety functions of other components*:**

Disposal & access tunnel seals: To prevent water circulation inside the repository and provide a separating function for the different zones of the repository.

Spacers: Spacers will be placed between the waste packages, if they are required by thermal constraints. Dependent on the heat output of the waste the space between overpacks can vary up to 4 m. These provide a thermal decoupling of the waste packages and therefore a heat flow reduction which dissipates by conduction in the rock (Andra 2005d). These will be steel envelopes containing a matrix of material that is yet to be defined by Andra.

PA/SA studies:

Dossier 2005 Argile (Andra 2005d).

Significant changes since first envisaged:

None.

Detailed variants worth recording:

None.

3. Development and Operation

Requirements on site:

The surface installations will cover approximately 1 km^2 and will comprise a nuclear area where waste packages are received and subsequently conditioned into disposal containers (an encapsulation facility), an industrial area with the technical facilities and materials required for underground works, and an administrative area (Andra 2005a). Additionally, a specific area could be set up to receive the excavated muck that might be used as access tunnel backfill.

The repository concept is designed to fit within the constraints of the site by aiming to keep

the underground installations as compact as possible, as this will reduced the excavated volume (limiting the operational cost and the volume of the spoil to be stored on surface), make optimum use of the underground footprint in the Callovo-Oxfordian formation, and ensure easier operation due to a simplified tunnel network.
For HLW, there would be three disposal zones, the first for historical C0 waste packages containing approximately 200 disposal tunnels, and two others for the disposal of type C waste currently produced or yet to be produced, each with around 2,400 disposal tunnels. This would require an underground footprint of approximately 5 km^2; this assumes reprocessing of all the UOX and MOX spent fuels and waste emplacement in the repository after 60 years of cooling. The footprint could be significantly reduced if the pre-disposal storage period were increased (Andra 2005d).

Demands on site characterisation procedure:

In a low or no-flow host rock which can be relied on to provide a significant diffusion barrier, the main demand from site characterisation is to demonstrate that these properties are stable, long-lived, homogeneous and that the extent (vertical and lateral) of the host rock is sufficient. Andra has, to a large extent, shown that the Callovo-Oxfordian exhibits such properties.

Excavation / construction processes: Construction of the overpack containers will be in two phases. First the container casing and lid will be pre-fabricated. For the casing, Andra (2005d) preferred to obtain a casing body and bottom with a single piece using an industrially proven technique (boring and hot-drawing a solid steel block where the cavity is obtained by metal deformation). In the second phase, the disposal packages will be made up in shielded cells in the repository surface installations by emplacing the vitrified waste primary package into the overpack, fitting the lid and welding it using the electron beam technique, and then inspecting the weld before transfer to the disposal tunnels.
To preserve the integrity of the geological formation the tunnel liner will be fitted as early as possible during construction. A horizontal boring technique can be used for excavation such that the disposal tunnel is bored out by a bit which cuts the rock at a diameter close to that of the liner external diameter and which is followed up as it advances by a tube which supports the rock. The permanent liner will be put in place while excavating to limit the ground disturbance and prevent the risk of destabilising the walls. The liner sections, welded together, are pushed (they do not rotate while emplaced) by a tube pusher fitted to the boring machine. They can be assembled by automatic welding, which is an industrially-proven process used in laying pipelines. The tube end is blanked off by welding on a metal plate using a robot (Andra 2005d).

Implications for requirement/location for encapsulation facility:

The waste will need to be encapsulated and it is likely, although not essential, that this will be carried out at a facility at the repository site.

Operational / emplacement procedures:

At the surface installations, waste packages delivered to the site will be removed from their transport casks and placed in the steel overpacks. They will then be inspected and stored temporarily. Most of these operations will be performed by remote-controlled devices in shielded compartments. Each container will then be placed in a shielded transport cask to ensure the radiological protection of operational personnel and transferred underground. During the operational phase, the last 8 m of the disposal tunnel (known as the cell head) will be fitted with a temporary tunnel liner for package emplacement. While in operation, the cell head will be closed by a very thick steel door, the shuttering device, to which the shielded transport cask docks, and which provides radiological protection to personnel present in the access tunnel. For C waste packages, a mobile robot integrated in the shielded cask will push the container into the disposal tunnel (this process is being tested within the scope of an ESDRED project). After filling the cell and whilst waiting for it to be closed, the shutter can be removed in order to be re-used on other disposal tunnels; a protective cap is then fitted in order to reduce air exchange with the access tunnel, and thus the corrosion rate (Andra 2005d).

Spent fuel packages of small diameter (CU2 packages with a MOX assembly) can be emplaced using the same method as for HLW packages, whereas those with a larger diameter (CU1 packages containing four UOX fuel assemblies) will be lifted by air cushion support pushed by a self-propelled carriage (Andra 2005a) - this process has been successfully tested in Sweden as part of the ESDRED project (Londe 2007).

When it is decided to close the disposal tunnel, the cell head liner section can be retrieved and the cell head can be sealed.

Key aspects and components for QA focus:

A thorough host rock characterisation is critical to ensure there is no potential for advective flow and that the host rock acts as an effective barrier to radionuclide transport. Seals on disposal and access tunnels to isolate the disposal areas from the rest of the repository will be very important to ensure waste isolation, as will segregation of the waste categories (repository layout). Focus on the quality assurance of the waste overpack construction, especially welds, is also a vital area.

4. Programme Management

Key stages and time plan flexibility / main decision points:

Andra (2005d) outline their future work programme as a transition from the current phase of basic feasibility to a phase of development, optimisation and detailed studies, possibly extending over a period of five years. It would focus increasingly on technological aspects and industrial implementation, while seeking to optimise the current proposed design. Beyond this phase, assuming that the various scientific results and techniques are positive, it would be possible to pass on to an industrial development stage, potentially leading to an industrial installation by 2025 (Andra 2005d).

A new law was passed by the French parliament in June 2006 stipulating that a site for a final repository should be selected no later than 2015. This will still be Andra's responsibility, but must involve local communities as much as possible (Virtual Repository 2007).

Retrieval options:

The 1991 Act referred to reversible or irreversible disposal and France has since decided to adopt a principle of reversibility. This has meant designing an underground facility that may be managed as a storage facility during its first phase. However, it is also a facility that may be gradually shut down without requiring any further human intervention. Thus, a stepwise approach is used to control the facility: the shutdown of the facility may be implemented progressively in order to gradually reduce the reversibility level as decisions are taken to move forward in the shutdown procedure (Andra 2005a).

After construction and the emplacement of the packages, the key steps for any given disposal area are:

1. sealing the disposal tunnels;
2. backfilling the access tunnels to the disposal area;
3. closing an entire disposal area dedicated to a specific waste category;
4. then, as decisions are taken, closing all operating areas;
5. finally, closing the main access tunnels and the shafts.

Andra has conducted studies of the technological possibility to retrieve packages in the different layouts of the repository, with special emphasis on the first step, during which the disposal tunnels are still unsealed, in order to assess the potential timescale of that phase, similar to a storage facility (Andra, 2007).

Andra (2005a) originally decided not to set a predetermined duration for reversibility. However, the new law of June 2006 requires a minimum reversibility period of 100 years (Londe 2007).

Pre-closure monitoring requirements:

The notion of reversibility is associated with that of monitoring of the repository with a view to following the evolution of the structures, whether mechanical, thermal, chemical or hydraulic. In order to achieve this, a series of measurement devices and data transmission networks will be placed in instrumented observation disposal tunnels, shafts, access tunnels, seals and backfills at construction. The resulting measurements will provide scientific and technical data that will be used as the basis for the reversible management of the repository and as a decision-making support tool (Andra 2005a, 2007).

Post-closure monitoring options:

As for pre-closure monitoring, post-closure monitoring will depend upon the stage of completion and the level of reversibility required.

5. Environmental Impacts

Spoil volumes / storage:

No figures have been published for the spoil volumes but excavation of the C and CU waste disposal tunnels would create of the order 0.1 to 1.5 x 10^6 m^3 of spoil, dependent upon the reprocessing scenario assumed. There will be significant additional spoil due to excavation of the access tunnels, ramp, shafts and underground infrastructure. There will also be extra spoil at the site due to excavation of the disposal tunnels for co-disposal of category B waste, although this is likely to be less than if a separate repository were constructed. Altogether, it is estimated that between 7 and 18 x 10^6 m^3 of spoil will be generated, depending on the scenario (Londe 2007).

Resources and availability:

Again, no figures have been published for the volumes of materials to be used but of the order of a few hundred thousand tonnes of steel will be required for the waste packages, dependent on the reprocessing scenario assumed. Additional steel will be required for the disposal tunnel liners as well as additional steel, concrete and bentonite for the disposal and access tunnel backfill and seals.

Both concrete and steel are readily available, although this may change in the future. It is also possible to recycle and reuse steel from nuclear power plant decommissioning. Excavated material could be used to backfill the access tunnels.

Transport of materials:

This depends on the amounts of materials and the site location.

Nature of surface facilities required:

This is expected to be similar to other mined concepts in terms of visual and noise impacts.

Any special noise or visual issues:

These would be expected to be similar to any other mined facility.

