Radioactive Waste
Management

NDA/RWM/155

Geological Disposal

Concept Status Report

October 2017

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Executive Summary

Geological disposal is the UK Government's policy for managing higher-activity radioactive wastes. The principle of geological disposal is to isolate the waste deep inside a suitable rock formation to ensure that no harmful quantities of radioactivity reach the surface environment at any time. To achieve this, the waste will be placed in an engineered underground containment structure – the geological disposal facility (GDF). This will be designed so that natural and man-made barriers work together to isolate the waste so that no harmful quantities of radioactivity ever reach the surface environment.

A wide range of geological environments in the UK could be suitable for hosting such a GDF. To identify potential sites where a GDF could be located, the UK Government favours a voluntarist approach based on working with communities that are willing to participate in the siting process. This means that the geological environment for the disposal facility will depend on the location of sites identified through discussions with local communities involved in the process.

Selecting the most appropriate solution for implementing geological disposal will require carrying out assessments and making decisions at different levels of detail. As a wide range of engineering solutions are available (some suitable for several geological environments and some more suitable for specific environments), options are continuously being developed and feasibility analysed for the disposal of the UK inventory of higher activity wastes. Each option is termed a 'geological disposal concept'.

As the siting process progresses, a successive programme of optioneering and optimisation will be undertaken to ensure that the most appropriate geological disposal concepts are selected and developed for the chosen site.

A geological disposal concept for a group of wastes is the engineered barrier system and its geometry (layout) required to deliver the safety functions and requirements defined in the disposal system specification, in a particular geological environment. A geological disposal concept is developed for a particular inventory or a particular type or group of wastes and geological setting.

A number of compatible geological disposal concepts could potentially be used in a single 'GDF concept'. A GDF concept for all UK higher activity waste would be expected to function as one integrated system, and must be tailored to site-specific characteristics.

RWM's strategy for the use of geological disposal concepts is to increase the scientific maturity of the options available for consideration as part of the disposal system to an extent that is sufficient to enable selection decisions to be made, based on geological information that becomes available through the site selection process, and to enable sound decisions to be made regarding waste packaging proposals.

The objective of this report is to document the current status of information available on generic geological disposal concepts. These concepts are summarised at a high level for ease of readership. The primary audience for this document is anticipated to be RWM and its contractors.

The report describes the approach being used to develop an understanding of geological disposal concepts for all types of higher activity waste and to prepare for concept selection once site specific information is available. The contribution that engineered barriers working as a combined system can make to safety in particular geologic environments is described, as are the components of typical engineered barrier systems. The combinations of components such as waste packages, buffers and backfill materials are discussed as well as the characteristics of the materials most commonly considered for use in each component. This report also describes, at a high level, the 'illustrative designs' for a sub-set of specific geological disposal concepts that underpin RWM's generic Disposal System

Safety Case and provides specific examples of other national geological disposal programmes concepts.

The current status of knowledge is set out as a gap analysis against RWM’s strategic objectives and the levels of concept maturity have been described in this report for the purpose of identifying where further work may be required to support the RWM programme.

In the future, geological disposal concepts will need to be described in sufficient detail to provide an understanding of how the concept could be implemented. It is currently envisaged that future concept development work will be documented and summarised in an updated version of this status report.

List of Contents

List of acronyms

AGR	Advanced Gas Reactor
CoRWM	Committee on Radioactive Waste Management
DNLEU	Depleted, Natural and Low Enriched Uranium
DSSC	Disposal System Safety Case
EBS	Engineered Barrier System
EDZ	Excavation Disturbed Zone
GDF	Geological Disposal Facility
HAW	Higher Activity Waste
HEU	Highly Enriched Uranium
HHGW	High Heat Generating Waste
HLW	High Level Waste
HSR	High Strength Rock
ILW	Intermediate Level Waste
ITA	In-tunnel Axial
ITB	In-tunnel Borehole
LHGW	Low Heat Generating Waste
LLW	Low Level Waste
LoC	Letter of Compliance
LSSR	Low Strength Sedimentary Rock
MBM	Mined Borehole Matrix
MOX	Mixed Oxide Fuels
NDA	Nuclear Decommissioning Authority
NGO	Non-Governmental Organisation
NRVB	Nirex Reference Vault Backfill
R&D	Research and Development
SF	Spent Fuel
WAC	Waste Acceptance Criteria
WIPP	Waste Isolation Pilot Plant

1 Introduction

1.1 Background

UK government policy is to manage the UK inventory of Higher Activity Waste (HAW) through geological disposal, coupled with safe and secure interim storage and ongoing research and development (R&D) to support optimised implementation. This is reflected in the 2014 White Paper Implementing Geological Disposal [1], which applies in England and Northern Ireland. Welsh government policy is also for geological disposal for the long-term management of HAW. Scottish government policy is for near-surface management of HAW where possible, located as near to the site where the waste is produced as possible.

The Nuclear Decommissioning Authority (NDA) has established Radioactive Waste Management Limited (RWM) to manage the delivery of geological disposal of HAW. This report is one of a set of status reports whose purpose is to describe the science and technology underpinning the safety cases for geological disposal of UK higher activity radioactive wastes. It describes the current status of work undertaken on development of geological disposal concepts.

RWM is also committed to keeping alternative radioactive waste management options under review, and periodically reviews developments in the area of alternative radioactive waste management options and considers the role that such options could play in relation to HAW management strategy. These alternative options are described elsewhere [2].

The range of geological environments that could be suitable for hosting a geological disposal facility (GDF) for such wastes in the UK is wide and diverse. To identify potential sites where a GDF could be located, the UK Government favours a voluntarist approach based on working with communities that are willing to participate in the siting process [1]. This means that the geological environment for the disposal facility will depend on the location of sites identified through discussions with local communities involved in the process.

Selecting the most appropriate solution for implementing geological disposal will require carrying out assessments of siting and GDF concept options, and making decisions at different levels of detail. International work over many decades shows that a wide range of engineering solutions is available to implement geological disposal and this experience, plus RWM's own work, is being used to develop GDF concept options and evaluate their feasibility for the HAW inventory and other UK-specific boundary conditions [3].

1.2 Objectives and scope

The objective of this report is to document the current status of information available in the UK and internationally on geological disposal concepts and abstract from this a set of generic GDF concepts that can be optimised to RWM's requirements, as GDF siting and safety assessment progresses. By generic, we mean that the options presented are adaptable to different site conditions and wastes in the RWM inventory, although some options have been developed for particular, but generally broad, types of geological environment.

The scope covers all GDF concept options currently under consideration by RWM. The set of generic options includes a sub-set that has been used to date as 'illustrative disposal concepts' on which are based current designs and assessments within the generic Disposal System Safety Case [4]. The scope of this report excludes deep borehole disposal, near surface and intermediate depth disposal, as these concepts have been defined as alternatives to disposal within a GDF [2].

1.3 Audience and users

The primary audience of this status report is expected to be RWM and its contractors.

The external audience of this status report is expected to include our regulators, academics, sister Waste Management Organisations, learned societies and stakeholders such as the Committee on Radioactive Waste Management (CoRWM) and Non-Governmental Organisations (NGOs). This report has been written for an audience with a scientific or technical background, with some knowledge of the context of geological disposal.

1.4 Relationship with other RWM reports

There are important interfaces between this and other RWM reports. Key interfaces with the Concept status report include:

- the RWM Concept Selection Process report [5] (this report is currently being updated to reflect the 2014 White Paper [1]), and Review of Alternative Radioactive Waste Management Options [2];
- the RWM Design Manual [6] and Design status report [7];
- the generic Disposal System Specification (DSS) [8,9], Derived Inventory [10] and generic Disposal Facility Designs [11];
- the suite of Waste Package Specifications [12,13] (associated with the Letter of Compliance (LoC) Disposability Assessment Process, will become Waste Acceptance Criteria (WAC) at a later stage of GDF development);
- the generic Operations Safety Case [14], the generic Post-Closure Safety Assessment [15] and generic Environmental Safety Case [16]; and
- the Engineered Barrier System status report [17], and Geosphere status report [18].

1.5 Previous concept reports

This Concept status report is intended to provide an update to the original concept option studies carried out by RWM in 2008 for geological disposal of low-heat generating wastes [19] and high-heat generating wastes [20]. It is the first issue of an intended series of Concept status reports that will describe the progressive narrowing down to preferred GDF concepts as siting proceeds.

The information provides updates where RWM and other national programmes have made significant changes or developments. While there is considerable R&D underway in all the major national programmes, the information herein is restricted to developments affecting the overall disposal concepts themselves, particularly in terms of layout, engineered barrier materials or operation, and the key issues that are arising.

1.6 Terminology

A list of acronyms used in this document can be found following the contents page. For more information about use of language and terminology in this and other RWM documents, please refer to our Glossary [21].

1.7 Report structure

The remainder of this report is structured according to the following format:

- section 2 provides an overview of our approach to concept development and how concepts are used to support the RWM technical programme;
- section 3 provides an introduction to the set of generic GDF concepts currently under consideration;

- section 4 provides a summary of the latest developments affecting each generic concept option and highlights recent concept studies undertaken by RWM and internationally for each, and;
- section 5 presents brief concluding remarks.

We have used coloured boxes at the beginning of each section to provide a short summary of the key points being presented and help the reader in following the arguments that are developed.

Appendix A (Concept Summary Sheets) provides more detail on each of the generic concepts currently under consideration by RWM and Appendix B (Illustrative Disposal Concepts) provides information on the sub-set that is being used to support the generic Disposal System Safety Case.

2 Approach to GDF Concept Development

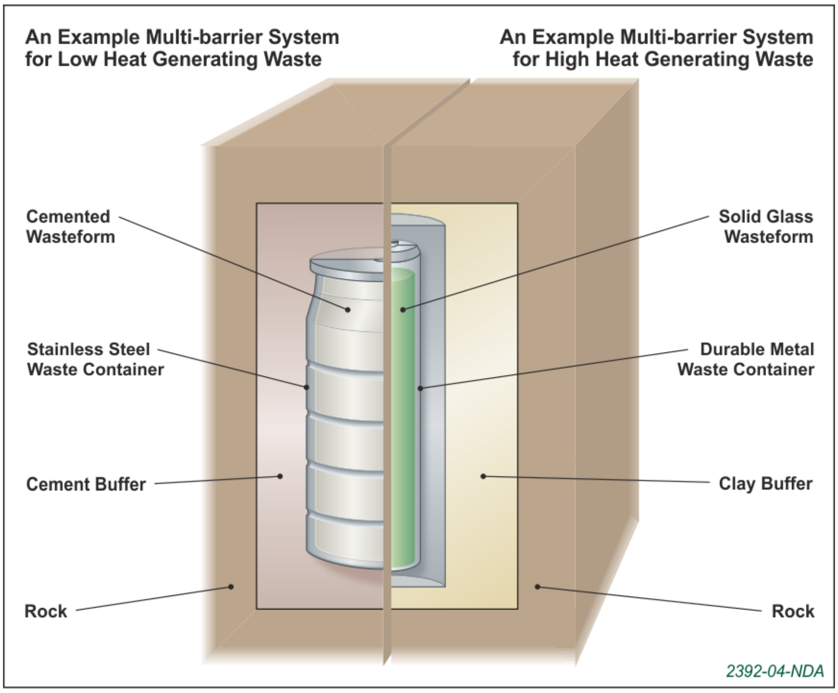
As the siting process progresses, a successive programme of optioneering and optimisation will be undertaken to ensure that the most appropriate disposal concepts are selected and developed for the chosen site.

2.1 Defining GDF Concept Options

A GDF concept is the description of the engineered barriers, natural barriers and disposal facility layout required to ensure that the radioactivity in the wastes is sufficiently isolated and contained that it will not cause unacceptable harm to people and the environment [21]. The concept and the layout of the components and structures deliver the safety functions and requirements defined in the Disposal System Specification [8,9]. The layout is a description of the shape of the emplacement spaces and the other underground excavations, and their arrangement with respect to each other and with respect to the host rock. A disposal concept is specific to a waste group (e.g. high-heat generating HLW and spent fuel; low-heat generating intermediate level waste) and host rock, and a GDF could incorporate more than one disposal concept, to accommodate different waste groups.

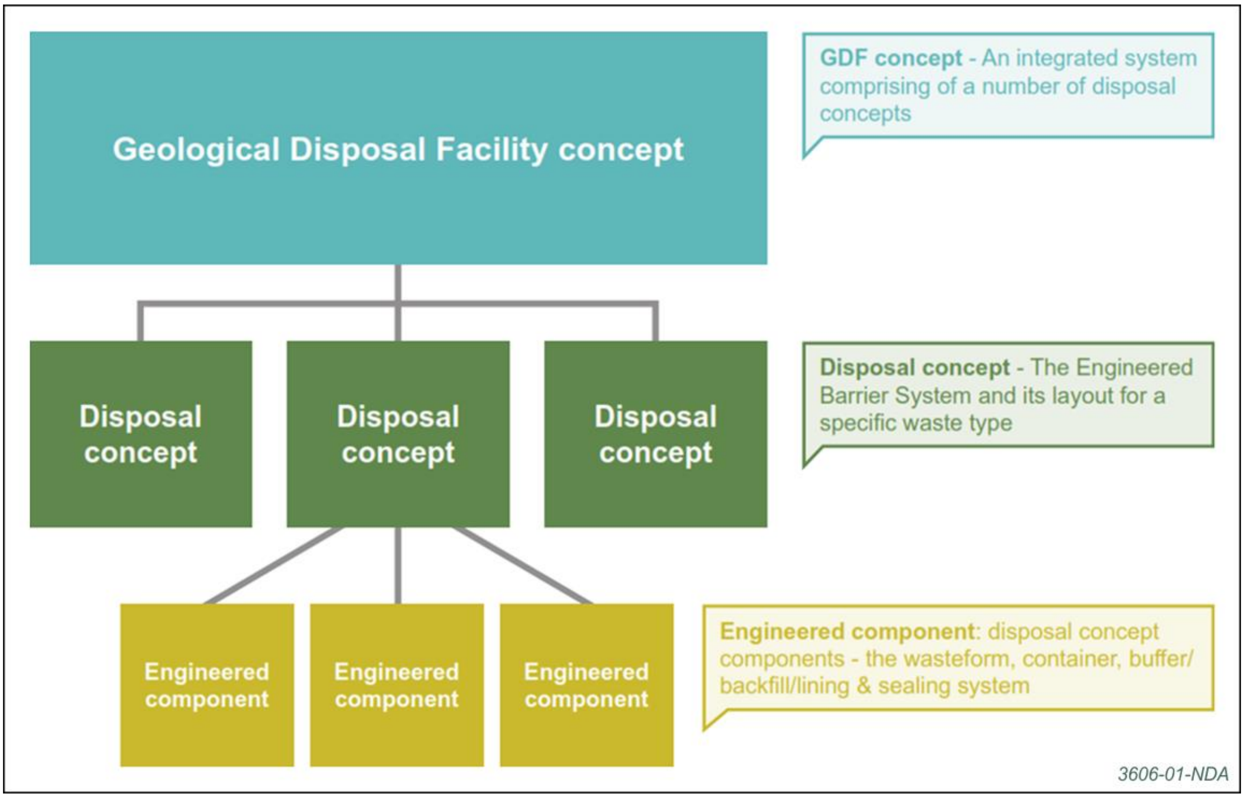
RWM has investigated a wide range of disposal concept options considered by waste management organisations around the world. All of the options developed are based on a multi-barrier approach, the nature of the barriers depending on the geological environment and the type of wastes to be disposed of. Generally, the barrier systems comprise the wasteform, the waste container, buffer/backfill material, mass backfill, plugs and seals and the geological environment. Examples of multi-barrier systems for both low-heat generating waste (LHGW) and high-heat generating waste (HHGW) are shown in Figure 1.

Figure 1 Schematic illustration of the multi-barrier approach



The LHGW and HHGW categories are differentiated in concept development, as thermal considerations are one of the main controls on the components, geometry and layout of a GDF. The two waste categories are further broken down into waste groups that reflect the key differences in waste packaging and assumed emplacement methods. A number of compatible concept options could potentially be used in a single GDF to dispose of specific waste groups, functioning overall as an integrated system. Such a system might also utilise a number of geological settings, if they are available at a site. This integration approach is summarised in Figure 2.

Figure 2 Hierarchy of concept terms



Compatibility means that the different engineered barrier systems (EBS) of the concepts that are selected will provide containment within the geological environment without compromising the performance of each other, or of the GDF as a whole (see Box 5). This requires understanding of potential interactions between the concepts used in the GDF, as well as consideration of other facility structures and facilities to support implementation, e.g. surface receipt facilities, transport infrastructure etc. These structures and facilities are not currently considered within the generic GDF concept options described here, but are developed as part of the engineering support for GDF design.

Four groups of generic HHGW concepts, and two groups of the generic LHGW concepts are identified in this report. Each group is described in Section 4, and in more detail in Appendix A. Multiple concept options are possible, for example the use of Supercontainers (see Box 4) or multi-level layouts (see Box 5).

The four groups of generic HHGW disposal concepts are:

- In-tunnel Borehole (ITB) concepts.
- In-tunnel and In-tunnel Axial (ITA) concepts.
- Vault-based (also known as Cavern) concepts.
- Mined Borehole Matrix (MBM) concepts.

And the two groups of generic LHGW concepts are:

- Vault-based concepts.

- Silo-based concepts.

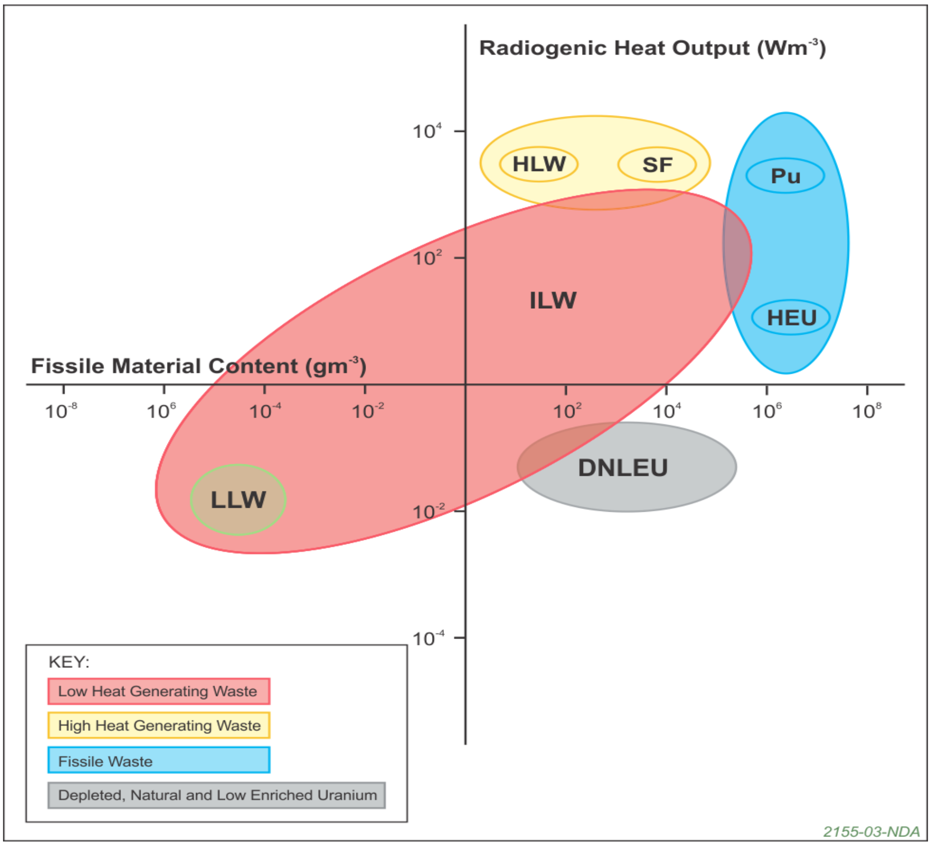
Unless there is good evidence that there would be significant positive benefits with respect to some of our requirements, RWM will seek to select, from the range of viable concept options, the concept options that offer greater reliability and are based on mature technology over those concepts that are less mature and/or more complex [5]. This will assist RWM in reducing overall project risk and uncertainty and may allow RWM to demonstrate the adoption of internationally recognised good practice, and demonstrate value for money. Box 1 provides further information on the optimisation of the GDF.

2.2 Disposal System Requirements

The process for concept selection is based on the requirements on the disposal system and on the disposal programme as a whole, which are contained within RWM's overall requirements management system. In particular, the characteristics of the waste and the geological environment provide constraints on the disposal system, and hence act as the main controls on the selection of a GDF concept and determine the performance that the engineered barrier system must provide.

RWM has developed a detailed description of the inventory for disposal for use in generic GDF design and assessment work [10]. Figure 3 indicates how the waste can be grouped by heat generation and fissile material content, both key factors which affect concept development.

Figure 3: Types of waste destined for GDF disposal



RWM has developed the Disposal System Specification (DSS) [8, 9] to define the requirements on the disposal system. The Disposal System Specification states that the disposal system fundamentally is required to:

> *"Manage the inventory of higher activity waste for disposal to protect people and the environment, both now and in the future, taking into account; safety, security, safeguards, socioeconomic impacts, and value for money."*

Within the DSS, the technical requirements are structured in a tiered manner. They include safety requirements and safety functions for the whole disposal system, which includes the GDF and the transport of the wastes to the GDF. The **safety requirements** specify what the disposal system, or parts of it (e.g. components of a GDF concept), must do in order to protect humans and the environment against hazards, and therefore meet regulatory and other relevant standards and requirements. For any GDF concept, **environmental safety functions** are assigned in the form of properties of the whole system, or parts of it, that have the potential to contribute to meeting one or more safety requirements. At a later stage, as a specific design is established for a GDF concept, the environmental safety functions are implemented through a set of **design requirements** that can be converted to engineering specifications for GDF construction and operation.

Box 1 Optimisation of Radiation Protection within GDF Concept Development

Optimisation of radiological protection for people is a key element of the specification, design development, and safety assessment for a Geological Disposal Facility (GDF) [4,22]. In the Guidance on Requirements for Authorisation the Environment Agency set out their expectations for the optimisation of radiological protection in accordance with the As Low As Reasonably Achievable (ALARA) principle and the application of Best Available Techniques (BAT) [23]. Their principles of optimisation in the management of radioactive waste' [24] state:

> "*all exposures to ionising radiation of any member of the public and the population as a whole resulting from the disposal of radioactive waste are kept as low as reasonably achievable (ALARA), taking into account economic and social factors.*"
>
> *"'Optimisation' is the process whereby an operator selects the management option and the practices applied that best meet the full range of relevant health, safety, environmental and security (including safeguards) principles and criteria, taking into account all relevant factors, e.g. social and economic considerations."*

Regulators will expect to see evidence of the balance between operational and post-closure safety being taken into account in decision making processes. One of the areas where RWM's approach to optimisation will be applied is in the selection of a disposal concept for each site under consideration. RWM has captured its interpretation of the requirements for radiation protection in GDF development and implementation in its Radiological Protection Policy Manual (RPPM) [25].

The concept selection process [5] and underpinning information will provide RWM with the appropriate technical underpinning to demonstrate that concept selection decisions support the development of an 'optimised' site specific design, i.e. a design which ensures that radiological risks to members of the public, both during the period of authorisation and afterwards, are as low as reasonably achievable, taking into account economic and social factors.

Optimisation will be required in all national programmes for implementing geological disposal. RWM seeks to maintain an understanding of the approaches being developed and implemented in other national programmes, and of developments in national and international guidance regarding optimisation, so that lessons learned can be factored into the UK programme. RWM participates in a range of international expert groups that consider approaches to optimisation, such as those organised by the Nuclear Energy Agency (NEA), International Atomic Energy Agency and European Commission as well as interacting more directly with individual radioactive waste management organisations in other countries. For example, RWM contributed to a working party in 2010 convened by the

NEA to review relevant approaches and available guidance and experience [26].

National programmes have used a range of approaches that are broadly similar to that described above, to ensure that requirements are properly defined and can be met by the GDF concepts that they have developed. Although there is not yet a common international terminology, factors such as safety functions and design requirements are now widely used in GDF concept and design development.

By developing an understanding of the environmental safety functions expected to be provided by a particular geological environment and the influences on them, the environmental safety functions required of the EBS in order to fulfil the overall long-term safety requirements for different types of waste can be identified and optimised as part of the disposal system development process. A general set of environmental safety functions that could be provided by different GDF barrier system components at different times after disposal are shown in Table 1. The barriers comprising any specific GDF concept may provide only a sub-set of these general environmental safety functions.

Table 1: General environmental safety functions that could be provided by different barrier system components in a GDF.

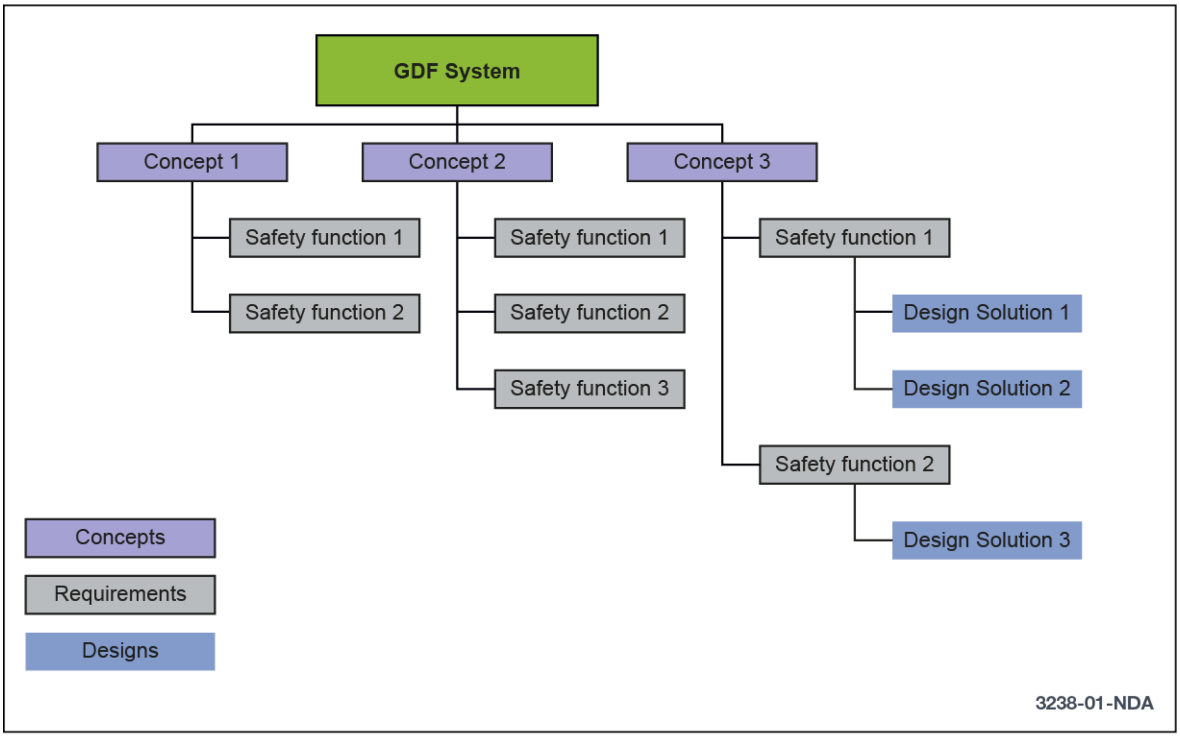
Barrier component	General environmental safety function
Geological environment	Isolate the wastes Protect the engineered barriers Limit contaminant transport to the surface environment
Wasteform	Limit the release of contaminants Stabilise the structure and geometry of the engineered barriers Protect the internal surface of the waste container Limit the potential for nuclear criticality
Container	Prevent or limit the release of contaminants Prevent disruption by over-pressurisation from gas generation Stabilise the structure and geometry of the engineered barriers Limit the potential for nuclear criticality
Local buffer/backfill	Protect the container Stabilise the surrounding host rock and the structure and geometry of the engineered barriers Limit the release of contaminants Prevent disruption by over-pressurisation from gas generation
Mass backfill	Stabilise the surrounding host rock and the structure and geometry of the engineered barriers Limit the release of contaminants Prevent disruption by over-pressurisation from gas generation
Plugs and seals	Limit the release of contaminants Stabilise the surrounding host rock and the structure and geometry of the engineered barriers Prevent disruption by over-pressurisation from gas generation

The environmental safety functions illustrated in Table 1 inform the development of the requirements specified in the Disposal System Specification [8,9], which are the main route by which GDF concept options are defined and managed. The concepts need to satisfy all the high-level requirements to an appropriate degree to make the proposed waste management solution acceptable. The selected GDF concept also needs to be technically feasible, affordable, and safe to operate. In turn, the selection of GDF concepts enables the translation of the high-level requirements in the DSS into system requirements, from which the more detailed design requirements can be established. Hence, the GDF concept selection process supports the RWM approach to iterative development of the disposal system. Further information on the iterative disposal system development can be found in the Overview of the generic Disposal System Safety Case [4], and in section 2.4 below.

The **concepts** developed for a particular group of wastes (e.g. HHGW) are described in terms of GDF layout, for example vaults or tunnels, including likely ranges for the dimensions of the different barriers and the spacing of waste packages. The concept description might specify the characteristics of a component of the EBS through high-level safety requirements (e.g. long-lived container material, low permeability buffer), which set out what the barriers must achieve. In the different GDF concepts discussed in this report and in different national programmes, various terms are used to describe engineered components that may seem similar but which may have slightly different safety functions in a particular design. We distinguish between a GDF concept (the subject of this report) and a GDF design.

A **design** is a description of an engineering solution to meet those specified requirements, of which there can be many variants. A design can be assessed to determine whether it adequately fulfils the requirements [8,9]. Design development follows after concept identification and is an iterative process, with successive design stages becoming more specific and detailed as more is learned about how a GDF concept fits to a particular geological environment and site. Figure 4 illustrates the relationship between GDF concept options, disposal system requirements and design solutions.

Figure 4 Relationship between disposal concept options, specified requirements and designs



2.3 Waste Packages and the Disposability Assessment Process

The RWM Disposability Assessment process has been established in support of the UK nuclear industry's ongoing work on the conditioning and packaging of higher activity wastes for disposal. The process has been extensively developed over a period of more than 20 years in cooperation with the site operators and regulators, and in a manner that aligns with regulatory expectations for the long term management of higher activity wastes [27].

Evaluation and assessments undertaken during a disposability assessment include the comparison of waste package performance against the package specifications and the safety assessments in the generic DSSC. The generic DSSC thus provides a benchmark for the disposability assessments. The evaluation and assessments carried out as part of a disposability assessment are described in greater depth in the generic DSSC report on waste packages and the assessment of their disposability [12].

The philosophy that underpins RWM's approach to disposability assessments is set out in the Disposability Assessment Aim and Principles (DAAPs) document [28]. Studies have been performed to determine how the choice of disposal concept could affect the waste packaging criteria (for example, [29]).

The main purposes of the Disposability Assessment process are to:

- give confidence to site operators that the implementation of their proposals to package waste will result in waste packages that meet the anticipated needs of the disposal system;
- aid in the identification of optimised solutions for the packaging of specific types of waste;
- provide RWM with confidence that the disposal concepts considered within the generic DSSC are appropriate for inventory for disposal; and
- permit the identification of wastes and proposed approaches to packaging that could challenge current disposal concepts and thereby allow early consideration of what changes may be required to those concepts to permit the resulting waste packages to be accommodated.

It may be appropriate to change some aspect of the illustrative disposal concepts to accommodate the proposed waste packages, if this can be done without any undue consequences for the overall safety and/or efficiency of the geological disposal system. Indeed, it may be that such a change could result in an improvement in overall safety and/or efficiency. Depending on the nature of the change, this could have consequences for the packaging specifications alone, or for the disposal concept and the DSSC in general.

At March 2015, a conditioned volume of approximately 30,200m^3 of waste had been recovered, conditioned, packaged and placed into interim storage. This volume represents approximately 8.5% of the total reported ILW in the 2013 UK RWI, and comprises 58,504 individual waste packages [30]. RWM's optioneering and optimisation of the GDF concept (see Box 1) must take account of the waste that has already been packaged.

2.4 GDF Concept Development Programme

Evaluating and developing GDF concepts provides a framework for the selection of optimised designs and the development of an optimised safety case. A robust consideration of options is necessary to meet our statutory obligations under the EPR10 [31] and IRR99 [32] to optimise radiological protection of the public and workforce. The decision making process on concept selection and the basis for the decisions will be clearly documented in order to comply with regulatory requirements and maintain confidence among our stakeholders.

At the current generic stage of RWM’s programme, all GDF concepts that are potentially viable for implementation in the UK are open for consideration. A key aspect of RWM’s work is to develop and keep up to date an adequate understanding of all the options that could meet our requirements, where necessary carrying out work to improve their technical maturity and to assure their applicability to UK boundary conditions [3].

2.5 Building the Knowledge Base

Whilst, in a UK context, a GDF will be a novel facility, there is growing international experience of GDF implementation that, with suitable consideration of the different regulatory regimes and geological settings, could assist RWM in establishing good practice for system optimisation and the reduction of radiological risk. RWM has proposed that technology transfer with sister Waste Management Organisations could provide a number of benefits, including potential cost reductions and programme acceleration [33].

RWM’s Science and Technology Plan [3] has been produced with a time-horizon of a decade, during which the vast majority of our planned generic research will be completed, with the associated reduction in knowledge gaps. At the current stage in our programme, without an identified host site for a GDF, the scope of the Science and Technology Plan has been constrained to those activities which can be conducted in a generic manner. The subsequent identification of specific geological environment(s), together with the appropriate GDF concept(s) will provide opportunities for optimisation of this plan.

As the siting process progresses, more information will become available, from both site investigations and from progress by overseas waste management organisations. Development issues may be encountered that require a change of approach, and as a result, maintaining an understanding of a range of concepts will support RWM’s management of long term project risk.

