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DESIGN OPTIONS FOR THE UK'S ILW GEOLOGICAL DISPOSAL FACILITY

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ABSTRACT

Over the last few years, a major national programme of public consultation has been under way in the UK resulting, in 2006, in the announcement by government of geological disposal as the most appropriate solution for the long-term management of the UK's long-lived and higher-activity radioactive waste and the launch, in 2008, of an implementation programme. The approach being pursued is to solicit volunteer communities to host a geological disposal facility, which may contain not only intermediate-level waste (ILW) and some low-level waste (LLW), but also high-level waste (HLW), any spent fuel (SF) declared as waste, and potentially other materials that may be declared as waste. These wastes have different physical, chemical, thermal and radiological characteristics, and different concepts will be required to accommodate their disposal, potentially in a single facility.

The volunteer approach means that the geological environment that might eventually emerge as the preferred location is not known at the outset. Indeed, the siting process may require evaluation of several different geological environments because the UK has rich geological variability for such a small landmass. Consequently, the Nuclear Decommissioning Authority (NDA), which is charged with designing, developing and implementing a geological disposal facility, has investigated facility designs that could be appropriate for a wide range of host rocks and geological environments.

This paper presents the results of a project carried out on behalf of the NDA to collate and report information on concepts for the geological disposal of ILW/LLW; a separate project carried out a parallel evaluation of options for disposing of

HLW and SF. Initially, the range of geological disposal facility design options available worldwide for the disposal of ILW/LLW was evaluated. Nine disposal concepts were identified and reviewed that would cater for any geological environment likely to arise in the UK. These concepts have different engineering and operational aspects. The appropriateness of each option for implementation in five different generic geological environments was assessed using expert judgement, with input from the NDA, consultants and the UK regulatory agencies. The paper presents a set of generic designs derived from the study and discusses the key issues that would need to be addressed should any of these designs be considered for implementation in specific geological environments in the UK.

The findings of this work are intended to provide a resource to support comparisons of alternative disposal concepts and the identification of designs suitable for the disposal of UK ILW/LLW in different geological environments.

INTRODUCTION

Research into the geological disposal of radioactive waste began in the UK in the 1970s. Research initially focused on studies on HLW disposal, but the need to carry out field-based research in a range of geological environments precipitated local opposition to the essential drilling programmes and the government of the day cancelled the programme in 1981. Thereafter, greater priority was given to research into ILW and LLW disposal. These wastes arise from electricity generation in nuclear power stations, the production and processing of nuclear fuel, the use of radioactive materials in industry, medicine and research, and from military nuclear programmes.

In July 1991, Sellafield was announced as the preferred site for a geological disposal facility (GDF) for ILW/LLW and the following year Nirex announced a plan to develop a Rock Characterisation Facility (RCF) at Sellafield in order to gather further information for the site investigation programme. Although the RCF was refused planning permission in 1997, investigations of the Sellafield site and development of the RCF design did inform development of the Sellafield GDF concept, the Deep Waste Repository (DWR).

The DWR concept was underpinned by option studies carried out by Nirex in the 1980s that led to the preference for steel and cement waste containers, waste emplacement in underground caverns, and the use of a cementitious backfill, in particular, the Nirex Reference Vault Backfill (NRVB). Following refusal of the Sellafield RCF planning application and subsequent appeal in 1997, Nirex focused on more general studies to develop the Phased Geological Repository Concept (PGRC) for a GDF in strong rock, but not associated with any specific site (Nirex, 2001; 2003a). The PGRC was based on the DWR multi-barrier approach, but a key development was the introduction of phasing of disposal operations to include a period of retrievable underground storage of waste packages.

In 2001, the UK Government began a concerted project to address the legacy of wastes from the historic development of nuclear energy. It initiated the 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 October 2006 the government accepted CoRWM's recommendations for geological disposal of higher activity wastes (published in July 2006) and made the NDA responsible for implementing this policy.

In 2008, the UK Government published a White Paper that set out requirements for implementation of geological disposal in the UK (Defra *et al.*, 2008). The White Paper emphasised CoRWM's recommendation of a commitment to undertaking a site selection process for a GDF based upon voluntarism. It became apparent that such an approach could lead to the consideration of several different geological environments. The UK possesses a diverse range of geological environments, many of which could prove suitable for geological disposal. Consequently, it became clear that a range of GDF concepts needed to be studied that are designed in different ways to address and take advantage of the varying properties of this range of rock formations and geological environments that might be available.

The White Paper defined a UK Baseline Inventory of higher-activity radioactive wastes that was based largely on the 2007 UK radioactive waste inventory (Defra and NDA, 2008). The Baseline Inventory included some 364,000 m³ of ILW and 17,000 m³ of LLW that would require disposal. In this paper, we discuss generic designs being considered for disposal of this ILW/LLW in the UK and the key issues that will need to be addressed if and when the designs are to be deployed in specific

geological environments. For example, decisions regarding the design of the facility will need to take account of wastes that are already packaged. The generic designs described here have been identified by evaluating a range of design options available worldwide for the disposal of ILW/LLW. The detailed findings of this study were reported by Hicks *et al.* (2008).