6. Key Uncertainties and Outstanding R&D

Remaining over-arching uncertainties include the relatively short periods of time over which experiments have been conducted, repository structures have not yet been tested at full scale, a detailed survey of the zone covering over 200 km^2 around the Meuse/Haute-

Marne site has not been conducted (although this is currently in progress), and certain repository components have been designed using simplified and particularly pessimistic models.

More specific outstanding issues include self-sealing of fractures within the EDZ of the tunnel and other locations; studies on rock deformation mechanisms; studies on the transient behaviour of the host rock during saturation and desaturation; and movement/transport of gas through the host rock and seals.

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In-tunnel (axial) with buffer and short-lived canister **Concept 3**

Opalinus Clay (Nagra, Switzerland)

1. Main Characteristics of the Concept

Waste (vitrified HLW and spent fuel) is encapsulated in steel overpacks emplaced axially along disposal tunnels and then surrounded by a thick buffer layer of bentonite which completely fills the tunnel with no further backfill. Waste packages are separated by sections of buffer. The disposal tunnels are closed with very substantial seals, to resist the bentonite swelling pressure, immediately after completion of waste emplacement.

Origin:

The original concept was developed by Nagra for Project Gewähr (Nagra 1985), the legally required demonstration of HLW disposal feasibility in Switzerland, for possible implementation in either crystalline basement rocks or sedimentary formations. However, the main emphasis of the Project Gewähr was disposal in crystalline rocks, in part because of the greater information available at the time of this study.

The earlier KBS-3 concept developed in Sweden concept for hard rocks aimed to avoid possible problems with the excavation disturbed zone (EDZ) around the tunnels by use of individual boreholes for waste packages. However, experience with tunnel-boring machines in Switzerland suggested that the EDZ would be minor if this technology could be used to excavate circular cross-section disposal tunnels, which allowed axial emplacement of the waste packages.

The Project Gewähr study was found by the Swiss Federal Government to satisfy the aims of demonstrating the feasibility HLW disposal in terms of construction feasibility (i.e. safe construction and operation are possible with current technology) and achievability of long-term safety. However, it was also judged that siting feasibility had not been demonstrated; due to the highly localised nature of the geological data used, the availability of sufficiently large areas of crystalline rocks had not been demonstrated. As a result, it was required that siting feasibility should be more convincingly demonstrated and that sedimentary formations should also be investigated in parallel to the crystalline studies.

The Project Gewähr concept was used almost unchanged for the Kristallin-I assessment of HLW disposal in crystalline basement under sedimentary cover in northern Switzerland (Nagra 1993). The Kristallin-I assessment included a major geosynthesis, which brought together and evaluated all the data collected during the regional field investigation programme that had run from the early 1980's.

The Project Opalinus Clay was the companion study for disposal in sedimentary rocks, following the completion of a deep borehole to investigate suitable formations, particularly the Opalinus Clay, in the Zürcher Weinland in northern Switzerland (Nagra 2002). By this time, the possibility of direct disposal of spent fuel also had to be taken into account in any potential repository concept, so the Project Opalinus Clay concept was modified to include co-disposal of vitrified HLW and spent fuel. In addition, this study also considered a co-located ILW repository (not further discussed here).

The Kristallin-I and Project Opalinus Clay studies, if accepted by the Federal Government regulators, will together complete the demonstration of disposal feasibility ("Entsorgungsnachweis") and provide input to the Federal Government decision on the future waste management programme in Switzerland.

Current and recent studies:

The most recent study was reported in the Project Opalinus Clay safety assessment (Nagra 2002a) which presented the results for an assessment of the concept in the Opalinus Clay. The Project Opalinus Clay also includes an engineering report (Nagra

2002b) and a geosynthesis report for the regional sedimentary host rock investigations (Nagra 2002c).

***Maturity*:**

This concept is similar to the KBS-3 concept in maturity with a considerable supporting database, including large-scale experiments and demonstrations, many of which have been carried out with international collaborators at the underground research laboratories at Grimsel (crystalline) and Mont Terri (sediments).

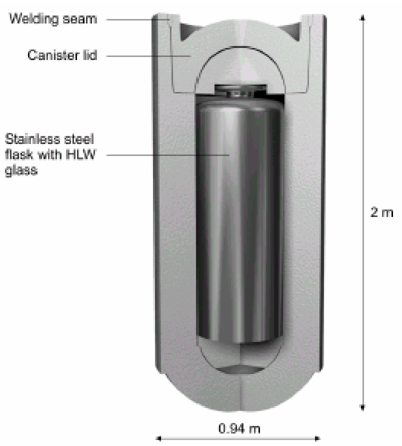
Wastes:

HLW and spent fuel are planned for disposal using this concept. The reference inventory considered in the Project Opalinus Clay comprises 2,065 spent fuel canisters and 730 HLW canisters. The contents of the spent fuel canisters vary: 935 canisters contain 9 BWR UO_2 fuel assemblies, 680 contain 9 PWR UO_2 fuel assemblies and 450 contain a mix of 3 UO_2 and 1 MOX PWR spent fuel assemblies. This smaller load is to keep the thermal output of the UO_2/MOX canisters consistent with that of the UO_2-only canisters and to meet the thermal limits on the bentonite and host rock.

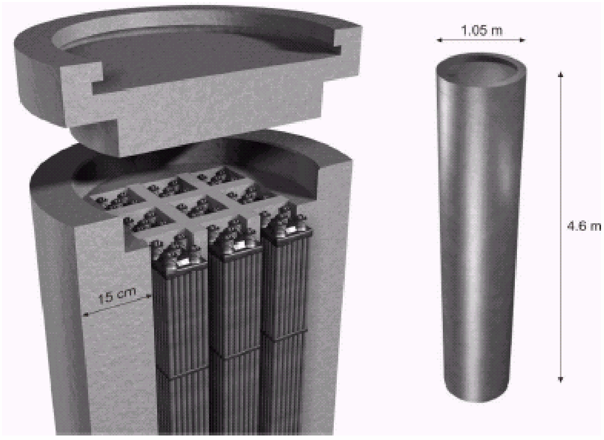
Repository depth or host formation constraints:

Implementation is straight forward, both from the perspective of engineering and safety case development, in rocks which are strong enough to support the disposal tunnel openings without a lining or support being used. The Opalinus clay has been found to support sufficiently large openings for the disposal tunnels without the use of extensive liners although the use of local rock support, in the form of mesh and rock bolts, is foreseen.

Illustrations

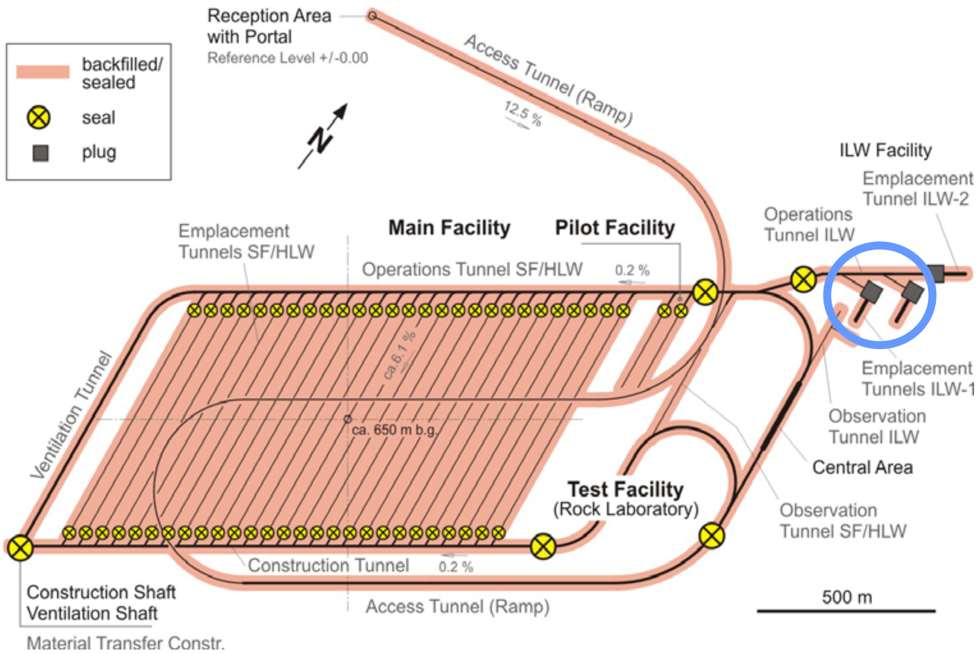


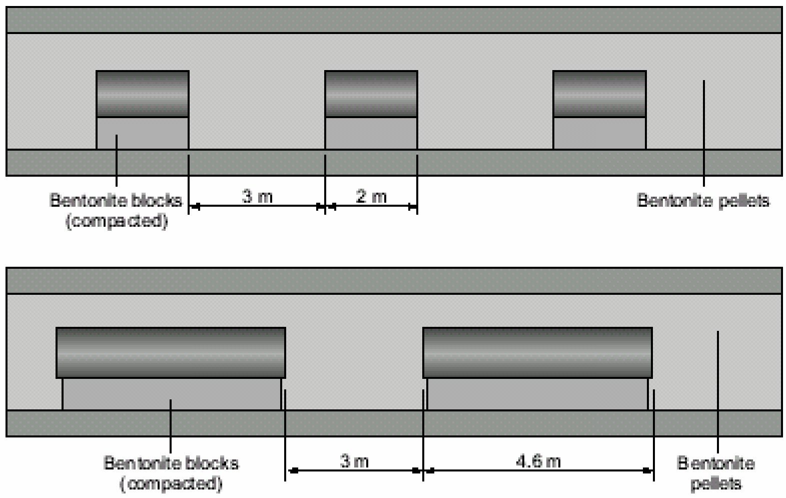
Carbon steel HLW canister.