3 General considerations in developing GDF Concept Options

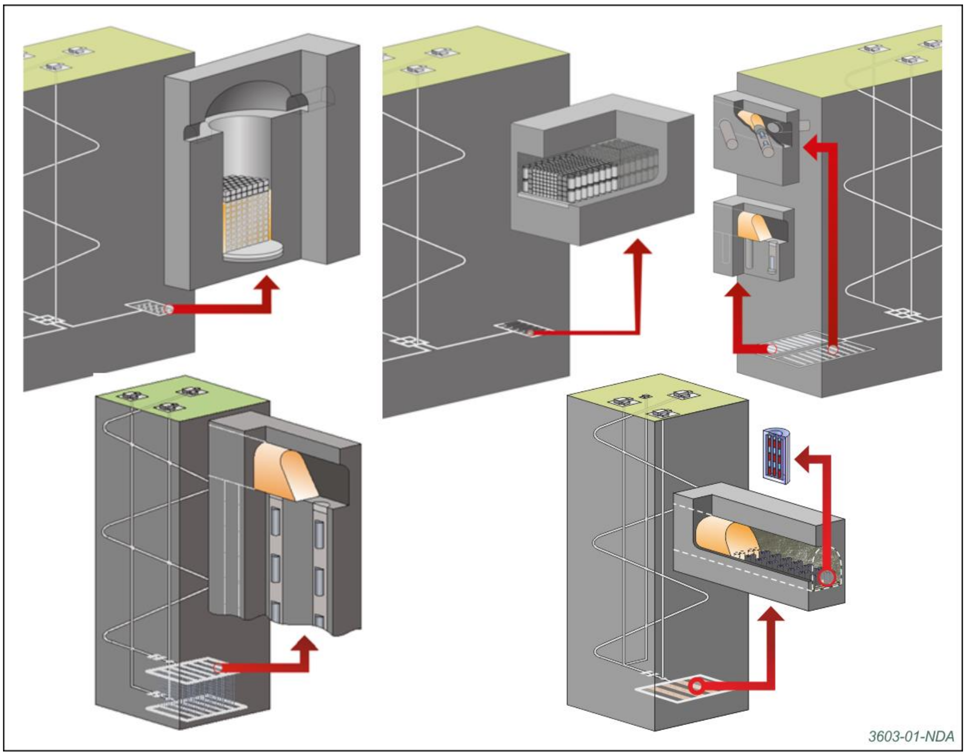
Meaningful selections of concepts and design components can only be made when we have sufficient site-specific information and can link feasible options for these site conditions to our overall programme requirements. A range of materials, both natural and synthetic, is available for fabrication of an engineered barrier system.

A number of general factors are common when considering the appropriateness of any GDF concept option. These include layout constraints and opportunities presented by different types of geological environment, the choice of engineered barriers and the potential for combining options in a single GDF. These are discussed below.

At the current stage of the programme RWM is examining a wide range of potentially suitable GDF concepts so that a well-informed assessment of options can be carried out at appropriate decision points in the GDF implementation programme.

As no site has yet been identified for the GDF, the host geological environment is not known. RWM has investigated a wide range of disposal concepts considered by waste management organisations around the world. From these, a sub-set of mature concepts has been identified and specific examples of these from other national programmes have been developed into **illustrative designs** [21] for three host rocks appropriate to the UK, as the basis for the generic Disposal System Safety Case (generic DSSC). These are purely illustrative, to enable the development and testing of our DSSC approach, and do not preclude the selection of other concept options in the future. A wider range of options is being assessed to determine whether they could provide advantages or solutions to our requirements with respect to specific waste types or site issues. For example, we are evaluating layout options that could provide a smaller footprint, or exploit vertical host rock volume rather than extending horizontally. Figure 5 shows examples from the range of layout options that are currently considered, together with associated engineered barrier systems.

Figure 5: Range of Concept Layout Options: clockwise, from top left: Silo for LHGW, Vault for LHGW, In-tunnel Boreholes (Vertical and Horizontal), Vault for HHGW, Mined Borehole Matrix.



3.1 Disposal Facility Layouts

Many of the factors that need to be considered when selecting a GDF concept and subsequently developing a design are a function of layout options, including:

- **Diameter of excavations**: The properties of the host rock will determine the maximum size of the excavations, requirements for lining etc., their shape, and the length of time for which they can be held open. The dimensions of the excavations will influence the emplacement geometry (can waste packages be stacked and if so how high, can HHGW waste packages be emplaced vertically etc.) and the dimensions of waste packages that can be accepted. The dimensions of the excavations may also influence the GDF footprint, the volume of backfill and/or buffer material required and the spoil volumes.
- **General layout of excavations**: It is necessary to consider whether a GDF would be developed on a single level (i.e. all at the same depth so having a large horizontal footprint and a small vertical footprint) or whether it could make use of the vertical extent of the host rock to reduce the horizontal footprint. The properties of the host rock (stresses and jointing) are likely to influence the orientation of excavations.
- **Waste packages – size, mass, orientation, stack height**: The maximum stack height for LHGW packages may influence the excavation size. The mass and eventual orientation (vertical or horizontal and number of packages per excavation) of HHGW packages influences the excavation size of emplacement and access tunnel excavations.
- **Extent of the excavation disturbed zone (EDZ):** the extent and potential connectivity of the EDZ depends on the characteristics of the host rock and the excavation techniques used. However, in general terms the extent of the EDZ scales with excavation diameter and the length of time for which the excavations are held open. It is also dependent on the construction technique. Limiting the extent and potential connectivity of the EDZ is a key driver for some GDF concepts.
- **'Dead ending'**, or not, of the waste emplacement areas: Dead end excavations offer advantages in terms of limiting the potential for groundwater flow along the excavations, because one end of the emplacement area is sealed by undisturbed host rock. There is thus one fewer engineered component in the system (tunnel end seal) and a reduced potential for connected pathways to develop between emplacement areas. However, such layouts may be more difficult to excavate and to ventilate than layouts that are open at both ends of the emplacement area.
- **Sealing**: Large aperture excavations may be more challenging to seal. The number, location and characteristics of seals are concept-dependent. For example, ramp/drift access to the emplacement areas may be more challenging to seal than vertical shaft access.
- **Ease of retrievability** (stages 2-4 of the NEA retrievability scale [34]): The layout influences whether or not it is necessary to emplace the buffer or backfill that surrounds the waste packages at the same time as the waste packages or whether the possibility exists for delaying emplacement of these parts of the EBS and hence enhancing the potential for easy retrievability. (Backfill and buffer material generally stabilises the rock considerably. It is noted that failing to backfill after packages have been emplaced increases the risk of rock fall on the packages, potentially resulting in significant impediments to retrievability.)

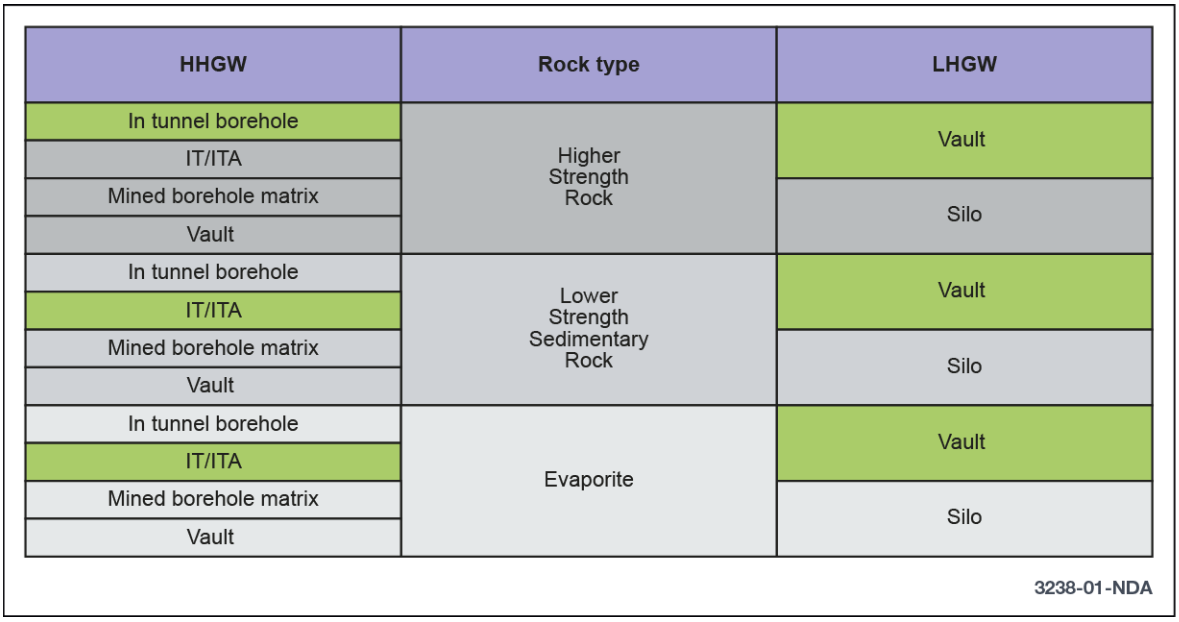
On the basis of the considerations outlined above, RWM has identified five generic layouts:

- Vaults or Caverns – large horizontal excavations;
- Silos – large vertical shafts;
- In-tunnel borehole (ITB) deposition – short boreholes (horizontal, angled or vertical) branching from a transport tunnel;
- In-tunnel and In-tunnel axial (IT/ITA) deposition – co-use of tunnels for transport and emplacement, and;
- Mined borehole matrix (MBM) deposition – long vertical boreholes.

More information is provided on all these layout options in Chapter 4 and Appendix A.

Owing to their potentially large volumes, two layouts, vaults and silos, are considered to be suitable for LHGW, and four layouts are considered to be suitable for HHGW: vaults/caverns, ITB, IT/ ITA, and MBM. In principle, all concepts could be implemented in all of the three generic geological environments of interest to RWM, although some would require very specific conditions to be present in order to be feasible for certain environments. Table 2 summarises the combinations of waste type and layouts currently considered and highlights those currently being used as illustrative designs. Figure 7 illustrates schematics for each layout.

Table 2: Summary of range of geological disposal concepts (those currently being used as illustrative designs are shown in green).



HHGW	Rock type	LHGW
In tunnel borehole	Higher Strength Rock	Vault
IT/ITA		
Mined borehole matrix		Silo
Vault		
In tunnel borehole	Lower Strength Sedimentary Rock	Vault
IT/ITA		
Mined borehole matrix		Silo
Vault		
In tunnel borehole	Evaporite	Vault
IT/ITA		
Mined borehole matrix		Silo
Vault		

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3.2 Engineered Barrier Component Options

In addition to a range of layout options, the concept selection process also includes consideration of options for the components of the engineered barrier system (EBS). The EBS is the combination of the man-made engineered components of a disposal facility, including the waste form, the waste container, the buffer or backfill (in intimate contact with the container), mass backfill (for void filling) and sealing systems [17]. The requirements on the engineered barriers, and the safety functions associated with each barrier, will be determined by the wastes being disposed and the geological environment. Table 3 illustrates broadly the range of EBS components under consideration, although this is constantly being refined as the waste inventory becomes better defined and management technology develops.

Table 3: Example engineered barrier component options identified for the disposal of different waste groups in different geological environments

Host Rock	Waste Group	Wasteform	Container	Buffer/local backfill	Mass backfill	Seals
Higher strength rock	HHGW	Ceramic	Copper with cast iron insert	Bentonite	Bentonite Crushed rock	Structural concrete and bentonite
		Vitrified				
		Metallic				
	LHGW	Grout encapsulated	Stainless steel (some with concrete annulus/liner), carbon steel, concrete	Cementitious material (Nirex Reference Vault Backfill)	Crushed rock	Structural concrete and bentonite
		Un-encapsulated	Carbon steel, cast iron (some with lead liner)			
Lower strength sedimentary rock	HHGW	Ceramic	Carbon steel	Bentonite	Crushed host rock	Structural concrete and bentonite
		Vitrified				
		Metallic				
	LHGW	Grout encapsulated	Stainless steel (some with concrete annulus/liner), carbon steel, concrete	Cementitious material	Crushed host rock	Structural concrete and bentonite
		Un-encapsulated	Carbon steel, cast iron (some with lead liner)			
Evaporite	HHGW	Ceramic	Carbon steel	Crushed host rock	Crushed host rock	Concrete, clay, asphalt, salt
		Vitrified				
		Metallic				
	LHGW	Grout encapsulated	Stainless steel (some with concrete annulus/liner), carbon steel, concrete	Magnesium oxide (although not a bulk backfill material)	Crushed host rock	Concrete, clay, asphalt, salt
		Un-encapsulated	Carbon steel, cast iron (some with lead liner)			

3.2.1 Wasteform

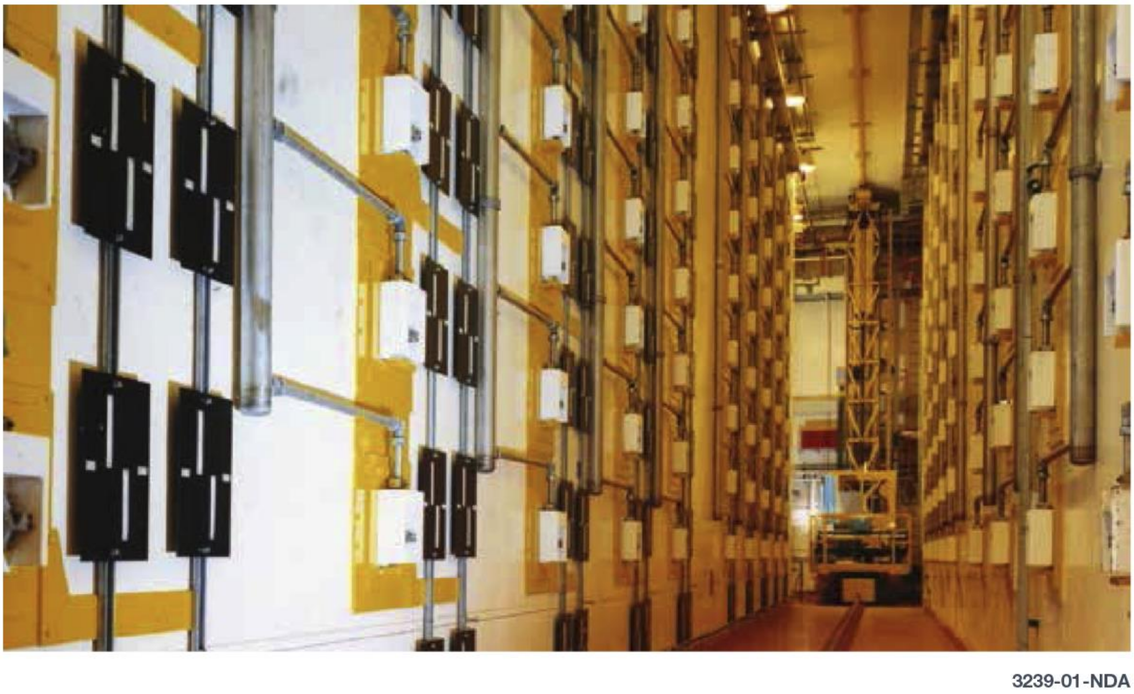
For a number of wastes the wasteform for disposal is already known and will not be changed as part of the process of developing a GDF concept, e.g. vitrified HLW, spent fuel and waste that has already been packaged in line with the disposability assessment process.

A cemented wasteform is most commonly used for ILW/LLW (the waste is either encapsulated or entombed (annular grouted) with cement). Other options that have been proposed include vitrified, polymer encapsulated and non-encapsulated wasteforms. A number of different wasteforms have been considered for plutonium bearing wastes, including ceramic and mixed oxide pellets ([35], see also Box 2). A full description of wasteforms is available elsewhere [21].

Box 2 – Options for separated plutonium

The UK is in a unique position owing to the potential quantity of plutonium that may be declared as waste. We have the world's largest stockpile of unirradiated civilian plutonium (see Figure 9) [36], accumulated from decades of reprocessing nuclear fuel, expected to peak at around 140 tonnes by the time reprocessing at Sellafield is halted at the end of this decade [37].

Figure 6: THORP Product Store showing current storage of plutonium.



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The priority for UK government policy is to provide a solution that puts UK owned plutonium beyond reach. In 2011, the UK government proposed a preliminary policy view to pursue reuse of UK civil separated plutonium as Mixed Oxide fuel (MOX) subject to a suitable business case. NDA are continuing to develop options capable of delivering the policy objective of putting the plutonium beyond reach including disposal and reuse options [38].

The design of any disposal concept for separated plutonium needs to take account of the fact that accumulation of Pu-239 could lead to a rapid transient criticality event. Pu-239 decays naturally to U-235 with a half-life of 24,000 years. If the timescale for package failure and the subsequent accumulation of fissile materials is comparable with, or longer than, the Pu-239 half-life, the likelihood of a rapid transient event will be reduced [39].

A broad range of concept options has been outlined for disposal of plutonium, making use of a variety of engineered barrier components, and three generic geological environments [40]. RWM has found that the disposal of plutonium as a ceramic wasteform would be viable from a disposal facility operational phase and post-closure phase perspective, although some uncertainties and knowledge gaps remain to be addressed. Further work would be needed for full lifecycle optimisation of plutonium disposal [41].

3.2.2 Container

ILW/LLW waste containers are typically drums or boxes, in some cases specialist versions of standard iso-freight containers. The materials used, or proposed, for their construction include stainless steel (generally austenitic 316L or 304L but duplex 2205 has also been considered), carbon (mild) steel, ductile cast iron and concrete (often reinforced). In some disposal concepts, the waste is emplaced directly in a disposal vault without the use of a disposal container. Some ILW/LLW containers, in particular many of the container types used in the UK programme, are vented to prevent gas pressurisation as a result of corrosion or degradation of the waste.

The choice of container material and design may be influenced by interim storage, transport and handling requirements and long-term performance requirements. Some containers are designed to provide sufficient shielding to allow contact handling, either through the use of thick walls or through the use of composite containers for example comprising a steel container with a concrete liner to provide shielding. Different materials provide different levels of durability and degrade in different ways. For example, stainless steel is susceptible to localised corrosion under certain conditions but has a very low general corrosion rate, whereas carbon steel has a higher, but predictable, general corrosion rate and is less susceptible to localised corrosion. Vented containers clearly provide less containment than fully sealed containers, a factor that should be taken into account when considering the safety functions that must be provided by other barriers in the disposal concept. The potential for ferrous materials to generate gas post-closure as a result of anaerobic corrosion also needs to be taken into account when developing a GDF concept.

HLW and spent fuel are typically packaged in robust metallic containers. The container provides a method for handling during transport and operations, and contributes to containment during the post-closure period. In all high strength rock (HSR) and low strength sedimentary rock (LSSR) HHGW GDF concepts, the container must provide containment while the waste is still producing heat energy in amounts that could adversely affect the performance of the disposal system [8], which is typically of the order of 1000 years but may be longer for certain waste types such as MOX[1]. Similar containers have been proposed for separated plutonium wasteforms.

Metallic container materials are generally classified as active or passive depending on their corrosion characteristics and hence on the design strategy employed to ensure the desired durability of integrity of the container. Active materials corrode uniformly at a known, but possibly very low, rate, and are generally not susceptible to localised corrosion. Passive materials develop a protective oxide film that inhibits corrosion and will not corrode while this layer remains intact and stable, but may be susceptible to localised corrosion during the period before this protective layer becomes established or if it becomes damaged. The choice also influences the strategy required for making the safety case and the supporting information that would be required. Either type of material could provide a very long container lifetime provided that it is used with a suitable buffer material. The range of candidate container materials currently being considered by RWM is [42]:

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[1] In the German safety case for a geological repository in salt, no credit is taken for the presence of the HHGW container, as sufficient safety performance is provided by the geosphere.

- Copper – very long container lifetimes are possible provided that microbial activity and the transport of oxidants and sulphide to the container surface are suppressed. Copper is an active material, albeit with a very low corrosion rate, under post-closure conditions. Its low strength means that a structural insert, typically made from cast iron, is required. Typically only considered for use with a compacted bentonite buffer.
- Carbon steel – an active material under post-closure conditions that provides good combination of mechanical strength and corrosion properties and is not susceptible to localised corrosion under expected conditions. Must be protected from development of biofilms. Anaerobic corrosion generates hydrogen and interactions with a bentonite buffer may degrade buffer performance. Suitable for use with a range of buffer materials.
- Cast iron – an active material similar to carbon steel but less studied as a container material (rather than as an insert). May be difficult to weld and less defect tolerant than carbon steel.
- Titanium alloys – a passive material under post-closure conditions with excellent corrosion resistance so very long container lifetimes are possible. Immune to microbial corrosion, pitting, stress corrosion cracking and sulphide. Commonly available grades may be immune to crevice corrosion during aerobic period. Would require structural insert to provide mechanical strength.
- Nickel alloys – a family of materials, which are passive under long-term GDF conditions so very long container lifetimes are possible. Resistant to microbial corrosion and suitable for use with a range of buffer materials. Some alloys susceptible to localised corrosion in presence of chloride and sulphide. Would require a structural insert to provide mechanical strength.
- Stainless steel – a passive material under post-closure conditions if used with a cementitious buffer. Susceptible to localised corrosion and stress corrosion cracking in presence of chloride. Would probably be used with an insert for structural strength.

In addition, the use of advanced coatings has been considered in order to improve the corrosion performance of disposal containers. Options include ceramic coatings, thermal spray metallic glass coatings, titanium carbide, graphite or diamond-like carbon [21, 43].

The most commonly proposed container materials for HLW and spent fuel are copper for concepts in which a very long container lifetime (hundreds of thousands of years) is required and carbon steel for concepts that place less emphasis on long-term container integrity and do not require such very long container lifetimes.

When selecting a container material, it is also necessary to consider the distribution of times at which the containers fail. If failures are likely to be spread over a long period and to be distributed throughout a GDF, the pulse associated with the Instantaneous Release Fraction would be dispersed and diluted in time and space. However, some disposal concepts may be more susceptible than others to a common-mode failure of the containers over a limited period of time, perhaps in response to a change in groundwater conditions.

For HLW and spent fuel, one of the most important factors that must be taken into account is the thermal output, which is a function of the waste type and the amount of waste per package. Many of the candidate materials for the EBS and the host rock have thermal limits that should not be exceeded if they are to perform their safety functions. Given that HLW and spent fuel would be placed in highly durable containers, it is sometimes useful to think of HLW/spent fuel disposal as initially addressing the heat aspects of the waste and then managing the radionuclides that remain once the container has failed. For spent fuel, the thermal output of the wasteform is determined by the fuel composition, reactor type and burn-up. For vitrified HLW and ceramic wasteforms, it is determined by the waste loading when the wasteform is manufactured.

A number of waste packagers are considering the use of Multi-Purpose Containers (MPCs) for the dry storage and transport of HLW and spent fuel. RWM has performed a number of studies to determine whether these MPCs could be used as a disposal container (see Box 3).

Box 3 RWM Concept Studies on Multi-purpose Containers (MPCs)

Multi-Purpose Container (MPC) concepts assume the use of MPCs emplaced in a range of geological host environments and facility layout configurations. These configurations allow for either prompt backfilling or a period of in-situ underground storage prior to backfilling, during which time the heat from the waste can be removed, thereby allowing the radiogenic heat output to fall to levels that will allow the relevant thermal limit to be met after backfilling of the facility. In Germany, the direct disposal of the Castor cask MPC is considered to be financially attractive due to the reduced requirements for waste handling, mainly due to the fact that waste does not have to be repackaged.

Currently available large capacity MPC systems (i.e. off the shelf commercial solutions) proposed by waste producers for storage and transport do not satisfy UK disposal requirements. As an alternative, a UK-specific MPC system has been designed to satisfy disposal requirements for UK PWR spent fuel from Sizewell B. This design specifies 12 PWR spent fuel assemblies contained in a basket arrangement within a stainless steel container that can be used with a variety of specific overpacks for storage at Nuclear Power Plants, transport to a GDF and disposal at a GDF (see Figure 7).

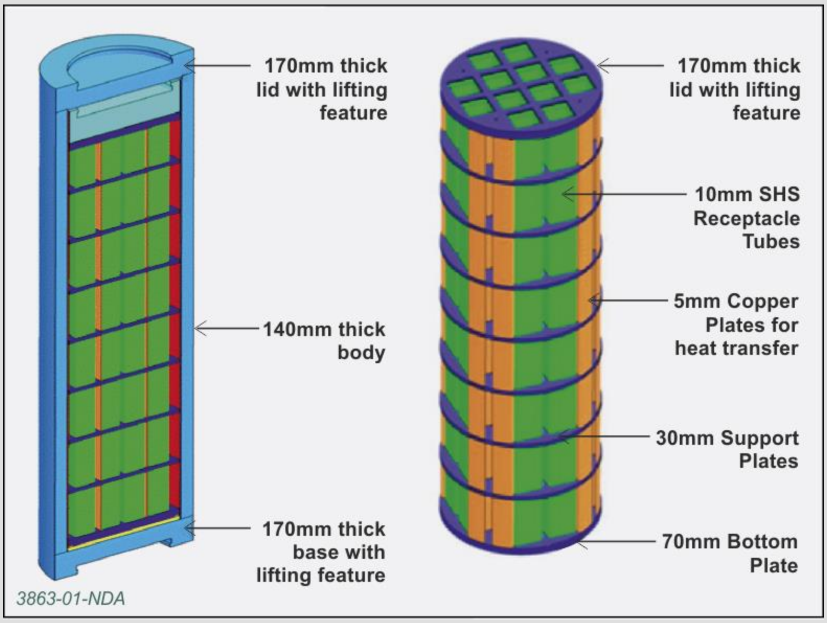


Figure 7: MPC basket with 12-fuel assembly arrangement (left) and MPC container with carbon steel disposal overpack (right).

In 2010-2016 RWM undertook a series of concept studies to consider the implications of MPCs for the UK disposal system [44,45,46]. Scoping level construction and operational assessments of a variety of MPC concept options identified significant specific design requirements relating to the management of heat, ventilation for extended open periods, maintenance and refurbishment of operational areas during extended open periods, the handling of larger waste packages, and the feasibility of in-situ backfill/buffer emplacement versus the possible use of prefabricated engineered barriers for disposal of packages with surface temperature above 65°C. The dominant issue for concepts in HSR and LSSR geologies is the high thermal output of the individual waste packages (i.e. the large number of SF assemblies per package), resulting in an extended GDF operational period in the order of ~ 100 years or more to accommodate some of the MPC waste packages.

In 2016, the NDA requested RWM to lead an assessment of the technical options of small MPCs (containing fewer than 12 spent fuel assemblies) that could potentially allow direct disposal of Sizewell B fuel, stored in casks, to a GDF. RWM found that, although direct disposal of small MPCs at the GDF is conceptually feasible, the economic case for a strategy change to a small MPC system for Sizewell B did not appear to be compelling. Sellafield Ltd is currently considering the use of MPCs for cooler HHGW [47].

3.2.3 Buffers and backfills

Backfill is a material used to fill voids in a GDF, and is the material that surrounds waste packages. This backfill typically performs a number of roles, most importantly filling voids to provide mechanical stability and buffering the composition of the water that comes into contact with the waste packages. Some GDF concepts do not include a backfill and instead rely on creep of the host rock to seal any voidage that remains following emplacement of the waste packages, or, some disposal concepts are robust to the long-term evolution of any voidage that remains after closure.

The choice of backfill material depends on the safety concept and on the properties of the host rock. Some GDF concepts rely on chemical conditioning of the near-field porewater to reduce radionuclide mobility whereas others provide containment by minimising the flow of groundwater through the waste packages. The properties of the host rock are also important as the backfill may be required to resist creep in the host rock, for example to stabilise the excavation disturbed zone. The backfill may play an important role in managing gas.

The materials that have typically been considered for use as backfill include:

- Cementitious materials – this category includes both high and low pH cements and relatively strong cement mortars that are designed to provide mechanical stability as well as to condition porewater.
- Clay-based materials – these materials are typically bentonite based and would be intended to provide hydraulic containment together with some buffering of the composition of the porewater. Clays typically provide a large surface area for sorption.
- Crushed host rock or a mixture of sand and host rock - designed primarily to provide mechanical stability. Magnesium oxide can be added to consume any carbon dioxide produced by the waste and control the pH.

Historically, relatively low strength, high pH, cementitious materials have been envisaged as the primary backfill material for an ILW/LLW disposal concept in the UK. The safety concept is based around the provision long-term chemical containment through the imposition of high-pH conditions and the provision of ample surfaces to which radionuclides can sorb [48].

HLW and spent fuel waste packages are usually surrounded by a buffer material to isolate and protect the container. The compatibility of the buffer material with the container material is a key consideration when designing a disposal concept. Not all possible combinations of container material and buffer material are sufficiently compatible to be plausible; for some container materials the range of compatible buffer materials is limited. The most commonly proposed buffer materials are:

- Bentonite, which may be highly compacted or pelleted. Bentonite buffers are usually designed to have a very low permeability and ensure that solute transport to and from the container is controlled by diffusion. The saturated density and swelling pressure are important properties for a bentonite buffer. Thermal alteration (temperatures above about 100°C) and interaction with steel corrosion products tend to degrade some of the properties of bentonite that are important for ensuring it is able to perform some of the safety functions often assigned to it.

- Cementitious materials, which may be designed to ensure a highly alkaline environment or a moderately alkaline environment. Cements can generally be customised to provide the desired strength, hydraulic properties and pH to complement the host rock and the container material.
- Crushed rock, most likely crushed host rock, but could also be mixed with other materials such as sand. This option is generally only applicable for concepts where the container requires only mechanical protection (i.e. container performance is not dependent on groundwater composition or flow rate).

The physical and chemical properties of buffer materials could be customised, within certain limits, to the particular disposal concept and disposal site. Depleted uranium aggregate for shielding or criticality control could potentially be included in a cementitious buffer, although this is not currently proposed by any waste management organisation. Employing a container without a buffer is also an option for plastically-deforming rocks such as rock salt, although in practice this option is equivalent to the case of a crushed host rock buffer.

3.2.4 Prefabricated EBS modules: ‘Supercontainers’

A pre-fabricated EBS module is a disposal unit that comprises the waste package and some or all of the other components of the EBS, for example the buffer or the local backfill (see Box 4). Owing to their size and the fact that they constitute the bulk of the EBS, they are sometimes referred to as ‘supercontainers’ and could be used in many of the generic GDF concepts considered here.

The relative timing at which the engineered barrier system is assembled can have a significant effect on operational procedures and can influence the way that post-closure safety functions are met. The use of prefabricated EBS modules envisages the assembly of the principal components of the EBS (waste package and buffer or backfill) on the surface, prior to transport underground. They are therefore a method for facilitating the emplacement of the engineered barriers to the required standards. They could be used, and have been proposed for use in a wide range of disposal concepts.

A key driver for using prefabricated EBS modules as part of the implementation of a geological disposal concept is the ability to readily quality assure the as-emplaced EBS components. Various implementations of prefabricated EBS modules have been proposed, including the Belgian Supercontainer concept, which considers emplacement of prefabricated EBS modules comprising a concrete buffer surrounding a HLW or spent fuel waste package and is emplaced axially within a disposal tunnel (the ITA concept), and the KBS-3H concept, which considers emplacement in sub-horizontal boreholes from tunnels (the ITB concept) of prefabricated EBS modules comprising spent fuel in a copper disposal container with a bentonite buffer and a titanium handling cylinder. Prefabricated EBS modules are also proposed for the disposal of ILW in France and Switzerland, where the GDF concepts both envisage emplacement of ILW packages in concrete boxes that contain the waste package and the local backfill. The disposal boxes act as both handling boxes and provide chemical conditioning of the GDF environment following closure. They also reduce the need to backfill the disposal vaults.

Prefabricated EBS modules present an approach to limiting operational doses to workers as the waste is shielded and protected by additional materials during operations. They also provide a route for managing the heat generated as a result of cement curing during backfill emplacement and the management off any gases generated as a result of this heating, because the backfill would be placed around the waste package and cured above surface, rather than underground *in situ*.

The major disadvantage of prefabricated EBS modules is their size and weight, which may make transport to and in the underground, and subsequent handling and emplacement, challenging. Some of the designs are intended to fit the disposal tunnels or boreholes with only a small tolerance, to remove the requirement for backfilling.

Box 4 RWM Concept Studies on Pre-fabricated EBS Modules / Supercontainers

A supercontainer is considered to be a disposal package which is pre-assembled and / or pre-fabricated prior to final emplacement within the GDF and comprises the disposal container and all, or part, of the buffer or local backfill (see Figure 8). The supercontainer, sometimes referred to as a pre-fabricated engineered module (PEM), is compatible with a wide range of waste types, facility layouts, and host-rock types. The supercontainer concept for spent fuel, MOX and borosilicate glass HLW has been developed as an integral part of the national waste management programmes in Sweden, Finland [49], Japan [50, 51], Canada [52] and Belgium [53] (for both hard rock and lower-strength sedimentary rock environments). In Canada, Belgium and Japan, the supercontainer is considered a part of their preferred concept design.

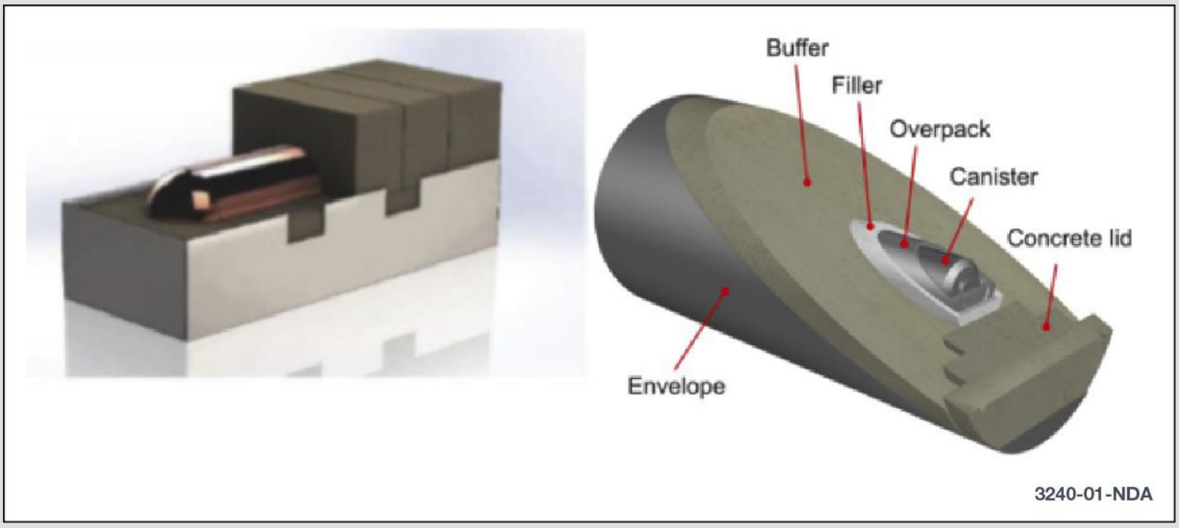


Figure 8: Canadian Mark II Supercontainer design for CANDU fuel (left): Rectangular steel outer box (1 m x 1 m x 2.8 m) housing a copper container encased within highly compacted bentonite blocks, total assembled weight 6,920 kg; and Belgian Supercontainer design for UO_2 spent fuel and borosilicate glass HLW (right): cylindrical stainless steel outer envelope (> 2 m x 6.2 m) housing a thick carbon steel container encased within a precast concrete buffer or local backfill, total assembled weight > 60 tonnes [54].

In 2016 RWM undertook an international review of prefabricated EBS modules / supercontainer designs under consideration internationally [54]. Outputs of this review indicated potential benefits for the use of supercontainers with a number of disposal concept layouts, material options and geological settings under consideration – although no UK specific design option has been developed to date.