The White Paper included a requirement for the NDA to consider the development of a single co-located GDF for the disposal of the UK's higher-activity radioactive wastes. The generic designs for LLW/ILW disposal described in this paper could be considered to represent the LLW/ILW disposal module of a GDF for HLW/SF and ILW/LLW. A parallel NDA project carried out an evaluation of options for the geological disposal of HLW and SF (Baldwin *et al.*, 2008; Chapman *et al.*, 2009).

DEVELOPMENT OF THE PHASED GEOLOGICAL REPOSITORY CONCEPT IN THE UK

The research carried out in the UK since the 1980s on waste packaging, GDF design, and backfilling led to the development of the PGRC, which the NDA currently presents as an illustrative example of a GDF for ILW/LLW in a higher-strength host rock. The PGRC envisages emplacement of ILW/LLW in a facility constructed at depth in a stable geology with a low groundwater flux through the near-field. Initially, the facility would be operated as a store in which the waste would be monitored and would be readily retrievable if deemed necessary. The elements of the PGRC are illustrated in Figure 1 (Nirex, 2003a; 2005).

The successive stages of waste immobilisation in steel and concrete containers, emplacement of waste packages in underground vaults, backfilling of vaults with a cementitious material, and GDF sealing and closure define a multi-barrier disposal concept in which each barrier performs a specific safety function, as illustrated in Figure 2. The safety of the GDF is not completely dependent on any one barrier and, after closure, does not rely on the actions of future generations.

Key stages in the development of the components of the PGRC are described below.

Containers and immobilisation matrices

Wastes must be made passively safe for disposal. Liquids and sludges must be converted into solid wasteforms and particulate matter and fragmented solid waste must be immobilised. In the UK, waste immobilisation is typically carried out using cement grouts.

Liquid or sludge wastes are mixed with cement to form a relatively homogeneous wasteform. Solid waste items are placed in containers which are then filled by pumping in a fluid cement grout. Wastes such as supercompacted drum wastes are typically surrounded by an annulus of grout or concrete within disposal containers.

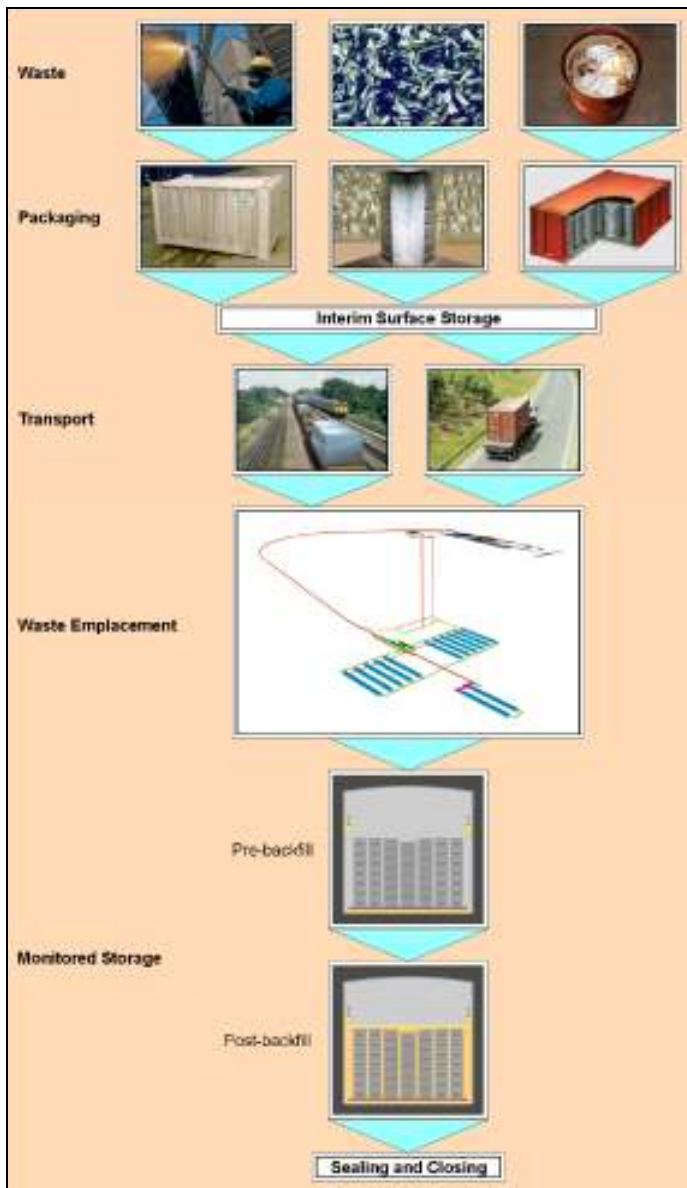


Figure 1: The components of phased geological disposal, in which packaged ILW and LLW are emplaced in a GDF that is eventually sealed and closed (Nirex, 2003b).

Options for safe handling and transporting waste packages depend on the extent of radiation shielding provided by the waste container. In an early conceptual design study, Nirex (1983) considered the possibility of packaging all wastes in self-shielding packages in order to simplify waste handling procedures. At that time, emplacement of self-shielded waste packages was not favoured because the shielding would result in increased package size and weight, an increase in the excavated GDF volume, and a substantial increase in disposal costs.