Carbon steel spent fuel canister for PWR and BWR SF.

Below: lay-out of the repository showing the large disposal area for HLW and SF and the smaller, isolated ILW facility (top, right corner).





Above: lay-out of the waste packages in the disposal tunnels (upper: HLW; lower: SF).

(Images courtesy of Nagra, Switzerland.)

2. *Long-term Safety Concept*

Multi-barrier concept:

The concept is implemented using an engineered barrier system of low-solubility waste matrix (either borosilicate glass as in vitrified HLW or the UO_2 in spent fuel), steel overpack and buffer of highly compacted bentonite clay, together with substantial tunnel seals, emplaced in tunnels in the host rock which provides the natural barrier.

EBS design and materials:

Waste package: An overpack of carbon steel is designed to provide complete containment for a relatively limited time to cover the period of heat generation from the

HLW and spent fuel. The overpack is 25 cm thick for the HLW and 15 cm thick for spent fuel. Based on studies of steel corrosion and mechanical behaviour under the expected chemical and stress conditions in the Opalinus Clay, a design lifetime of 10,000 years for the overpacks is considered reasonable. In the case of SF, a copper canister with a steel insert based on the SKB design (Werme 1998) was also considered. For HLW, an overpack containing 2 flasks is also an option.

Buffer: Apart from the compacted bentonite blocks on which the waste packages are emplaced, the buffer is composed of compacted bentonite granules. The buffer material comprises about 80% by volume very dense bentonite granules (dry density of ~2.1 – 2.2 Mg m^{-3}) and ~20% bentonite powder. On emplacement, the material is expected to have an average dry density of 1.5 Mg m^{-3} (Röski 1997).

Disposal tunnel: The disposal tunnel diameter is 2.5 m and, based on the preliminary layout as given in Nagra (2002b), is expected to have a length of ~800 m, which includes a 20 m waste package (WP) handling zone at the entry to the disposal tunnel. The spacing between disposal tunnels is 40 m and both HLW and SF waste packages are placed 3 m apart (WP pitch of 5 m and 7.6 m, respectively).

Disposal tunnel seals: The buffer material is expected to attain a high swelling pressure during saturation, thus the tunnel seals must resist the swelling pressure to maintain the buffer density and the disposal positions of the waste packages. The disposal tunnel seals are compound constructions of a high-density bentonite-filled section of about 12 m, separated by an intermediate wall built of dry stone-work (of rock such as granite or basalt to avoid interactions with bentonite), and a 6 m-long gravel-filled interval up to the end of the disposal tunnel, which is closed with a plug. Then, in the wider handling zone at the entrance to the tunnel, a 20 m bentonite-sand backfilled interval is terminated by a concrete wall keyed into the host rock (Nagra 2002b).

Access tunnels and infrastructure: The HLW and SF disposal tunnels are grouped into a single large disposal panel surrounded by an access tunnel which has different functions depending on its position. Excavation and construction is carried out from one end of the disposal tunnels using the construction tunnel; waste emplacement operations are carried out from the opposite end of the disposal tunnels using the operations tunnel and these two tunnels are connected by a ventilation tunnel that also connects to the construction and ventilation shaft. Access to the repository is via a ramp for the waste packages with one shaft for transport of personnel and materials and for ventilation.

Safety functions of the barriers:

Waste: To provide containment of the radionuclides in the spent fuel pellets and Zircaloy cladding or the borosilicate glass matrix and attenuation of releases due to slow corrosion rates of spent fuel pellets/Zircaloy cladding or dissolution of the borosilicate glass after overpack degradation.

Overpack: Prevents inflow of water and release of radionuclides for several thousands of years – usually no benefit is taken in the safety case for containment beyond the planned containment period. Once radionuclides are released from the overpack, the corrosion of the overpack ($Fe \rightarrow Fe_3O_4$) is expected to provide redox buffering around the waste and to immobilise radionuclides on the corrosion products.

Buffer: To provide confinement due to the long resaturation time and plasticity of the material, which allows self-sealing following physical disturbance. After degradation of the overpack, the buffer provides attenuation of releases due to low solute transport rates (due to diffusion), retardation of the radionuclide transport (due to sorption) and low radionuclide solubility in the pore water.

Host rock: Provides confinement due to absence of water-conducting features and mechanical stability to protect the waste packages. After degradation of the overpack, radionuclide releases are attenuated due to the low groundwater flux and retardation of radionuclide transport (sorption and colloid filtration).

Geosphere: The role of the geosphere is to protect the EBS (e.g. from glacial erosion) while providing retardation and dispersion of radionuclide releases.

Safety functions of other components:

Disposal tunnel seals: The disposal tunnel seals may play an important role in preventing transport of radionuclides along the disposal tunnel EDZ (which, although small in extent, is nevertheless likely to represent a potential fast flow pathway when compared to the adjacent bentonite or unfractured host rock matrix) linking to adjoining access tunnel/EDZ and providing a short-circuit to the surface.

PA/SA studies:

Crystalline basement under sedimentary cover: Project Gewähr (Nagra 1985); Kristallin-I (Nagra 1994).

Sedimentary formation: Project Opalinus Clay Safety Report (Nagra 2002a).

Significant changes since first envisaged:

The concept as originally envisaged used compacted bentonite blocks to construct the buffer. However, the use of high density bentonite granules for the bulk of the buffer emplaced using a conveyor or pneumatic system allows short operational times, around 1 – 2 years, for completion of a disposal tunnel (ca. 800 m in length) and minimises alteration of the host rock.

Detailed variants worth recording:

None.

3. Development and Operation

Requirements on site:

The repository laid out in the Opalinus clay (Nagra 2002b) has a total area of about 2 km^2, of which less than 1 km^2 is the single disposal panel of 27 disposal tunnels for ~3,000 HLW and spent fuel packages (average area/waste package of ~300 m^2). The single panel lay-out takes advantage of the lateral extent, near horizontal situation and uniformity of the Opalinus Clay formation and the apparent paucity of fracture zones and other features that would require adjustments, such as respect distances and unused tunnel length.

The Opalinus Clay formation is not thick (ca. 100m at a depth of 600 – 700m below ground level) but provides more than 40m of host formation above and below the repository which, given its favourable properties and those of the surrounding formations, is considered adequate.

Demands on site characterisation procedure:

The regional geological investigations over about 20 years in north Switzerland combined with the data from the deep borehole at Benken (Zürcher Weinland) have allowed Nagra to make some statements about the Opalinus Clay in this region as a host rock for repository for long-lived wastes (Nagra 2002a,c):

- The geological environment is simple with predictable structural, hydrogeological and geochemical properties over a scale of several kilometres. The Opalinus Clay is sufficiently homogeneous to allow confident prediction of its behaviour on the time and space scales of interest for repository safety.
- The potential siting area is tectonically stable on a timescale of the next few million years, being characterised by a low rate of uplift and associated erosion and average *in situ* stresses and heat flows.

Further, the sediments overlying the basement in this region and the basement rocks themselves are not considered to have any significant natural resource potential.

Excavation / construction processes:

Conventional use of a tunnel boring machine (TBM) for excavation of disposal tunnels with the additional use of road-header machines for larger access/operations tunnels and other underground spaces is expected. Shaft excavation will use raised boring methods. Drill and blast methods are probably not needed, based on experience of other excavations in the same formation (Nagra 2002b).

Implications for requirement/location for encapsulation facility:

An encapsulation facility is required, probably located with the surface facilities above the repository.

Operational / emplacement procedures:

The waste packages are transported from the surface encapsulation facility to the underground facility, possibly to an intermediate buffer store, in a shielded transport container on a 'rack-and-pinion' electric railway. At the time of emplacement, the waste package is transferred to the handling section of the disposal tunnel in the shielded transport vehicle and then transferred across to the deposition vehicle where it is positioned on a pedestal of compacted bentonite blocks supported by a steel frame. This assembly is moved into the disposal position in the tunnel and set down, after which the deposition vehicle withdraws. The pedestal positions the waste package centrally in the tunnel axis. The buffer material is then filled around the waste package using a conveyor or pneumatic system from a hopper vehicle preceded by the pump/conveyor apparatus. The whole procedure is carried out remotely, monitored by cameras and other sensing equipment mounted on the vehicles. The sequence is repeated for all the waste packages in the tunnel after which an additional section of buffer is placed followed by the tunnel seal section (Nagra 2002b).