A range of above ground and below ground supercontainer assembly options are considered by each of the international cited options. As the present UK GDF illustrative designs do not include a facility to assemble supercontainers, the potential feasibility to add such an area to the current designs and broader implications are planned as future work [3] and would consider: (1) Subterranean assembly at the GDF (as proposed by SKB and Posiva); and (2) At surface level at the GDF (as proposed by ONDRAF / NIRAS).

3.2.5 Mass backfill and support structures

Mass backfill is the bulk material used to backfill the excavated volume outside the areas containing the waste packages. The primary role of mass backfill is to provide long-term mechanical stability to ensure that all of the other barriers can function as intended. The properties of the mass backfill may also be important for the management of gas, for example by providing a volume into which gas could migrate, or for the management of water flow around the disposal areas. In cases where the mass backfill is primarily providing mechanical stability, it is typically composed of crushed host rock, possibly mixed with other materials such as sand. In concepts where the mass backfill plays a role in managing flows of groundwater or gas, the composition may be more sophisticated. For example, tailored sand and bentonite mixtures can allow gas to flow once a threshold pressure has been exceeded, but have a low permeability to water when fully saturated [17]. In some concepts for HHGW packages (ITA and CAV), mass backfill also plays an important role in the rate of heat transfer away from the buffer material.

Examples of excavation support structures include rockbolts, mesh, pre-fabricated reinforced concrete and shotcrete [7]. Support structures are essential for sedimentary rocks, might be necessary to allow for retrieval in evaporites, and are partially necessary in hard rock formations to enhance worker safety. Support structures introduce additional needs in terms of time and money for the installation, may influence hydrochemistry, and might have to be removed before closure.

3.2.6 Sealing system

Sealing systems comprise engineered seals and plugs. Engineered seals would be used to control the flow of fluids in the excavated tunnels. Seals may also be used where appropriate on parts of the rock that are more permeable. Complementary with the engineered seals, the plugs may be considered as the mechanical component of a sealing system, resisting the water and seal swelling pressures that will develop. Seals are made of multiple components, including low-permeability clays (including bentonite) and high-strength concretes. Materials such as bitumen and asphalt may also be included. A particular consideration for the sealing system for some disposal concepts is the need to use seals that are practical for large openings (e.g. vault entrances).

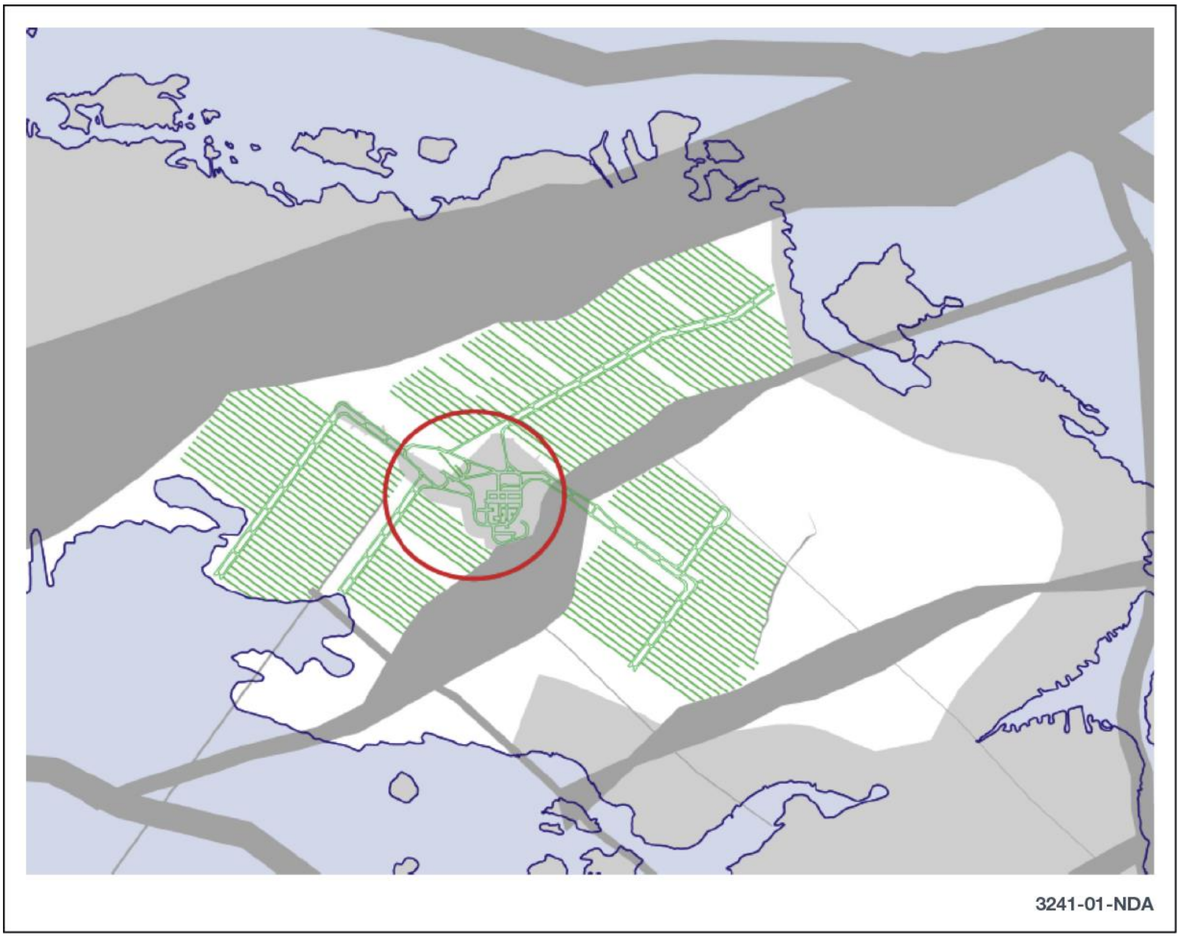
A key consideration in the design and installation of a sealing system is the requirement to key the seals into the host rock and seal any excavation disturbed zone (EDZ) that has developed, for example by removal of the disturbed material as part of the installation process. In some cases, some of the plugs and seals are only required to provide a mechanical and hydraulic function during the operational period and have no role following closure. In other cases, particularly in LSSR, the plugs and seals may need to be permeable to hydrogen to prevent over-pressurisation of the GDF in the post-closure phase.

3.3 Tailoring a Disposal Concept to Site Characteristics

Section 3.1 discussed general excavation size and layout considerations for any GDF concept, which are affected by the nature of the host rock formation. Owing to the wide variability in properties and geometry of the geological environments that could emerge from the siting process, other considerations also need to be taken into account because they will involve tailoring GDF concepts to actual site conditions. At the extreme, this variability can affect the feasibility of deploying a concept in a particular location. These are discussed with respect to the three generic geological environments being considered by RWM:

- **High-strength rocks**: HSR include large bodies of igneous and metamorphic rock such as granites and gneisses. They can display internal structural and compositional variability and complexity that lead to variable engineering and hydraulic properties across a potential GDF rock volume. Appropriate GDF concepts would take advantage of volumes of relatively homogeneous rock with favourable properties and avoid volumes with less favourable properties or variability leading to small-scale heterogeneity in key properties. Many bodies of HSR have considerable vertical extent, allowing deployment of multi-level concepts. A key feature of HSR is the presence of deformation and fracture zones at many scale ranges, which will control the size and geometry of vault and tunnel 'panels', as some major features will need to be avoided – for example, if they are hydrogeologically significant. As a consequence, a GDF is unlikely to comprise neat, equally-sized, rectangular disposal panels. This is illustrated in Figure 9. At a smaller scale, fracture size and frequency can constrain the location of suitable deposition positions for waste packages.
- **Lower-strength sedimentary rocks**: LSSR typically include sedimentary formations such as clays, shales and mudstones and mixed formations that, owing to their hydrogeological environment have low through-flow of groundwater. They can be considerably more extensive laterally than HSR environments in the UK, but suitable host rock lithologies within a sedimentary succession might be relatively thin vertically – thus tending to favour GDF concepts that can utilise a large footprint. Nevertheless, major structural features such as faults and deformation zones can also constrain panel size and geometry, as with HSR. Small scale vertical and lateral lithological variations (particle size, mineralogy, porosity etc) can lead to heterogeneity in key engineering, chemical or hydrogeological properties that might constrain useable rock volume, meaning that more homogeneous formations of adequate thickness are likely to provide the most flexibility.
- **Evaporites**: are present in the UK as bedded deposits of halite and other minerals, typically within a thicker sequence of sedimentary rocks. They are generally of limited thickness and can display internal mineralogical variability, both of which constrain the choice of appropriate GDF concepts.

Figure 9: Disposal tunnel layout can be affected by the need to allow a 'respect distance' to certain major deformation zones. This is seen on an example layout of disposal tunnels (green) for the spent fuel repository at Olkiluoto in Finland [55]. The white areas show the potential rock volume (taking account of geological and local planning constraints) and the dark grey shading shows the respect volumes around major fracture zones. The red circle shows the rock characterisation facility and the first panel of disposal tunnels.

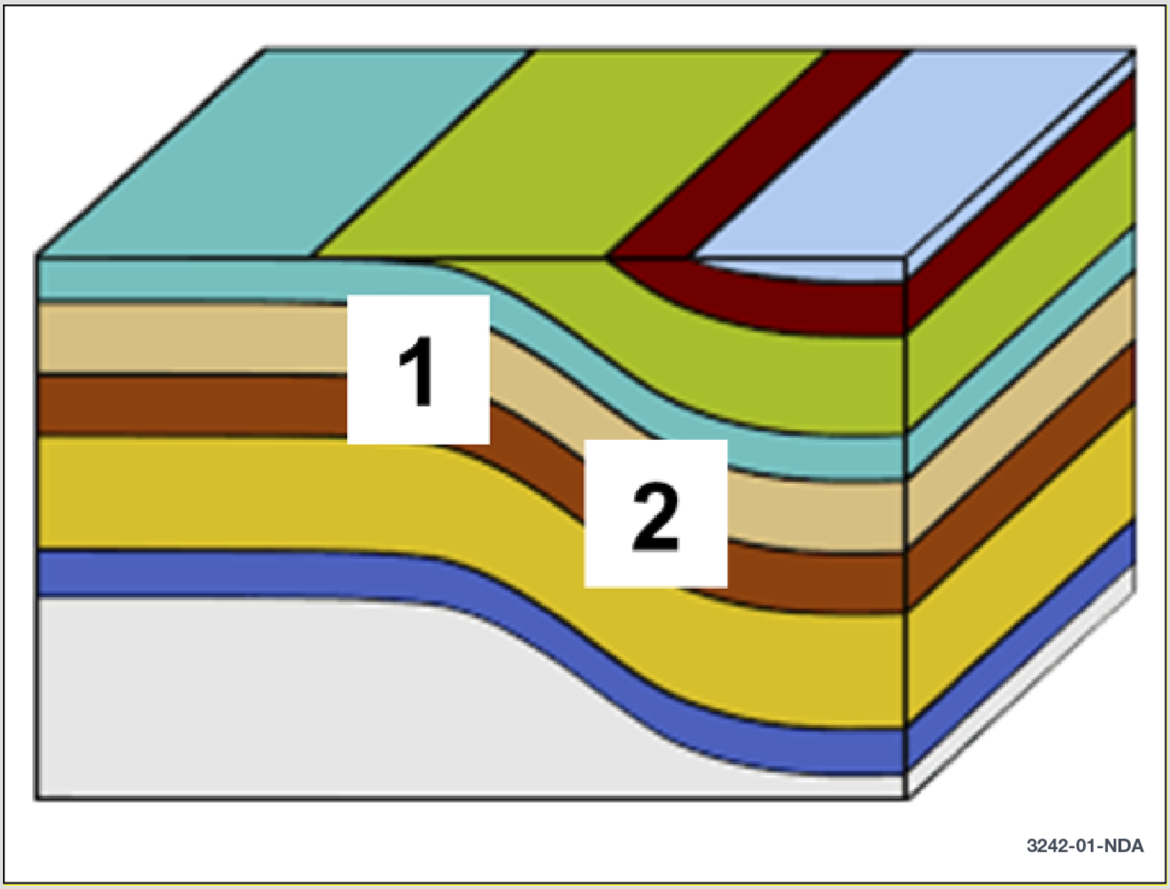


A potential site might contain more than one geological environment (for example, HSR overlain by LSSR) or more than one potential host formation (for example, several clay units within a thick sequence of mixed sedimentary rocks), allowing flexibility in both choice of concept and combinations of concepts, as well as the depths and relative positions of different regions of a GDF (see Box 5).

The hydrogeological and geotechnical conditions encountered at a site will also affect concept selection and are likely to require adaptation of a generic (e.g. illustrative) design to account for or take advantage of specific conditions. For example, high and anisotropic stresses in a potential host rock might require adaptation of tunnel and disposal hole dimensions and orientations, or might preclude the use of certain excavation types or support systems, thus limiting the range of applicable concepts. Extensive vertical heterogeneity in the hydrogeological or mineralogical properties of a thick sequence of sediments or evaporites might make long vertical deposition holes impractical. Similarly, marked heterogeneity in thermal conductivity and diffusivity properties across a body of high-strength rock will affect the optimum spacing and location of package disposal positions. Stratification in the hydrochemical composition of groundwaters at different depths could affect the feasibility of using certain types of EBS material and constrain the depth at which a GDF concept could be deployed. It is inevitable that any concept will need to be adapted to take advantage of the beneficial features and mitigate against any adverse conditions found at a specific site. Experience from other national programmes suggests that mitigation will normally mean a policy of avoidance of volumes of rock with less favourable properties, rather than extensive modifications to an otherwise suitable concept or design. This would be expected to result in constraints on depth, geometry and location of disposal rock volumes within a host formation or across a site.

Experience from other national programmes suggests that the initial identification of feasible concepts can be done at the time that a potential site emerges from the siting programme. The range of potential geological environments will be evident from regional baseline information. However, it is not until preliminary site investigations have been carried out that key factors concerning potential GDF depth, underground access options and, critically, the likely shape and extent of viable rock volumes, and their positions relative to each other, will be clarified. This information will indicate concept options that best match RWM's requirements and those that present specific opportunities to optimise the disposal programme, and could exclude some concepts as unfeasible or too difficult to implement.

Box 5 RWM Concept Studies on Multi-level and Multi-horizon Disposal



As current facility planning is conceptual, co-located disposal areas of the facility are typically considered in a single horizon. However, it is also possible and conceivable that different disposal areas of the GDF (for different waste types) could be located on more than one horizon or 'level' (see Figure 10). The different horizons used could be at different elevations within the same host rock, or different elevations within different host rocks.

A multi-level concept study was conducted by RWM in 2016 [56] which indicated that multi-level design offers the potential benefits of reduced footprint, improved scheduling, and the flexibility to tailor design to the post-closure requirements of different waste streams, for example by disposing of less hazardous waste in nearer surface facilities. The potential drawbacks highlighted included a modest increase in design complexity, spoil and the required quantities of construction materials, and therefore possibly cost, and potentially more complex post-closure interactions. A key aspect of the study considered the vertical separation required for high-heat generating wastes between disposal horizons (to less than approximately 100 m) and testing of thermal dimensioning tools (see Box 9) in readiness for application during siting.

3.4 Compatibility of Disposal Concepts

The disposal of LHGW and HHGW in separate areas of the same facility is referred as co-location by RWM. Co-location refers to the emplacement of the inventory for disposal in a single facility with shared surface facilities, access tunnels, construction support and security provision.

An important component of demonstrating the viability of concept options would be to demonstrate that any potential interactions between the different waste types and engineered barriers would not compromise the safety of the facility. The potential for one GDF disposal area to interact with another disposal area during GDF construction, operation and post-closure, through a range of coupled thermal, hydrogeological, mechanical, chemical and gas (THMCG) interactions, will be considered in the site characterisation and design process (see Box 6). Disposal areas will be separated by a distance sufficient to ensure that any interactions between disposal areas do not compromise the required performance of the overall disposal system. Previous work has indicated that LHGW and HHGW GDF disposal areas can be co-located without compromising key safety functions of different barrier components and, subsequently, high-level requirements have been specified in the DSS to ensure compatibility of disposal concepts is a component of associated evaluation methodologies [57,58,59].

Box 6 Respect Distances Between Co-located Disposal Areas

The layout of the EBS for each co-located waste group in the GDF will need to be designed such that potentially detrimental thermal, hydraulic, mechanical, chemical (including biologically-promoted chemical processes), gas (THMCG) and other interactions between wastes and EBS materials are avoided. This will ensure that the environmental safety functions of the EBS and the geological environment are maintained as required after GDF closure. That is, disposal areas need to be separated by a distance sufficient to ensure that any interactions that do occur between them do not compromise the required performance of the disposal system [59].

For example, the performance of some EBS materials may be sensitive to temperature or pH conditions to the extent that minimum separation distances need to be defined between individual waste packages or between disposal areas for different waste groups in order to mitigate thermal or chemical interactions. RWM has determined that a separation distance of 500 m between LHGW and HHGW disposal areas will ensure that, in most cases, the magnitude of any co-location interaction is likely to be within the uncertainty bounds that would be considered when evaluating the normal evolution of a disposal area independently [56]. For the illustrative GDF designs considered in the generic DSSC, co-location interactions between the LHGW and HHGW disposal areas are assumed to be insignificant. This is appropriate at this generic stage. At the site-specific stage, the necessary separation distances will be determined by consideration of the properties of the geological environment and the GDF design.

3.5 RWM Tools to support Concept Development

A number of models and toolkits have been developed by RWM that will be used to support future concepts studies. These include scoping-level tools and more detailed models to allow qualitative and quantitative comparison of concept options. Many of the toolkits have also been used to support the generic DSSC and assessment outputs presented for the illustrative designs (see Appendix B). As concept studies continue to be progressed, so too will the development and testing of assessment toolkits in readiness for application at sites as part of the GDF siting and development process. Current toolkits available or in development include:

- Post-closure Insight models [60] (see Box 8);
- Thermal dimensioning models [61, 62] (see Box 7);
- Footprint and spoil calculator;
- Cost calculator;
- Tunnel and vault calculator (see Box 9); and
- the Nuclear Operational Safety Manual (NOSM) and associated tools.

Box 7 Hot Stuff – Bounding Temperatures and the RWM Thermal Dimensioning Tool

Heat generation by waste packages has the potential to result in damage to the wasteform and/or the waste container, and could affect the performance of the geological disposal system as a whole, by causing damage to other components of the EBS, notably any buffering materials [63].

Surrounding rocks will expand as a result of the temperature rise, and this may lead to an uplift of the ground surface above the GDF. The magnitude of any uplift depends on the heat output of the waste, the design of the GDF (in particular, its footprint and depth) and key properties (the thermal conductivity, specific heat capacity, density, thermal expansion coefficient and Poisson’s ratio) of the GDF materials and surrounding rocks [18, 64].

For planning purposes the bounding EBS temperatures for the three illustrative concepts for HHGW are currently defined in the DSS as:

- For HSR; a maximum temperature of 100°C on the inner surface of the bentonite.
- For LSSR; a maximum temperature of 125°C at the mid-point of the buffer material.
- For EVR; a maximum temperature of 200°C in the backfill material.

These assumptions have a significant effect on GDF design, affecting the footprint and/or the time of backfill and/or the waste emplacement strategy.

The Thermal Dimensioning Tool (TDT) is a software tool that is able to perform thermal analysis for a range of disposal concepts, including multi-purpose containers and other containers emplaced in vaults or tunnels (see Figure 11) [61]. The TDT has the following capabilities:

- It has the ability to perform thermal dimensioning for a range of concepts;
- It uses analytical and semi-analytical expressions to solve the relevant heat conduction problem to take full advantage of the speed and ‘accuracy’ inherent in these results, when applied to simple geometrical configurations of the waste;
- It can model the consequences of parametric uncertainty;
- It supports good principles of quality assurance of data; and
- It has a simple, clear user interface to help the user construct a model.

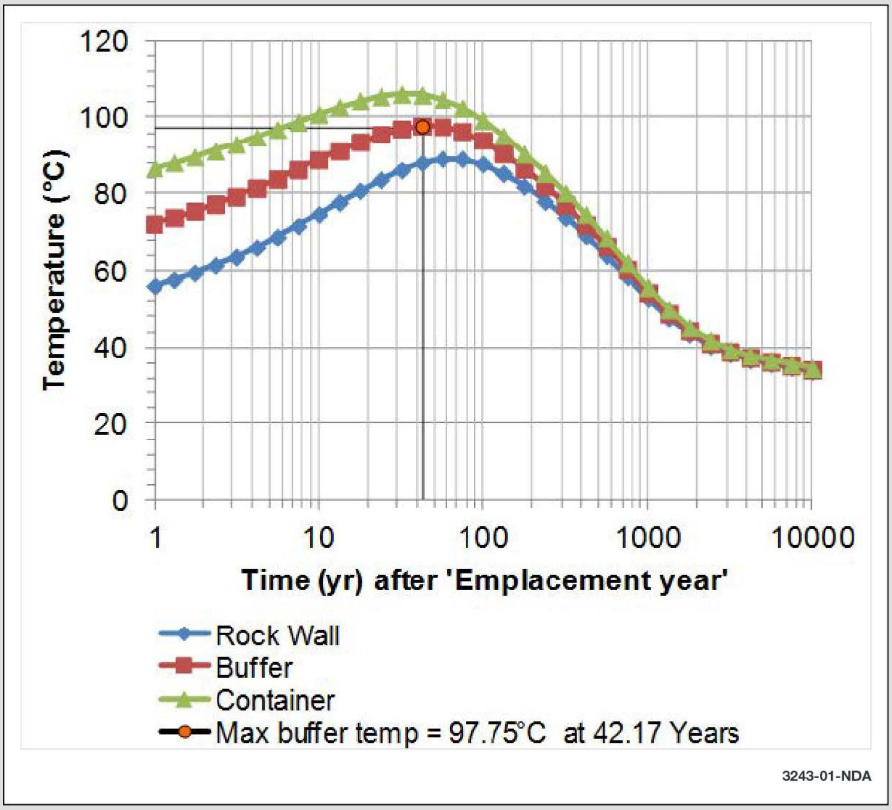


Figure 11: Temperature of PWR SF as a function of time after emplacement in different parts of the EBS. Rock wall refers to the interface between the buffer and the host rock. Buffer refers to the inside face of the buffer. Case is for emplacement 2075.

The TDT is used to understand the consequences of placing a maximum temperature constraint on the buffer material (or host rock). The process of exploring the waste package loading and the separation of the HHGW packages to ensure specified thermal limits are not exceeded, is termed thermal dimensioning [65]. This analysis is an important aspect of determining the size, schedule and cost of a GDF.

Box 8 Helpful Insights – Post-closure Modelling Tools

In the post-closure period, the assessed radiological risk from a disposal facility to a person representative of those at greatest risk should be consistent with a risk guidance level of 10^{-6} per year (roughly equivalent to a dose guidance level of 20 microSv/year) [8].

It is possible to gain considerable understanding of the post-closure performance of the GDF, and even to quantify that understanding, by consideration of the basic physics of the disposal system. This is often termed ‘insight modelling’ and is discussed in Section 2.1 of the PCSA [5].

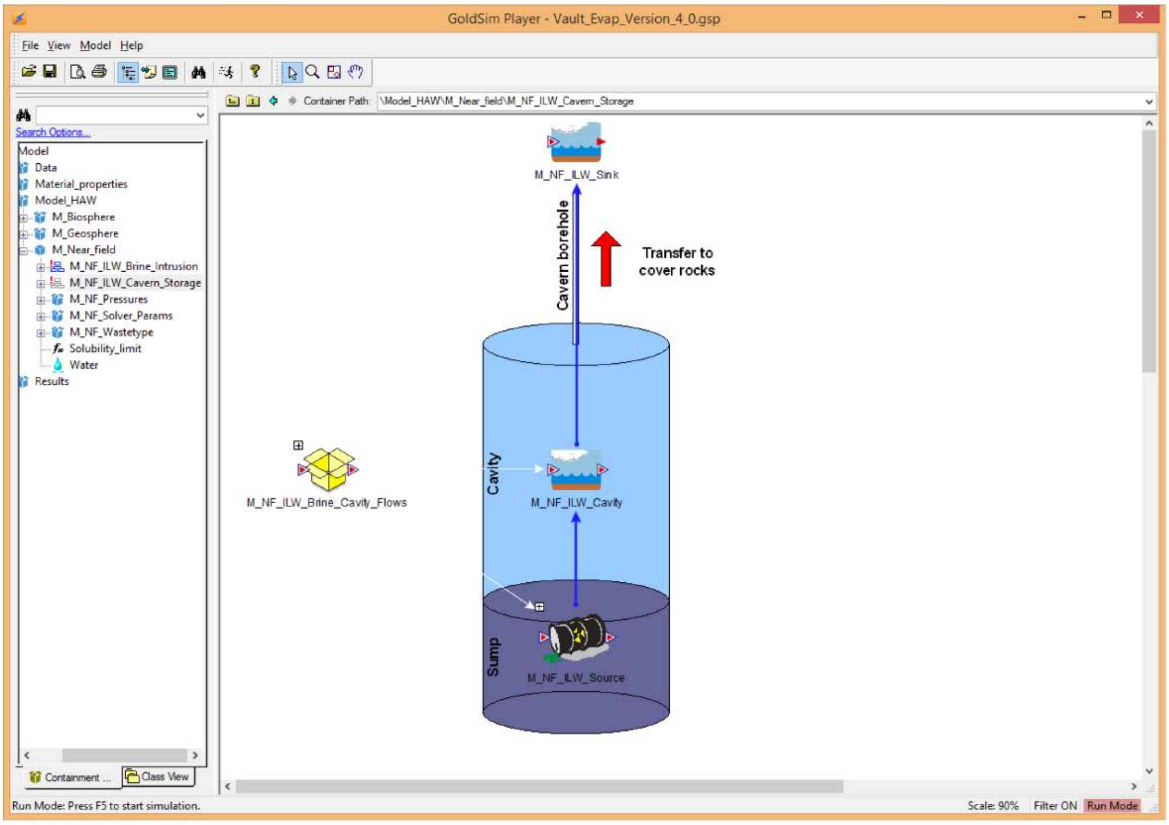
A simple system evolution over time, suitable for quantitative modelling, can be expressed as follows:

- Failure of containers;
- Radionuclide release from the wastes and dissolution in water;

- Transport through local and mass buffer/backfill;
- Transport through the geosphere and discharge into the biosphere.

By focusing on the development of simple models for generic concepts (for example, see Figure 12), similarities and differences in the ways in which the different concepts provide post-closure safety, at a broad level, have been identified [66].

Figure 12: Screenshot of the High-level Model for the Cavern Storage Scenario [66]



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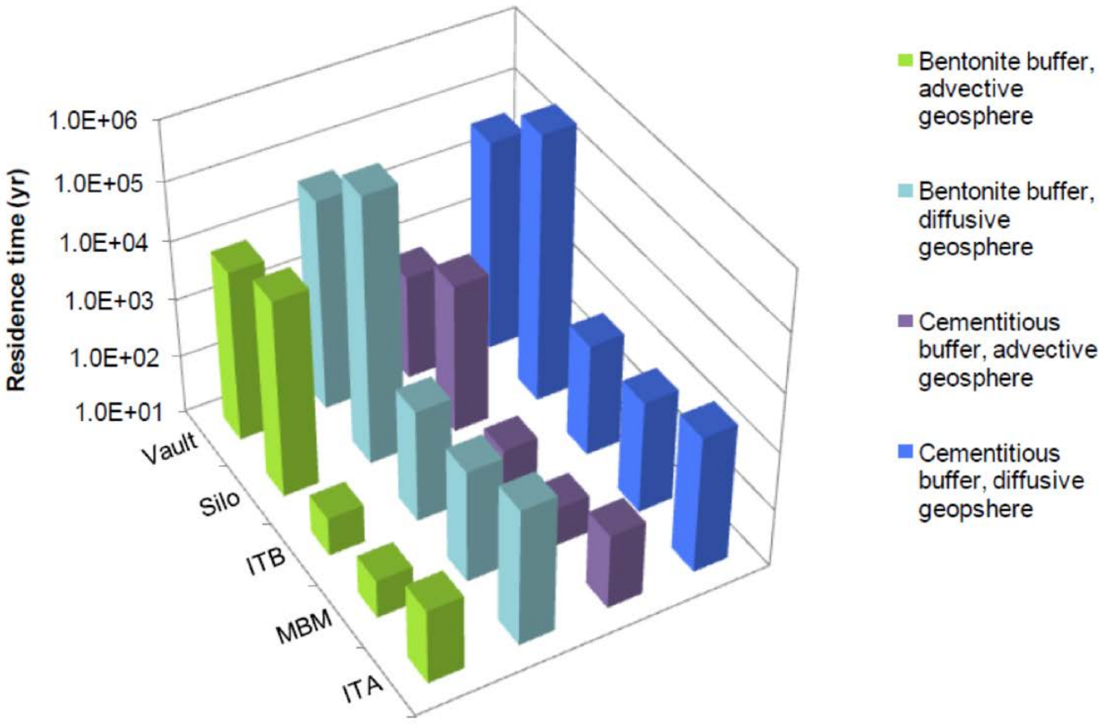
Depending on the concept modelled, buffer specification and geosphere properties, the calculated residence times in the buffer material for a non-sorbing, long-lived, soluble species vary from approximately 100 years to several hundred thousand years (see Figure 13).

Figure 13: Illustration of estimates of the ‘residence time’ (corresponding to a non-sorbing, long-lived, soluble species) in the buffer for various combinations of GDF design, buffer material and geosphere properties [66].



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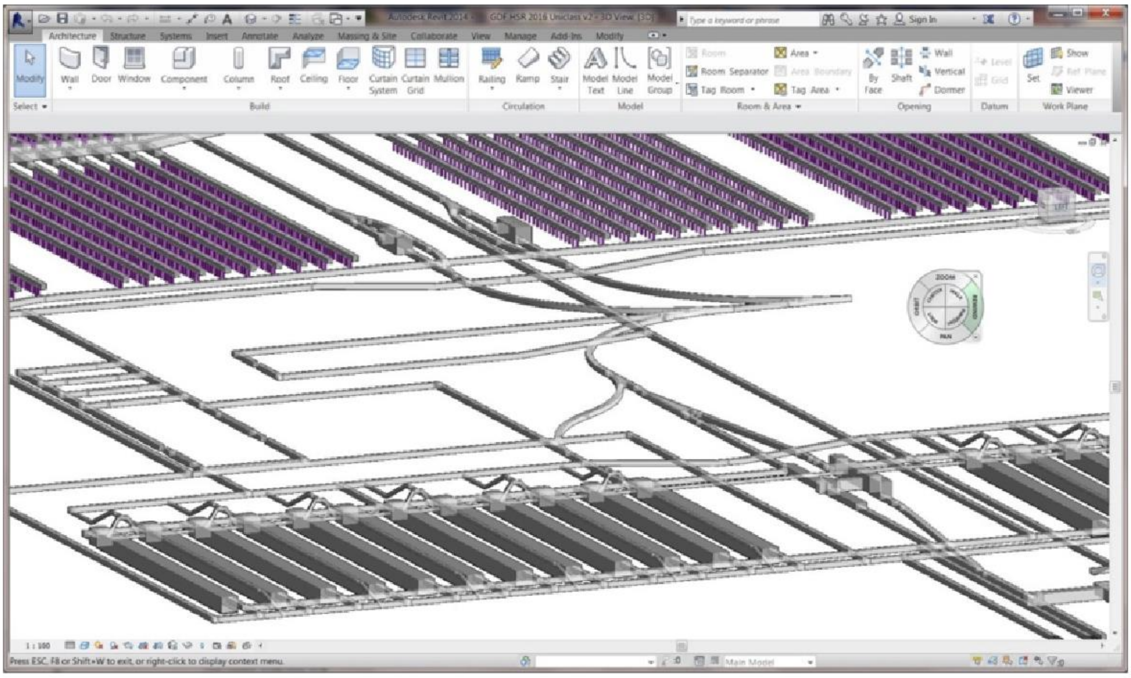
Box 9 RWM Tunnel and Vault Calculator

The tunnel and vault calculator (see Figure 14) is a tool developed by RWM to enable the calculation of the total number of tunnels (HHGW) and vaults (LHGW), required for a given inventory of waste. In order to calculate the number of tunnels and vaults a number of input parameters are required, including; the inventory, the type of waste package (dimensional envelope), the spacing’s required between waste packages, the waste package stack height and the tunnel (including deposition hole)/vault profile and length. The tunnel and vault calculator can also calculate the required backfill quantities for the disposal vaults and the quantities of bentonite buffer and the total tunnel backfill required for the disposal tunnels.

Figure 14: Autodesk Revit 3D model of a GDF in Higher Strength Rock



Press ESC, F8 or Shift+W to exit, or right-click to display context menu.

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4 Concept Descriptions

At the generic stage, the identification of broad groups of waste-specific disposal concepts focus on distinctions related to engineering issues, in particular the geometrical layout of the GDF. These broad groupings are referred to as generic concept descriptions by RWM.

As discussed in Section 3, the impacts of implementing a range of concept options for different waste types will be considered further as an input to the siting process [5]. During early siting, it is unlikely that much sub-surface data on the geological environment will be available. This will limit the extent to which disposal concepts can be tailored to the geological environment, and, in particular, will limit the extent to which choices can be made on EBS materials. However, broad information on the geological structure of potential candidate sites is likely to be available, and this is expected to be sufficient to develop a preliminary understanding of the likely host rock type, volumes of rock available and possible depths at which the GDF disposal areas can be constructed. At this stage, and with the current level of available information, it is both convenient and appropriate to consider the existing waste-specific disposal concepts at the level of broader groupings that have similar construction and operational fundamentals.

The identification of broad groups of waste-specific disposal concepts has thus focused on distinctions related to engineering issues, in particular the geometrical layout of the GDF. This approach leads to generic concept groups that are distinguished by their impact on utilisation of the available space (spoil volume and footprint) and by the operational procedures required for implementation. All of the disposal concepts are considered to be safe given certain assumptions (e.g. assumptions regarding the inventory, disposal schedule and geological environment), and, therefore, transport, operational and post-closure safety is also implicitly accounted for in each of the waste-specific disposal concepts.

Using the approach described above, four groups of generic HHGW concepts, and two groups of the generic LHGW concepts have been identified. At this stage in the programme, when engineering issues have not been explicitly addressed during the identification of uranium and plutonium disposal concepts, we assume that depleted, natural and low-enriched uranium (DNLEU) will be disposed of using a disposal concept for ILW/LLW, and high-enriched uranium (HEU) and plutonium will be disposed of using a concept for HLW and spent fuel. Although this assumption is reasonable at this stage of GDF implementation, the optimised end point of concept selection may be different disposal concepts for different types of waste.