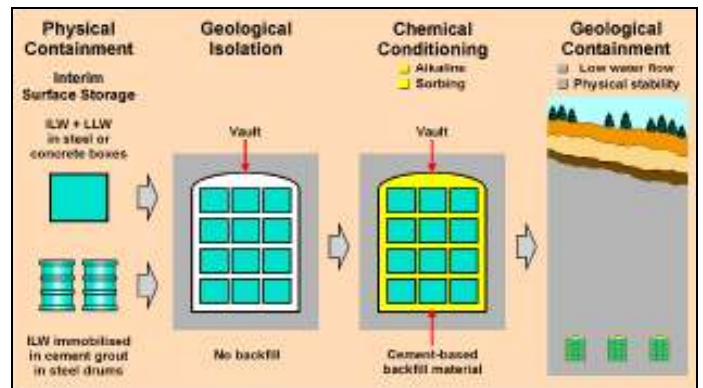


Figure 2: The components of the multi-barrier GDF concept for ILW and LLW (Nirex, 2003b).

Nirex also considered the option of implementing reusable shielding for waste package handling and transport operations away from the GDF, and adding sufficient shielding to waste packages at the disposal site to enable semi-remote handling operations. This option was estimated to result in a smaller radiological detriment than reusable shielding alone, but would be more expensive.

Since these early studies, the option of using unshielded waste packages for most wastes and remote handling equipment to emplace such waste packages in a GDF has been adopted. Shielded packages are only used for sufficiently benign wastes and these waste packages would be placed in separate vaults from those containing the unshielded packages.

Research on waste containers has focused on the development of a range of standard containers for ILW and LLW to simplify quality control procedures and waste package transport and handling, and to allow operations to be optimised around a limited number of variants. The 500 litre Drum, 3 m³ Box, 3 m³ Drum and 2 metre Box may be used as unshielded packages and the 2 metre Box and 4 metre Box may be used as shielded packages (Nirex, 2007).

Waste producers may develop their own containers, but these containers must meet the same requirements as the standard containers. NDA assesses waste producers' proposals for waste packaging for compatibility with the PGRC and compliance with the Generic Waste Package Specification through the Letter of Compliance (LoC) process.

Within the GDF, the container and immobilised wastefrom provide a physical barrier, limiting groundwater access to the wastes and thereby limiting dissolution and subsequent transport of radionuclides. The containers will not provide absolute containment, because most will be vented to prevent the build up of internal gas pressure, but they will prevent the release of many short-lived radionuclides before they have decayed to insignificant amounts (Nirex, 2003b).

GDF Design

Nirex undertook research on ILW disposal in the 1980s that included study of concepts appropriate to various generic host rock formations (soft plastic clay, hard mudrock, crystalline rock and saliferous rocks) (Nirex, 1983). The various GDF configurations and designs considered were directly dependent on the stability of the host formation, with the size of the disposal cavern or tunnel dependent on the competency of the rock.

Nirex (1987) proposed a GDF situated either under land or under the seabed and suggested cavern, tunnel, and borehole disposal options. Subsequently, offshore and land-based concepts were investigated in a number of design studies that considered the suitability of caverns, silos, boreholes, shafts, block-and-pillar vaults, and tunnels for ILW disposal in different geological environments.

Based on these early conceptual design studies, Nirex concluded that caverns could be constructed in strong, unfaulted granitic rock by established engineering methods. Lined tunnels were preferred in softer sedimentary formations. Caverns or disposal shafts were considered feasible for off-shore locations in hard rock. Caverns were thought to be viable in off-shore chalk environments, but disposal shafts were not considered to be practicable because of the requirement for costly shaft support and lining. The construction and operation costs of an off-shore facility were noted to be intrinsically greater than a land-based option.

The DWR concept, proposed by Nirex (1992) for a GDF at Sellafield, consisted of an array of vaults (600 m and 900 m long) excavated in hard, low-permeability rock (the Borrowdale Volcanic Group) at a depth of around 900 m. Unshielded ILW vaults would be segregated into separate compartments along the length of the vault by concrete walls to enable controlled backfilling in batches. During the period leading up to the Sellafield RCF planning application, the DWR concept underwent many revisions, including adjustments to vault dimensions, backfilling schedules, removal of bin walls from the design and a change from shaft to drift access ways (Nirex, 1998a;b).

The generic GDF studies undertaken by Nirex after the refusal of the Sellafield RCF planning application in 1997 assumed, for assessment purposes, a GDF depth of 650 m, with an upper sequence of high-permeability sedimentary rocks overlying a sequence of low-permeability sedimentary rocks and with low-permeability hard rocks at GDF depth (Nirex, 2001; 2003a). The design assumed 300 m long horizontal vaults for waste emplacement within rock of such quality that minimal rock support and drainage would be required. GDF access would be achieved through one drift and two shafts.

Backfilling

Research undertaken on backfill materials led to the selection of the NRVB as the reference backfill for the generic GDF design. NRVB is a cementitious material that is chemically and physically compatible with the wasteforms in

the UK ILW inventory, which are generally cementitious. Other backfill options have been considered as reported by Francis *et al.* (1997). These options included no backfill, loose aggregates, clays, and cement-based materials. Nirex (Francis *et al.* 1997) selected a cementitious backfill in preference to a clay backfill because preliminary studies indicated that, as a chemical barrier, the cementitious material would provide superior radionuclide containment.