4. Programme Management

Key stages and time plan flexibility:

The key decision points for implementation of this concept are:

- to begin underground excavations, initially as an underground rock characterisation facility, after surface-based investigations confirm the properties of the site (Construction phase 1);
- to proceed with the repository construction after confirmation of the properties of the host rock and site (Construction phase 2);
- when authorisation is given to begin waste emplacement, based on additional site data obtained during construction. The first waste may be emplaced in a pilot repository separately from the main disposal tunnels. The pilot repository would be monitored for the duration of the operational period to provide confidence in the eventual decision to close and decommission the facility (Construction phase 2);
- beginning operation of the main repository, with simultaneous construction and waste emplacement in adjacent tunnels (Construction phase 3 and operation);
- the rate at which to emplace the waste and whether it should be done in campaigns;
- backfilling access tunnels and closure of the repository.

Once disposal begins, reversal of the decision would require a major effort to retrieve the emplaced waste. However, the nature of the separated deposition tunnels means that it may be possible to implement sections of the repository in campaigns with periods of quiescence in between, when activities were limited to maintenance and monitoring of the site. Such an operational plan is not currently foreseen for the expected waste (Nagra 2002b).

The operational period for the pilot repository is expected to be about 2 years during which 50 SF canisters and 20 HLW canisters will be emplaced. The main repository will be operated for about 15 years with an average emplacement rate of 3.1 SF canisters and 1.1 HLW canisters per week.

At the end of the operational period the repository will be at a stage where only the access tunnels are left open and all disposal tunnels (including the ILW caverns) are sealed.

Once the decision is made to begin closing the repository, the access tunnels and the ventilation shaft would be backfilled and sealed, leaving open only the access ramp, the monitoring tunnels for the ILW and the pilot repositories and the underground repository. These would then be backfilled and sealed in the final closure operations.

Retrieval options:

Once the disposal tunnels are sealed, retrieval of waste packages requires mining out of the bentonite. This can be carried out by mechanical digging, and appropriate schemes have been designed for this purpose (Nagra 2002b). SKB have also looked at removing bentonite with the se of water jets. Retrieval may be relatively straightforward during the period when the bentonite is not fully saturated. However, removal of a single waste package is clearly not possible without removal of all preceding ones.

Pre-closure monitoring requirements:

The pilot repository will be monitored during the operational phase but this is expected to cease before final closure of the repository underground facility.

Post-closure monitoring options:

Underground monitoring of the pilot repository continues after closure of the main repository but will cease before final backfilling and closure of the underground facility.

Workforce requirements:

Construction phase 1 (exploration phase): approximately 20 – 25 persons; construction phase 2 (main construction phase): approximately 100 – 120 persons; construction phase 3 (excavation of disposal tunnels): 8 – 12 persons. Operations personnel: approximately 25 – 30 persons underground.

5. Environmental Impacts

Spoil volumes/storage:

The excavated volumes calculated for the three construction phases are:

Phase 1 (5 years): 420,000 m^3;

Phase 2 (3 years) 400,000 m^3;

Phase 3 (15 years): 195,000 m^3;

giving a total of 1.015×10^6 m^3.

The spoil is not used in backfilling the disposal tunnels thus will build up over the excavation period unless transported off the site, which is expected. Some spoil may be used in conjunction with bentonite to backfill the access tunnels as the repository is closed and decommissioned although, currently, sand is specified as the admixture with bentonite in the backfill material.

Resources and availability:

Bentonite per waste package is around 35 or 50 tonnes, depending on whether the waste package is for HLW or SF, respectively. This implies a total for the disposal tunnels of the order of 0.15×10^6 tonnes and a further $\sim 0.5 \times 10^6$ tonnes for seals and mixing with sand for backfilling access tunnels when the repository is closed.

Packaging all the HLW and SF in steel canisters will require about 60,000 tonnes of steel, all of which will need to be imported unless recycled steel is considered adequate.

Transport of materials:

Transport is expected to be via rail and road.

Nature of surface facilities required:

Low rise buildings are planned on an area of about 300 x 150 m to include all offices, operations buildings, equipment stores, encapsulation facility and the access ramp portal building. A smaller site of about 100 x 100 m will include the shaft head building, personnel and office buildings, workshops and the excavation spoil management area (covered).

Any special noise or visual issues:

This is expected to be similar to other mined concepts in terms of visual and noise impacts.

6. Key Uncertainties and Outstanding R&D

Currently outstanding and open issues being investigated include:

- Self-sealing of fractures within the EDZ of the tunnel and other locations;
- Studies on rock deformation mechanisms to enhance system understanding;
- Heater experiment at Mont Terri to enhance understanding of the transient system when temperatures are increased;
- Studies on the transient behaviour of the host rock during saturation and desaturation, as well as interaction of the Opalinus clay with the bentonite buffer;
- Practicality of using bentonite granules to fill tunnels;
- Movement/transport of gas through the host rock and seals.

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SF: In-tunnel (axial) with short-lived overpack **Concept 3**
HLW: Mined deep borehole matrix **Concept 10**

Salt Dome (DBE Technology, Germany)

1. Main Characteristics of the Concepts

The present reference concept for SF uses a massive, self-shielded container (a POLLUX cask). This is emplaced axially on the flat floor of an unlined drift excavated in salt host rock. The drift is backfilled with crushed salt. For HLW, the reference concept comprises the emplacement of HLW containers (without any overpack) in long (possibly up to 300 m) vertical boreholes drilled from the floor of disposal drifts. The same method is also being considered as an alternative for emplacement of thin-walled steel SF containers of the same diameter. The boreholes are unlined and the space between containers and in the narrow annulus around them is filled with crushed salt.

Origin:

The concept of disposal in salt formations has been extensively studied since the 1960s, with the earliest work in Germany and the USA (Germany was involved in Project Salt Vault in the USA from 1962-7). Since the USA focus moved away from salt domes, there has been almost no work outside the German national programme. The current German concept was essentially developed between 1985 and 1994. Experimental work on the concept has been carried out in the Asse salt mine since the early seventies, with the latest full scale tests starting in 1990 and ending in 2003 (Krone, 2007). Some full-scale experiments in Germany have involved participants from other countries, for example, the Netherlands, Spain, France and the USA were involved in the HAW project looking at the vertical borehole concept, which originated in 1982, and in the later BAMBUS project (Bechthold *et al.* 2004) on drift backfill behaviour.

***Maturity and current status*:**

Considerable work has been carried out on the drift disposal concept for SF. Experimental and safety assessment studies, along with full-scale, long-term in-situ tests of the POLLUX cask thermal and corrosion behaviour and backfill/host-rock evolution have been supported by extensive engineering trials of fully developed emplacement machinery. The drift emplacement approach for SF was critically reviewed against other approaches in 1990, using a decision analysis system (Einfeld 1992) and scored highest. This is amongst the most mature HLW and SF disposal concepts in the world and was considered ready for deployment at Gorleben in the late 1990s, before a political moratorium was placed on the programme in October 2000.

The vertical borehole concept for SF is less developed and has only been partly tested in situ. The origin of the alternative concept is largely economic: disposal of the massive POLLUX casks (each costing several hundred thousand EUR) which are expected to have a post-emplacement lifetime of at least 500 years can be avoided by direct emplacement of less expensive waste containers into boreholes, giving the same level of isolation.

The most recent design and safety update study for the proposed repository in the Gorleben salt dome was in 1998 (Filbert and Engelmann 1998) although the work has not yet been published owing to an extant political moratorium on the project that came into force in 2000. A full-scale experiment on drift disposal (TSDE: thermal simulation of drift emplacement) was carried out from 1990 to 1999 (Droste *et al.,* 2001). Work is still underway to bring the vertical borehole concept for HLW and SF to the same level of maturity as the drift emplacement concept for SF (Bollingerfehr and Filbert 2007).

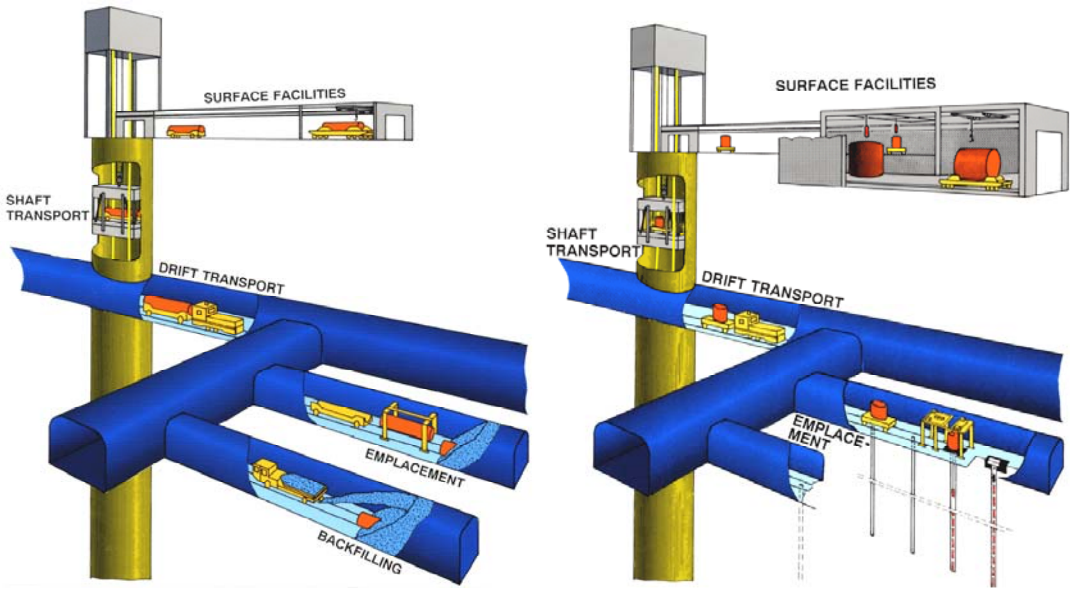
Wastes:

The drift concept has been developed for SF but could presumably also be adapted for HLW, whilst the vertical borehole concept has been developed for both SF and HLW. The borehole concept is also appropriate for other small-volume, long-lived wastes such as reprocessing wastes (an alternative, thin-walled steel container is envisaged to hold compacted fuel assembly components: the CSD-C container, which is approximately 0.4 m in diameter and 1.3 m long).