The four groups of generic HHGW disposal concepts are:

- In-tunnel Borehole (ITB) concepts.
- In-tunnel Axial (ITA) concepts.
- Vault-based (CAV) concepts.
- Mined Borehole Matrix (MBM) concepts.

And the two groups of generic LHGW concepts are:

- Vault-based (VLT) concepts.
- Silo-based (SLO) concepts.

Each group is described in the sections below. All of these concepts have previously been considered to some extent for each of the three generic host rock types recognised by RWM [21]. (As noted in Section 1, deep borehole disposal, which was previously identified as a potential concept [20], is now considered to be a potential alternative to disposal in a GDF for some groups of waste [2].)

Box 10 – Current RWM Definitions

Borehole: a generalised term for any cylindrical excavation (horizontal, sub-horizontal or vertical) made by a drilling device. This term is usually used for excavations less than 2m diameter.

Drift: An inclined tunnel, also known as a ramp or decline, providing access from the surface to the underground facilities. (Note that in general mining terminology, *all* horizontal or sub-horizontal development openings are termed ‘drifts’.)

Gallery: See tunnel.

Shaft: A vertical excavation, expected to be around 8m in diameter, providing access from the surface to the underground facilities. (Note that in civil engineering, a shaft is an underground vertical *or inclined* passageway.)

Silo: A large vertical sub-surface excavation, around 20 to 40 m diameter, with a height of 45 to 70 m.

Tunnel: a horizontal underground passageway, usually between 2m and 6m in width. RWM currently uses this term to refer to excavations which are single/blind entry with access from one end only, as well as excavations with an entry and an exit (the more standard definition of a tunnel).

Vault: A large horizontal excavation, currently assumed in RWM’s illustrative designs to be 9 -16m in width, and 5-16m in height.

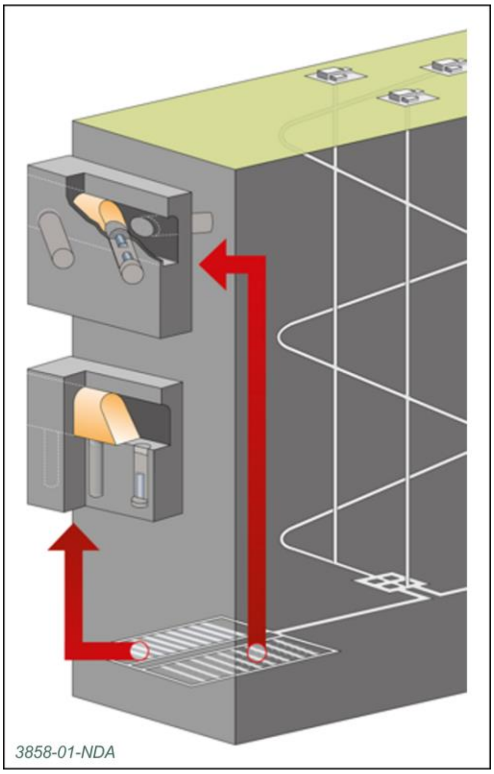
In practice, it can be hard to clearly distinguish between concepts. Box 10 provides a summary of how RWM is currently using some key terms in our illustrative designs [11].

4.1 In-tunnel Borehole (ITB) Concepts for High-heat Generating Waste

In-tunnel borehole concepts envisage waste emplacement in small diameter boreholes (for example, see Figure 15). These boreholes may be vertical or horizontal and they may each contain a single waste package or multiple waste packages. The dimensions of each borehole are sufficient to take the waste packages and any surrounding buffer material. The boreholes are dead-ended and of medium to large diameter (e.g. 0.6-1.5 m) drilled from deposition tunnels. Borehole length typically ranges from less than 10 m to several tens of metres. Such concepts often contain provision for retrievability, for example design features to facilitate later removal of the waste from the boreholes. In-tunnel borehole concept variants have been developed in Sweden and Finland (KBS-3V), Canada, Japan, Germany and Belgium [7].

A particular feature of these concepts is the isolation of the waste package from potential fast transport pathways that may be present within an excavation disturbed zone (EDZ) surrounding the disposal tunnels, and which could be created in some rocks excavated using drill and blast excavation techniques. This concept typically requires detailed characterisation of emplacement boreholes and complex emplacement operations involving rotation of the waste package within the emplacement tunnel.

Figure 15: Schematic illustration of an in-tunnel borehole concept for HHGW



This layout supports either vertical or horizontal emplacement of waste packages. The use of deposition holes for waste emplacement was originally developed in response to uncertainty about the extent and properties of the EDZ around a relatively large-diameter tunnel in a higher strength host rock. It was unknown whether the EDZ could provide a long, interconnected, high-porosity and high-permeability zone in which water flux might be high and which could provide fast advective pathways to water-conducting fracture zones, thus circumventing part of the geological barrier. The deposition holes were intended to isolate each waste package and place it 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 (this places significant requirements on the quality of the rock at each deposition hole site).

In-tunnel deposition hole concepts are mature and have been extensively studied, particularly in Finland and Sweden. Both Posiva (in Finland) and SKB (in Sweden) have submitted licence applications based on the KBS-3V concept, with Finland gaining approval in 2016 by the Finnish radiation safety authority STUK to construct a final repository for this type of concept. Andra are developing in-tunnel deposition hole concepts in which multiple waste packages are placed in horizontal deposition holes in LSSR.

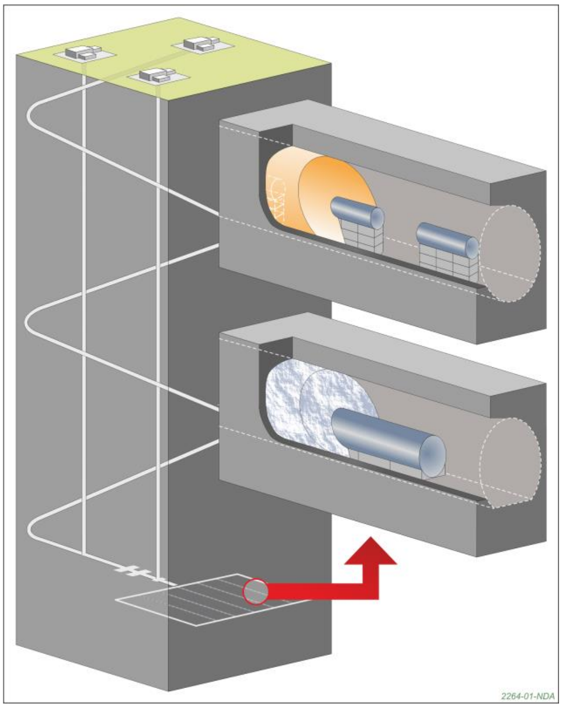
These concepts were included in the HLW and spent fuel Concept Report as Concepts 1 and 2, and are further described there [20]. RWM has investigated technology transfer specifically for this concept layout with the French [67] and Swedish reference designs [68]. RWM also include this layout option as an illustrative design within the generic DSSC [4], based on the Swedish KBS-3V reference design adapted to UK wastes. This concept is described further in Appendix A1.

4.2 In-tunnel Axial (ITA) Concepts for High-heat Generating Waste

In-tunnel axial concepts envisage the emplacement of waste packages axially within emplacement tunnels (for example, see Figure 16). Depending on the characteristics of the host rock and the host geological environment, the void space around the waste packages may be filled with a low-permeability buffer (e.g. bentonite) or an inert void filler such as crushed host rock (e.g. halite in evaporitic environments). In-tunnel axial concept variants have been developed in Switzerland, Germany, Japan, Spain, Belgium, the USA and Canada.

A particular feature of these concepts is that a larger volume of buffer is emplaced around the waste package, which requires special techniques so that required densities can be achieved (for bentonite), but could allow for higher temperatures in the GDF and consequent earlier emplacement of waste packages or closer spacing.

Figure 16: Schematic illustration of an in-tunnel axial concept for HHGW



Axial emplacement reduces operational complexity compared to borehole emplacement, as there is no need to rotate the waste package during emplacement. Axial emplacement would also reduce the excavated spoil volume, as the deposition tunnels are utilised for emplacement (there is no requirement to excavate the additional emplacement boreholes used in the ITB concept). Footprints for axial and deposition hole concepts are generally equivalent, as the footprint is largely determined by a similar approach to thermal dimensioning.

Axial disposal concepts are mature, and have been studied for many decades. There has been extensive testing, including full-scale emplacement tests, of axial disposal concepts in URLs. In geological environments with high humidity or significant inflow of groundwater, including granites and clay rocks, difficulty has been experienced in the emplacement of pre-compacted bentonite blocks around waste packages. Therefore, in such environments, emplacement of bentonite pellets is usually envisaged. The buffer density achieved by pellet emplacement is generally less than can be achieved through use of pre-compacted blocks, which may influence the safety functions that can be performed by the buffer. Emplacement of a cementitious buffer presents further challenges; as a result of these difficulties, pre-fabricated EBS modules using a range of backfill materials complement this concept option.

These concepts were included in the HLW and spent fuel Concept Report as Concepts 3 and 4, and are further described there [20]. RWM include this layout option as an illustrative design within the generic DSSC for LSSR [4], based on the Swiss Nagra reference design for HHGW and adapted to UK wastes. This concept is described further in Appendix A2.

4.3 Vault Concepts for High-heat Generating Waste

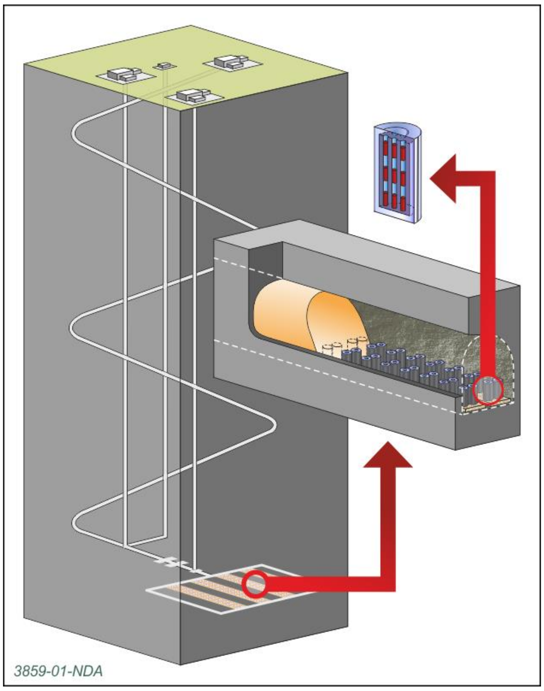
Vault concepts, also known as Cavern concepts (CAV), for HHGW involve placing waste packages, vertically or horizontally, in a vault and then surrounding them with a buffer (Figure 20). The HHGW vault concept is potentially flexible (although the maximum size of the vault would depend on the host rock) and could be implemented for two different motives:

- The layout potentially allows for large, heavy, waste packages with a high waste loading to be emplaced in vaults with the expectation that there is a long period (hundreds of years) to allow for cooling and inspection, and to provide for retrievability if required at a later date.
- The layout could be adopted for operational reasons to facilitate the emplacement of standard sized waste packages with the buffer being emplaced soon after the waste packages.

Vault disposal concepts generally envisage relatively dense emplacement of waste packages, which would reduce the footprint of a GDF and also reduce spoil volumes. The use of large waste packages and relatively straightforward emplacement procedures would allow for accelerated emplacement. A geological environment in which the vaults can be maintained in an open state for long periods may be required. After any open period, a buffer would be emplaced around the waste packages, vault seals emplaced and access tunnels backfilled.

Vault concepts have been investigated in the Japanese programme. These concepts were included in the HLW and spent fuel Concept Report as Concepts 8, 9 and 11 [20]. The schematic (Figure 17) shows a large capacity MPC but waste packages in this layout would not necessarily be any larger than for other layouts. Vault disposal concepts for HHGW potentially provide for flexibility in the disposal containers, and the buffers and backfills that can be used. The size of the vaults could allow for emplacement of either MPCs or pre-fabricated EBS modules utilising the full range of design solutions available. Composite buffers and backfills could be emplaced, and this could provide some flexibility to manage thermal issues (see below).

Figure 17: Schematic illustration of a vault layout for HHGW

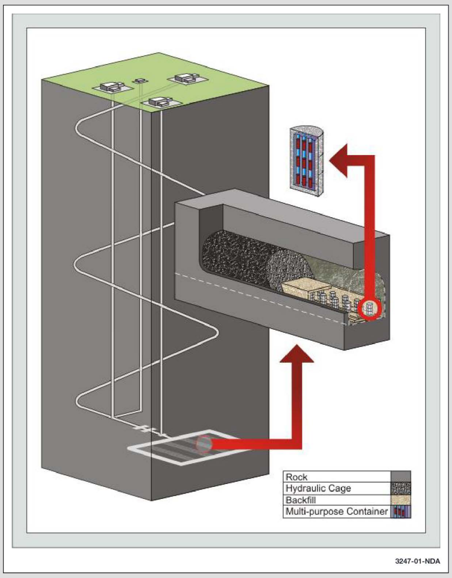


Keeping vaults containing large waste packages open for the long periods that are likely to be required before the buffer can be emplaced would require significant maintenance, and, potentially, active cooling and ventilation [46]. Disposal concepts using this layout are vulnerable to incomplete closure or loss of institutional control if it includes a long open period.

Dense waste emplacement could result in high temperatures following closure. There is a trade-off between the size of footprint and the required open period: dense packing of the waste means that emplacement of the buffer would have to be delayed for longer. Conversely, spreading waste over more vaults reduces the maximum temperature in the buffer allowing earlier closure, but at the expense of increased footprint.

RWM has recently undertaken a concept study to develop an outline design for a HHGW vault [69] and considered cost and footprint implications compared with other illustrative design layouts for HHGW considered in the generic DSSC [4]. This concept is described further in Appendix A3. Box 11 discusses the use of hydraulic cages, which could be used in combination with a number of disposal concepts, including vaults.

Figure 18: Hydraulic cage



Box 11 – Hydraulic Cage Options

The hydraulic cage option [20] relies on a highly permeable layer of crushed rock to form a preferential pathway for groundwater flow and thus prevent advective flow driven by hydraulic gradients through the wastes. 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. The Richard repository for LHGW in Czechia has installed a hydraulic cage to improve the safety of the facility.

Hydraulic cages were initially proposed to modify water flux for long-term safety, but RWM currently believe that no credit could be claimed for the presence of a hydraulic cage within the post-closure safety case.

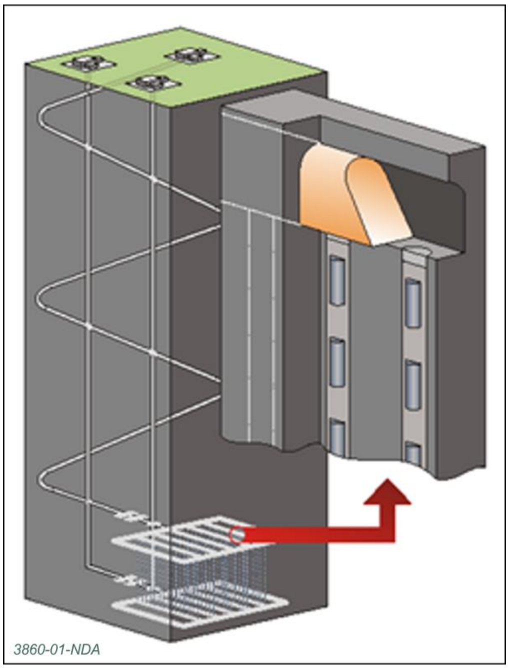
A hydraulic cage could be used to improve conditions during the operational phase if a site has a high groundwater flux, although this would be expensive option, requiring additional excavations.

4.4 Mined Borehole Matrix Concepts for High-heat Generating Waste

MBM GDF concepts envisage disposal of waste packages in stacks in long vertical boreholes, which are typically located between tunnel systems at two depths and are 200-300m in length (for example, see Figure 19). The emplacement boreholes would most likely be constructed by raised boring from the lower tunnel system, and waste packages would be emplaced in the emplacement boreholes as supercontainers or as waste packages around which a buffer would be placed. The length of the boreholes would be constrained by the geometry of the host rock.

MBM concepts have been investigated in the German and Japanese programmes. MBM concepts were included in the HLW and spent fuel Concept Report as Concept 10, and are further described there [20]. RWM has also recently undertaken a concept study to develop an outline MBM design [70], described further in Appendix A4.

Figure 19: Schematic illustration of a mined borehole matrix (MBM) layout for HHGW



Implementation of this layout would require a vertically extensive host rock, such as a granite pluton. The boreholes could be lined with a steel liner to facilitate emplacement. Alternatively, in a host rock that is expected to creep (for example, salt), waste packages could be emplaced in unlined boreholes and closure could be provided by encapsulation of the waste by the host rock.

Mined borehole matrices potentially allow for relatively dense emplacement of waste, leading to a small footprint and low spoil volume. Development of concepts using this layout would need to consider the potential for mitigation of dropped waste packages, consider how the compressive stress from the mass of the waste package stack would be managed, and evaluate the high temperatures likely to be present owing to the dense emplacement of the waste. Thermal considerations will define the borehole spacing and the separation distance of waste packages within a borehole [70].

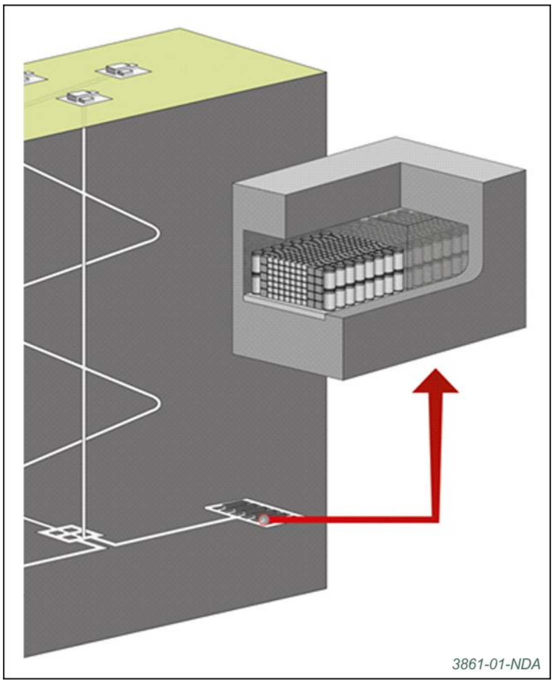
Raise-boring is a standard mining engineering technique, with extensive worldwide experience. Significant work has been undertaken on these disposal concepts for the specific case of disposal in salt domes and a mined borehole matrix disposal concept is part of the reference case approach to geological disposal of radioactive waste in Germany.

4.5 Vault-based Concepts for Low-heat Generating Waste

The illustrative disposal concepts recognised for LHGW in the generic DSSC are all based on disposal of ILW/LLW containers in vaults, with distinctions recognised as a result of the nature of the waste packages (shielded or unshielded), the approach to emplacement of the EBS (no backfill, emplacement of backfill as a supercontainer, emplacement of backfill prior to emplacement of waste packages, and emplacement of backfill after waste packages) and changes in the concept in relation to the geological environment (quantity of backfill and size of openings).

Vaults are large dimension excavations within which waste package are stacked (see Figure 20). Disposal vaults for LHGW typically comprise a ‘D’ shape excavation with vertical sides and an arched roof. Vaults typically have a long aspect ratio: lengths between 125 and 900 m [19], and cross-sections between 25x35 m [19] and 10x5 m [7] have been considered within the UK programme, drawing from experience of underground excavations internationally at the depth range considered for a GDF [11]. Larger or smaller vault dimensions could be used in a GDF.

Figure 20: Schematic illustration of a vault for LHGW



Disposal of ILW/LLW in vaults allows for a range of waste package types to be disposed of in the same region of a GDF. The design of the vaults could build on experience from the operation of ILW surface storage facilities, and, therefore, there would be precedent experience that could be used in design of the various systems that will be required to emplace waste packages and in development of operational safety cases.

Vaults allow for a range of backfills to be emplaced, with flexibility in the timing and manner in which the backfill would be emplaced. This provides opportunities for optimisation of the operational safety case and the provision of post-closure safety functions (e.g. cementitious backfill to provide chemical conditioning of the GDF to provide sorption and low solubility). If the host rock properties allow it, emplacement of backfill could be delayed, allowing for a period of monitoring and provision of relatively straightforward retrievability.

Operation of vaults often envisages the use of an overhead or straddle crane, especially in cases where remote handing is required. Alternatively, waste packages could be emplaced using a stacker truck or similar technology or some form of conveyor system. Straddle cranes would potentially be required to operate for long periods (decades), whilst maintaining high-precision placement of waste packages. At the same time, during the long open periods that are envisaged for some vault-based disposal concepts, vaults would potentially experience the effects of rock creep, which would require mitigation, and consideration has to be given to the possibility of rock fall in the operational safety case.

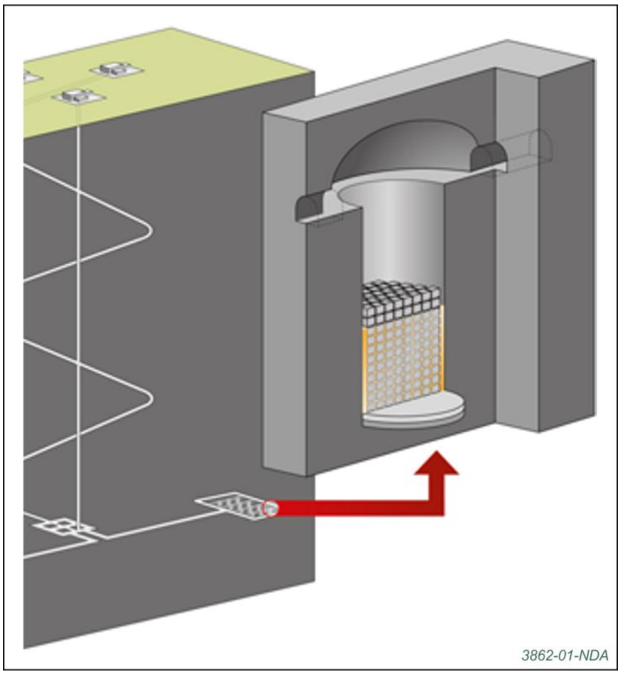
As vaults are oriented horizontally, the footprint is larger than for silo concepts, in which there is a more three-dimensional arrangement of waste packages, although the relative impact on footprints depends on the nature of the geological environment, the disposal concept and the properties of the waste. The maximum size of the waste stacks would be determined by a range of factors including host rock properties, mechanical properties of the waste packages and thermal considerations. Vaults with small cross-sections would result in significantly increased footprints and potentially larger spoil volumes compared to vaults with large cross-sections. The use of cranes rather than stacker trucks also tends to result in a less efficient use of vault volume, but it enhances the potential for retrievability. However, in some vault concepts, additional waste packages may be emplaced in the crown space used for crane operation after the main part of the vault has been filled. Waste packages may also be placed in the access tunnels. Relatively large quantities of backfill materials are envisaged for many vault concepts, for backfill, in the GDF sealing system, and to provide rock support.

There is experience in the UK of the development of disposal concepts, designs and safety cases for vault-based geological disposal of ILW/LLW in a higher strength host rock using a cement-based backfill [4,71]. The use of vaults is also considered in most other national programmes investigating geological disposal of ILW/LLW (see, for example [19]).

4.6 Silo-based Concepts for Low-heat Generating Waste

An alternative to the use of vaults for the disposal of ILW is the use of silos. Silos are cylindrical underground openings with the major axis vertical (for example, see Figure 21). The domed roof and curved walls are inherently stable and require less rock support than a vault. A silo in hard rock could have a maximum diameter of about 35 m and a height of 70 m [72]. A benefit of a silo compared to a vault is the larger stack volume below the crane rail in proportion to the volume above the crane rail; silos offer a way to limit the fraction of potentially unused space.

Figure 21: Schematic illustration of a silo for LHGW



Silos have been used for near-surface disposal of ILW/LLW, for example in the SFR repository in Sweden [73] and the VLJ repository in Finland [74]. Silos were also considered as an option for the disposal of ILW in the UK during early conceptual studies undertaken in the 1980s [19]. RWM has recently undertaken a review of international silo concepts for LHGW and undertaken concept studies to understand the implications of this layout option for UK wastes [75], described further in Appendix A.

4.7 International Developments to Disposal Concepts and Alternatives to Geological Disposal

The Concept Reports for HHGW and LHGW were published in 2008 [19, 20]. Since that date, national programmes have continued to undertake research, development and demonstration (RD&D) of disposal concepts and disposal designs for disposal of all HAW in a GDF. A review of key developments in GDF concept options as a result of RD&D is provided in each of the tables contained in Appendix A.

Any management steps that reflect a departure from disposal of HAW in a GDF can be considered as alternative radioactive waste management options. RWM recently published a review of recent developments in the published literature in the field of alternative radioactive waste management options [2], building on past reviews (for example, [76,77, 78]). This includes consideration of:

- Alternative steps in long-term radioactive waste management, which could alter the nature, and/or reduce the quantity, of waste requiring geological disposal. Such options include long-term interim storage, and waste treatment techniques, including thermal treatment, enhanced encapsulation, and partitioning and transmutation (P&T).
- Alternatives to geological disposal for certain wastes, which could remove the need to manage some components of the HAW inventory (and/or some nuclear materials not yet declared as waste) through geological disposal. Such options include near-surface and deep borehole disposal.

4.8 Capturing Knowledge on GDF Disposal Concepts

As the GDF science and technology programme [3] progresses, knowledge from concept studies will continue to be generated. This Concepts Status Report is the main knowledge base upon which RWM will continue to expand as an input to siting and in preparation for future decisions relating to concept selection. The level of detail at which disposal concepts need to be defined and described will evolve as the geological disposal facility (GDF) programme develops. It is linked to the nature of the decisions that need to be made at the time, and the amount of information that is expected to be available to support the decision-making process. As the maturity of the programme increases, and site-specific information becomes available, the level of detail at which it is appropriate to define a disposal concept will increase as the concept is tailored to the specific site characteristics under consideration.

Given the current absence of information concerning site characteristics, it is not appropriate to develop information about disposal concepts to a high level of detail at the current stage of the programme. What is required instead is a good basic understanding of how the disposal concept would meet operational phase safety objectives and post-closure safety functions, and quantitative information where this is necessary to understand viability/feasibility, to allow comparison between concepts, and to identify strengths and weaknesses. Therefore, to build upon the generic concept descriptions illustrated in Section 4.1 to 4.6, more detailed concept summary tables are included in Appendix A to capture information and knowledge from completed concepts studies undertaken by RWM and by other waste management organisations internationally. The tables follow a common structure that aligns with aspects likely to be considered in future decision making processes relating to concept selection [5]:

- Title capturing the key features of the concept including layout, type of barriers and, if relevant, nature of host rock;
- Main drivers for the concept;
- Description of the main characteristics of the concept;
- Long-term safety concept: A description of how the different barriers will work together to provide post-closure safety;
- Construction and Operational safety;
- Implementation Options: the flexibility of the concept with respect to host rock, waste type and timescales;

- Monitoring and Retrievability Considerations: A description of any opportunities offered, or restrictions introduced, with respect to retrievability and monitoring by the disposal concept;
- Maturity of technology;
- Knowledge gaps- highlighting potential areas of focus for future work;
- Environmental impact;
- Lifecycle costs;
- International concept developments 2008-2017;
- Summary, and;
- References

The concept summary tables provide information on what constitutes the disposal concept; they do not evaluate the concept with respect to its relative performance against other options. Therefore, the tables do not include the evaluation of concepts against attributes or factors. This would be completed as part of options evaluation cycles at different stages of siting.

5 Concluding Remarks

The science and technology underpinning geological disposal concept options currently considered in the UK disposal programme is well established. The knowledge base includes information from our own concepts studies, undertaken by RWM, in addition to capturing new understanding from work undertaken internationally. The key message emerging from the body of work presented in this status report is that it is important to continue to develop understanding for a broad range of options.

RWM’s strategy for the use of GDF concepts is to increase the scientific maturity of the options available for consideration as part of the disposal system to an extent that is sufficient to enable selection decisions to be made, based on geological information that becomes available through the site selection process, and to enable sound decisions to be made regarding waste packaging proposals.

It is currently envisaged that any future concept development work will be documented and summarised in an updated version of this status report; providing a revised or more detailed range of options.

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A1 In-tunnel Borehole (ITB) Disposal Concepts for High-heat Generating Wastes (HHGW)

Mature concepts exist for:

☑HLW ☑Spent Fuel ☑Supercontainers

☑HSR ☑LSSR ☑EVR

Main drivers for HHGW ITB concepts

Retrievability - the ITB concept allows the access/emplacement tunnel to be left open and individual disposal holes to be accessed if required, without the need to excavate tunnel backfill.

Operational flexibility - the ITB concept allows individual emplacement holes to be isolated readily and access/emplacement tunnels to be rapidly sealed, thus reducing vulnerability to perturbations.

Post-closure – due to the reduced amount of buffer material needed (compared to ITA or CAV), this concept improves the heat transfer from the HHGW to the host rock, resulting in lower maximum buffer temperatures.

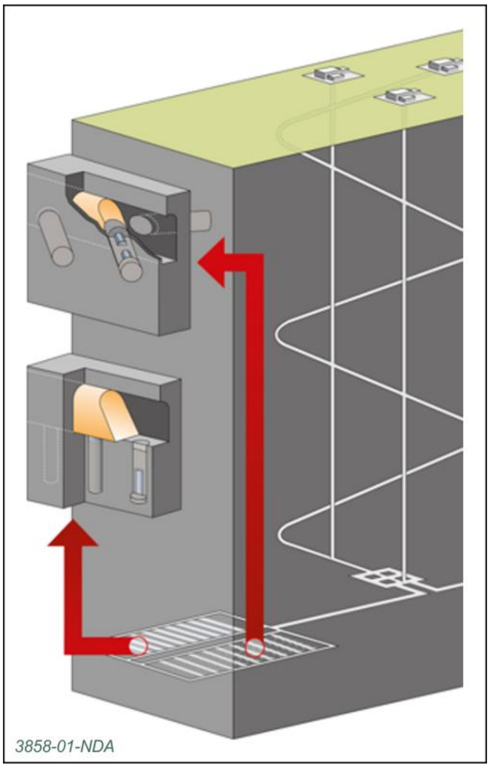
Main characteristics

In-tunnel borehole (ITB) disposal concepts for HLW and SF have been under development for over 35 years. The defining characteristic is that waste containers are emplaced in boreholes, drilled either vertically into the floor of an access and emplacement tunnel, or horizontally to sub-horizontally into the walls of the tunnel. The initial development of this concept was driven by an early concern that a “domino effect” failure of a series of SF packages might occur in a HSR, in-tunnel (ITA) disposal concept, were a redox front to develop from an initial canister failure and propagate along the tunnel.

Although considered in several national programmes, the principal developers of the ITB concept at present are:

- horizontal to sub-horizontal boreholes in LSSR: France (Andra) and Belgium.
- horizontal to sub-horizontal boreholes in evaporite: Germany (DIREGT concept).
- horizontal to sub-horizontal boreholes in HSR: the KBS3-H concept of SKB and Posiva, Sweden and Finland; KAERI, Republic of Korea.
- vertical boreholes in HSR: the KBS-3V concept developed by SKB and Posiva, Sweden and Finland.

Figure A1-1: Schematic of the horizontal (top) and vertical (bottom) ITB concept



The use of supercontainers is being considered in Sweden and Finland for horizontal emplacement of SF in HSR. The diameter of the boreholes is larger than in other ITB concepts – effectively small diameter tunnels – and this concept (KBS3-H, discussed below), although treated here as a variant of horizontal ITB, overlaps in some respects with the ITA concept.

For HSR and LSSR, the components of the EBS and their dimensions vary with the characteristics of the HHGW, the desired emplacement density, and the expected performance of the geological barrier, etc.

In the vertical ITB concept, waste packages are 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). If 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 HHGW, a general characteristic of this design is that the thermal load is spread over a large area. The access/emplacement tunnels are backfilled with low permeability materials (e.g., compacted bentonite blocks, bentonite-sand blocks and/or pellets after all the disposal boreholes in the tunnel are filled, and a massive concrete and bentonite composite plug is emplaced at the end of each tunnel that will withstand the swelling pressure of the tunnel backfill as it absorbs water.

In the horizontal ITB concept, waste packages are emplaced in longer (tens of metres) boreholes, of medium to large diameter (e.g. 0.6 to 1.5 m), drilled in the walls of disposal tunnels, with massive plugs constructed at the tunnel end of each disposal hole, once it is filled. The tunnels might be backfilled immediately or could remain open for many decades, if required. The waste is emplaced in a metal canister (or “overpack” in the case of HLW containers). In the Republic of Korea concept developed for HSR, the engineered barrier components are similar to those for vertical borehole disposal in HSR. In the French concept developed for LSSR, there is no buffer.

Long-term safety concept

In common with all other concepts being considered by RWM, the post-closure safety concept is based on the multi-barrier principle, which means that the safety of the facility is not completely dependent on the functions of any one single barrier. The different barriers complement each other via mechanisms that are largely independent of each other. In addition to the natural barrier provided by the host rock, the concept uses an engineered barrier system (EBS) consisting of:

- a low solubility waste matrix (vitrified HLW; uranium dioxide spent fuel);
- a durable waste package: generally a waste container with an overpack – in HSR concepts, a corrosion resistant overpack is used;
- in HSR, a buffer between the package and the disposal borehole (usually of highly compacted bentonite clay);
- in LSSR, a steel borehole liner might be required to facilitate package emplacement, but is not expected to act as a key barrier in the EBS;
- a low permeability tunnel backfill: depending on the geological environment, of compacted clay or a bentonite-crushed rock mixture.

In all variants, the EBS acts in concert with the host rock to reduce any flow of water from the rock, to and around the waste, thus limiting the rate at which radionuclides can be dissolved from the waste, mobilised, and enter the rock-groundwater barrier. The EBS will prevent any such mobilisation until after the initial thermal period of a few hundreds or thousands of years and continue to function thereafter to limit considerably any migration of residual radioactivity from the wastes. In HSR environments, the buffer also acts as a physical protection for the waste package against possible shear movements in the rock in the distant future.

The preservation and longevity of buffer properties is a central aspect of HSR variants of the ITB concept. Thus, consideration is given to potential degradation due to processes such as ‘piping’ of bentonite by short duration, high hydraulic gradient flow of water immediately after closure or subsequent chemical erosion in the distant future if groundwater chemistry changes.

Post-closure Criticality is generally not identified as a concern, owing to the dispersed distribution of waste and limited interaction between packages.

Operational and construction safety

Construction of the long total lengths of tunnels required for ITB concepts increases construction risks compared to more compact concepts, such as the MBM or CAV concepts. Operational risks can be improved by the use of advanced excavation technology such as tunnel boring machines.

Several advanced designs based on ITB use disposal tunnels that are up to hundreds of metres long but blind-ended. These tunnels will be accessed by people during pre-emplacement operations and represent potential escape hazards in the event of mining accidents.