The main purpose of a cementitious backfill is to provide a high pH environment throughout the GDF near-field to limit radionuclide solubilities in the long term. Research culminated in the selection of the preferred and patented NRVB mixture of Portland cement, water, hydrated lime and limestone flour. Such a mixture produces a porous cement (promoting homogeneity and allowing gas migration), has high alkalinity for long-lived chemical conditioning, results in good void filling, has an absence of organic additives (which avoids formation of metal-organic complexes), and has relatively low strength compared with other cements (aiding package retrievability, if required) (Crossland and Vines, 2001).

Various methods of emplacing backfill were considered. By 1997, the design had developed to one in which the backfill is delivered from a backfill gallery above and between adjacent vaults, with the backfill pumped from these galleries through predrilled holes into the vaults (Nirex, 2003a).

Until the late 1990s, waste retrievability was considered, but was limited to reversing the waste package emplacement steps in the time prior to backfilling, or mining out packages after the GDF had been backfilled and sealed. Nirex carried out a study (Dixon *et al.*, 1997a) on backfill timing options, which concluded that deferred backfilling offered simplified civil and mechanical engineering, would not require bin walls, would enable the most recent backfill knowledge to be applied and would also make package retrieval easier during the open period. Nirex (1998a) therefore proposed deferred backfilling of all vaults until just before GDF closure as the reference design. Retrievability remains an important element of the disposal process and is built into the PGRC through its phased approach.

REVIEW OF ILW/LLW DISPOSAL CONCEPTS

In order to develop an understanding of how different types of multi-barrier disposal concepts are suited to different geological environments, information on the following nine concepts for the disposal of ILW/LLW or transuranic (TRU) waste investigated in other countries was compiled:

1. Belgium. In-tunnel disposal of ILW/LLW in a plastic clay host rock, with waste containers shielded in concrete disposal units that are emplaced axially in the concrete-lined tunnels. No specific site has been selected but the design reference case assumes the disposal facility will be constructed 200 to 250 m deep in the Boom Clay.

2. France. In-tunnel disposal of ILW/LLW at a depth of about 500 m in an indurated clay host rock (the Callovo-Oxfordian Formation), with waste containers packaged in concrete overpacks that are stacked in the concrete-lined tunnels; a separate disposal region is included for wastes that contain organic matter.

3. U.S. In-vault disposal of TRU waste at a depth of 655 m in a low-permeability salt host rock, with remote-handled waste packages inserted in vault walls, contact-handled waste packages stacked on vault floors, and with MgO included as backfill.

4. Switzerland. In-tunnel disposal of TRU waste at a depth of 600 to 750 m in an indurated clay host rock (the Opalinus Clay), with waste containers packaged in concrete disposal units that are stacked in the concrete-lined tunnels, and with gas-permeable mortar included as a backfill; wastes that contain nitrates and chelating agents are isolated in a single disposal tunnel.

5. Switzerland. In-tunnel disposal of ILW/LLW in a low-permeability marl host rock at Wellenberg, with waste containers packaged in concrete disposal units that are stacked in the concrete-lined tunnels, and with gas-permeable mortar included as a backfill. The concept was abandoned in 2002 following the results of local referendums.

6. Japan. In-tunnel disposal of TRU waste in hard or soft host rocks, with waste containers grouted into steel emplacement containers that are stacked in the tunnels (concrete-lined in soft rocks), and with grout included as a backfill; a bentonite barrier is included for some wastes, and wastes that contain nitrates are isolated in a separate disposal region.

7. Sweden. SFL 3-5 concept for in-cavern disposal of ILW/LLW in a crystalline host rock, with wastes packaged in concrete and steel containers that are stacked in the caverns (low-activity wastes) or grouted in concrete vaults within the caverns (high-activity wastes); the caverns are backfilled with crushed rock that acts as a permeable hydraulic cage diverting flow around the wastes. Note that plans for ILW/LLW disposal in Sweden have changed recently and the SFL 3-5 GDF will not be developed.

8. Canada. In-room disposal of ILW/LLW at a depth of 680 m in a low-permeability limestone host rock, with LLW and shielded ILW containers stacked in separate rooms (no backfill).

9. Germany. In-cavern disposal of ILW/LLW at depths of 800 to 1300 m in a sequence of argillaceous formations utilizing a disused iron ore mine at Konrad, with waste

containers cemented into steel emplacement containers that are stacked in the caverns; the caverns are backfilled with grout.

Detailed datasheets were compiled that described each disposal concept and the safety functions of the barrier systems (see Hicks *et al.*, 2008). By considering the range of GDF designs (i.e. tunnels, caverns, vaults, or rooms), disposal package options (i.e. remote handled or contact handled), and backfill/buffer options (i.e. no backfill, backfill for structural support, or buffer for chemical conditioning) that have been developed for different host rocks, a set of generic concepts was identified for different types of geological environment.

Development of the generic concepts involved defining a set of generic geological environments in terms of hydrogeological, chemical, and mechanical properties. The geological environments, shown as G1 to G5 in Table 1, refer to the environments at GDF depth and are identical to those previously identified by Baldwin *et al.* (2008) in the study of HLW/SF disposal concepts. The hydrogeological properties influence the isolation capability of the geological environment and degradation behaviour of engineered materials; chemical properties affect the stability of natural and engineered materials such as clays and metals in the GDF; and mechanical properties determine the size of openings that can be constructed and the types of support system and maintenance that will be required, and influence the ability to retrieve waste after emplacement. These descriptions apply at disposal facility depth only.