Repository depth or host formation constraints:

The main disposal drifts proposed for the Gorleben salt dome are located at a depth of 870 m. The repository depth is not a critical constraint for the drift concept because this only requires sufficient lateral extent of homogeneous rock salt that is sufficiently vertically isolated from surrounding formations in which water flow could take place. For this reason, and from the UK perspective, although the concept was developed for dome salts, it could also be suitable for bedded salts of sufficient thickness to provide isolation from surrounding formations. The borehole concept requires sufficient vertical extent of homogeneous rock to make vertical boreholes attractive: 100 – 300 m lengths are being considered – this is quite feasible at Gorleben as it was developed for the considerable thicknesses (up to thousands of metres) of salt found in salt domes. It may be difficult to adapt economically to bedded salts, unless individual units are several tens of metres thick.

Illustrations



Schematic illustrations of the drift emplacement concept for SF (left) and the borehole emplacement concept for HLW (right), which could also be used for SF containers. *(Images courtesy of DBE TECHNOLOGY GmbH, Germany).*

2. Long-term Safety Concept

Multi-barrier concept:

The salt dome disposal concept is intended to rely principally on the geological barrier provided by the dry, impermeable salt surrounding the disposal zone. The degree of physical isolation provided by the salt means that the properties of the waste-form and the EBS are of minor to no importance as barriers once the disposal tunnels and repository are sealed.

EBS design and materials:

In the drift concept, disassembled SF is placed into POLLUX casks (1.5 m diameter, 5.5 m length), which are welded shut. The inner part of the POLLUX container is made of stainless steel, while the thick outer wall is made from nodular cast iron (which is relatively light and ductile). A loaded POLLUX cask weighs about 65 tonnes and has a surface dose rate of less than 0.2 mSv/h. Each cask will hold the fuel from up to ten disassembled PWR assemblies (Closs and Papp 1998); about 5 tHM.

In the borehole concept, unshielded COGEMA HLW fabrication containers (0.4 m diameter and 1.3 m long) have no overpack, while SF is emplaced in thin-walled (50 mm), steel, BSK-3 containers of the same diameter as the HLW containers (Bollingerfehr and Filbert 2007). Each container is 5 m long and holds fuel rods from 3 PWR fuel elements (about 1500 kgHM) or 9 BWR elements. Filled BSK-3 containers weigh around 5 tonnes. As noted above, non-fuel components of the disassembled fuel elements will also be disposed in the boreholes, in CSD-C containers.

The backfill for both concepts comprises finely crushed, dry rock salt, emplaced immediately after the containers are deposited, with no special treatment (Müller-Hoeppe *et al.* 2006).

Safety functions of the barriers:

The waste containers in both concepts are intended to isolate and completely contain the wastes during the emplacement operations. For the drift concept for SF, 500 to 1000 years of containment is assumed (conservative). It is important to provide complete containment whilst the repository is open and operational, even though individual disposal tunnels will be sealed once completed. For the borehole concept, containment is essential during borehole filling. As boreholes are filled, waste will be emplaced through a borehole-lock, which will have the function of a hot-cell access door, separating the borehole from the non-active disposal drift area. Clearly, containment during these operations is essential, but as with the reference concept, once the disposal boreholes are completed and sealed, the container has no long-term safety function.

The crushed salt backfill initially isolates the container from the rock but is intended to creep under the influence of both overburden pressure (as tunnel or borehole walls close-in owing to the plasticity of salt) and temperature, eventually to become solid with almost identical properties to the surrounding, undisturbed host rock salt.

The host rock salt exhibits creep at high stresses without fracturing – a process that is accelerated at the high temperatures initially surrounding the waste packages (~150 – 200 ^{o}C) and that has been demonstrated in several *in situ* tests. This effectively seals the waste packages into impermeable rock, preventing any access of water from surrounding formations, so long as the salt dome remains stable (expected to be many millions of years).

Safety functions of other components:

Disposal tunnels will be sealed with 'dams' constructed of mixed media, including salt concrete (concrete made with crushed salt aggregate). The objective of these structures is to isolate the disposal region of the repository during operations (Bollingerfehr 1996).

Upon completion, the remaining regions of the repository will be backfilled with crushed salt, with periodic emplacement of dams to act as tunnel seals. The shafts will be sealed with complex, multi-component seals using both salt concrete and bitumen.

The objective of all these seals is to prevent access of waters from overlying formations into the salt dome. Until tunnel wall creep under natural stress conditions has restored the backfill properties to values similar to the intact rock, water must be kept out of the disposal regions of the backfilled repository.

PA/SA studies:

Integrated safety assessments have been carried out periodically for many decades. The

European Community PAGIS project was among the earliest comprehensive comparisons studies of different host rocks and the salt component of the study evaluated the vertical borehole concept. During the 1980s a series of assessments were carried out: Study on Alternative Disposal Techniques - SAE (1984); Analysis of Mixed Concepts - SAM (1989); Analysis of Repository Concepts - SEK (1996). The most recent (unpublished) safety update for Gorleben was in 1998 (Filbert and Engelmann, 1998) but no full-system assessment has been made recently. Currently, DBE TECHNOLOGY GmbH, BGR and GRS are developing and testing the salt dome safety concept within a joint R&D project funded by the Federal Ministry of Economics and Technology via its project unit at the Karlsruhe Research Center (Krone et al., 2006). The aim is systematically and convincingly to prove the safe isolation of the emplaced HLW and spent fuel for the likely case of undisturbed repository evolution, where zero releases are expected.

Disposal in salt domes allows a robust and relatively simple safety case to be made. In this respect, dome salts are often regarded as the ideal repository host rock. The perceived weakness that drilling intrusion might introduce water into the disposal region with significant impacts (dissolution of the host rock) have been countered by safety analyses that suggest (a) the probability of intrusion is low (there are more than 200 salt domes on land in the Northern German Zechstein Basin; Krone, 2007) and (b) if the borehole is sealed after encountering repository materials or waste, which is the expected response, the impacts are low (see, for example, Wollrath *et al.*, 2007, for an equivalent analysis of intrusion into ILW disposal caverns in the Morsleben salt dome). Nevertheless, this aspect of the safety case requires careful evaluation.

Significant changes since first envisaged:

The development of the borehole concept as an alternative approach for SF emplacement is the only major adaptation since the reference drift concept was developed. As noted above, the objective is to reduce the requirement to dispose of expensive POLLUX casks.

3. Development and Operation

The site and site characterisation:

The Gorleben salt dome was selected in 1977 by the State Government of Lower Saxony and approved by the Federal Government as the preferred location for the repository. Extensive regions of homogeneous halite can be accessed for the disposal region. It has been investigated since 1979 (Brewitz and Rothfuchs, 2007). Investigations ran for four years and covered an area of about 300 km^2. They involved a 150 km line length of seismic profiling, four deep boreholes to 2000 m, 145 boreholes from 10-275 m, 44 boreholes into the top of the salt dome and numerous monitoring boreholes (Kühn, 2007). Between 1985 and 1996 two shafts were sunk to greater than 880 m depth, which allowed underground exploration and rock characterisation to begin. Although implementation of the repository is currently subject to a political moratorium, no factors or characteristics have been found that call its suitability into question (a set of ‘doubts’ expressed in 1998 was countered by further, internationally reviewed work). Gorleben is considered to be one of the best-studied repository sites globally, and the safety concept to be one of the most robust.

Operational / emplacement procedures:

In both the drift and the borehole concepts, the disposal drifts are excavated using either blasting or road header machines. Owing to the strength of the rock salt in the salt domes considered, no support is generally required, although the tunnels require periodic scaling.

<u>Drift concept:</u> A fully tested (1000 operational cycles) emplacement system has been developed for eventual deployment at the repository. The POLLUX casks are transported underground in the waste handling shaft by a shaft hoisting system capable of handling loads of up to 85 tonnes. The transport carts use a rail system and are hauled by battery powered locomotive to the disposal drift. An emplacement device located in the drift lifts them from the transport cart and places them on the drift floor before itself being moved

away to allow backfilling. Backfill is emplaced by a separate machine.

Borehole concept: The emplacement system developed for the handling and disposal of HLW- BSK 3- and CSD-C-canisters comprises a transfer cask that provides appropriate shielding during the transport and emplacement process, a transport unit (consisting of a mining locomotive and a transport cart) and an emplacement device (Bollingerfehr and Filbert, 2007). In the emplacement drift, the transfer cask is lifted off the transport cart by the emplacement device and swivelled into an upright position after the transport cart has been removed. After lowering the transfer cask onto the borehole lock and opening the transfer cask and borehole lock, the canister is lowered to the planned position in the borehole with the canister grapple.