The additional requirement to excavate emplacement boreholes would be expected to increase the risks during construction due to the high stress locations created within the tunnels (junctions, areas with changing cross-sections).

Features that improve construction and operational safety (e.g. tunnel liners, extensive grouting) may complicate developing a post-closure safety case. A high-quality tunnel floor may be needed for operation of the large and heavy waste package emplacement machine.

The waste emplacement operations are inherently difficult for the ITB concept, owing to the small cross-sectional area of the access/emplacement tunnels compared to the size of emplacement machines and small clearances. Although fully automatic emplacement may be possible, in case of perturbations that require human intervention, the ability to provide high protection levels may be limited. This may be more problematic for some supercontainer designs due to the larger waste package size, weight and smaller clearances.

Designs where access/emplacement tunnels are kept open for an extended period (e.g. the French concept) require consideration of longer-term operational hazard potential, over several decades after waste emplacement.

Implementation options

Flexibility with respect to host rock variability; total tunnel length and GDF footprint are large in ITB concepts and consequently will be constrained by large-scale heterogeneities at disposal depth, such as major fracture zones in HSR or lithological variations in LSSR. In HSR, where no borehole liner is used, the need to account for larger fractures intersecting disposal boreholes (affecting, for example, mechanical response to earthquake shear) or localised water inflows may result in a significant fraction of disposal hole positions being excluded from use, possibly increasing footprint, environmental impact and cost.

Flexibility with respect to waste type: ITB design variants can be developed for all waste types, by varying the materials and geometry selected for the EBS.

Flexibility with respect to scheduling: As construction, operation and closure of tunnels and panels of tunnels can run in parallel in different regions of the GDF, there is some inherent flexibility with regard to scheduling.

Retrievability options

Although packages in short boreholes are retrievable in principle for some period after emplacement, the length of access/emplacement tunnels, small clearances and rapid backfilling approach make retrieval a more challenging issue compared to some other options. The vertical removal of large and heavy packages is particularly difficult. Retrieval from long, horizontal boreholes would be more complex, although the French LSSR package design is specifically intended to assist for a period after emplacement, were retrieval required. A number of detailed retrieval concepts have been developed for different designs.

Maturity of technology

Most cited in-tunnel borehole disposal concepts are currently classed as having high technical maturity levels, with non-active full-scale industrialisation ongoing in France, Finland and Sweden and GDF construction already licensed and taking place in Finland. Other programmes with adaptations of the KBS-3V concept are also contributing to the increasing knowledge base on technology demonstration for this concept. Large-scale demonstration programmes have been completed or are ongoing internationally at URLs in France, Sweden, Finland and the Republic of Korea, with a current focus on sealing and backfilling and upscaling of technology options towards full-scale industrialisation.

Knowledge Gaps

The RWM Science and Technology Plan provides a comprehensive description of priorities for further work identified by RWM for progressing their generic designs for ITB disposal for high-heat generating wastes in a HSR environment [A1.1]. Further knowledge gaps are also identified by different programmes, reflecting the stage of their programme with respect to siting and licensing. Common aspects are tunnel and borehole construction, quality of as-emplaced EBS and operational safety. The testing (full-scale demonstration) of tunnel end-plugs and sealing materials, and the design and construction of EBS emplacement equipment and deposition holes in specific geological settings are the subject of international R&D projects.

Environmental impact

The main issues relate to the large facility footprint, the volume of broken-out rock, much of which will not be reused, and the volume of backfill required. These are all likely to be larger for ITB disposal, compared to either ITA or CAV concept options.

Life cycle costs

GDF cost is affected by many factors, but the most significant are the inventory of waste, the timing of waste arisings, the timing and duration of each phase of implementation, the geological environment at the site of the GDF and the design of the GDF itself [A1.2].

Due to the complexity of construction and waste handing operations, an ITB option might be expected to be more expensive than an equivalent EBS using ITA emplacement. Alternatively, the use of longer boreholes, with several packages emplaced in each borehole, would reduce the amount of broken-out volume expected, resulting in lower costs compared to ITA construction.

International concept developments 2008-2016

Sub-horizontal – Horizontal ITB in LSSR: Andra (France)

There have been some developments to the basic concept for disposal in the Callovo-Oxfordian clay at the Bure site in eastern France, but these are relatively limited changes and were largely described during the update to 'Dossier Argile' of 2005, in the 'Milestone 2009' reports [A1.3, A1.4]. The current concept for HLW disposal in clay remains as illustrated below [A1.5].

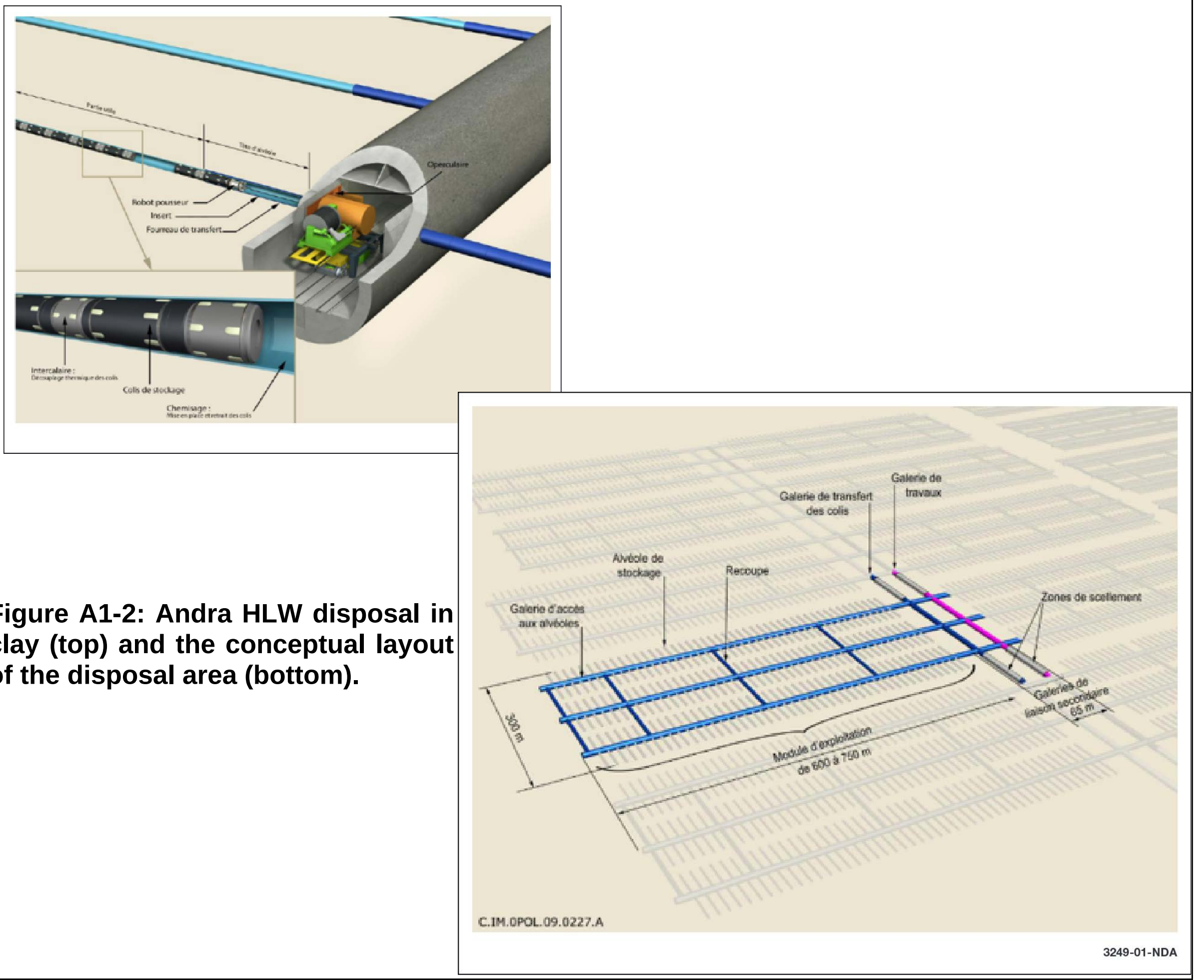
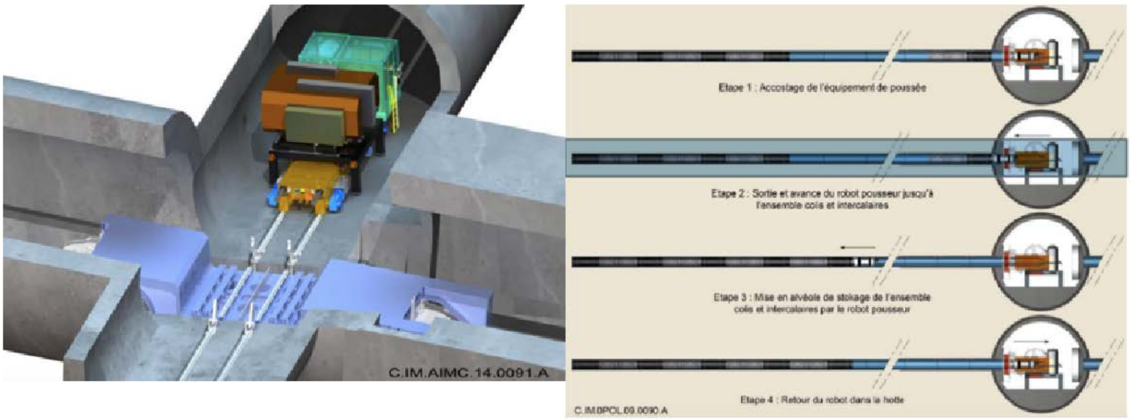


Figure A1-2: Andra HLW disposal in clay (top) and the conceptual layout of the disposal area (bottom).

The optimum length of disposal boreholes (*alvéoles*, in the figure) is a topic of current evaluation. At present, it is envisaged that waste containers will be transferred to the 500 m disposal depth using a funicular system in a 4.2 km inclined tunnel, with a 12 degree incline. The transfer vehicle will have a 130 tonne payload. The lower transfer station is illustrated in Figure A1-3 [A1.5].

Figure A1-3: The lower transfer station (left), the sequence of actions in the emplacement of a container using the robot pusher (right) [A1.5].



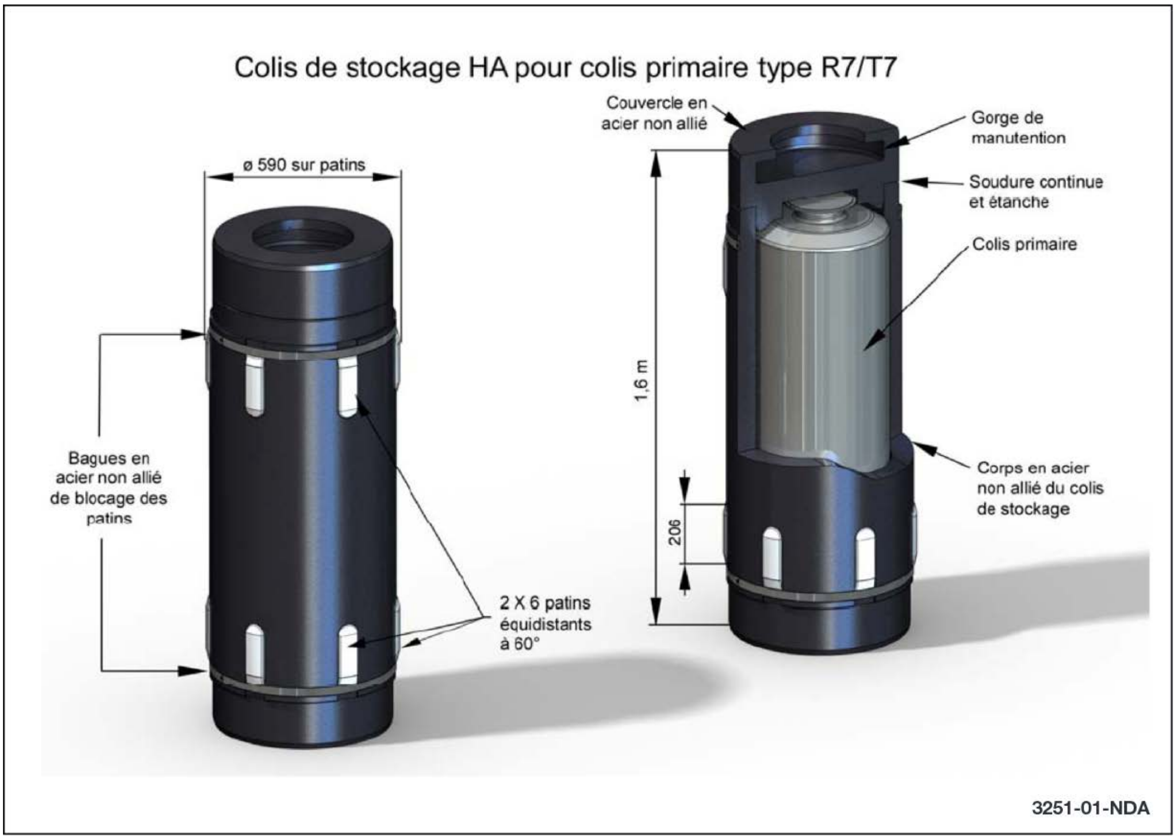
Using the Bure URL, Andra has developed and tested a two-stage technique for drilling and lining the disposal boreholes. The holes have a wider insert at the head-end, which acts as a sheath for the initial transfer of containers into the disposal holes, then a narrower lined hole where the canisters are deposited. Liners for both the insert and main hole are emplaced in 1 to 3 m lengths.

Andra has developed (and is testing at Bure), various means of inserting waste containers into the disposal holes, including the use of a robot pusher, as shown above. Containers have to be removed from the shielded transport container illustrated above, introduced into the transfer head of the disposal borehole and then emplaced deep inside the borehole. A first transfer system, using a pusher chain, introduces the containers and the second system, the robot pusher, complements the first and moves containers within the borehole. Both systems are designed to permit container retrieval. The sequence of actions in the emplacement of a container using the robot pusher is illustrated above [Figure A1-3].

Andra has developed various overpack container geometries and dimensions for HLW to accommodate different primary waste packages. Currently, HHGW in the French programme is HLW from reprocessing but, if considered necessary in the future, similar designs have been developed to dispose of spent fuel. The basic overpack consists of a non-alloyed steel shell of 55 mm thickness. The mass of the disposal package (comprising the primary package containing vitrified HLW and the overpack) is about 2 tonnes. It is handled using a gripping groove, which is machined directly into the closing cover. Andra intends to examine the possibilities of using recycled steel for manufacturing the overpacks, from the dismantling of nuclear installations. The overpack will be welded closed using electron beam welding.

The overpack has a number of inert ceramic pads on the outside to separate the steel of the overpack from the steel of the borehole liner. These will also facilitate emplacement and retrievability (allowing sliding of the containers within the borehole liner). One material option under study is zirconia.

Figure A1-4: The primary overpack design for vitrified HLW [A1.3], showing the ceramic sliders (patins), and cut away to show the primary vitrified HLW package. A similar design exists for SF packages.



At present, Andra has a number of concept optimisation studies underway or planned [A1.6], including work on access tunnel liners, on the engineering of package handling and transfer and on options for using longer disposal boreholes (up to 150 m). One such study is to assess the viability of relaxing the maximum temperature constraint in the centre of the HLW glass containers from 50 to 90°C [A1.7] which would allow consideration of a more compact repository (e.g., more closely spaced disposal boreholes).

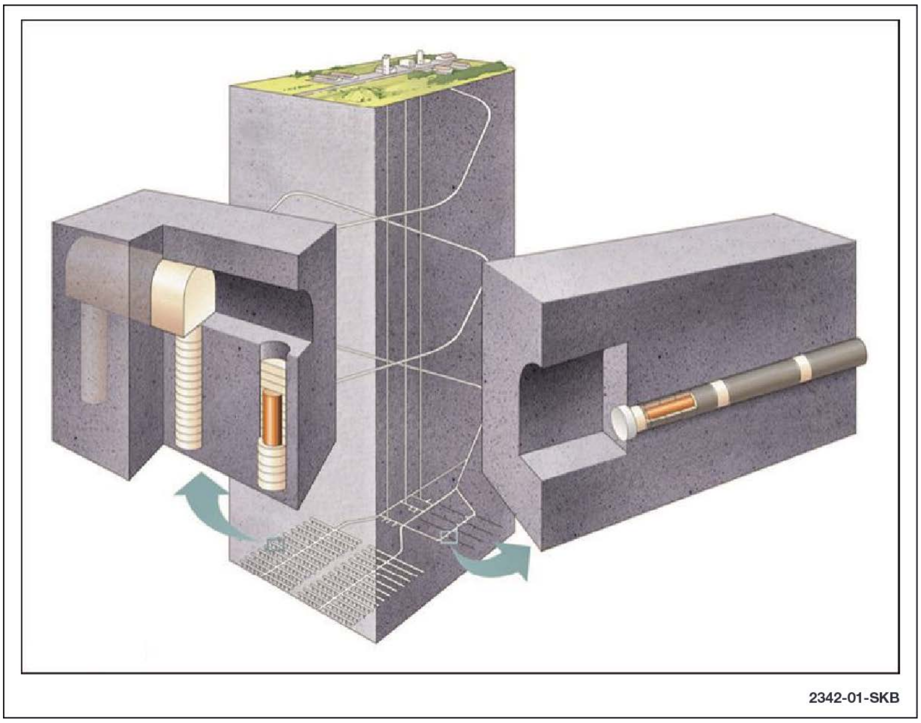
Further work is taking place on techniques for sealing shafts and tunnels in the facility, although these are not necessarily concept specific.

Vertical Boreholes in HSR: Posiva (Finland) and SKB (Sweden):

The KBS-3 concept remains the most advanced system for SF disposal, having been subject to construction license regulatory reviews in both Finland and Sweden that were completed in 2015-16. A construction license has been granted to Posiva (Finland) and the first tunnel excavation work into the actual disposal rock volume from the Onkalo facility at Olkiluoto began in December 2016. Posiva expects to submit a second license application in about 4 years time, to begin operating their GDF.

The advanced state of the concept is reflected in the considerable amount of R&D that has taken place in both countries, including advanced testing of the EBS components, construction of underground openings at full scale in URLs and development of methodologies that use specific rock characteristics to identify acceptable positions within disposal tunnels for canister emplacement.

Figure A1-5: Schematic of the KBS-3 concept, showing the vertical (KBS-3V) reference design on the left and the horizontal (KBS-3H) design on the right [3]



The KBS-3V concept itself remains largely unmodified since the 2008 RWM concepts study. SKB's current RD&D plans [3] are focussing on improving the knowledge base on the dissolution behaviour of the fuel and of different fuel types (e.g. higher burn-up; damaged assemblies), on how to define actual heat outputs for specific containers (affecting design and placement of packages) and on improving criticality assessments.

For the copper containers, SKB will carry out further work to improve understanding of localised corrosion by sulphide in groundwaters, of copper corrosion in pure, oxygen-free water (an issue which has gained prominence only in the last five years), of radiation-induced corrosion and of stress corrosion cracking, with a focus on the GDF's unsaturated period. Studies in both Sweden and Finland have estimated that the length of time that the disposal volume will take to saturate with water as it is progressively closed (which is site-specific) is likely to be highly variable from location to location, with the longest times estimated being up to several thousands of years, so understanding of how this affects container integrity is important.

SKB will carry out its testing on different copper materials (e.g. the basic material, welded parts, cold-worked parts). The issue of very long-term creep of copper (under hydrostatic load) onto the internal components has also proved an important matter during regulatory review in both Sweden and Finland. It is recognized by both SKB and Posiva that further study is needed and current work focuses on the impact of phosphorus in the copper on its ductility.

It is an indication of the advanced nature of both national programmes that continued design refinement (e.g. copper grain size specification) and practical demonstration of canister manufacturing, inspection and quality testing are important components of current and future work, along with work to transfer the industrial techniques to a fully active environment.

A similar observation can be made about the status of bentonite buffer specification and manufacture. SKB notes that the designs for buffer and backfill need to be revised [A1.8] and present work is at the stage where industrial manufacturing (e.g. pressing) procedures need further testing and qualifying, for example, to enable products that have uniform properties to be manufactured, despite the inevitable variability of the source materials that will be used over the GDF lifetime. Development of buffer and backfill emplacement machinery from the current prototype stage is also underway.

Again, buffer behaviour (especially mechanical) during the period from emplacement up to full saturation is a critical topic of R&D. One aspect of this is the potential for 'piping erosion' under the high hydraulic gradients that will exist in the GDF in the early period after closure of deposition tunnels and of the whole GDF.

Figure A1-6: Full-scale prototypes of the copper canister and cast iron inserts (for PWR and BWR fuel assemblies).

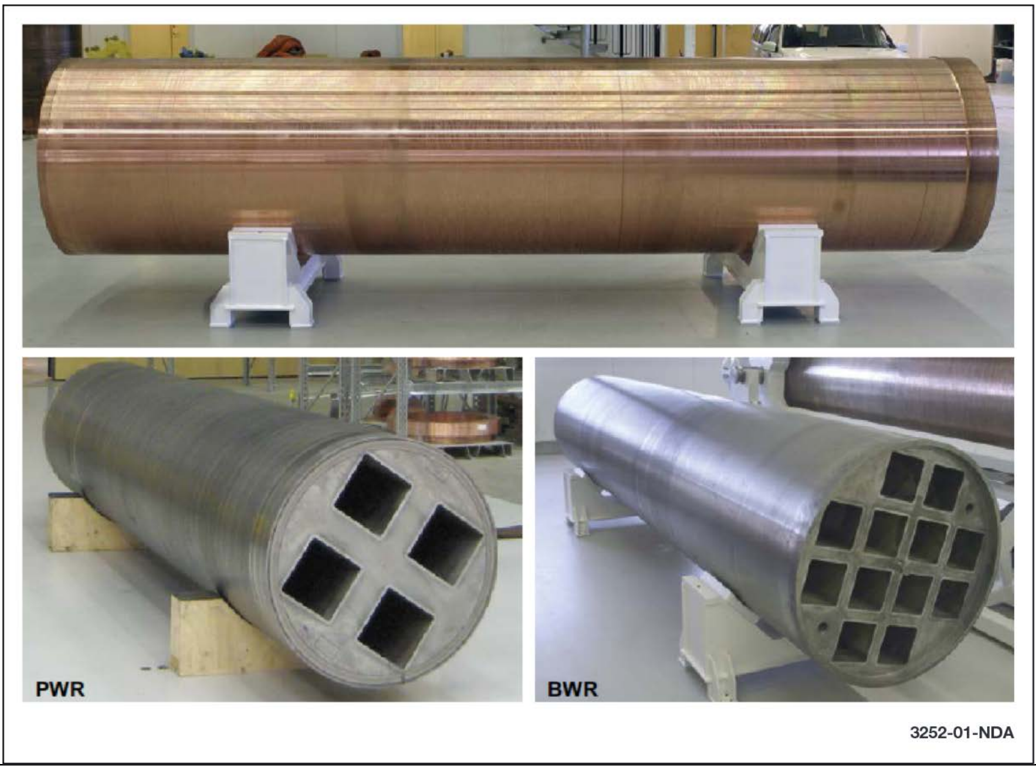
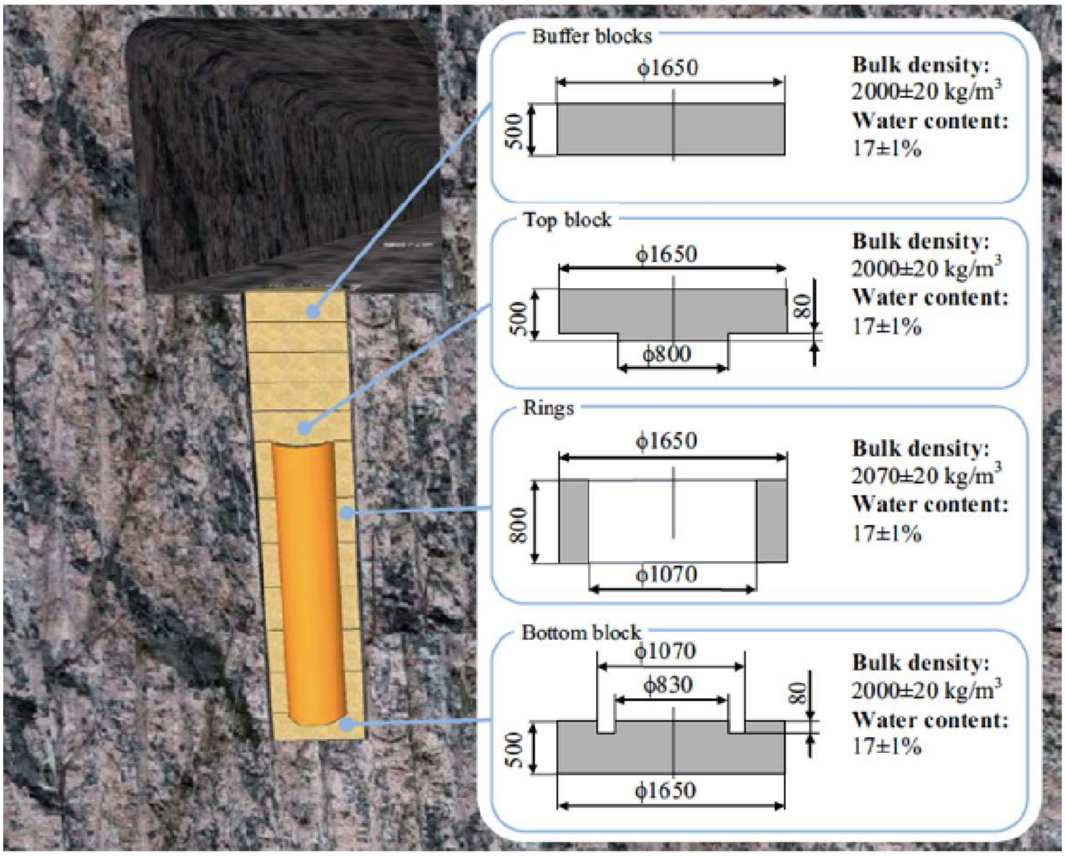


Figure A1-7: There is a design requirement for buffer blocks with differing properties, as illustrated below [A1.9].



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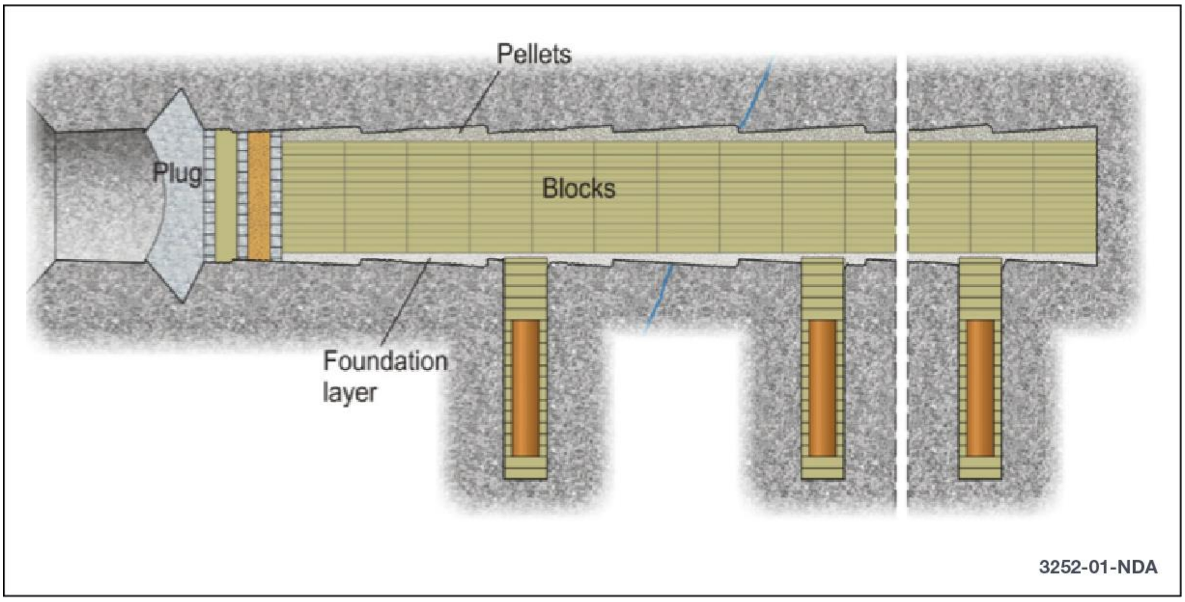
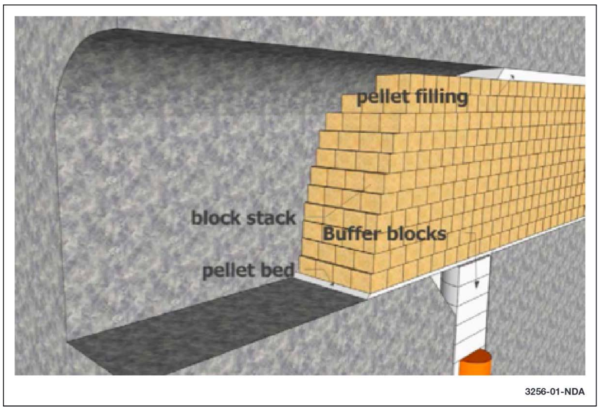
A further aspect is to improve knowledge of the behaviour of the buffer in the deposition boreholes in the early period between buffer emplacement and the emplacement of the overlying backfill in the disposal tunnel. The interaction between these two materials (e.g. the potential for upward swelling of the buffer into the backfill, which might reduce the buffer density to below its design requirement) in the early post-closure period has significant safety case relevance.

Figure A1-8: The relationship between the disposal tunnel closure materials, including the multi-component disposal tunnel end-plug and high-density bentonite pellets [A1.10].



In the longer term, a key issue for buffer performance is more detailed understanding of the potential for ‘chemical erosion’ whereby incident groundwaters liberate clay material in colloidal form, which could be transported away by water moving through fractures and lead to a loss in buffer density and, thus, containment performance.

Figure A1-9: Full-scale testing of tunnel backfill (compacted bentonite block) emplacement technology at 450 m depth in the Äspö HRL in Sweden (left), schematic of tunnel backfill (right) [A1.11].



With respect to GDF construction techniques, there is now considerable practical experience available, in the Prototype Repository experiment at Äspö and in the Onkalo facility in Finland. At Onkalo, Posiva has developed and tested a deposition hole drilling (raise-boring) machine, with construction of several full-size canister deposition holes [A1.12] in two demonstration tunnels. A key objective of the development was to show that deposition holes could be constructed to the necessary tolerances of verticality and smoothness. A major factor was to stabilise and brace the machine against the tunnel walls and roof, and to provide a firm foundation. Various foundation approaches have been tested, including laying a concrete plinth, horizontal rock sawing and floor reaming.

An important area that remains to be optimised and demonstrated under routine operational and active-handling conditions is the emplacement of the buffer and canister in the deposition holes. Issues remain concerning protection (e.g., from moisture) of the buffer blocks during emplacement, centralising and inserting the container and ensuring verticality, and the possible use (and performance-related implications) of a copper levelling baseplate in the bottom of deposition holes.

Horizontal to sub-horizontal boreholes in HSR: Republic of Korea

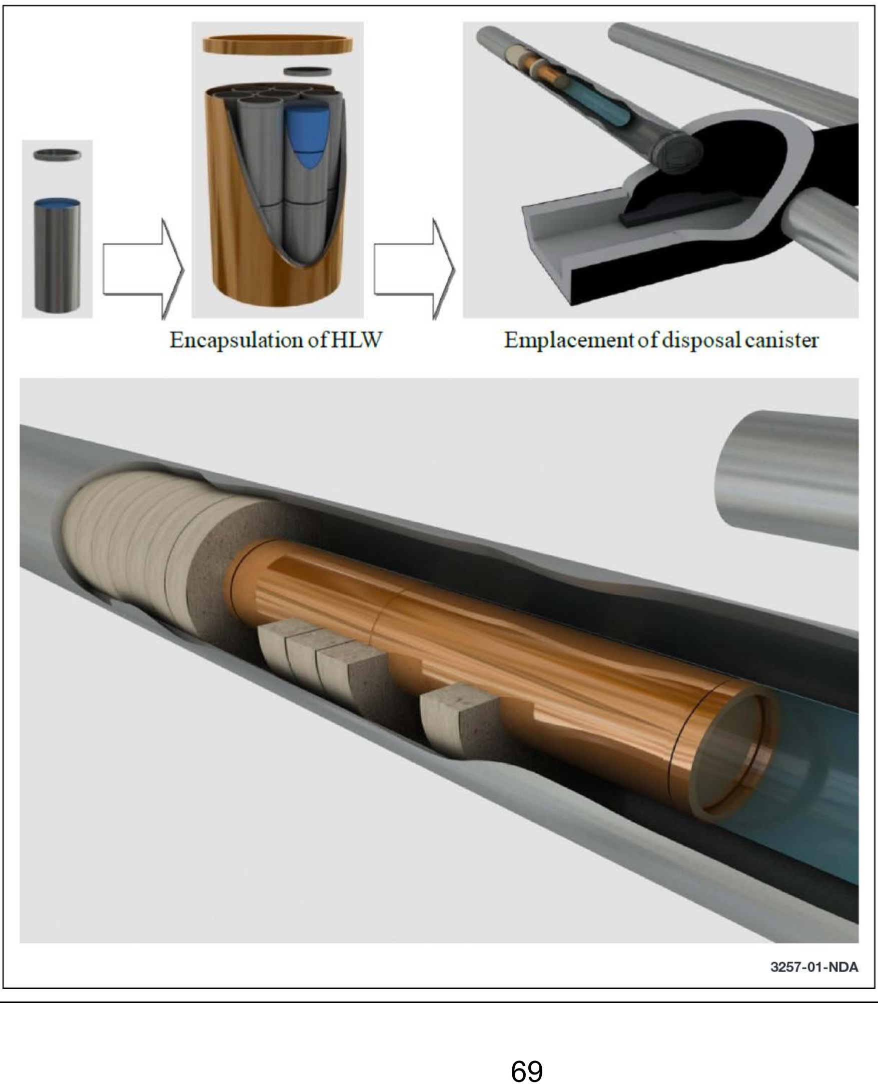
The GDF concept currently under development in the Republic of Korea (ROK) uses horizontal boreholes drilled from access tunnels, with granite the favoured host rock [A1.13]. The waste form is a monazite ceramic containing mainly fission-product residues from pyro-processing of SF. Most of the Cs and Sr will have been separated and removed into other waste forms, which will be stored for around 100 years to allow significant cooling before being considered for disposal. Consequently, the ceramic HLW emits considerably less heat than HLW from conventional reprocessing. The current focus is on developing solutions for the ceramic waste form.