Seven generic GDF concepts were identified and summarised in a series of diagrams (Figures 3 to 9) that illustrate the key components of the concepts in the different geological environments.

Table 1: Geological environments considered as potential GDF host rocks (Baldwin *et al.*, 2008).

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.

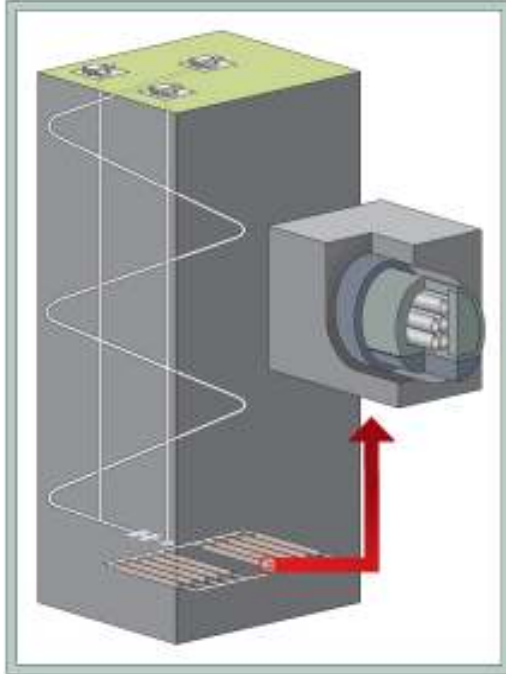


Figure 3: Shielded disposal packages placed in concrete-lined tunnels (not backfilled) in lower-strength rock with little or no groundwater flow (e.g. Belgian ILW/LLW).

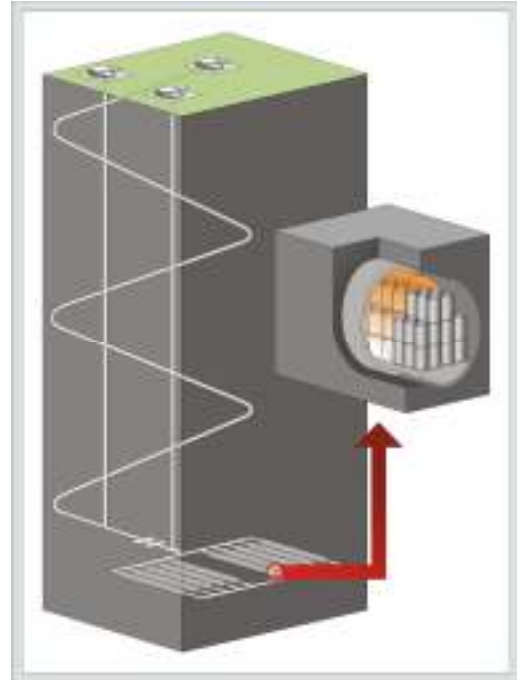


Figure 5: Unshielded disposal packages stacked in concrete-lined tunnels or caverns (grout backfilled) in lower-strength rock with little or no groundwater flow (e.g. Japanese TRU, Swiss TRU, Swiss ILW/LLW, and German ILW/LLW).

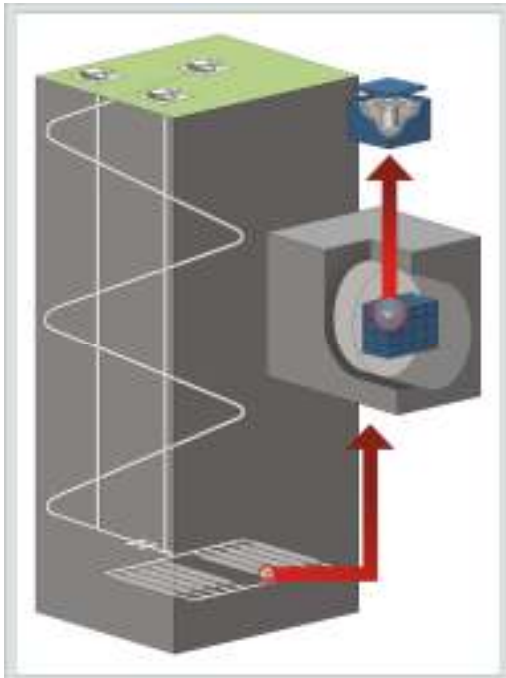


Figure 4: Unshielded disposal packages stacked in concrete-lined tunnels (not backfilled) in lower-strength rock with little or no groundwater flow (e.g. French ILW/LLW).

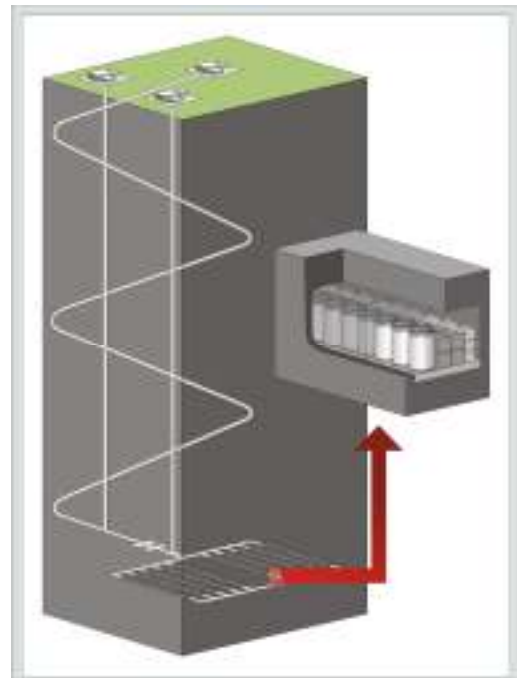


Figure 6: Shielded waste packages stacked in disposal rooms in higher-strength rock with little or no groundwater flow (e.g. Canadian ILW/LLW).