4. Programme Management

Retrieval options:

The German concept does not include a provision for retrieval. Nevertheless, an engineering study indicated retrieval to be feasible, if considered necessary (Engelmann *et al.* 1995).

***Workforce requirements*:**

Repository operations are estimated to employ about 100 staff.

5. Environmental Impacts

Spoil volumes/storage:

Waste rock salt is dumped at the site, as its purity is not good enough for commercial purposes. However, such waste rock salt will used for backfilling.

Resources and availability:

There are no heavy demands on any type of material at any stage of this concept.

Transport of materials and nature of surface facilities required:

The wastes are either already present at the Gorleben site in storage or would be transported by rail to the site for encapsulation (an encapsulation facility already exists, and has been fully licensed for pilot operation). The Gorleben exploration mine is at an advanced stage of construction (surface facilities, shafts, access works, etc). These facilities will be part of the future repository, should the site be found suitable.

Any special noise or visual issues:

The salt dump is kept lower than the trees in the surrounding forest.

6. Costs

The Gorleben site characterisation facility is already partly constructed. The costs to date of the project are estimated to be 1.44 BEUR. It currently costs 20 MEUR to keep the facility open during the moratorium and it is estimated that a further 300 MEUR will be needed to complete the development and exploration phase of the project.

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In-tunnel (axial) with supercontainer (concrete buffer) **Concept 6**

Boom Clay (ONDRAF/NIRAS, Belgium)

1. Main Characteristics of the Concept

Waste is emplaced axially in circular tunnels, lined for support, in the form of a supercontainer in which the waste, overpack and buffer are pre-assembled at a surface facility into an enclosed steel handling shell (also known as an envelope). The buffer material is ordinary Portland cement (OPC)-based concrete. The disposal tunnel diameter is significantly larger than the supercontainer, which sits on a small pedestal at its disposal position. Additional cement-based backfill will be used to fill the annulus around the supercontainer.

Origin:

In the 1990s ONDRAF/NIRAS assessed a preliminary reference design, the SAFIR 2 design for disposal of vitrified HLW and spent fuel in an underground repository. This comprised an alloy steel overpack surrounding the waste container placed in a steel tube, with a clay-based buffer, in concrete lined horizontal tunnels in the Boom Clay. The SAFIR 2 report (ONDRAF/NIRAS, 2002) identified some weaknesses in the SAFIR 2 EBS design that were subsequently confirmed by a Nuclear Energy Agency (NEA) peer review (NEA, 2003), primarily relating to uncertainties in the EBS performance. In particular, it was considered certain types of corrosion, such as localised corrosion or stress corrosion cracking, might threaten the integrity of the overpack during the thermal phase (a few hundred years for HLW and up to a few thousand for spent fuel) (Bel *et al.* 2006).

In response to the concerns over the SAFIR 2 design, ONDRAF/NIRAS conducted a review of corrosion and materials issues relevant to EBS design (ONDRAF/NIRAS, 2004a) and this review led to a revision of the design. The review recommended a Contained Environment Concept which would establish and maintain a chemical environment around the overpack favourable to achieving complete containment of the radioactivity, at least during the initial thermal phase when the waste would produce heat as a result of radioactive decay. In accordance with the Contained Environment Concept a supercontainer was designed comprising a carbon steel overpack surrounded by a Portland Cement (PC)-based buffer and a stainless steel envelope (Bel *et al.* 2006). ONDRAF/NIRAS included the supercontainer in a process of multi-criteria decision analysis (MCDA), which compared several alternative EBS designs and identified the supercontainer as the preferred design (ONDRAF/NIRAS, 2004b).

This EBS design is based on containment during the thermal phase. The benefits of a concrete buffer in providing a high-pH environment and limiting external fluid penetration are deemed to outweigh any negative impact of alkaline fluids on the Boom Clay or waste form (Bel *et al.* 2006).

***Maturity and current status*:**

SCK·CEN (Belgian Nuclear Research Centre) began research in 1974 to determine whether radioactive waste could be buried in Boom clay. Subsequently, an underground research laboratory named HADES was set up (at a depth of over 200 meters) in the early 1980s to study this clay as a potential host formation. Since its creation in 1980, ONDRAF/NIRAS has managed and coordinated the Belgian Research & Development programme in close collaboration with SCK·CEN and with financial support from the European Commission.

The Belgian Research & Development programme is dedicated to determining whether it is technically and economically possible to come up with a safe solution for the deep geological disposal of radioactive waste. This programme can be divided into three phases (ONDRAF/NIRAS, 2007):

<u>Phase one (1974 - 1989):</u> In May 1989 ONDRAF/NIRAS submitted the SAFIR Safety Assessment and Feasibility Interim Report to its supervising minister. The report concluded that the poorly indurated layers of clay, and Boom clay in particular, could be considered for the disposal of radioactive waste because they provided sufficient long-term protection due to the low permeability to water of Boom clay, its high capacity to retain radionuclides, and its plastic and restorative qualities (cracks and fissures mend spontaneously over time).

<u>Phase two (1990 - 2000):</u> In December 2001, ONDRAF/NIRAS published the SAFIR 2 report, which reinforced confidence in the clay to act as a natural barrier and the work carried out showed that it would be possible to construct a repository at a depth of 200 or even 250 meters in Boom clay.

<u>Phase three (2001 - date):</u> Phase three focuses on certain aspects of demonstrating, to scale and at the actual depth, the feasibility of the solution studied and the integration of all existing data. In addition, it must define the repository architecture for all types of waste destined for disposal in a deep geological layer. The PRACLAY experiment plays a fundamental role during this third phase.

Although the revised Belgian design is relatively new, ONDRAF/NIRAS can build on the extensive database available for Boom clay. ONDRAF/NIRAS is preparing safety cases to demonstrate the long-term safety of its deep disposal concept for Category B and C wastes, which will include the assessment basis, an overall description of the disposal system, and a description of the scientific and technical data and understanding relevant to the assessment of system safety and feasibility. The finalised EBS design is not yet published, but reports are in preparation for the end of 2007/early 2008 and very preliminary studies by ONDRAF/NIRAS exist (Bel *et al.* 2005, 2006).

Wastes:

The supercontainer concept by ONDRAF/NIRAS is designed for Category C waste, which includes all conditioned high-level waste containing significant amounts of beta and gamma emitters with a short life span and large quantities of long-lived alpha emitters. Most waste in this category emits considerable amounts of heat (more than 20 W/m^3). This category of waste consists of fission products from the reprocessing of spent nuclear fuel (vitrified HLW), the spent fuel itself (UOX and MOX), if it has been declared to be a waste, and any other excess fissile materials (ONDRAF/NIRAS, 2007).

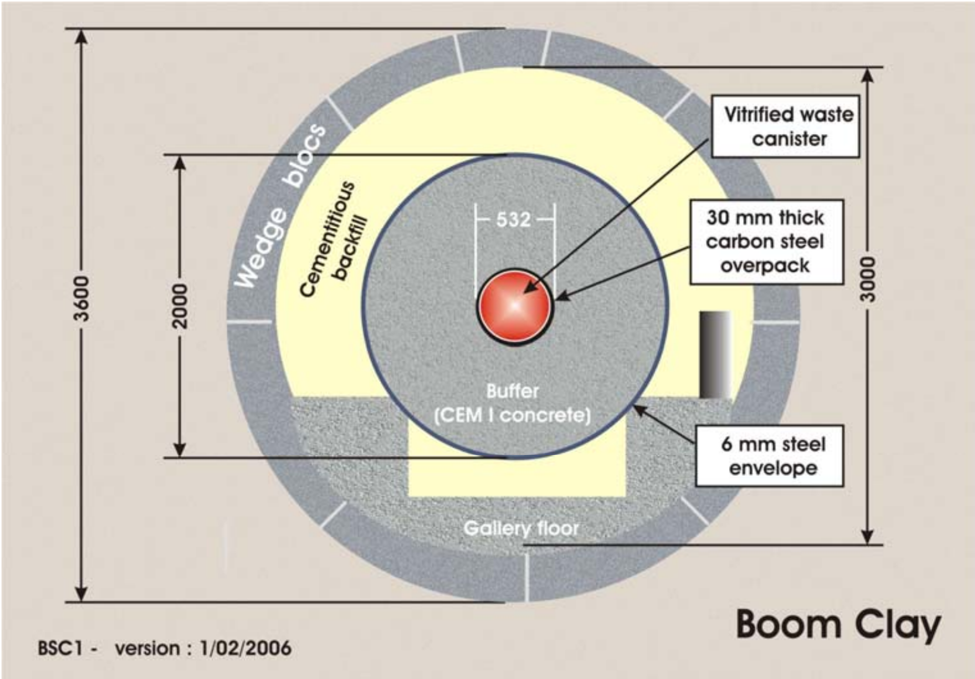
The number of waste packages to be disposed of varies according to the reprocessing option. A batch of spent fuel has been reprocessed at the COGEMA facility (now known as AREVA NC), producing 387 canisters of vitrified HLW (de Bock 2007). However, it is uncertain whether further reprocessing of Belgian waste will take place. If all suitable spent fuel is reprocessed then about 2,000 supercontainers will be required. If no further reprocessing takes place then about 2,800 supercontainers will be necessary.