The waste form is contained in steel canisters within a cast iron container, with a 10 mm thick, cold-sprayed, copper coating. This concept is also being developed in Canada and is being considered in Switzerland, as discussed elsewhere in this section. A feature of the ROK approach is that the spray is applied after the containers are sealed, thus providing a continuous layer of copper without a weld. Containers are about 1 m diameter by 1.7 m long.

An advantage of the spray-coat approach is that it uses considerably less copper. It is estimated that about 375,000 tonnes of copper would be needed for ROK wastes if KBS-3 type containers were to be used: the spray-coated canisters would use about 80% less [A1.13].

Although KBS-3V is also considered as an option, the horizontal concept reported here has similarities with KBS-3H and with the Andra concept for HLW. The containers would be inserted into horizontal boreholes and surrounded by a buffer of locally-sourced Ca-bentonite.

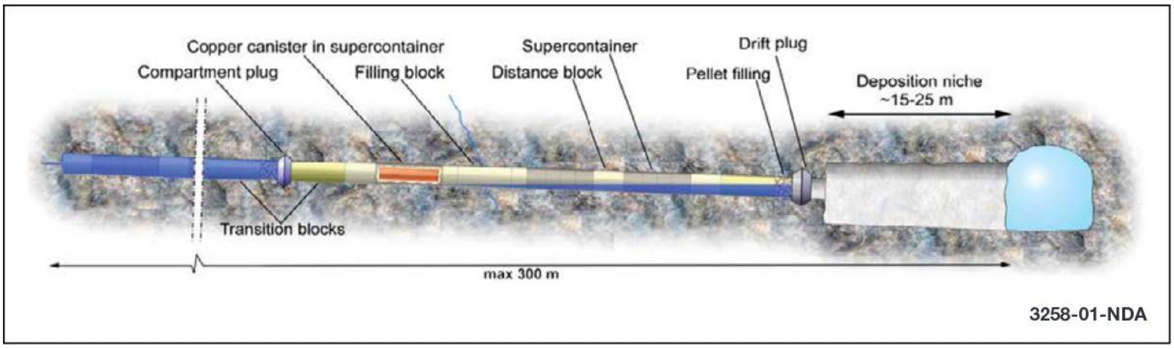
Figure A1-10: Republic of Korea disposal concept [A1.14].



Supercontainers in sub-horizontal boreholes in HSR: SKB (Sweden) and Posiva (Finland)

The KBS-3H concept (illustrated in Figure 5 and described in detail elsewhere in the RWM concepts study) uses sub-horizontal deposition drifts up to 300 m long constructed from the GDF main tunnels. SF is inserted into these drifts in supercontainers, comprising a KBS-3 copper canister surrounded by a bentonite buffer, held together by a perforated outer metal shell. Bentonite ‘distance blocks’ are placed between supercontainers. Deposition drifts are divided into two sections by compartment plugs and a drift end plug is installed in the access zone of the drift.

Figure A1-11: The KBS-3H concept [A1.8].



One attraction of the concept is that the rock volume that needs to be excavated is smaller than for vertical (KBS-3V) deposition, which also means that smaller volumes need to be backfilled. Also, the supercontainers are constructed above ground, enabling close QC of disposal packages.

A full-scale demonstration of 3H technology has been underway since 2013 in the Äspö HRL (the Multi Purpose Test: MPT). The project has included the manufacture of the components, assembly and deposition of a supercontainer and distance blocks, and installation of a compartment plug, with associated filling components.

SKB and Posiva have carried out a joint evaluation of concept status and how work with KBS-3H should continue, assessing technical maturity, outstanding technical and operational questions, and questions regarding post-closure safety and development and operation costs. The conclusion [A1.8, A1.15] is that much technical development remains to be done to bring 3H to the same maturity as 3V. This includes the selection of materials for and the design of the supercontainer, detailed design of the above-ground packing station, deposition hole plugs, the intended grouting solution and the design of a supercontainer deposition machine.

The joint evaluation also concludes that the current MPT experiments need to be supplemented with a full-scale heater test at actual facility depth, to show that the bentonite swells and homogenises as intended, outside the supercontainer.

An evaluation of post-closure safety has shown that the considerably smaller quantity of bentonite between each supercontainer compared to that between canisters in 3V vertical deposition, means that KBS-3H might be significantly more sensitive to chemical erosion of the buffer [A1.8]. A concern is that bentonite erosion at one canister position could spread to other, nearby positions.

SKB considers [A1.8] that the remaining development work for 3H is too extensive to be able to justify parallel development effort (with 3V), even if there are large potential economic advantages of horizontal deposition. SKB also observes that it remains to be established that changing to 3H would not entail an impairment of post-closure safety.

During the next few years, technology development will thus focus on completing, industrializing and optimising the 3V system, with further research in the area of chemical erosion of bentonite. If safety issues are solved, SKB intends, in the longer term, to re-evaluate whether the economic advantages could justify a change to 3H.

Horizontal and vertical boreholes in Salt: DBE (Germany)

The German concepts for a geologic repository in salt, especially horizontal emplacement of Pollux casks and vertical emplacement of BSK in boreholes, have been demonstrated in 1:1 scale test facilities and are developed to a stage ready to be licensed. Borehole disposal in supercontainers (the 'DIREGT' project, using Castor containers) has also been investigated.

Summary

- ITB options have been widely studied for different HHGW in a wide range of HSR and LSSR geological settings: a range of different EBS concepts is available to meet specific requirements.
- Especially for larger sites, this option spreads the heat loading and can simplify development of a safety case
- QA practicality and operational safety are open issues, which are driving the increased interest in borehole liner and supercontainer options.

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A2 In-tunnel and In-tunnel Axial (ITA) Disposal Concepts for High-heat Generating Wastes (HHGW)

Mature concepts exist for:

☑HLW ☑Spent Fuel ☑Supercontainers
☐HSR ☑LSSR ☑EVR

Main Drivers for HHGW in-tunnel disposal concepts

Construction and operation – In-tunnel concepts are relatively simple. Feasibility can be demonstrated with existing technology.

Operational flexibility - In-tunnel concepts allow access/emplacement tunnels to be rapidly sealed, thus reducing vulnerability to perturbations.

Post-closure - for larger sites, this option could spread the heat loading.

Main characteristics

In-tunnel disposal concepts for geological disposal of HLW and SF have been under development for over 35 years and variants have been published for different geological environment, including HSR, LSSR and EVR. Waste packages are emplaced along disposal tunnels, either laid on the floor or centralised on the tunnel axis (In-tunnel axial: ITA). A characteristic of the geometry of this concept is that the thermal load of the wastes is spread over a large area.

Some characteristics depend on the host geological environment:

- In EVR, a high emplacement density can be implemented by using high volume canisters and small package / tunnel pitches; the resulting higher temperature will accelerate creep and self-healing of the rock.
- For HSR, this option reduces the excavated volume, simplifies handling and can reduce problems with water inflow, compared to ITB, although the dimensions and properties of intersected fractures in the rock will limit useable waste container locations along the tunnels.
- For LSSR, this option is geotechnically simpler to construct and manage than, for example ITB.
- Supercontainer variants can reduce potential problems with assuring quality in the potentially large volumes of tunnel buffer/ backfill.

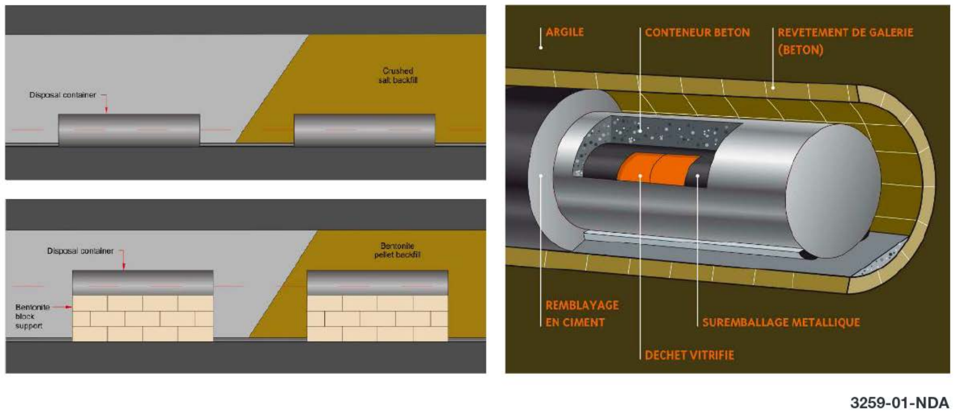
The most mature in-tunnel variants can be subdivided as follows, and are illustrated in Figure A2-1:

- The simplest design is for EVR host rock, which was developed in the 1980 and 1990s in Germany. In a minimal EBS, the waste package is laid on the emplacement tunnel floor and the tunnel backfilled with crushed halite, which will be compacted as the host rock creeps and progressively closes the tunnels, to provide a relatively homogeneous barrier;
- ITA emplacement in LSSR in development in Switzerland, in which buffer or backfill (generally clay-based) is emplaced around waste packages that are located centrally along the tunnel axis. Earlier work also considered ITA in HSR but most of the development work has been for clay-rich LSSR. There are a number of different approaches to backfill emplacement, focused on ensuring that barrier quality can be assured.
- ITA emplacement of supercontainers in lined tunnels in LSSR (clays); developed in Belgium and, most recently, under assessment in the Netherlands.

For ITA of conventional waste packages, the components of the EBS and their dimensions vary with the characteristics of the HHGW, the desired emplacement density, and the expected performance of the geological barrier. In this concept, waste, encapsulated in overpacks, which provide complete containment for some hundreds or thousands of years, is emplaced axially along disposal tunnels and surrounded by a thick buffer layer of bentonite that completely fills the tunnel, with no further backfill. Waste packages are separated according to the thermal dimensioning constraints of a specific design. The disposal tunnels are sealed immediately after completion of waste emplacement with substantial plugs, to resist the bentonite swelling pressure.

In ITA disposal of supercontainers, the concept developed in Belgium leaves a small annulus between the container and the tunnel lining, which is backfilled with cement.

Figure A2-1: Schematic of in-tunnel concepts, with packages placed on the tunnel floor in EVR (top left), the ITA concept being developed in Switzerland for LSSR (bottom left) and the Belgian concept for ITA emplacement of supercontainers (right) [A2.1].



Long-term safety concept

In common with all other concepts being considered by RWM, the post-closure safety concept is based on the multi-barrier principle, which means that the safety of the facility is not completely dependent on the functions of any one single barrier. The different barriers complement each other via mechanisms that are largely independent of each other. In addition to the natural barrier provided by the host rock, the concept uses an engineered barrier system (EBS) consisting of:

- a low solubility waste matrix (vitrified HLW; uranium dioxide spent fuel);
- a durable waste package: generally a waste container with an overpack – in HSR concepts, a corrosion resistant overpack is used;
- in both HSR and LSSR, a buffer between the package and the tunnel wall or liner (clay, highly compacted bentonite, bentonite pellets etc);
- in LSSR, a concrete tunnel liner will be required to facilitate package emplacement, but is not expected to act as a barrier in the EBS;
- in EVR, a crushed halite backfill that will eventually be compressed by creep of the host rock until it has similar barrier properties to the unexcavated evaporite.

In all variants, the EBS acts in concert with the host rock to reduce any flow of water from the rock, to and around the waste, thus limiting the rate at which radionuclides can be dissolved from the waste, mobilised, and enter the rock-groundwater barrier. The EBS will prevent any such mobilisation until after the initial thermal period of a few hundreds or thousands of years and continue to function thereafter to limit considerably any migration of residual radioactivity from the wastes. In HSR environments, the buffer/backfill in the tunnel also acts as a physical protection for the waste package against possible shear movements in the rock in the distant future. The use of supercontainers that isolate backfill during the early period, when temperatures and hydraulic gradients are higher, is potentially beneficial.

The preservation and longevity of buffer properties is a central aspect of HSR variants of the ITA concept. Thus, consideration is given to potential degradation due to processes such as ‘piping’ of bentonite by short duration, high hydraulic gradient flow of water immediately after closure or subsequent chemical erosion in the distant future if groundwater chemistry changes.

Post-closure Criticality is generally not identified as a concern, owing to the dispersed distribution of waste and limited interaction between packages.

The potential impact of preferential flow paths along the tunnel excavation disturbed zone (EDZ) in HSR might need to be taken into account (e.g. by placing regular cut-off seals). Any EDZ can be significantly reduced by appropriate excavation and tunnel completion methods. Orienting emplacement tunnels perpendicular to the hydraulic gradient, the use of dead-end tunnels and the use of high quality tunnel seals, are available engineering solutions.

Operational and construction safety

Construction of the long total lengths of relatively small diameter tunnels required for in-tunnel and ITA concepts increases construction risks compared to more compact concepts, such as the MBM or CAV concepts. Operational risks can be improved by the use of advanced excavation technology such as tunnel boring machines. Several advanced designs based on ITA use disposal tunnels that are up to hundreds of metres long but blind-ended. These tunnels will be accessed by people during pre-emplacement operations and represent potential escape hazards in the event of mining accidents.

Features that improve construction and operational safety (e.g. tunnel liners, extensive grouting) may complicate developing a post-closure safety case.

The waste emplacement operations are difficult for the ITA concept, owing to the small cross-sectional area of the emplacement tunnels compared to the size of emplacement machines and small clearances. Although fully automatic emplacement may be possible, in case of perturbations that require human intervention, the ability to provide high protection levels may be limited. This will be more problematic for supercontainer designs, which can almost completely fill the tunnel annulus (e.g., Belgian concept), due to the large waste package size and mass, and the smaller clearances.

In-tunnel designs assume that tunnel backfilling runs in parallel with package emplacement and sealing/plugging of each tunnel occurs immediately after it is filled, so the in-tunnel concept can be developed to have inherently low risks associated with any operational perturbations that could occur.

Implementation approach

Flexibility with respect to host rock variability; total tunnel length and GDF footprint are large in ITA concepts and consequently will be constrained by large-scale heterogeneities at disposal depth, such as major fracture zones in HSR or lithological variations in LSSR. In HSR, where no tunnel liner is used, the need to account for larger fractures intersecting disposal tunnels (affecting, for example, mechanical response to earthquake shear) or localised water inflows may result in a significant fraction of package positions being excluded from use, possibly increasing footprint, environmental impact and cost.

Flexibility with respect to waste type: ITA design variants can be developed for all waste types, by varying the materials and geometry selected for the EBS.

Flexibility with respect to scheduling: As construction, operation and closure of tunnels and panels of tunnels can run in parallel in different regions of the GDF, there is some inherent flexibility with regard to scheduling.

Retrievability options

Although packages in tunnels are retrievable in principle for some period after emplacement, the length of tunnels, the small clearances and rapid backfilling approach make retrieval a more challenging issue compared to some other options. Retrieval of supercontainers would be more complex, owing to their mass and accessibility. A number of detailed retrieval concepts have been developed for different ITA designs. For example, the concept for retrieval in the German ITA concept is to excavate a drift adjacent to the emplacement drift, and then extend the drift to include the emplacement drift.

Maturity of technology

Most cited in-tunnel axial disposal concepts are currently classed as having high technical maturity levels. Handling machinery has been developed and tested for both EVR and LSSR environments and extensive in situ tests have been made in a number of URL projects.

Knowledge Gaps

- The technology for tunnel construction is well developed and advancing rapidly in a number of different civil engineering areas. For repository implementation, a key issue is balancing engineering measures to improve safety of construction and operation against those facilitating assurance of post-closure safety, which may need further study.
- In terms of implementation, a major concern is assurance of the quality of the as-emplaced EBS – which has been the driving force for the development of supercontainer variants. These have not been studied to the extent of conventional in-situ EBS construction and this is an area where further work is required.
- Operational safety is also an issue, especially when very large networks of disposal tunnels must be operated for periods of decades. Extremely high equipment reliability is required, along with established technology to respond to even relatively unlikely perturbations.

Environmental impact

The main issues specific to in-tunnel as opposed to other options relate to the repository footprint, the volume of broken out rock and the volume of backfill required. For example, at least for HSR and LSSR, these are both likely to be smaller for in-tunnel compared to ITB, but larger than CAV.

Life cycle costs

GDF costs are driven more by operational and strategic decisions (e.g. extent of cooling before disposal, any requirement to keep tunnels open for retrievability, the duration of emplacement activities) and EBS materials and emplacement options, rather than the concept geometry. In general, however, due to lower broken-out volume and more straightforward waste handling operations, an ITA option might be expected to be less expensive than an equivalent EBS using ITB emplacement.

International concept developments 2008-2016

In-tunnel axial in LSSR: Nagra (Switzerland)

The ITA concept has been developed principally in Switzerland, for use in the Opalinus Clay formation. The fundamental concept remains unchanged since 2008, with HLW and SF canisters emplaced on a plinth of bentonite blocks and surrounded by a buffer of bentonite granules, as discussed further below.

Figure A2-2: Cutaway model of the Nagra ITA concept for SF [A2.3].

3260-01-NDA

The emplacement tunnels for SF and HLW have an initial internal diameter of about 3 m, with single-shell, sprayed concrete lining and lengths restricted to about 1,000 m, with respect to conventional safety and operational considerations. The spacing between individual emplacement rooms is about 40 m in the current concept. The concept foresees prior and spatially separate emplacement of HLW in order to extend the time available for cooling of SF before emplacement [A2.3].

Nagra has moved ahead with developing concepts for the canisters to be used for HLW and SF disposal. This includes further development of the geometric shape, dimensions, material, welding and fabrication, and inspection options for steel canisters, including the internal supporting structures [A2.4]. As with many national studies, the focus of design development is to show how designs meet specific requirements defined for a component, emphasizing the importance of having a functional requirements management system (RMS). Thirty specific requirements were defined for the canisters.

Plain-carbon steel is the currently preferred material type for steel canisters, and a bespoke carbon steel composition with a low hardenability is suggested with respect to weldability (where electron beam and narrow-gap, gas tungsten arc welding are suggested). The current designs are about 5 m long for SF and 3 m long for HLW, with a diameter of about 1 m (SF) or 0.7 m (HLW) and a wall thickness of about 140 mm. The canisters are gas-tight.

The final canister design will not, however, be selected before 2040, so alternative canister types are under consideration [A2.5], including the use of an outer, corrosion resistant shell around a steel inner container and (jointly with NWMO, Canada) the use of copper-coated steel containers, as shown in the image of a full-scale prototype (courtesy of NWMO) in Figure 3 [A2.3] and discussed further here, in the VLT1 section.

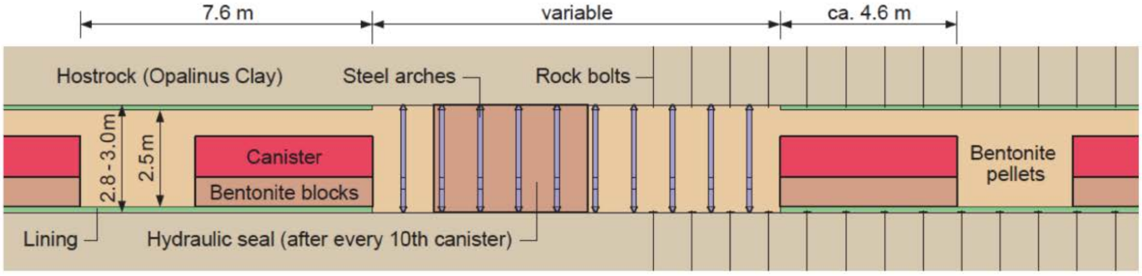
Figure A2-3: Full-scale test model of a NWMO copper-coated steel container [A2.3].

3261-01-NDA

Canisters will be emplaced co-axially, spaced at 3 m intervals, supported by pedestals of compacted bentonite blocks. Immediately after emplacement of a canister, that section of the emplacement tunnel will be backfilled with highly compacted granular bentonite. Nagra observes [A2.3] that the technology for producing high-density, granular bentonite is now fully developed and considerable success has been achieved in emplacing compacted bentonite granulates and mixtures at full scale in URL tests in Switzerland and France. It is notable that most of the concept developments during the last decade that are described in this report utilise high-density, granular bentonite.

As with the canister, a set of requirements for the bentonite buffer has now been derived [A2.6]. The intermediate tunnel seal system is shown in Figure 4 [3] and a full-scale tunnel test involving canisters, seals and plugs, and using heaters is underway at the Mont Terri URL.

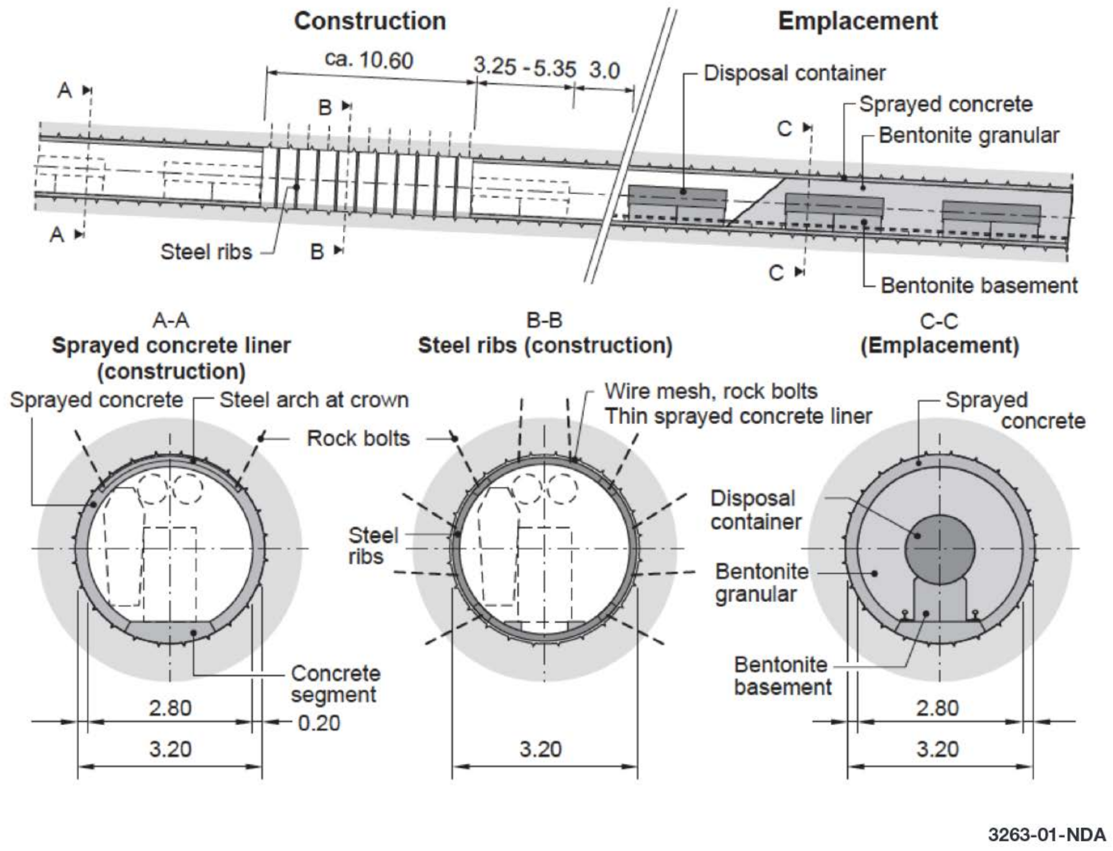
Figure A2-4: Intermediate tunnel seal system between groups of waste packages as developed for LSSR by Nagra [A2.2].



3262-01-NDA

Nagra has tested tunnel support systems for the Opalinus Clay at full scale (a 3 m diameter, 50 m long tunnel at Mont Terri) using two different systems: low-pH shotcrete and steel arches. Despite some challenges, the support methods were successful [A2.2], but, more work is considered necessary, some of which can only be done when rock at repository depth (c. 500 m) is accessible. Work on tunnel construction methods aims at selecting a technique that is able to advance approximately 12 m per day (equivalent to 6 m per machine per day, assuming two tunnelling machines are used). Up to 20 km of emplacement tunnels have to be excavated in 13 years, according to Nagra's schedule. Two potential concepts are being considered: conventional mining (e.g., using a roadheader and rock support close to the face) or a full-face tunnel boring machine (TBM), either using a gripper TBM and sprayed concrete liner or a shield TBM with segmental liner. The current Nagra ITA concept is summarized in Figure 5 [A2.2].

Figure A2-5: Components and geometry of the ITA concept as developed for LSSR by Nagra [A2.2].



The SF/HLW repository will be compartmentalized to increase robustness against detrimental phenomena by emplacing intermediate bentonite seals at frequent intervals along the disposal tunnels. These are designed to provide direct physical contact between the bentonite of the seal and the Opalinus Clay host rock. Again, requirements have been defined for these intermediate seals [A2.6]. Final sealing of the disposal tunnels will consist of highly compacted granular bentonite. The requirements are still under development and construction feasibility will be demonstrated before the construction license application.

Nagra has also made significant advances in developing alternative repository access systems, the designs of shaft and portal surface facilities, and schemes for shaft and tunnel construction, the order of waste emplacement and general management of the construction and emplacement operations for HLW and SF [A2.7, A2.8]. Those eventually selected will be dependent on the site chosen for the GDF.

In the next 5-10 years, Nagra foresees that developing the concept to demonstrate retrievability will also be a major focus of its RD&D work [A2.2].

Summary

- In-tunnel options have been widely studied for different HHGW in a wide range of geological settings: a range of different EBS concepts is available to meet specific requirements.
- Especially for larger sites, this option spreads the heat loading and can simplify development of a safety case
- QA practicality and operational safety are open issues, which are driving the increased interest in supercontainer options.

Key References

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[A2.2] Nagra, *Entsorgungsprogramm – daran arbeiten wir*. Brochure. December 2016.

[A2.3] Nagra, The Nagra Research, Development and Demonstration (RD&D) Plan for the Disposal of Radioactive Waste in Switzerland. Nagra Technical Report 16-02, 2016.

[A2.4] Holdsworth, S.R., Graule, T. and Mazza, E., *Feasibility evaluation study of candidate canister solutions for the disposal of spent nuclear fuel and high level waste*. Nagra Working Report NAB 14-90, 2014.

[A2.5] Patel, R., C. Punshon, J. Nicholas, P. Bastid, R. Zhou, C. Schneider, N. Bagshaw, D. Howse, E. Hutchinson, R. Asano and F. King. *Canister Design Concepts for Disposal of Spent Fuel and High Level Waste*. Nagra Technical Report 12-06, 2012.

[A2.6] Leupin, O.X. and Johnson, L.H., *Buffer requirements for a SF/HLW repository in Opalinus Clay*. Nagra Working Report. NAB 13-46, 2013.

[A2.7] Nagra, *Generische Beschreibung von Schachtkopfanlagen (Nebenzugangsanlagen) geologischer Tiefenlager*. Nagra Technical Report 16-08, 2016.

[A2.8] Nagra, *Projektkonzepte für die Lagerkammern und Versiegelungsstrecken und deren Bewertung*. Nagra Working Report 16-45, 2016.

A3 Vault Disposal Concepts for High-heat Generating Waste (HHGW)

Mature concepts exist for:

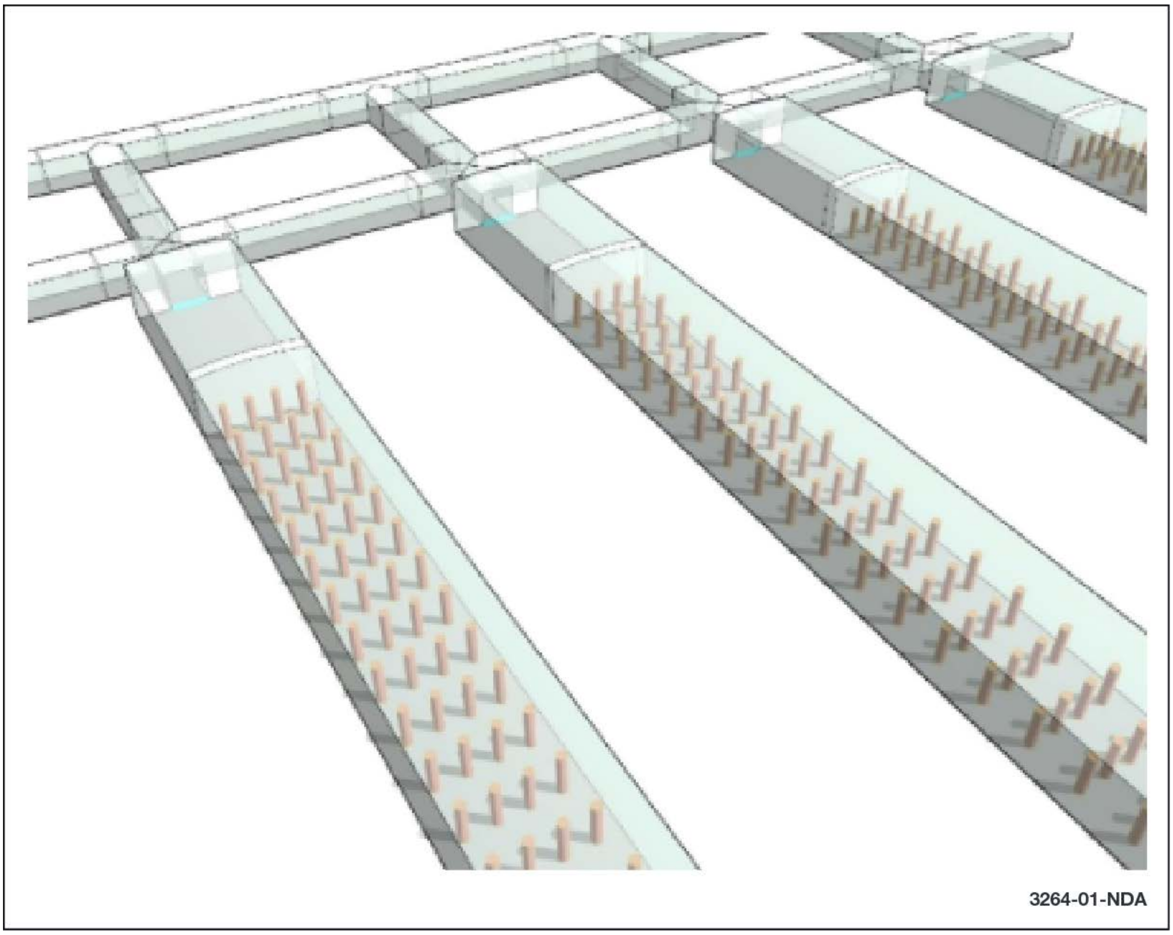
☐HLW ☐Spent Fuel ☐Supercontainers
☐HSR ☐LSSR ☐EVR

Main Drivers for HHGW vault (CAV) disposal concepts

Siting - Potential for a reduced GDF footprint, achieved by the use of long-term decay storage prior to backfilling.

Main characteristics

Figure A3-1: General lay-out of vault concept for HHGW [A3.1]



Vault-based disposal concepts (caverns – CAV) are typically characterised by excavated underground openings with large spans (up to ~16 m, depending on the rock type) [A3.1] and relatively tight package spacing for emplaced wastes. Implementation for HHGW assumes use of either purpose-designed disposal containers or Multi-Purpose Containers (MPCs) emplaced in large, excavated volumes at depth (the vaults). Backfill materials, either cementitious or bentonite, would then be emplaced around the containers and the vaults sealed.

Although vaults of various types have been used for disposal of L/ILW for many years, consideration of their potential application for HHGW is relatively recent. Consequently, there are no mature CAV examples where the components and systems have been constructed and brought together at full-scale, extensively tested and subject to iterative and detailed safety assessment.

Heat management in the high packing density of CAV vaults is a significant consideration, leading to the development of concepts that incorporate delayed backfilling and closure. This approach might have benefits for programmes requiring ease of retrieval for an extended period.

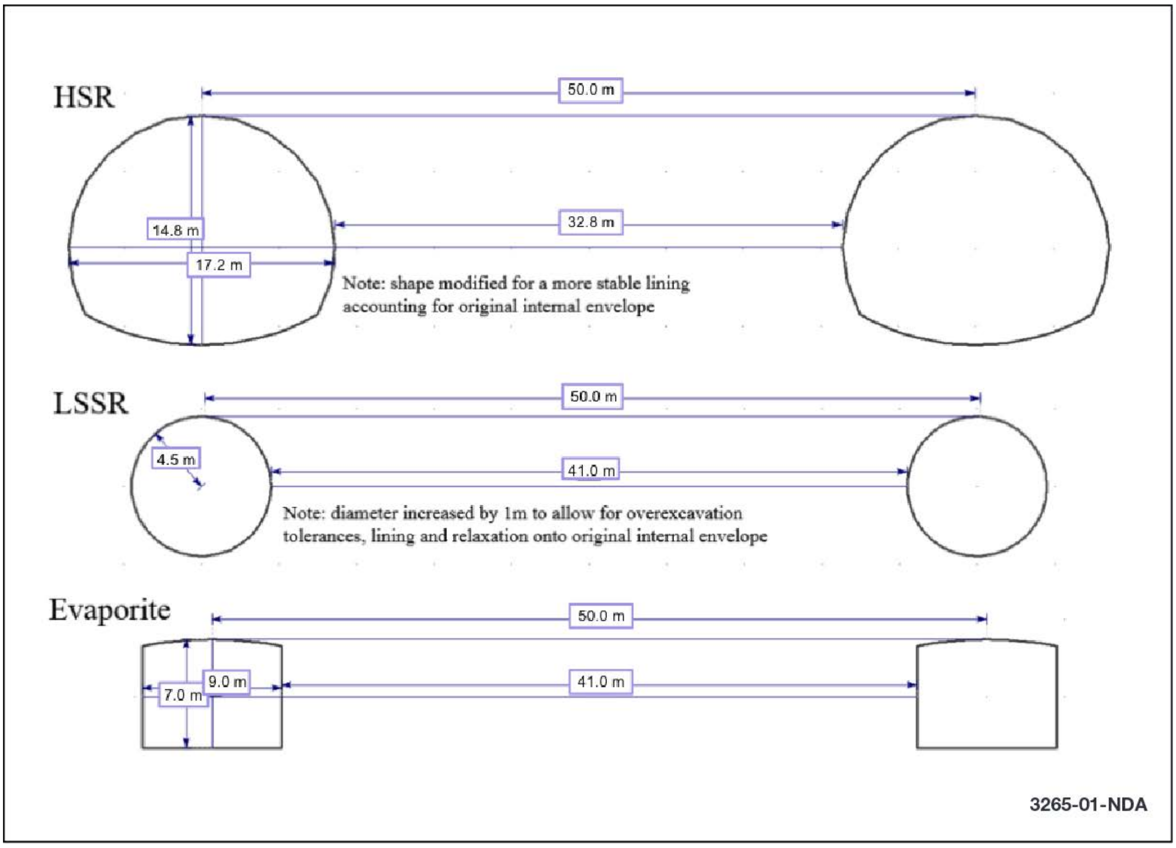
The majority of past development work on the CAV concept originate from conceptual desk-based studies, predominantly in Japan, driven by the potential for reduced footprint and an extended open cooling period (up to 300 years before backfilling), which would extend the period over which relatively straightforward waste retrieval would be feasible. The concept is included in NUMO's alternatives for HLW disposal in Japan [A3.2], although no full performance assessment calculations have been carried out internationally for vault concepts (for HLW and SF disposal). The figure above shows a conceptual illustration of a CAV system: in this case, disposal containers are shown stored vertically within the vault, prior to backfilling.