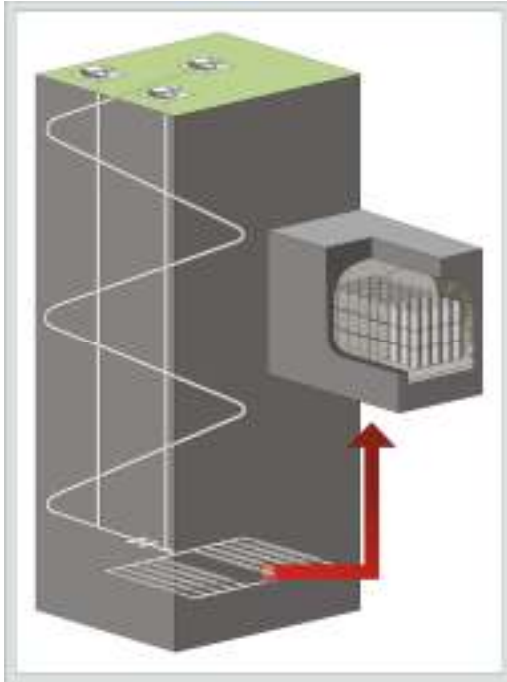


Figure 7: Unshielded disposal packages stacked in tunnels or caverns (grout backfilled) in higher-strength rock with little or no groundwater flow (e.g. UK PGRC and Japanese TRU).

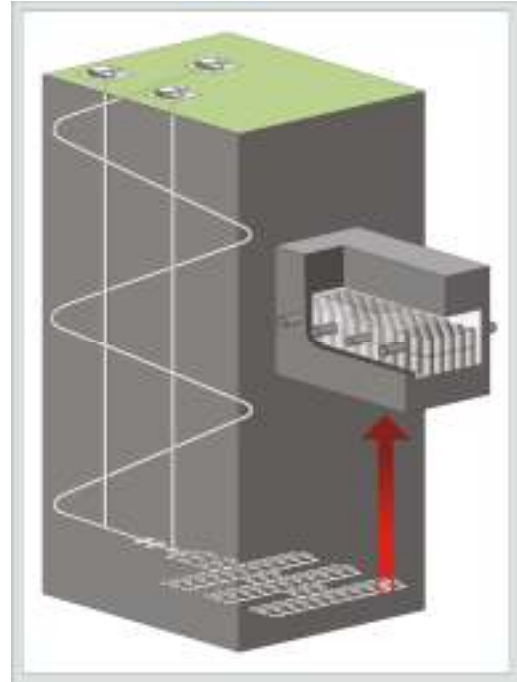


Figure 9: Contact-handled disposal packages stacked in emplacement rooms and remote-handled packages inserted in vault walls in plastic evaporite rock with no groundwater flow (e.g. U.S. TRU).

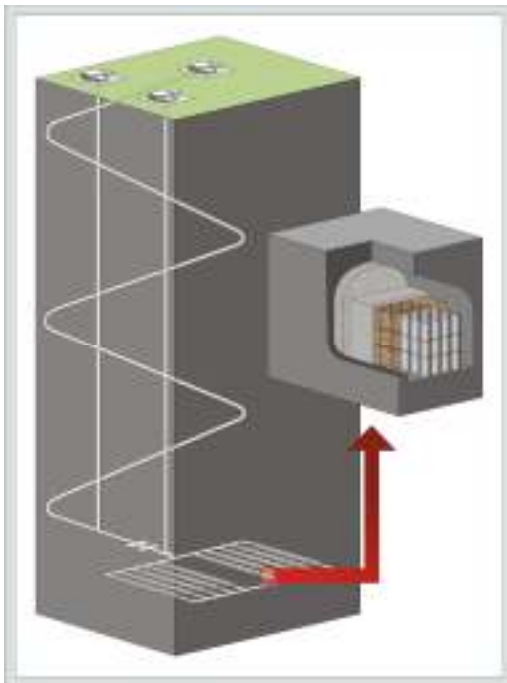


Figure 8: Unshielded disposal packages stacked in vaults (grout backfilled) with surrounding hydraulic cage in higher-strength rock with potentially significant groundwater flow (e.g. Swedish ILW/LLW).

GDF concepts developed for lower-strength rocks (plastic or indurated clay) generally involve disposal tunnels or caverns that are concrete-lined for mechanical stability (Figures 3 to 5). The low-permeability host rock is generally regarded as the most important barrier to long-term migration of radionuclides, and the tendency for cracks and fissures to self-heal over time is a key quality of such rocks. The Belgian, French, Japanese (soft rock), Swiss, and German concepts are in this category.