Repository depth or host formation constraints:

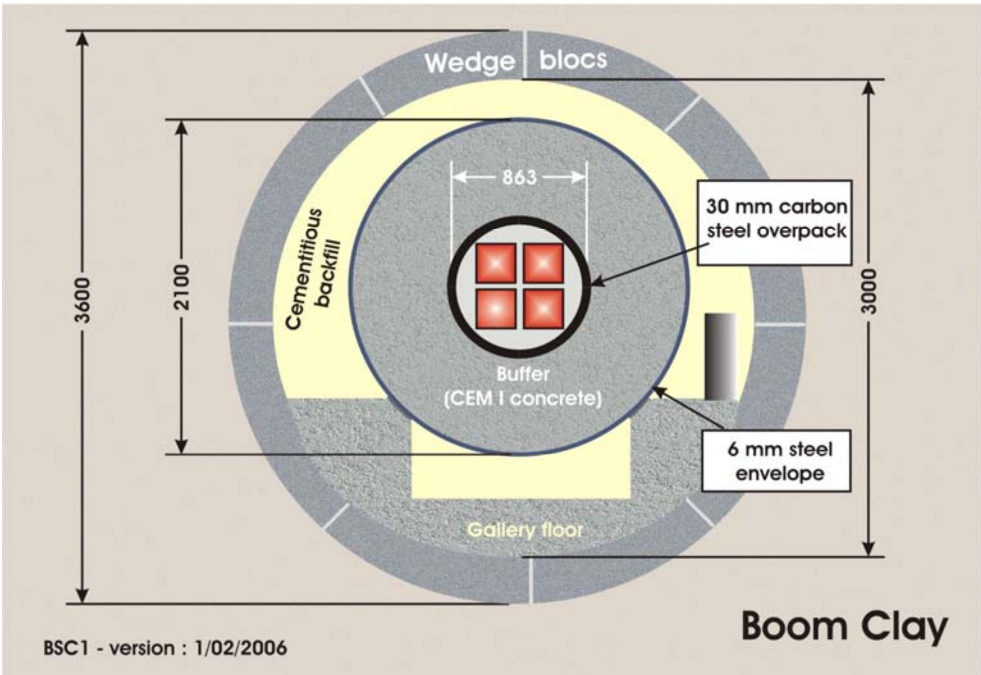
The research carried out by ONDRAF/NIRAS, with the collaboration of SCK·CEN (the Belgian nuclear research centre in Mol) and several engineering offices and universities, must determine whether disposal in the poorly indurated layers of Belgian clay can guarantee long term protection. The salt rock used in Germany is not found in the Belgian subsoil and granite formations, such as those used for disposal in Sweden and Finland, lie more than 2,000 meters deep (ONDRAF/NIRAS, 2007). Boom clay has been stable for several million years so it should remain so for the periods required for radioactive waste to become harmless.

Boom Clay (in the nuclear zone of Mol-Dessel), a poorly indurated argillaceous formation, is the reference medium for hosting such a disposal facility in Belgium. Most of the information related to the Boom Clay comes from the underground research laboratory (HADES) located beneath the Mol-Dessel region in north-east Belgium and this region also serves as a reference site for research associated with the Category B and C waste disposal programme. The Ypresian clays (at the Doel nuclear zone) are considered to be the alternative host formation for the research and evaluation of the deep disposal solution. However, the choice of a site is not yet decided as numerous other factors, both of a technical and social nature, are yet to be resolved (ONDRAF/NIRAS, 2007).

Illustrations



Cross-section in a disposal gallery for vitrified HLW. *(Images courtesy of ONDRAF/NIRAS, Belgium).*



Cross-section in a disposal gallery for spent fuel. *(Images courtesy of ONDRAF/NIRAS, Belgium).*

2. Long-term Safety Concept

***Multi-barrier concept**:*

The principle of multiple safety function uses a series of successive barriers, each with its own function within the scope of the long-term safety of the repository, that are selected and designed in such a way that the overall performance of the disposal system does not depend on any single barrier alone. The waste form itself provides the first barrier, in the form of a low-solubility waste matrix (UO_2 in spent fuel or borosilicate glass in HLW). The ONDRAF/NIRAS EBS design then surrounds the waste with a carbon steel overpack, a concrete matrix buffer, and finally a stainless steel shell to form the supercontainer. Each supercontainer is emplaced in the repository before backfilling and sealing of the disposal tunnels.

It should be noted that the ONDRAF/NIRAS EBS design is still under development and all values stated here are subject to change.

***EBS design and materials**:*

Supercontainer: The supercontainer consists of the waste, overpack, buffer and handling shell. Each HLW supercontainer will contain two stainless steel canisters of vitrified waste and will be 2.0 m in diameter, approximately 4.0 m long and weigh 30 tonnes. Supercontainers containing four UOX spent fuel assemblies will have a diameter of approximately 2.1 m, a length of 6.1 m (in case 14ft fuel is contained), and weigh a maximum of 60 tonnes, whilst for MOX spent fuel the same measurements will be approximately 1.6 m, 5.2 m and 31 tonnes and the supercontainer will contain only one fuel assembly (Bel *et al*. 2005; Fabry *et al*. 2006).

Overpack: The carbon steel overpack will be 30 mm thick. Carbon steel was chosen because its corrosion behaviour in the highly alkaline environment that will be conditioned by the surrounding cement is well known and because carbon steel is much less prone to localised corrosion processes than other steels (ONDRAF/NIRAS, 2004a). For HLW, the space between the HLW canisters and the overpack will be filled with silica glass frit, or an equivalent inert granular material or powder, and the residual void space evacuated before the overpack is sealed by welding. The overpack will have a diameter of around 0.5 m. For spent fuel, each assembly may be placed in carbon steel boxes for ease of handling and these may be filled with sand as a criticality control or an inert gas to protect against corrosion. These boxes will be supported within the overpack by a carbon steel or cast iron basket and the residual void space evacuated before the overpack is sealed by welding. The external diameter of the overpack will be around 0.9 m for UOX SF and 0.4 m for MOX (Bel *et al.* 2005; Fabry *et al.* 2006).

Buffer: A Portland Cement (PC)-concrete buffer, around 0.7 m thick, has been chosen because this will provide a high pH environment around the overpack that will be present for the duration of the thermal period, inhibiting corrosion (Bel *et al.* 2005, 2006). The formulation of the concrete is chosen to minimise the formation of unfavourable cement phases such as ettringite with high SO4 content (high molar volume which can cause cracking or localised stresses if within a restricted volume) or hydrogarnet from high Al (low molar volume, increases porosity and permeability). ONDRAF/NIRAS is currently evaluating the performance of normal and self-compacting PC-concrete.

Handling shell: The supercontainer will be encased in a cylindrical envelope, made from 6 mm-thick stainless steel sheeting with a solid welded bottom and lid (Bel *et al.* 2005). It is not yet decided whether the steel envelope will be constructed with openings, to allow free entry and exit of water and gas, or whether it will initially be sealed. The method of attaching the lid is also yet to be decided.

Backfill: The void space between the tunnel and the supercontainer will be filled with a cementitious material before the tunnels are sealed with concrete and clay plugs. The exact composition of the backfill and it emplacement mechanism have yet to be determined, although it is likely to be based on a Portland Cement with a carbonate aggregate.

Disposal tunnels: The tunnels, 3.6 m in excavated diameter, will be lined and supported with ~0.3 m thick concrete wedge blocks. Each tunnel will be ~1000 m long and there will be approximately 50 m between disposal tunnels, except for spent fuel, where there will be 120 m inter-distance.

Safety functions of the barriers:

Supercontainer: The "supercontainer" and its components provide a permanent radiation shield. In addition to this, it is constructed at surface level, which keeps handling operations in the subsurface to a minimum thus ensuring optimum protection for the operators.

Overpack: The overpack safety function is to confine the radionuclides during the thermal phase, a period of several hundred years for HLW and up to a few thousand years for spent fuel.

Buffer: The primary function of the concrete buffer is to provide a high-pH environment at the surface of the overpack during the thermal phase. High-pH conditions will fully passivate the carbon steel and keep corrosion rates low, thereby ensuring that the overpack will completely contain the waste during the thermal phase. The buffer also functions as a radiological shield so that dose rates at the outer surface of the supercontainer are low and the containers can be handled without using additional shielding, of benefit during the operational phase.

Handling shell: The function of the steel envelope is to provide mechanical strength and thereby facilitate fabrication of the buffer and handling of the supercontainer (Bel *et al.* 2006). The shell may, if sealed, also prevent water ingress from the Boom Clay for a time, and may facilitate monitoring during the operational period by allowing instrumentation to be attached to the external surface of the supercontainer. However, no reliance is placed on the envelope for ensuring long-term radiological safety, and it is possible that it may be manufactured with vents, or it may even be decided not to have an envelope at all (this is yet to be decided).

Backfill: Backfill reduces the void space around the supercontainer to improve mechanical integrity of the EBS and protect the buffer from early cracking, enhancing the longevity of the overpacks. By providing high pH conditions, corrosion of the steel handling shell will also be limited, reducing H_2 gas generation.