A cooling period may be required for thermal output of the disposal containers to reduce below the thermal constraints of the host rock and prior to the emplacement of the backfill and vault seals. The cooling duration is dependent on the rock type, waste type, waste package configuration, spacing of the packages within the vault and any thermal constraints assumed or set by either regulatory guidance or safety assessment. Some preliminary thermal and radionuclide release calculations have been performed and are reported in Nagra Project reports [A3.3]. Vaults can be designed with the potential to remain open, without backfill, for extended periods prior to permanent backfilling and closure, noting the increased risk of rock fall and collapse for this scenario, as well as the probable need for active cooling with a system qualified to nuclear safety requirements.

To accommodate the UK inventory of HHGW, a number of underground vaults would be required. Depending on the design/waste type, waste packages would be placed at defined spacings during any storage phase. Packages might be redistributed prior to closure, when backfill materials and other engineered components (e.g. liners), compatible with the site-specific geological conditions, are emplaced. The design and layout of the vaults is determined by some key inputs, including: thermal controls (i.e., meeting thermal limits on parts of the EBS for a range of vault package densities), vault constructability (vault excavation stability at depth, support technology used), maintenance (for open vaults/operations up to 300 years) and waste package handling and transport requirements.

From an engineering, cost and safety point of view, it is desirable to minimise excavated disposal areas, but to use a sufficient size to allow for safe and effective emplacement of the disposal packages and other engineered barriers. For the vault layouts, the dimensions and geometry of excavations assumed are based on current mining and tunnelling experience, and also take into account the current RWM generic illustrative designs. Documented CAV concepts in strong competent rocks, under reasonably isotropic stress conditions, at relevant depths are typically characterised by excavation cross-sections of about 200m^2 to 250m^2 [A3.1], but these may be significantly smaller in less favourable geological settings. As technology for construction of large caverns at depth is advancing rapidly, such values are likely to be conservative for a suitable site.

Figure A3-2: Typical vault concept excavation profiles in HSR, LSSR and EVR [A3.4].



Suggested possible excavation profiles are shown in Figure A3-2 [A3.4]. It should be noted that the possible excavation profiles are used as illustrations only, and would be dependent on the geological setting. The excavation profile will have a large impact on the footprint and costs of the facility and, as such, will require optimising. Since some vault concepts assume an open period prior to backfilling, vault excavation stability and support structure maintenance need to be considered.

Additional drivers for considering the use of vaults for HHGW include:

- Increased rate of transport to and emplacement into the GDF, especially when large MPCs are considered;
- Vaults could operate as underground interim storage facilities and contribute to reducing the need for additional surface interim storage;
- Ease of emplacement of waste packages and reduced time taken for operation;
- Potentially reduced excavation complexity (compared to ITB and ITA concepts);
- Eased reversibility, especially before vaults are sealed (potentially allowing more time to build public acceptance for final facility closure).

Long-term safety (overview from [A3.5])

A number of different EBS combinations are possible with this concept and their respective safety functions will vary depending on the properties of waste and the geological setting. Studies undertaken on CAV to date in the UK assume that the key physical and chemical processes that impact on the migration and transport of radionuclides from the disposal containers to the biosphere include: container failure, release of radionuclides from the wasteform, transport through the backfill, and entry into and transport through the geosphere.

For the case of EVR, there is little difference in performance of the EBS for a vault compared to the reference in-tunnel concept, apart from higher initial heat that may cause more rapid creep and sealing of the waste package in the host rock. There is also potential for more inwards migration of fluid inclusions along the thermal gradient. However, negligible release of radioactivity is expected for the evolution scenarios. Scenarios that can give rise to releases are those causing degradation of the EVR rock – due to either natural or anthropogenic perturbations. For the more compact vaults, the probability of impact of localised perturbations would be less.

In vault-based concepts for HSR and LSSR, the backfill is more extensive and more voluminous compared to in-tunnel variants, and a more substantial liner/mechanical support system may be required. The resultant EDZ (due to both mechanical and chemical impacts) would also be larger. The impacts of these features need to be evaluated in detail for different waste, waste packages, and waste package density/thermal management options (requiring "4D" models that include all major structures and their evolution with time). Based on current system understanding, general trends to be expected include:

- HSR / HLW; bentonite is considered as the local backfill (to assure glass longevity and provide colloid filter), whilst the mass backfill could be clay-based or sand/crushed rock depending on site-specific considerations. High density emplacement of disposal containers would result in similar total fluxes on non-solubility-limited radionuclides to in-tunnel options, although this will be more spatially localised with possible impacts on extent of dilution and sorption of radionuclides (if this is non-linear). For solubility-limited radionuclides, total release rates would decrease with those for very long-lived radionuclides spread over longer periods of time. Such impacts may be greater for MPC options.
- HSR / SF; for backfill the considerations are the same as for HLW, trends as above would be expected. For cement-based backfill, the impact of aging would need to be considered, especially if this led to fracturing and potential advective flow paths through the EBS. Releases from the GDF may occur within a high pH plume, which could significantly increase the mobility of some key radionuclides (e.g. ^{135}Cs).
- LSSR / HLW; for bentonite backfill, the trends are the same as for the HSR case. The use of concrete backfill could potentially cause rapid degradation of the glass matrix. A thick host rock diffusive barrier would be required (as in the Belgian concept). If the LSSR contains advective flow pathways (e.g. sand channels), such an option might be precluded.
- LSSR / SF; as for HSR.

Operational and construction safety

In the CAV concept, disposal containers are assumed to be emplaced in vaults vertically for HSR and EVR, and horizontally for LSSR.

In HSR and EVR a similar process to that developed in the RWM generic illustrative designs is followed, where the disposal container is removed from the Disposal Container Transport Container (DCTC) in a specially constructed hall, where it would be turned into the vertical orientation and lowered into a pit in the transfer hall floor using an overhead crane. The lid would be unbolted and appropriate handling equipment used to pick the disposal container out of the DCTC and transport it to its respective emplacement vault. Each vault will be equipped with a shielded reception area. An overhead crane would be used to transport the disposal container into its respective position in the vault.

For LSSR, where the disposal container is emplaced horizontally, a transfer trolley would be used to lower the disposal container onto a pre-constructed stand.

For both options, the emplacement process would use shielding. The backfilling of a vault will be completed once all of the containers have been emplaced and the relevant cooling period has elapsed. It is intended that a remote overhead backfill gallery system, similar to that envisaged in the RWM illustrative designs for LHGW, would be used for HHGW.

In terms of construction underground, risks generally scale with the length and cross-sectional area of the excavation, and any specific complexity of the construction process. Although mechanical stability concerns are less, work in small cross-section tunnels is generally more hazardous than in larger vaults, especially in terms of recovery in case of perturbations.

For both HSR and LSSR, key differences in terms of operational safety are associated with the cooling phase before backfilling. Delayed backfilling, however, increases both risks associated with perturbations during the open period and potential radiation exposure during inspection, waste movement operations to allow for support structure maintenance, re-orientation of packages in transfer from storage to disposal mode, etc.

Implementation approach

Flexibility with respect to host rock variability: In general, significant decay storage periods are required in HSR to achieve acceptable levels of thermal management assuming a bentonite or cementitious backfill as an integral part of the EBS. Due to its assumed rock mass quality, the HSR geological setting allows a larger vault to be constructed than the other two settings (salt dome geology would also allow large vaults, but the probability of this geological environment is very low for a UK GDF). The high density spacing was set to maximise the number of containers that will fit in a vault, this in turn reduced the number of vaults required. However, the cooling periods required for some waste types, particularly mixed oxide fuel (MOX), on this high density spacing are such that a vault cannot be designed with the required design life at present, unless the thermal constraints can be adapted to suit the specific requirements of the backfill for this concept.

The cooling period for disposal containers in CAV in LSSR is highly dependent on the spacing and density of the waste packages in the vault. Thermal studies suggest that high densities of waste packages will require long cooling periods. The conceptual design shows that a limit of 2 rows of disposal containers is required to allow a long life excavation of reasonable dimensions to be constructed in LSSR. The associated increase in footprint is expected to increase the overall cost of this concept to significantly greater than that of the generic illustrative designs.

All rocks show natural variability in composition and properties, the extent and scale of which is dependent on the geological setting. Because of higher emplacement density, a compact vault option would be expected to include less variability in the disposal zone than an ITA or ITB option. Alternatively, “dispersed” vaults could be located to utilise the best quality rock in a larger footprint.

Although less critical for EVR, the more robust liner for vaults in HSR and LSSR may allow more flexibility to engineer through zones of poor rock (faults, breccia, sand channels, etc.) than panels with many smaller tunnels.

Flexibility with respect to waste type: If considered in isolation, the decay characteristics of high burnup MOX provide particular decay storage challenges for HSR and LSSR, due to the prolonged cooling time that may be necessary. Wastes such as HLW and AGR fuel present fewer heat management problems for high density disposal in a vault. New-build SF is likely to be the controlling factor in determining the overall open period before closure of the vaults – acceptable durations can be achieved by spacing out the waste containers, but this is at the expense of the additional footprint requirement.

As yet, options of mixing wastes (in either packages or vaults) has not been examined in the UK, although the benefits of this have been shown elsewhere. In the case of long open periods, for example, new-build SF could be emplaced into vaults already containing decades older, lower heat output waste in order to spread the thermal load more evenly.

*Flexibility with respect to scheduling [*A3.*6]:* The CAV concept could allow waste to be transported to a GDF sooner than the dates in the current RWM anticipated programme. As the illustrative vault concept designs include robust disposal containers (copper and steel variants) that are comparable with the generic illustrative designs, it is also realistic to assume a GDF emplacement rate of 200 containers per year for HLW and SF into vaults. Increased rates of production of disposal containers – or MPCs – can be readily accommodated for the HSR and LSSR storage vaults, although implementation logistics would need to be confirmed for EVR.

The Disposal System Specification includes a requirement *for planning purposes at the generic stage* that the design of the HHGW disposal modules in HSR shall be based on a temperature limit of 100°C on the surface of the bentonite at any time following emplacement. The design of the HHGW disposal modules in evaporite rock shall be based on a temperature limit of 200°C on the backfill at any time following emplacement. With respect to LSSR, the design of the HHGW disposal modules in LSSR shall be based on a temperature limit of 100°C on the surface of the bentonite at any time following emplacement. It is clear that these interim temperature limits could be revisited in a process of strategy and design optimisation whereby the EBS components, layout and geometry, along with the waste and package characteristics, are balanced and adapted to allow flexibility in CAV design and operational scheduling. In order to check potential for optimisation with respect to scheduling, both temperature limits and backfill requirements need to be assessed on a site-specific basis.

Retrievability options

As EVR caverns are inherently similar to ITA concepts in evaporite formations, procedures for retrieval are effectively the same. The main difference is the higher heat loading of the former, which increases the rate of sealing by creep. This may make retrieval slightly more difficult for a certain time after emplacement (site-, disposal concept- and waste-specific).

For HSR and LSSR, emplacement of the waste packages has been examined for the case of overhead cranes and other handling equipment. After emplacement, recovery using the same equipment is straightforward for the entire cooling period. Reversibility is, however, dependent on the integrity of the waste packages, disposal vaults and emplacement equipment. After vaults are backfilled and sealed, retrieving the disposal containers becomes significantly more difficult, but the large area within the vaults make this easier than a tunnel option for as long as liners provide some kind of mechanical support.

Maturity of technology

The general CAV concept has been considered feasible for many years and, owing to recent interest in the use of supercontainers or PEMs, its technology maturity is considered of medium maturity. As supercontainer concepts have gained momentum owing to the simplification of EBS quality assurance during construction and emplacement (see for example, the 2016 conceptual design by NWMO [A3.7]), combined with cost optimisation to reduce unnecessary excavated volume, this has resulted in several facility design variants adopting large tunnels or small vaults with stackable prefabricated engineered modules. A key differentiator between programmes is thermal loading of the spent fuel or HLW to be disposed, but providing such thermal considerations can be managed, there are no major technology developments required that are not considered feasible. Technology demonstration for such concept variants is ongoing at several international URLs.

Knowledge Gaps

In the preliminary assessment, which is based on outline descriptions, no viability-threatening issues have been identified for CAV concepts for HHGWs in the three illustrative geological settings considered. If CAV concepts continue to be considered in the future, a large amount of work would be required to identify fully the knowledge gaps that require addressing through the RD&D programme. Included in this would be the following knowledge gaps identified from recent studies:

- For the HSR geological setting, the cooling periods and open duration for the vaults *based on the assumptions used in this study* could be as long as 300 years for a medium spacing density. This design life is at the upper end of what is currently considered feasible within the mining and civil engineering industries. Assumptions for this simple analysis need to be checked against the international state-of-the-art and, if required, measures examined to reduce the design life to a more acceptable duration (e.g. reducing the density of the disposal containers).
- Vault temperature must be controlled during the cooling period to ensure that it does not reach unacceptable levels (e.g. affecting access, crane handling or other infrastructure that may be needed for package movement or retrieval prior to backfilling). Equipment will need to be designed to operate in these elevated temperatures and supplemented by positive ventilation systems.
- Assuring the EBS – and in particular local backfill – is emplaced to specification in a quality assured manner is a challenge for all disposal concepts. This is of less concern for EVR due to sealing by creep of the host rock, but is important for any concept that requires handling compacted bentonite in a humid environment, especially in restricted areas (e.g. KBS-3 [A3.8]). Some work has been done for underground L/ILW concepts incorporating a bentonite barrier, and other options for prefabricated local EBS units have been proposed if this would be required. For concrete backfill, pumpable, self-levelling formulations are well established in the construction industry, but further work is required to ensure that the additives required (superplasticisers, setting agents, etc.) would not have a detrimental impact on long-term performance.
- The support and reinforcement requirements for a CAV system range in complexity depending on which geological setting the vault is to be constructed in. This needs further study, in

particular related to resilience in the event of operational perturbations.

- It is expected that the high dose rate within the vaults during the cooling period will limit personnel access for inspection and maintenance for this time. A remote monitoring system will be required to inspect the storage containers for the cooling period. Should a container or the vault infrastructure require maintenance during this time it is expected that some or all containers may need to be removed from the vault in question and stored in a designated reserve storage area. Prior to closure, selected waste packages may be moved to this reserve area to reduce maximum local thermal loadings.
- Large shield doors may be required at the entrance to a vault and there would be reliance on the doors to operate regularly during emplacement of the waste into the vault. After that they would be used very little and only required if repair or inspection was needed, or during backfilling and closure. The concept, requirements and optimised design of such doors need to be examined further.

Environmental impact

In all geological environments, the high-density spacing layouts in CAV deliver significant footprint savings compared to other concept options. There is a wide range of packing densities and layouts that could be selected to optimise the CAV concept to waste type, geological setting and potential thermal limits.

The footprint benefits are offset by significantly longer operational periods to allow for cooling to take place and therefore have associated increased costs, with the exception of some of the EVR layouts.

Part of the inventory, in particular HLW and AGR spent fuel requires no extended open phase, and if a mixture of HLW/SF concepts were to be considered, CAV may provide a reduced footprint for a number of the waste groups without needing an extended open phase and the additional costs that this would bring. Small overall footprint saving would be at the cost of the added complexity of adopting a mixed concept approach.

Life cycle costs [A3.6]

Further research and clarification is necessary to be able to provide a more accurate comparison of costs. However, at a very high-level, CAV costs are driven by a trade-off between the cooling time required for each waste emplacement density, the required numbers of vaults (determined by assumed density of waste package), and the different design of the vault for each of the different geological settings. Conversely, the CAV concept could reduce the cost of interim surface storage facilities, by replacing them with storage underground. Underground storage would have costs associated with ventilation, monitoring systems, maintenance and repair work, as well as staffing costs.

Lower density spacings clearly have increased costs relative to high density spacings in each of the geological settings, due to the higher number of vaults and extra access tunnels that would need to be constructed and fitted out with equipment. This may be partly offset by the reduction in the extended open period required.

International concept developments 2008-2016

The current Canadian concept being developed by NWMO for the disposal of SF (natural uranium) from Candu reactors is unique in using a square section disposal cavern (termed ‘placement room’ by NWMO) and a prefabricated EBS using moulded and machined, rectangular, highly-compacted bentonite ‘Buffer Boxes’ to hold the spent fuel containers [A3.9]. Although it is significantly different to the generic concept described above (and could be regarded as an ‘in-tunnel’ concept), it is included here in the CAV section owing to the geometry of the placement rooms used for disposal and the manner in which boxes will be stacked within them, although it is should be noted that there are no internal structures (e.g. concrete vault floors or walls) within these caverns.

The boxes arguably have several features in common with supercontainers, especially in that they are manufactured on the surface and transported underground with the fuel containers already in place, but are not classed here with the supercontainer group considered by RWM in the current project, as they have no outer metal shell.

Figure A3-3: The Canadian Vault disposal concept [A3.10].

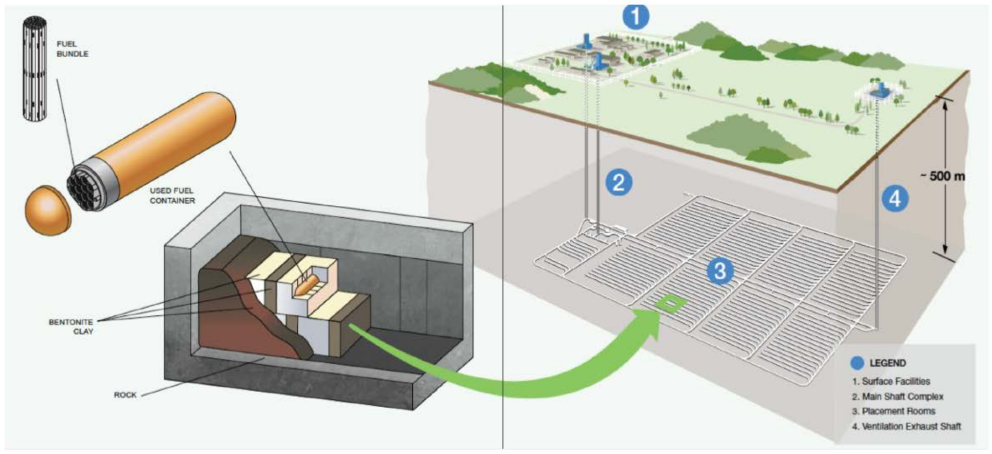
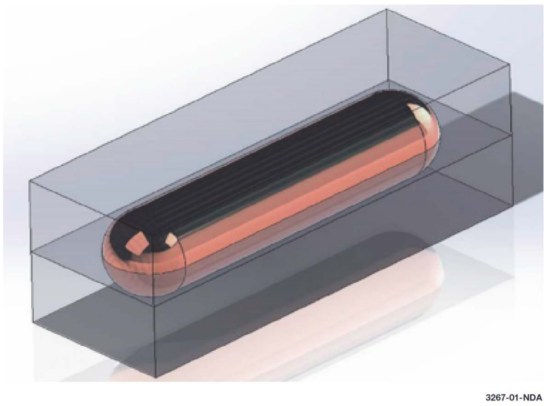


Figure A3-4: The bentonite box used in the Canadian Vault concept for HHGW [A3.9].

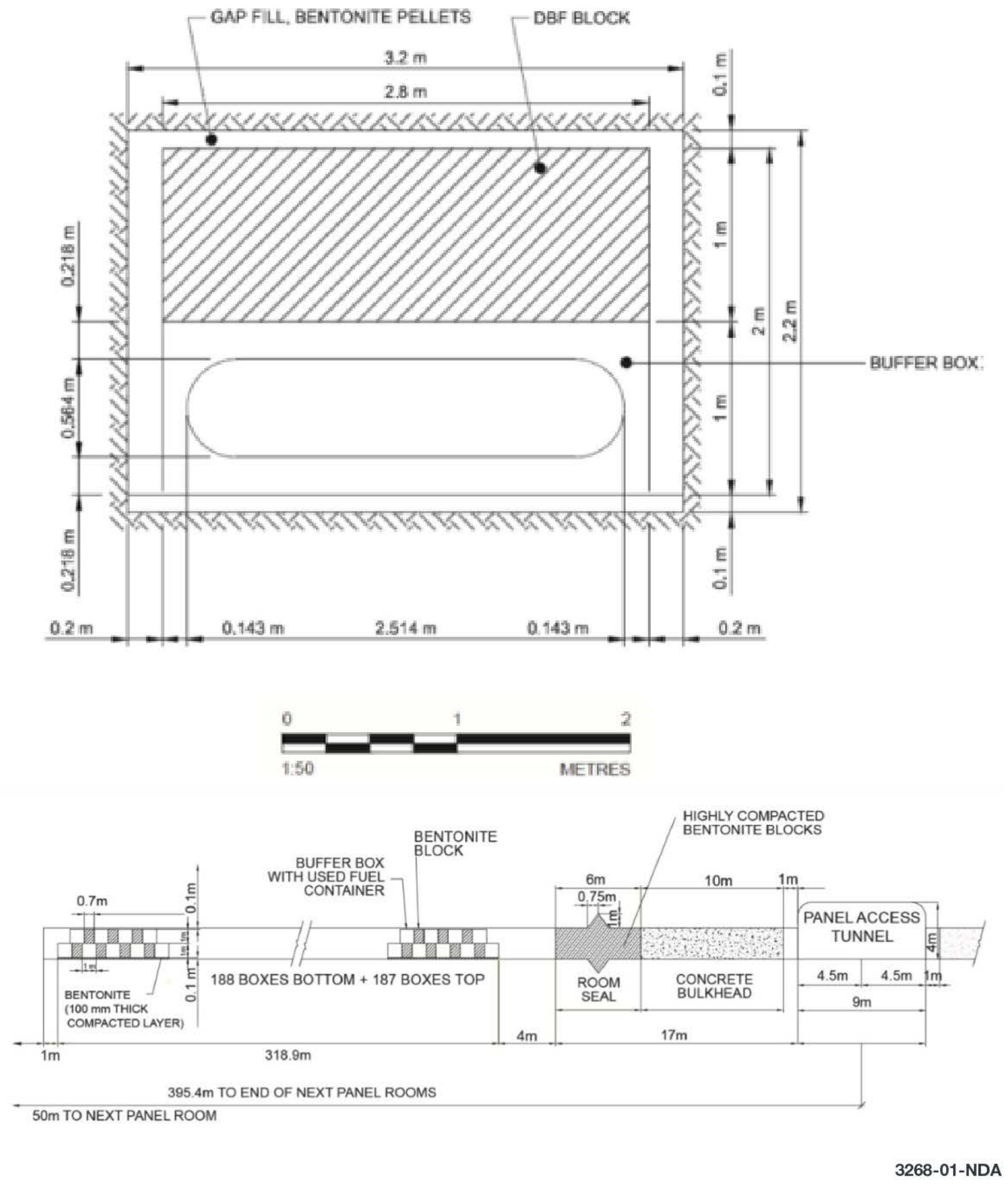


The NWMO concept is developed for use in HSR (crystalline basement) and in strong sedimentary rocks (using limestone as the reference).

The two halves of a bentonite box are machined to accept the fuel containers, which are constructed of steel with a fully bonded coating of 3 mm of copper. Candu reactor fuel bundles are comparatively much smaller than, for example, PWR fuel assemblies, hence the small size of the containers, but the large numbers that will be needed to dispose of about 3.6 million Candu fuel bundles. The bentonite boxes have dimensions of 1 x 1 x 2.8 m and a mass of about 7 tonnes when loaded with the fuel container.

Buffer boxes will be stacked two-high in the placement rooms, between dense spacer blocks, and surrounded by bentonite pellets, blown into place. Centre-to-centre distances of boxes will be 1.5 m in crystalline basement rocks and 1.7 m in limestone. The spacer blocks are to be made of a dense mixture of aggregate, clay and bentonite. The filled bentonite boxes can be stacked closely together because the heat output from the fuel container is only around 200W after 30 years of cooling (in comparison, UK fuel containers have a heat output in the order of 1000W after 100 years of cooling.)

Figure A3-5: Two cross sections of placement rooms: (top) lateral, across room; (bottom) axial, along the length.



An observation is that work in European URLs (e.g. the FEBEX experiment at Grimsel in Switzerland) has shown that it can be difficult to handle bentonite blocks in a humid underground environment, owing to their absorption of water and friability, so this would be a key issue for this concept to address. The NWMO concept assumes that the host rock will have very low bulk hydraulic conductivity.

The disposal caverns (placement rooms) have relatively small dimensions: 3.2 m wide by 2.2 m high. They will be constructed in panels and will be blind-ended, about 300 m long in crystalline basement rocks and 340 m long in limestone, and oriented parallel to the maximum stress direction. Centre-to-centre distances between rooms will be 20 m in crystalline basement rocks and 25 m in limestone. On completion of each placement room, a seal will be constructed at the room entrance. The concept is intended to allow retrieval of containers prior to closure of the GDF.

The proposed use of rectangular section disposal rooms is unusual, given that significant stress concentrations might be expected to occur at the corners in high-strength, crystalline basement rocks, especially if the in situ stress regime is strongly anisotropic. This issue will presumably need to be addressed as the concept develops and potential siting areas emerge.

The current assumption is that 10% of potential box positions in the disposal caverns will not be useable, owing to inflows from the host rock. A further observation is that determining whether locations are acceptable for disposal containers has become a major aspect of R&D, rock characterisation and construction planning in both Finland and Sweden, as discussed previously.

The access shaft for transporting the boxes into the GDF will have a diameter of about 7m and will be capable of hoisting a loaded, tyre-based, transfer trolley of 57 tonnes, in a horizontal position.

Summary

- There may be benefits to emplacing HHGW in vaults, including increased rate of transport to and emplacement in the GDF (assuming vaults could operate as underground interim stores), ease of emplacement of waste packages and reduced time taken for operation, reduced excavation complexity (e.g., compared to the ITB and ITA concepts), and significantly reduced GDF footprints (so long as thermal constraints can be met).
- A key assumption is that the CAV concept for HSR and LSSR would include a period of deferred backfilling, until the heat output of the emplaced waste inventory has sufficiently decayed to meet any thermal limits that might be placed on the GDF at specific sites to assure operational and long-term safety.
- For HSR geological assumptions and the designs developed, the cooling periods and open duration for the vaults based on the assumptions used in this study could be as long as 300 years. This design life is at the upper end of what is currently considered feasible within the mining and civil engineering industries. There is a trade-off between the cooling time required for each waste emplacement density (derived from thermal modelling), the required vault numbers (determined by the assumed spacing density of the waste packages), and the different designs of the vault for each of the different geological settings.
- At this preliminary stage of assessment, based on these simple outline descriptions, no viability threatening issues have been identified for CAV concepts in the three illustrative geological settings considered. In keeping with good practice, these conclusions would be reviewed if such disposal concepts are further developed.

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Sedimentary Rock Environment. NWMO Report No: APM-REP-00440-0015 R001, May 2016.

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A4 Mined Borehole Matrix (MBM) Disposal Concepts for High-heat Generating Waste (HHGW)

Mature concepts exist for:

☐HLW ☐Spent Fuel ☐Supercontainers
☐HSR ☐LSSR ☑EVR

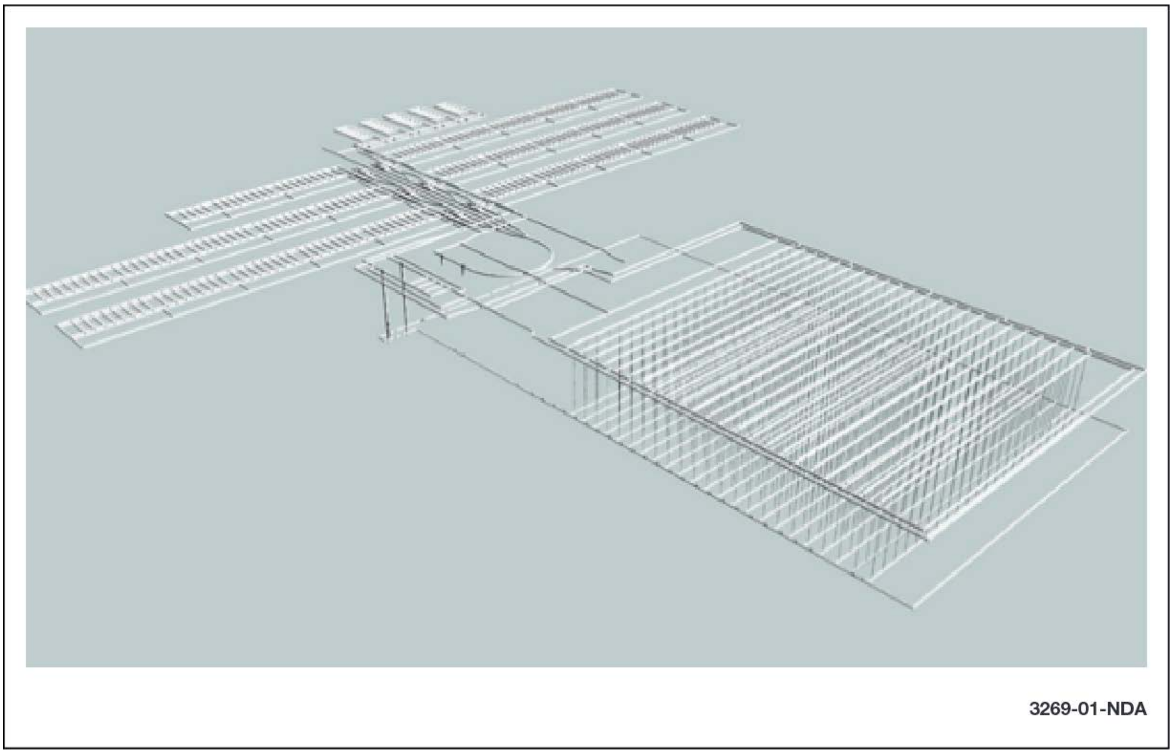
Main Drivers for MBM disposal concepts

Siting / GDF footprint - The key driver for considering the use of the MBM concept is the potential to utilise a rock body of small lateral extent but significant thickness.

Main characteristics [A4.1, A4.2]

A Mined Borehole Matrix (MBM) concept would comprise up to several hundred vertical boreholes of the requisite diameter to accept waste disposal containers or supercontainers. The boreholes would accommodate vertically stacked packaged waste and incorporate the required backfill components of the engineered barrier system (EBS). Emplacement of the packaged waste within the MBM disposal concept is not envisaged to begin until after any required cooling period of specific waste types. Figure A4-1 presents a visualisation of how a MBM concept could be configured (the MBM is to the right of the image).

Figure A4-1: Conceptual GDF including a Mined Borehole Matrix disposal concept for HHGW [A4.1]



Depending on the construction technique used, the boreholes could either be drilled 'blind' from an upper gallery, or could be accessible at the top and bottom, connecting horizontal galleries at two levels. The vertical boreholes are sealed at one or both ends, and backfilled with either cementitious backfill or bentonite. The access tunnels will also be backfilled, once all boreholes are closed. The use of borehole liners may be required in LSSR (and possibly some HSR) to maintain borehole stability, manage water inflow and ease recovery in case of emplacement problems.

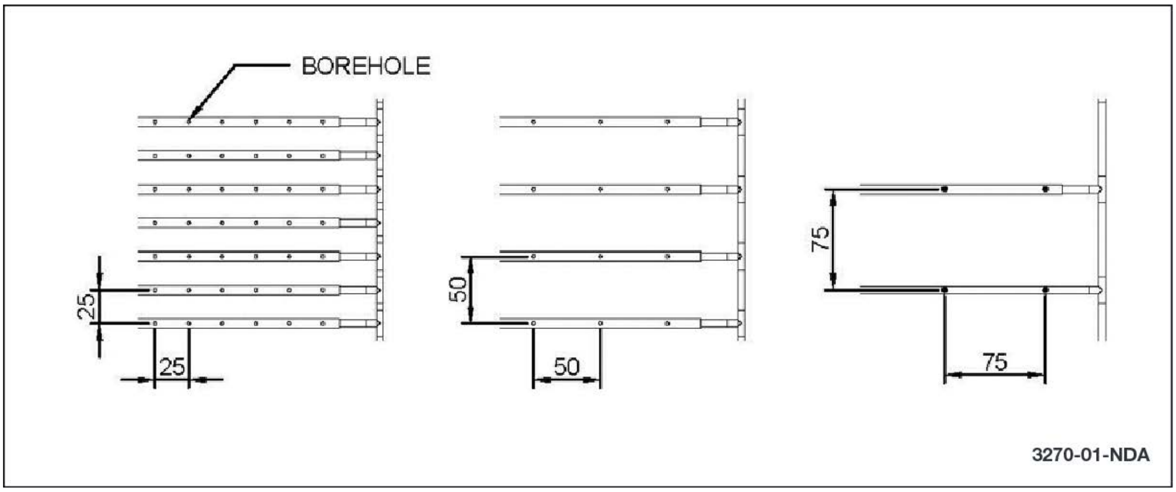
As this concept is effectively a vertical disposition of features of either the ITB or ITA concepts, broadly equivalent EBS components and materials are envisaged. The following EBS combinations are assumed, although different configurations could be considered and would be optimised for the waste inventory and geological environment:

- For HSR, copper supercontainers with a bentonite backfill;
- For LSSR, carbon-steel supercontainers with cementitious backfill;
- For EVR, a standard disposal container crushed rock backfill.

RWM has considered aspects of backfill emplacement, including quality assured emplacement, load bearing capacity in the package stacks and the ability for bentonite to achieve the necessary swelling pressures typically considered in other disposal concepts. This has led to consideration in the analysis of a supercontainer in HSR and LSSR.

The spacing between containers depends on the power output of the containers, the maximum allowable buffer temperature, and the rate of heat transfer through the EBS and host rock. Scoping calculations suggest that the number of containers that might be emplaced in a 300m deep borehole varies from 37 down to as few as 2 or 3 per borehole for some of the higher thermal output wastes, such as MOX fuels. High, medium and low density spacings of boreholes could be considered for each geological setting, an example of which is shown in Figure 2 (from high to low, left to right).