These concepts generally include concrete in immobilisation matrices, emplacement packages, and tunnel liners, and may include grout backfill. These materials provide an alkaline (and generally reducing) GDF environment which limits the solubility of many radionuclides. Radionuclide release is also constrained by sorption on concrete. Disposal tunnel, cavern, and shaft seals play an important role in preventing transport of radionuclides along adjoining access tunnels and to the ground surface. However, the role of cementitious and other engineered barrier system (EBS) materials in limiting radionuclide migration is generally not considered to be as important as the role of the low-permeability geosphere. In particular, the grout backfill used in the German concept has no long-term safety requirement.

GDF concepts developed for higher-strength rocks where there is little or no groundwater flow generally involve disposal tunnels, rooms, or caverns that include rock bolts for mechanical stability (Figures 6 and 7). The Canadian and

Japanese (hard rock) GDF concepts are in this category and the UK PGRC would also lie in this category.

In the Canadian concept, the low-permeability geological environment, including rocks overlying the host rock, is regarded as the most important barrier to long-term migration of radionuclides.

Backfill is not used in the Canadian concept, but has an important post-closure role in the Japanese hard rock concept where there may be low groundwater flow. The highly alkaline (and generally reducing) environment generated by the grout backfill is expected to limit the solubility of many radionuclides and radionuclide release is expected to be constrained by sorption on the backfill. In the Japanese concept, a bentonite buffer may also be included to ensure diffusion-dominated solute transport and to act as a barrier to colloid migration.

The only GDF concept reviewed that has been developed for strong rocks where there is low but potentially significant groundwater flow is the Swedish concept. The role of the EBS in limiting radionuclide migration is far more important in this case than for concepts in which there is little or no groundwater flow. The Swedish concept involves a multi-barrier system in which cementitious materials provide chemical conditioning and minimise flow around the waste, and a crushed rock backfill (hydraulic cage) serves to divert flow away from the waste packages (Figure 8).

The U.S. WIPP GDF relies primarily on a thick low-permeability salt rock horizon to provide a barrier to radionuclide migration and to enclose the waste as a result of salt creep (Figure 9). Emplaced MgO will also serve to buffer the pH such that actinide solubilities are limited.

EVALUATION OF CONCEPTS

Each of the nine disposal concepts was assessed in terms of issues regarding its implementation in the five broad geological environments shown in Table 1, its advantages and shortcomings 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. Specific information on the appropriateness of the concepts was elicited by using a set of evaluation factors (Table 2). The review focused on consideration of technical and engineering feasibility factors because most other evaluation factors did not allow any significant distinguishing comments to be made. However, the range of evaluation factors may become more significant once specific sites are identified.

The results of the review were recorded on evaluation matrices for each national disposal concept examined, with comments provided for each evaluation factor with respect to each geological environment. The detailed results of the review are presented in Hicks *et al.* (2008).

Table 2: GDF evaluation factors

Headline Factors	Sub-factors
Technical & Engineering Feasibility	Flexibility
	Ease and implications of retrievability
	Maturity of technology / R&D requirements
	Timescale for implementation, construction, operation and closure
	Ease of facility construction and waste emplacement
Safety	Risk to the public
	Operational safety
	Ease of making a post-closure safety case
Impact on the Environment	Non-radioactive waste arisings, radiological and chemical pollution
	Resource and security of supply
	Land use area and density
	Nuisance
Socio-Economic Impact	Socio-economic impacts on the local community
	Burden to future generations
Waste Security and Safeguards	Safeguards capability and security
Cost	Total lifetime cost and spend profile

DISCUSSION OF CONCEPT EVALUATIONS

A key focus of the evaluation process was the flexibility of a concept and its barrier system for implementation in different geological environments and its ability to accommodate the UK ILW inventory.

The Belgian design for ILW/LLW utilises a large concrete monolithic disposal package to provide shielding in order to facilitate waste handling. The monolith concept could be adapted to cater for UK waste packages, although, as noted above, the use of shielded packages for all wastes was judged to be unfavourable when considered in early UK GDF studies. The size of monoliths needed to provide sufficient shielding for UK waste packages has not been determined in the present study, but estimates of GDF footprint have been made based on consideration of the Belgian design. A GDF for UK ILW constructed in a lower-strength host rock would be on the order of 10 km²; such an extensive GDF may not be feasible in the UK, although tunnelling at different levels would reduce the GDF footprint. Alternatively, it may be possible to stack monoliths in large tunnels or caverns in higher-strength host rocks.

Many of the concepts considered (e.g., Belgian, French, Swiss, Canadian, German, and U.S) rely on a low-permeability host rock to provide the principal barrier to radionuclide migration. Indeed, the Canadian concept relies on a multiple geological barrier provided by a low-permeability limestone host rock and approximately 200 m of overlying low-permeability shale. The role that any EBS might have in limiting radionuclide release and migration after GDF closure is generally considered to be of secondary importance. For example, a grout backfill is included in the German concept to ensure stability of the disposal cavern walls and roof and is not required to perform any barrier function with regard to GDF post-closure safety. For such concepts to be considered for geological environments in which potentially significant groundwater flow occurs, the role of the EBS in GDF post-closure performance would become more important. The effects of groundwater movement on the evolution of the EBS and on radionuclide migration after GDF closure would require evaluation and the EBS may require modification to meet GDF post-closure performance requirements.