Host rock: The role of the host rock is to provide a barrier to radionuclide transport so that retardation and decay, or dispersion, of released radionuclides occurs during transport to the biosphere; the Boom Clay will act as a very effective barrier to the migration of radionuclides (ONDRAF/NIRAS, 2002). However, data on the behaviour of radionuclides in the Boom Clay at elevated temperatures (over 25°C) is limited and difficult to quantify accurately. Therefore, the disposal concept for Category C wastes requires containment of the radioactivity during the thermal phase, so that radionuclides do not enter the Boom Clay when temperatures are high.

Safety functions of other components:

Disposal tunnel seals: The disposal tunnel seals play an important role in preventing transport of radionuclides along the disposal tunnel engineered disturbed zone (EDZ) and linking to adjoining access tunnels/EDZ's and/or providing a short-circuit to the surface.

PA/SA studies:

None currently published.

Significant changes since first envisaged:

None.

Detailed variants worth recording:

None.

3. Development and Operation

Requirements on site:

Belgium has yet to select a site for its geological disposal concept but the Boom Clay and the Mol–Dessel nuclear zone are known as the reference host formation and the reference site for the research programme, whilst the Ypresian Clays and the Doel nuclear zone form the alternative. No site requirements have been published but the disposal concept specified has been designed for a host environment of poorly-indurated clay (implying environments G3 or G4 in this study), which will act as a barrier to radionuclide migration.

Demands on site characterisation procedure:

In a low or no-flow host rock which can be relied on to provide a significant diffusion barrier, the main demand from site characterisation is to demonstrate that these properties are stable, long-lived, homogeneous and that the extent (vertical and lateral) of the host rock is sufficient.

Excavation / construction processes:

ONDRAF/NIRAS plans to co-dispose of Category B (equivalent to long-lived L/ILW) and Category C waste in different areas of the same geological disposal facility, with the area for Category B waste being constructed and operated first. Excavation and construction of all the disposal tunnels will be by tunnel boring machine (TBM) in combination with a wedge block technique for tunnel lining: such constructional feasibility has been demonstrated at the underground research facility in Mol (Bel *et al.* 2005).

Implications for requirement/location for encapsulation facility:

The large size of the full supercontainer means that transport may not be very efficient and could potentially cause damage to the concrete buffer parts, suggesting that supercontainer assembly is preferably carried out on site.

The supercontainer will be fabricated in four main stages: Stage 1 will emplace the buffer concrete in the steel envelope to from a ‘U’-shaped vessel; Stage 2 will emplace the waste overpack into the vessel; Stage 3 will fill the small annulus between the concrete vessel and overpack with a specific concrete or powder; and Stage 4 will emplace the concrete lid before sealing of the supercontainer. Stages 2 to 4 will be carried out in a “hot cell” to protect workers from radiation (Bel *et al.* 2006).

Operational / emplacement procedures:

A preliminary feasibility study compared three different transportation techniques (rail, wheel and air cushion) at different areas of the repository (above ground, in the access tunnel and in the disposal tunnel). All three techniques were shown to be feasible although the air cushion was considered the best because of its ease of use, robustness, manoeuvrability (enabling 90^o turns), minimised tunnel dimensions and safe energy supply. However, some technical issues remain to resolved, related to geometrical tolerances of the tunnel floor, the compressed air supply and the mechanical stability of the disposal package during transportation.

ONDRAF/NIRAS has begun a basic design study, in collaboration with Babcock Noell and Belgatom, for the underground transportation of the supercontainer by use of a trolley on air cushions. Currently, it is proposed to supply the compressed air by means of a long rigid duct mounted along the length of the disposal tunnel wall or floor. This duct will be provided with equidistant connection points to which an air supply hose can be connected. This air supply hose, which can be wound on a drum attached to the transportation trolley, needs then to be disconnected after a certain distance (e.g. 100 m) and reconnected to the next supply point of the duct. When a waste package has arrived at its disposal location, the air cushions will be deflated, and the waste package lowered onto a concrete support structure on the floor of the disposal tunnel. The trolley will then return to collect a following waste package. Within the HLW disposal tunnels, there will be an alternation between sequences of waste emplacement operations and backfill operations.

Key aspects and components for QA focus:

The major component of the long-term safety is the geosphere barrier; thus characterisation of the site and host rock properties is a key issue. For the shorter term (thermal period), the integrity of the concrete buffer and the initial condition of the overpack (free of defects) before emplacement in the supercontainer are also very important to ensure early performance requirements are met. As the supercontainer and its components will be constructed in above ground facilities, this should enable easier quality assurance.

4. Programme Management

Key stages and time plan flexibility:

ONDRAF/NIRAS estimate construction of the repository for Category B waste from 2025 to 2040, with operation and emplacement for the first waste disposal group between 2040 and 2050, with the second group of Category B waste emplaced between 2055 and 2065. The additional construction required for Category C waste will take place between 2065 and 2080, with operation from 2080 to 2090. This assumes the following (Bel *et al.* 2005):

- Site preparation and construction of the shafts: 10 years.
- Construction of specific access and disposal tunnels: about 5 years for long-lived L/ILW and 15 for HLW.
- Disposal operations: 10 years.
- Overall repository closure and preparation for long-term institutional control: 10 years.
- Post-conditioning activities are not in the critical path of planning.

The time schedule for any monitoring and sealing and closure of the disposal tunnels is not yet specified.

Retrieval options:

Retrievability is not a requirement and is therefore not actively pursued in this design. Details of any waste retrieval options for this design have not been published but, in principle, the absence of bentonite and the presence of the handling shell / concrete buffer should make retrieval over the initial period quite straightforward. However, any grout backfill would still need to be excavated, either through water jetting or mining techniques, which could be an argument for a different backfill material if retrievability were to be required.

Pre-closure monitoring requirements:

No special requirements beyond expected site characterisation and monitoring activities have been noted.

Post-closure monitoring options:

Underground monitoring of limited parts of the disposal area (or a dedicated ‘pilot’ section) may be possible for the period before backfilling and closure.

5. Environmental Impacts

Spoil volumes / storage:

No figures have been published for the spoil volumes but a first evaluation has resulted in the following indicative data (de Bock 2007): 0.13 x 10^6 m^3 of spoil from the excavation of the first section of the repository (in principle for category B waste) and 0.10 x 10^6 m^3 of spoil from the excavation of the second section of the repository (in principle for category C waste).

Resources and availability:

Again, no figures have been published for the volumes of materials to be used but of the order of ten thousand tonnes of steel and a hundred thousand tonnes of concrete will be required for the supercontainers. Additional concrete will also be required for the tunnel liners. For backfilling the disposal drifts with a specific cement, about 2 tonnes per metre of drift will be needed (De Bock 2007).

Both concrete and steel are readily available, although this may change in the future. It is also possible to recycle and reuse steel from nuclear power plant decommissioning.

Transport of materials:

This depends on the amounts of materials and the site location.

Nature of surface facilities required:

The surface facilities may be somewhat larger than non-supercontainer concepts if the encapsulation facility is combined with the supercontainer assembly facility.

Any special noise or visual issues:

This is expected to be similar to other mined concepts in terms of visual and noise impacts.

6. Key Uncertainties and Outstanding R&D

Uncertainties in the components of the supercontainers, decisions still to be taken, and further research requirements include:

- Effectiveness of passivation and the overpack thickness.
- Investigation of other ferrous metals than carbon steel for the overpack to reduce gas generation.
- Develop a design for sealing drifts, tunnels and shafts.
- Design for the supercontainer supports.
- Decision on the technology for underground transport of the supercontainers (air cushion or rail transport, descent of the supercontainer through the shaft in vertical or horizontal position)
- Composition and mechanism for emplacement of the different supercontainer concrete phases
- Design of the steel envelope and supercontainer closure mechanism (whether the envelope should have vents to allow the escape of gas generated within the supercontainer and to allow rapid saturation of the buffer concrete after the tunnels are sealed, or whether an envelope should be present at all).
- Boom Clay boundary conditions (particularly, the likely composition and persistence of disturbed pore water compositions).

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Appendix B Acronyms

AGR	Advanced Gas-Cooled Reactor NPP
CDC	Concrete Disposal Cask
CoRWM	Committee on Radioactive Waste Management
DSSC	Disposal System Safety Case
EBS	Engineered Barrier System
EDZ	Engineered Disturbed/Damaged Zone
GTS	Grimsel Test Site, Switzerland
HLW	High Level Waste
ILW	Intermediate Level Waste
IRF	Instant Release Fraction
LILW-LL	Long-Lived Low and Intermediate Level Waste
MPC	Multi-Purpose (transport/storage/disposal) Container
MRWS	Managing Radioactive Waste Safely programme
NDA	Nuclear Decommissioning Authority
NPP	Nuclear Power Plant
OCRWM	USA Department of Energy (DOE) Office of Civilian Radioactive Waste Management
OPC	Ordinary Portland Cement
OPG	Ontario Power Generation, Canada
PGRC	Phased Geological Disposal Concept for ILW
PWR	Pressurised Water Reactor NPP
SF	Spent Fuel
TCHM	Thermal, Chemical, Hydrogeological and Mechanical properties
tHM	Tonnes of Heavy Metal
WP	Waste Package