In particular, the Canadian and U.S. concepts involve minimal engineered barriers and would not be directly transferrable to geological environments in which groundwater flow occurs. However, several of the concepts that rely on the low-permeability of the host rock do include the use of cementitious materials that could serve to limit radionuclide release and migration in the long term, such as:

- Waste packages (grouted wasteforms) may be placed in pre-fabricated concrete disposal containers (shielded in the Belgian concept) or grouted into disposal containers for ease of handling (e.g., French, Swiss, and German concepts).
- Disposal packages may be emplaced in tunnels or vaults that have pre-fabricated concrete liners or walls (Belgian, French, and Swiss concepts).
- Openings may be backfilled with grout after waste emplacement (Swiss and German concepts).

If these concepts were to be implemented in host rocks in which potentially significant flow occurs, then the role of the cementitious materials in limiting radionuclide migration (e.g. low permeability, maintenance of alkaline conditions to limit radionuclide solubilities, and sorption) would become more important. The role of cementitious materials in limiting radionuclide migration is important in the Japanese concept for higher-strength rocks and is also a key feature of the PGRC. The functions of other components, such as bitumen immobilisation matrices and steel containers, would also be of greater significance to GDF post-closure safety assessments where groundwater flow is significant.

The only GDF concept reviewed that has been developed for strong rocks where there is low but potentially significant groundwater flow is the Swedish concept. The concept involves a multi-barrier system in which cementitious materials provide chemical conditioning and minimise flow around the waste, and where a crushed rock backfill (hydraulic cage) serves to divert flow away from the waste packages. Clearly, such a barrier component would not be required for host rocks in which there is insignificant groundwater flow.

The U.S. WIPP concept is the only concept considered in this study that involves disposal in an evaporite rock. The viability of the concept is strongly dependent on the characteristics of the salt host rock: its low permeability provides a barrier to radionuclide migration and salt creep ensures that void spaces are closed and that the wastes are isolated. The concept could be adapted to low-permeability plastic clay host rocks, although differential creep of the clay may create significant perturbations to the local host-rock permeability and open up preferential pathways for both gas and groundwater flow rather than enclose the waste.

The wasteform is an important factor to be considered in the design of the EBS, and several of the GDF concepts reviewed include separate barrier concepts or disposal regions for particular wasteforms:

- In the French concept, waste is conditioned by type: bitumen is used for sludge from effluent treatment; cladding, end pieces, and technological (operational) wastes are compacted; and other wastes are immobilised in concrete. Wastes that may contain traces of fissile materials are placed in specific low-porosity, low-permeability concrete disposal packages for long-term retention of radionuclides. The GDF includes a separate disposal zone for wastes that contain organic matter (e.g. bituminised waste).
- In the U.S. WIPP GDF, remote handled TRU containers are placed in holes in the disposal room walls, and contact handled TRU containers are stacked in the disposal rooms.
- In the Swiss concept for TRU wastes, packages that contain nitrates and chelating agents (which could cause increases in radionuclide solubilities or decreases in sorption) are placed in a separate tunnel away from other wastes.
- In the Japanese concept, different tunnel/cavern designs and disposal regions are envisaged for four distinct groups of waste: 1) spent silver absorbent; 2) fuel hulls and ends; 3) concentrated liquid waste; and 4) wastes that include combustible materials. In particular, the tunnel spacing for the Group 2 wastes will be determined based on consideration of the heat

output of these wastes, and the Group 3 wastes, which contain nitrates, will be located some distance away from the other waste groups in order to limit the potential impact of a nitrate plume.

- In the Swedish concept, different engineered barriers are used for high-activity and low-activity wastes. The concept involves construction of concrete vaults within caverns for high-activity waste packages, with space between the waste containers filled with a porous concrete grout. Such vaults would not be constructed for low-activity wastes.
- In the Canadian concept, ILW and LLW waste packages would be emplaced in separate disposal rooms.

A further issue of relevance to GDF design is any requirement for waste package retrievability. The feasibility of waste package retrievability depends to a large extent on the use and timing of backfilling. Retrievability is a statutory requirement of the French design and this is facilitated by the construction of in-tunnel concrete vaults in which disposal packages are stacked without backfilling. For a tunnel layout, such as in the Belgian concept, selective retrieval of a disposal package from anywhere within the GDF would be difficult because of the number of package movements that may be required.

DISCUSSION

The PGRC serves as an illustrative example for the disposal of the UK's ILW/LLW in a strong rock, to be considered and, if necessary, adapted within the ongoing geological disposal implementation programme. To support the NDA's assessment of GDF concepts, this study has collated information on the range of ILW GDF design options previously considered by Nirex as well as information on ILW disposal concepts that have been developed in other countries. This information provides a resource for use by the NDA to support the identification of concepts suitable for the disposal of ILW/LLW in the UK.

The review of disposal concepts has found that the selection of the EBS and its required performance with regard to post-closure safety clearly depend on both the wasteforms in question and on the GDF host rock. If the host rock and overlying rocks are considered to provide substantial barriers to radionuclide migration, there may be no strong requirement for an EBS to fulfil a post-closure safety function. However, even where the host rock is considered to be the principal barrier, specific packaging concepts may be required for particular wasteforms (for example, to limit the potential for post-closure criticality), or certain types of waste (such as waste containing nitrates) may need to be isolated in order to ensure post-closure performance requirements are met. There does not appear to be

any one concept amongst those reviewed that could not be implemented in the UK for the disposal of the UK's ILW/LLW, provided a host rock with the required properties could be identified and the required performance of the associated EBS could be demonstrated.

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