Figure A4-2: Plan view for three different borehole spacing densities [A4.1]



The MBM concept originates from early work carried out for disposal in EVR salt domes, and has been considered in a number of other national waste management programmes [A4.1, A4.3]. The conclusions derived by others suggest that MBM may provide a solution for sites with a small available footprint of suitable host rock with sufficient vertical extent but limited lateral extent. The advantage of this concept is that it makes use of the vertical extent of the host rock and creates a small repository footprint while reducing surface operations and costs/environmental impact /operational complexity compared to equivalent depth boreholes drilled from the surface. In addition, the technology for construction and operation of the MBM concept is already partially used in industry and would not require large R&D programmes to be developed. Depending on the geological setting, the need to avoid major water-bearing or low strength features in the rock (especially large sub-horizontal fracture zones in HSR), or major lithological variations in LSSR, would restrict the depths of disposal holes or make the layout irregular in both depth and laterally.

Long-term safety concept [A4.4,A4.5]

The long-term performance of all GDF disposal systems is based on the performance of the individual natural and engineered barriers, as well as the integrated system, so the discussion already presented for ITB and ITA concepts is also relevant to MBM and is outlined in the safety narrative developed by RWM [A4.5].

The text below provides high-level discussions of some aspects of post closure safety for MBM in HSR, which is considered to be the bounding case, as the geosphere potentially provides less resistance to the transport of radionuclides to the biosphere than LSSR or EVR, following any mobilisation from the EBS. More detailed discussion can be found in [A4.1].

MBM boreholes could extend to a few hundred metres in length (the assumed length here is 230 m) so the identification, avoidance or possible mitigation of intersected flowing features and major changes in rock thermal, chemical and geotechnical properties that could affect the performance of large sections of, or even a complete borehole, need to be taken into account. Management of backfill erosion could be a significant issue in some settings. Backfill loss is likely to be more difficult to control compared to the ITB concept, in which this can be mitigated by abandoning an individual deposition hole rather than trying to seal sections of the borehole (MBM). A borehole liner may be suitable for consideration to mitigate this risk.

Radionuclide transport pathways in the EBS and rock of the MBM itself will be dependent on the geological setting. In HSR these are similar to those relevant to ITB and ITA concepts for those containers near the MBM access tunnels. Away from the tunnels, those pathways involving the transport through the EDZ of the tunnel would reduce, and pathways through the main body of the host rock would be longer for the majority of waste containers.

The average depth of a MBM could be greater than a concept based on a single horizon, such as ITB or ITA. This could give rise to a number of beneficial factors, including longer transport pathways to the biosphere and potentially lower hydraulic conductivity fractures at greater depth.

Three main challenges to criticality safety are envisaged for the MBM concept. Two of these relate predominantly to the scenario of waste package stack slumping.

1. *Fissile limits for individual waste packages:* A hypothetical post-closure stack slumping scenario has previously been used to determine the fissile limits for LHGW in vaults. Without design optimisation, a similar approach for the high integrity containers in MBM could challenge the current packing assumptions in terms of the amount of fissile material per package.
2. *Justification of low likelihood and consequences of credible post-closure criticality events.* This must consider the mechanisms for and likelihood of criticality scenarios, but these are largely also applicable to other disposal concepts.
3. *Package separation.* Evaluation of whether a hypothetical criticality event in (or close to) one waste package could lead to an increase in the likelihood of criticality for a neighbouring package. In MBM, this would need to extend to consideration of a hypothetical criticality event in one borehole having an effect on a package in a nearby borehole.

At this preliminary stage of assessment, based on a high-level outline description, no viability threatening issues have arisen from the preliminary analysis of post-closure safety. However, if the MBM concept is taken forward for further analysis then:

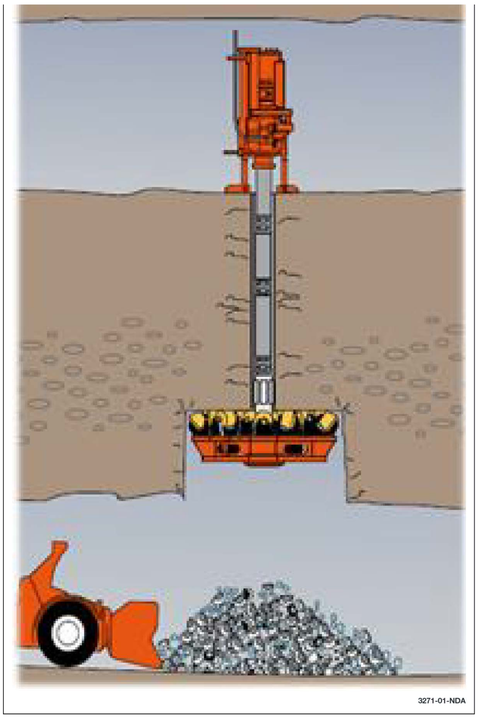
1. A quantitative safety assessment would need to be developed.
2. Safety function indicators and criteria would need to be developed for the canister, buffer (or waste package) and the host rock.
3. Further work would be needed to build confidence in the robustness of the barriers (using the multi-barrier principle) to potential events such as bentonite erosion.
4. Further work would be required to demonstrate the sensitivity of the disposal system to rare or extreme events (e.g. earthquakes or glacial loading).

Operational and construction safety

Construction:

Several borehole construction methods have been considered. The methods most compatible with the requirements of the MBM concept are raise boring, down boring and blind shaft boring. The main differences between variants involve whether holes are open ended – requiring a lower gallery (e.g., Figure 3) – or whether they are “blind”, i.e., with a dead end. Construction of a lower gallery requires additional efforts (with associated risks), but provides better characterisation of the host rock mass. Depending on the host rock, the lower gallery may also allow partial drainage and de-gassing of the rock, reducing problems during borehole excavation. Open-ended holes do, however, require additional work to emplace high quality lower plugs before emplacement of the waste packages commences.

Figure A4-3: Principle of raise bore construction between an upper and lower level [A4.1]



In most circumstances, boreholes would be lined during construction (an exception may be EVR). The specification of the lining would depend on the geological setting but, typically, would be made of steel and dimensioned to ensure borehole stability and, if required, any mechanical support of waste packages.

MBM construction risks are mainly associated with the use of shaft drilling equipment under high mechanical loadings and conditions with limited available space. In particular, recovery from perturbations (e.g. borehole collapse trapping the drilling equipment) may be inherently hazardous and hence well-proven technology that is as robust and resilient is required.

Rock quality and strength will need to be considered when selecting borehole diameters and liners (liners are also important for water management, assurance of safety during emplacement and ease of recovery in case of problems) but, at this stage, boreholes in the range of 2.5 m in diameter are within the range found in typical civil engineering and mining applications.

Operation:

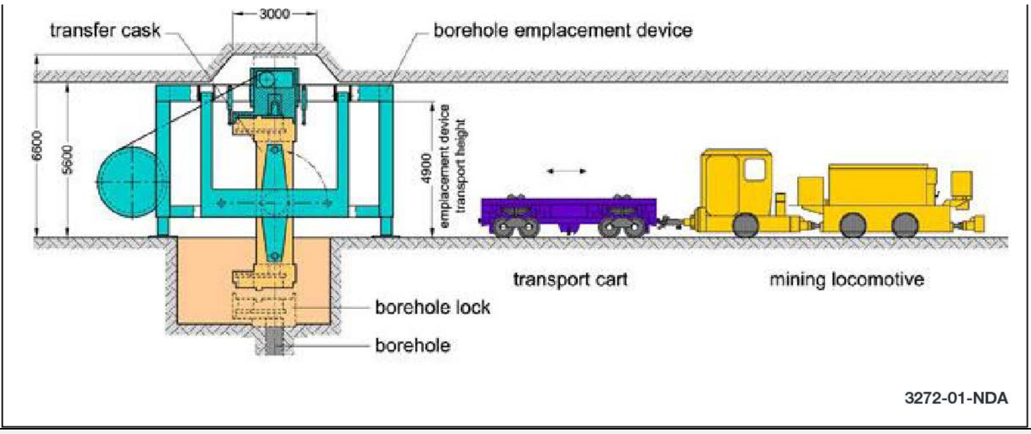
The transportation of waste containers underground to an MBM must consider that the containers are likely to need to be rotated from the horizontal to vertical position (although the rotation could be done prior to transportation to the MBM; for example in a large cavern). The ESDRED (Engineering Studies and Demonstration of Repository Designs) project developed and tested equipment for the vertical emplacement of waste containers.

The equipment illustrated in Figure A4-4 uses a side panel, whereby the transfer cask pivots to the horizontal position to receive the disposal container from the transport cart, then swings back to the vertical position to emplace it in the borehole. Therefore, the container can be handled by remote handling systems. The weight of the container being manoeuvred in the ESDRED study is 53 t, so the equipment would be suitable for the approximate 25 t disposal container but would need to be developed further in order to emplace much heavier supercontainers on a routine basis. Additional handling and emplacement aspects will need to be considered, such as how the emplacement packages will be handled, the possible use of in-hole mechanical support of the column of packages, emplacement quality assurance and recovery of a dropped or jammed packages.

An alternative to lowering the disposal containers into boreholes could involve adapting raise boring equipment. The waste package could be picked up using a grapple attached to the raise borer, in a similar manner to that intended for use in the KBS-3V (ITB) concept. The container could then be lowered into the correct position within the borehole. The equipment would need to be adapted for longer boreholes for MBM. If heavier supercontainers are used, then their weight will need to be considered with this method of emplacement.

Operational safety considerations could lead to a preference for a tele-operated or completely automatic system. Risks to operators would arise during response to perturbations – equipment failures, stuck waste packages, waste package drops, etc. Radiation doses would be inherently limited by self-shielding of the disposal containers especially supercontainers, but, if required, additional shielding could be included. Perturbations specific to the MBM involve those resulting from borehole or equipment failures after waste emplacement has commenced. If the disposal container is damaged, it may need to be recovered for inspection and, if necessary, repackaging.

Figure A4-4: General lay-out for a vertical emplacement of waste container [A4.1]



Implementation approach

Flexibility with respect to host rock variability: One of the early considerations for MBM concepts focused on the issues of buffer emplacement into vertical boreholes: in particular, how to ensure quality assured emplacement and address load bearing capacity and the ability of bentonite (if used) to achieve the necessary swelling pressures. The issues that arose from these considerations have meant that a supercontainer for use in HSR and LSSR has been adopted. A disposal container is assumed to be used for EVR host rocks.

Flexibility with respect to waste type: Of particular importance to the MBM concept is consideration of the thermal output profiles from the HHGW packages. Together with assumed thermal limits for EBS components and host rock, these determine borehole and container spacings for the borehole matrix, the number of waste packages within each borehole, and the total number of boreholes required [A4.1]. Assessments have not yet considered mixing wastes with different thermal loadings in a single hole, although this may allow optimal use of excavations. There is some flexibility during the construction phase to vary the diameter of the boreholes, so that alternative waste packages may be emplaced.

Flexibility with respect to scheduling [A4.1]: The MBM conceptual design assumes waste packages have cooled sufficiently to be ready for borehole emplacement, prior to arrival at the GDF. Therefore, the disposal schedule and emplacement rate used in the analysis is the same as those used within the RWM illustrative design programme. The thermal analysis does not appear to affect the disposal schedule or emplacement rate, although the required spacing between containers will determine the footprint and cost of the HHGW GDF.

Using the LSSR medium density layout as an example from RWM's initial study, 898 boreholes are required to dispose of all of the HHGW inventory. These boreholes would be constructed over 115 years of waste emplacement (note that this would need to optimised and is used here as an example). This is one of the higher numbers of boreholes that would realistically be considered and is, as such, bounding. This rate equates to approximately 8 boreholes constructed per year, or one every 47 days. Estimates from mining and manufacturing sources have concluded that a period of 45 days per borehole would be required to set up, construct and demobilise a borehole construction location that is in line with this requirement. Emplacement of 200 containers per year equates to one container every 1.8 days, which is again a reasonable duration taking account of the operations to position a disposal container and the speed of lowering of the container into the borehole.

Retrievability options

An inherent disadvantage of the MBM concept is the difficulty in retrieving emplaced packages. Reversal of the emplacement process has been demonstrated in the German BSK concept. Retrieval after backfilling using cement would be more challenging, as the backfill material would be expected to fill the lifting pocket and prevent the lifting device attaching. In LSSR, where some strata may swell, borehole collapse may also make it difficult or impractical to retrieve packages. In Germany (salt dome geology), borehole liners (with sand backfill) have been proposed to improve the ease of retrievability.

Retrievability options would need to be considered further, to demonstrate that the waste packages could feasibly be retrieved from a borehole in a MBM.

Maturity of technology

In Germany, the MBM concept, in a salt dome geology, has been developed to a fully licensable stage. Drilling technology is readily available on the market, but must be chosen and adapted (for example, dimensions of the drilling equipment, length of drill rods, size of preventer) to best fit the constraints of the site. Transport and emplacement technology has been demonstrated by some thousand test runs in a 1:1 scale test facility.

In the UK, the MBM concept is considered to be of low technical maturity owing to its consideration only within limited feasibility and conceptual design studies. For the work conducted within the UK disposal programme, the concept is defined by bounding parameters associated with specific EBS options underpinned by limited scoping assessments and consideration of technology readiness levels for applicable engineering solutions.

Knowledge Gaps

Given the low technical maturity of this concept in the UK, there are significant knowledge gaps with respect to the underpinning science and technology that could be used to support a future safety case at a specific site. A large amount of work would be required to fully evaluate feasible technology options and engineering solutions for this concept. From the limited work undertaken by RWM, a sub-set of knowledge gaps is identified below [A4.1]:

- Assuring the quality of the emplaced EBS is critical to post closure safety, hence the adoption of supercontainers for HSR and LSSR. The design and performance of supercontainers needs to be established and tailored to waste- and geological setting-specific requirements.
- A key issue is the possibility of packages becoming wedged in a borehole during emplacement. Equipment to mitigate against this possibility will need to be developed. A possible option could be to ensure the edges of the package are rounded (chamfered) to reduce the possibility that the container would become stuck, or inclusions of an operational procedure that introduces a dummy package run through the borehole to check that there has been no deterioration in borehole condition. Other options for checking the integrity of the borehole prior to emplacement could be considered, e.g., using a laser scanner incorporated into the lifting head that records borehole wall profile evolution. However, even if the probability is low, it cannot be precluded that packages could jam in the event of partial borehole collapse during emplacement. Concepts and technology for response to such incidents need to be developed.
- The possibility of a waste package being dropped is one of the main fault scenarios identified. Emplacement technology could be developed to reduce the likelihood of waste package drop. Options to reduce the consequences of drops include filling the borehole with a suitable backfilling fluid before emplacement, which would greatly limit the maximum drop velocity. Work would be required to develop suitable options (e.g. slow-setting, low-pH grout). More standard options to mitigate the potential risks of a container drop in a vertical borehole include the use of two ropes (redundancy and diversity) and locking the transport canister to the borehole in order to ensure that, in the unlikely case of a canister drop in the borehole, no radioactive material and radiation would be released from the borehole.
- For development of the safety concept, further work would be needed to build confidence in the robustness of the barriers, with particular focus on the 3D models needed to realistically evaluate performance of such an emplacement matrix – taking into account possible high pH or redox plumes.

Environmental impact

Three simple variations of the MBM concept were developed for each geological environment to bound high, medium and low density spacing of boreholes, with the requisite number of 230 m long boreholes to accommodate the different waste types, to meet the thermal constraints set for the different host rocks. In all geological environments and at all densities, the footprint is lower for a MBM concept using 230 m long boreholes than the corresponding ITB or ITA layouts and concepts used in the current RWM illustrative designs. This ranges from a reduction of 88%, 78% and 63% respectively for high, medium and low density layouts in EVR; 45%, 45% and 23% respectively for high, medium and low density layouts in LSSR; and 33%, 27% and 19% respectively for high, medium and low density layouts in HSSR.

Although footprint is reduced in all cases considered in the scoping study analysis, some significant variations occur in terms of the spoil generated:

- EVR rock reduced excavated spoil in all cases. This is because the thermal capacity of the rock means that fewer boreholes are required.
- In LSSR, excavation volumes are significantly higher in medium and low density layouts, caused by the increased length of service and access tunnels in this layout.
- In HSR the medium and low density layouts are similar in excavated volume to that from the generic designs developed for the update to the 2010 generic DSSC.

Of particular note in this analysis are the high spoil volumes for the low density spacing in HSR and LSSR. This is driven by the large number of boreholes required due to the need to space containers out further within the boreholes to maintain the overall thermal loading within the 100ºC limits for these host rocks. This effect is also seen in the overall cost for these layouts.

Life cycle costs [A4.2]

Further research and clarification of excavation methods and development of equipment is necessary to be able to provide a confident comparison of costs. However, at a high-level:

- The calculated cost of the MBM scenarios studied, when compared to RWM's generic illustrative designs, vary between +15% and -6%.
- The three scenarios studied in the EVR environment all show overall cost reductions compared to the generic illustrative designs.
- The cost increases calculated in HSR and LSSR are driven by the need to develop an assumed second or duplicate horizon to facilitate construction of the boreholes and also the capital cost of specialised boring and package handling machines.

International concept developments 2008-2016

The English version of the final report for the German BSK concept was published in 2010 [A4.6].

Summary

- Emplacing HHGW in a MBM could significantly reduce the required footprint of a GDF.
- A key assumption is that the MBM concept would meet acceptable thermal limits that might be placed on the GDF at specific sites to assure operational and long-term safety. The current work has been undertaken using a post-closure thermal target of 100°C on the surface of the backfill for HSR (and 200°C for EVR). Additional thermal dimensioning sensitivity calculations were undertaken at 125°C for LSSR [A4.1]. Such constraints could change in the future and greatly impact the conclusions on cost/benefit of this option.
- Another key aspect of the work has been the consideration of the use of supercontainers for HSR and LSSR to assure quality of the EBS. This requires further development of concepts and technology.
- A potential disposal site is unlikely to have uniform depth or distribution of suitable host rock to accommodate a large, idealised MBM layout, such as that shown in Figure A4.1. However, an optimised mix of borehole spacing, depth and inter-container spacing might be adopted to maximise the volume of host rock available.
- At this preliminary stage of assessment, based on this outline description, no viability threatening issues have been identified for MBM concepts. However, further work is required to fill knowledge gaps. In keeping with good practice, these conclusions would be reviewed as the disposal concept is further developed.

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A4 Vault Disposal Concepts for Low-heat Generating Waste (LHGW)

Mature UK concepts exist for:

☑ Shielded-ILW ☑ Depleted, Natural & Low Enriched Uranium packages
☑ Unshielded-ILW ☑ Robust Shielded-ILW (e.g. Ductile Cast Iron Containers)
☑ Nuclear New Build packages

Main Drivers for LHGW vault disposal concepts

GDF Footprint - Reduced thermal constraints, compared with HHGW concepts, allows for efficient packing densities to be achieved within the vaults. Low heat generation allows for close proximity of individual waste packages, which in turn allows for stacking or the combining of waste packages into stillages or purpose built boxes.

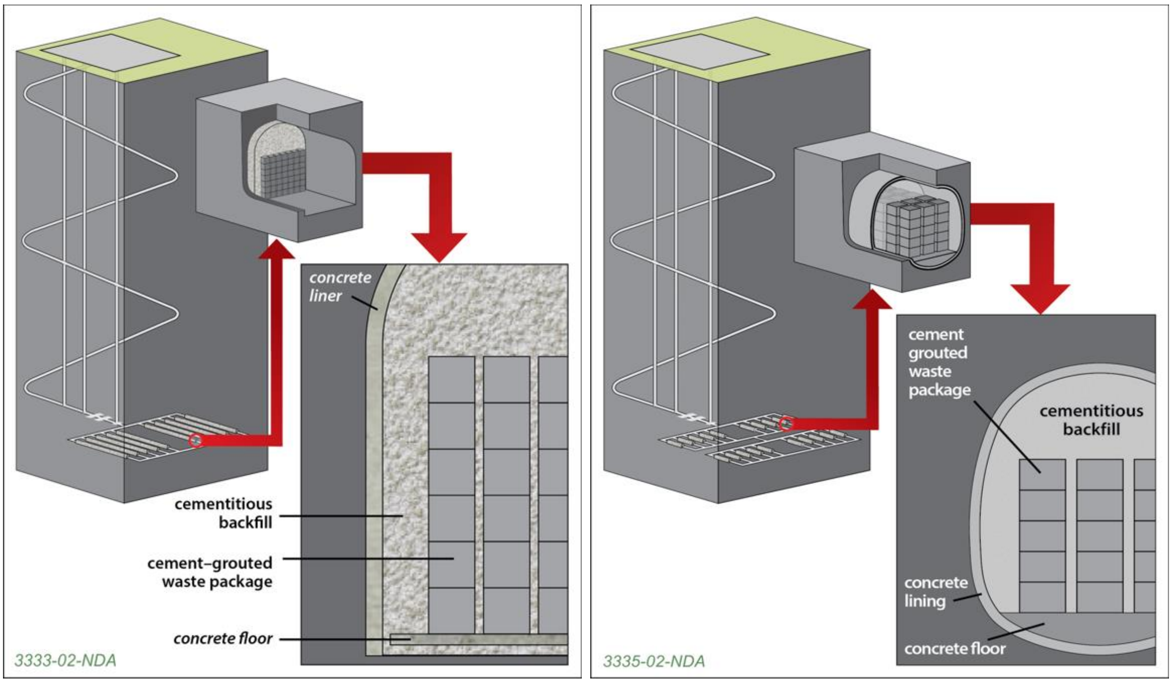
Reversibility - Before the vaults are backfilled, it would be relatively easy to access an emplaced package.

Operational flexibility – The number of potential emplacement sites for a package within a vault is relatively high.

Main characteristics

RWM include and maintain a broad range of vault concepts for disposal of LHGW in a range of rock types, drawing on concepts developed in the UK and international vault concepts adapted to the UK context [A5.1]. In particular RWM have developed conceptual designs that are scaled for the UK Inventory for geological disposal and key concept issues have been interpreted for UK-specific factors [A5.2]. The LHGW vault concept for higher strength host rock is based on the UK Phased Geological Repository Concept (PGRC), previously developed by Nirex for a higher strength, low permeability rock [A5.3]. In this concept, ILW and LLW, typically encapsulated in a cementitious grout in stainless steel containers will be emplaced in disposal vaults excavated in the rock. The use of rock bolts, metal mesh and shotcrete is envisaged to provide engineered support to the excavations. Concrete linings are likely to be required in the access tunnels. At some point the disposal vaults will be backfilled with a cementitious material, such as Nirex Reference Vault Backfill (NRVB), designed to provide a chemical barrier over the long term. Access tunnels will also be backfilled with cementitious material and low permeability seals [A5.4].

Figure A5-1 RWM Illustrative Vault Disposal Concept for LHGW in higher strength rock (left), lower strength sedimentary rock (right) [A5.1]



The vault disposal concepts for LHGW recognised internationally are all based on disposal of ILW/LLW containers in vaults, with distinctions recognised as a result of the nature of the waste packages (shielded or unshielded), the approach to emplacement of the EBS (no backfill, emplacement of backfill as a supercontainer, emplacement of backfill prior to emplacement of waste packages, and emplacement of backfill after waste packages) and changes in the concept in relation to the geological environment (quantity of backfill and size of openings).

Long-term safety

RWM's generic ESC [A5.5] provides confidence that a LHGW vault could be constructed in a way that provides long-term environmental safety in a range of geological environments. Long-term safety would be assured by the presence of a system of natural and engineered barriers and the complementary environmental safety functions that they provide.

Operational and construction safety

Details of construction methods and materials are provided in the generic Disposal Facility Designs report [A5.6]. Safety during construction would be provided by working to a well-defined safety management system, and by establishing a strong safety culture.

The Generic Operational Safety Assessment [A5.7] identifies the non-radiological safety assessment during construction and operations at a GDF.

Implementation approach

Flexibility with respect to host rock variability: Vaults are potentially suitable for HSR, LSSR and EVR. To enable the design to be adapted, the underground facilities have been designed in banks of vaults and disposal tunnels that could be individually positioned to avoid structural features such as faults.

Flexibility with respect to waste type: Vault design variants can be developed for all waste types, by varying the materials and geometry selected for the EBS.

Flexibility with respect to scheduling: The large floor area in a vault provides multiple individual locations for packages. An area near the exit of the vault could be reserved for packages requiring special emplacement.

Retrievability options

The illustrative designs each set out retrievability options for LHGW vault concepts in each geological setting [A5.2]. For the illustrative vault designs in each geological setting, it is assumed vaults would remain open until all the waste has been emplaced, when a decision to backfill all vaults could be taken. Assuming appropriate control of environmental conditions to ensure package integrity, reversal of the emplacement process would only require re-use of the remote handling systems in the vaults, or the re-use of a stacker truck. Once vaults are backfilled the waste packages would be more difficult to retrieve, and a programme of backfill removal would be required. Studies have been undertaken to demonstrate retrievability of LHGW packages. In particular, Nirex demonstrated the feasibility of using high-pressure water jets to retrieve ILW packages from disposal tunnels backfilled with NRVB [A5.8].

Maturity of technology

This concept has high maturity. All cited vault concepts for LHGW have been the subject of extensive planning programmes, supported by laboratory and in-situ testing, for more than 20 years. Further details can be found in the section on international developments below.

The UK and Swiss [A5.9] cited vault disposal concepts for LHGW are currently classed as having relatively high technical maturity levels, although neither are at full-scale industrialisation / pre-operation commissioning. Both are defined by bounding parameters associated with a specific EBS underpinned by scoping assessments and generic research and development.

Knowledge Gaps

The RWM Science and Technology Plan provides a comprehensive description of priorities for further work identified by RWM for progressing their generic designs for vault disposal for low-heat generating wastes in a HSR and LSSR environment [A5.10]. Further knowledge gaps are also identified by the Swiss implementer Nagra, for their disposal programme towards the disposal of LHGW in Opalinus Clay [A5.11]. Common aspects are:

- Further development and testing on a large scale of the engineered gas transport system for the mitigation of repository-induced effects;
- In relation to radionuclide release processes, experience from prior safety assessments shows that reducing uncertainties in the release rate of C-14 from L/ILW are of high priority. As part of international efforts, the release rate of C-14, a dose-determining radionuclide, in the gaseous and the liquid phase, including the description of its molecular form, continues to be assessed in targeted experiments which are expected to be concluded in the next years;
- Long-term gas production experiments from organic materials in L/ILW are continuing internationally together with corrosion and gas generation experiments from metals to refine the description of the source term in the gas impact analysis
- Fundamental understanding, modelling capabilities and data needed to describe the post-closure evolution of the GDF, to evaluate the safety function indicators, and to support the dose calculations required to evaluate the consequences of any resulting radionuclide releases. Particular focus is on the understanding of the temporal evolution of the conditions anticipated in the repository. Given the scale and timeframes involved, numerical thermo-hydro-mechanical (THM) modelling is an important aspect, but it needs to be underpinned by targeted laboratory and URL experiments.

Environmental impact

Vaults are currently used for all LHGW packages in all of RWM's generic illustrative designs.

Life cycle costs

Vault cost is affected by many factors, but the most significant is the geological environment at the site of the GDF.

International concept developments 2008-2016

Vaults in Evaporite

US - WIPP truck fire and radiological release events (2014) [A5.12] – these events have design implications for underground equipment and ventilation systems.

Germany – Morsleben - Stabilisation measures (backfilling) were undertaken in 2003 - 2011 to prevent cavern collapse [A5.13]. RWM is currently collaborating with DBE on identifying opportunities for technology transfer.

Vaults in HSR

Sweden - SKB plans to extend the existing SFR repository with six new rock vaults with a length of 240–275 metres so that it will be about three times larger than it is today. Just like the existing SFR, the extended section will be sited in the bedrock below the sea off Forsmark. The extension is planned at a depth of 120–140m. To enable this extension, SKB submitted the applications required by the Nuclear Activities Act and the Environmental Code to the Radiation Safety Authority and to the Land and Environment Court at the end of 2014. These comprise about 6,000 pages and include, for instance, an environmental impact assessment and an analysis of the safety of the facility both during operations and after it has been sealed.

Canada – A 680m deep geologic repository ILW facility has been proposed in Kincardine. A four-year multi-phase program of geoscientific investigations to verify the suitability of the geology beneath the Bruce nuclear site to safely host the DGR was completed in July 2010. In 2016, the Canadian government requested further studies into the DGR, before making a decision on the environmental assessment. [A5.14]

Germany – Konrad, an old iron ore mine in coral oolite, is due to open 'not before 2022' for LHGW in ductile cast iron containers. (The infrastructure areas are constructed in sedimentary rock, and the emplacement areas are erected in a hard-rock type geology). The Konrad facility is fully licensed (including the operation license) and currently being constructed (the excavation of the first emplacement field is finished). A significant amount of work has been required to make the old mine workings (at approximately 800m deep) suitable for waste disposal.

Hungary – Bátaapáti – Puram’s facility for ILW started accepting waste in 2012. Two inclined shafts serve the construction and operation of the subsurface part of the facility, where the disposal of the waste takes place. The shafts, each with a length of 1700 m and an inclination of 10%, were excavated parallel, at a distance of 25 m from each other. Both of them have a cross section of 21-25 m^2. The length of the first disposal chamber, the I-K1 chamber is 90 meters, the section size is almost 96 m^2 and its depth from the surface is about 250 meters. [A5.15]

Vaults in LSSR

France – Cigéo – Andra's application for a construction licence for a 500m deep geological repository just outside the village of Bure in the Champagne-Ardenne region of eastern France was submitted in 2015. Andra currently expects to start construction in 2020.[A5.16]

Summary

- Vaults are currently used for all LHGW packages in all of RWM’s generic illustrative designs.

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A5 Silo Disposal Concepts for Low-heat Generating Waste (LHGW)

Mature UK concepts exist for:

☐ Shielded-ILW ☐ Depleted, Natural & Low Enriched Uranium packages

☐ Unshielded-ILW ☐ Robust Shielded-ILW (e.g. Ductile Cast Iron Containers)

☐ Nuclear New Build packages

Main drivers for silo concepts

GDF footprint - For silos, efficient use of the excavated volume is higher than for vaults because proportionately less space is needed for crane movements.

Geology / Siting - Vertically orientated disposal silos may be needed to avoid relatively closely spaced, sub-vertical layout-determining features (e.g. water-bearing fractures) in the host rock.

Main characteristics

Silo-type repositories have been built and are in successful operation for the disposal of radioactive low heat generating wastes (LHGW) in Finland (the VLJ repository at Olkiluoto) [A6.1], in Sweden (the SFR repository at Forsmark) [A6.2] and in South Korea (the Wolsong repository) [A6.3]. These three repositories have a number of similar features. Most importantly, they:

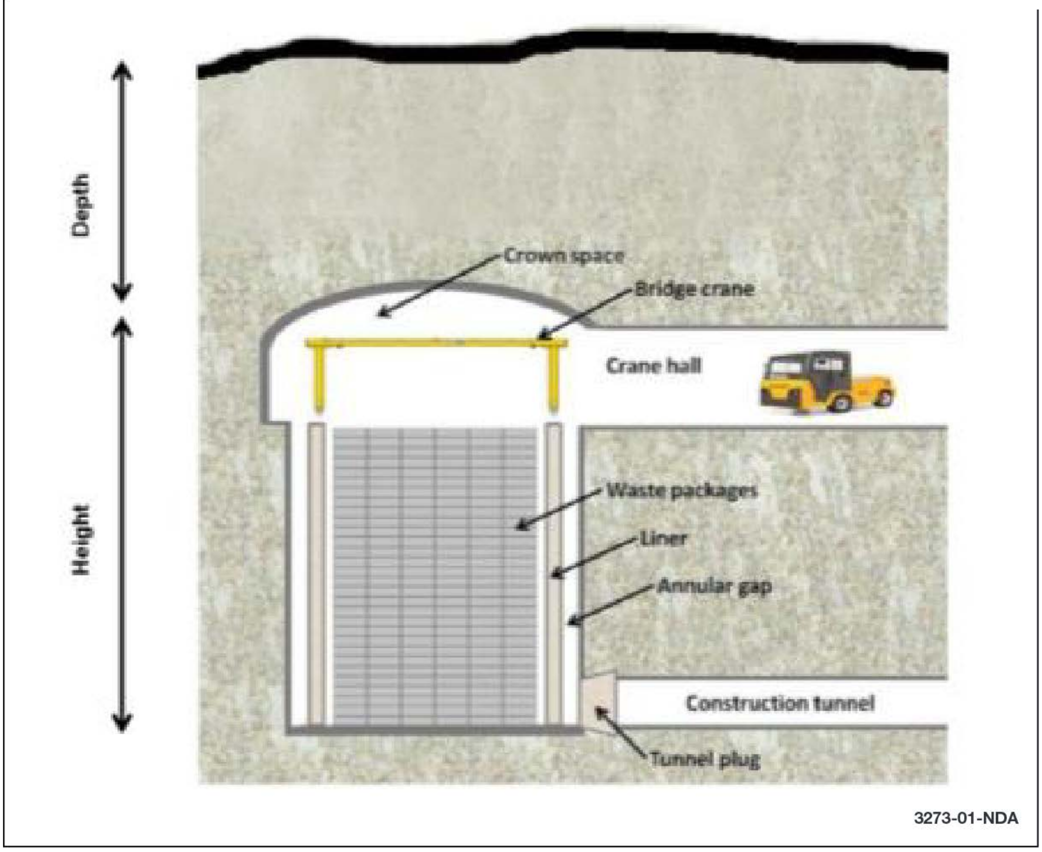
- are relatively shallow, with the tops of the silos in the range 70 to 80 mbgl (metres below ground level)
- have excavated diameters of approximately 20 to 40 m, heights of 45 to 70 m, and volumes of around 20,000 to 45,000 m^3 for each silo;
- are constructed in higher strength rock;
- are used for the disposal of low level waste (LLW) and short-lived intermediate level waste (ILW) from routine reactor operations;
- use standard sized packages that are emplaced vertically from the top of the silo using a bridge crane, with packages stacked in several 10s high; and
- are based on an engineered barrier design that includes a reinforced concrete liner to limit groundwater flow and, in the case of the Wolsong repository in South Korea, to provide mechanical support for the host rock.

In addition to radioactive waste disposal, silos are used for other purposes, including the storage of gas, housing neutrino detectors, and to host municipal facilities. Some of these silos are both larger (up to 85 m diameter) and deeper (up to 1 km) than the existing silo-type repositories [A6.4].

The volume available for disposal in a silo is always less than the full excavated height because space is required at the top for cranes to operate and to emplace wastes. This is generally referred to as the 'crown space' and the rock roof here is usually curved to provide maximum mechanical stability [A6.4].

Deep silos (at depths usually considered for geological disposal) are potentially viable in higher strength rock (or salt) where they offer some possible advantages over vault concepts (e.g. greater useable volume). This assumes feasibility of constructing a wide and deep silo which is generally only possible in hard rocks that can sustain large span excavations (i.e. a diameter of approximately 34 m and a height of 70 m to have the same disposal capacity as a reference UILW vault, about 35,000 m^3: The volume of the excavated rock would be in the region of 55,000 m^3 compared to 81,000 m^3 for a vault).

Figure A6-1: The main features of a generic silo-type repository (not to scale).



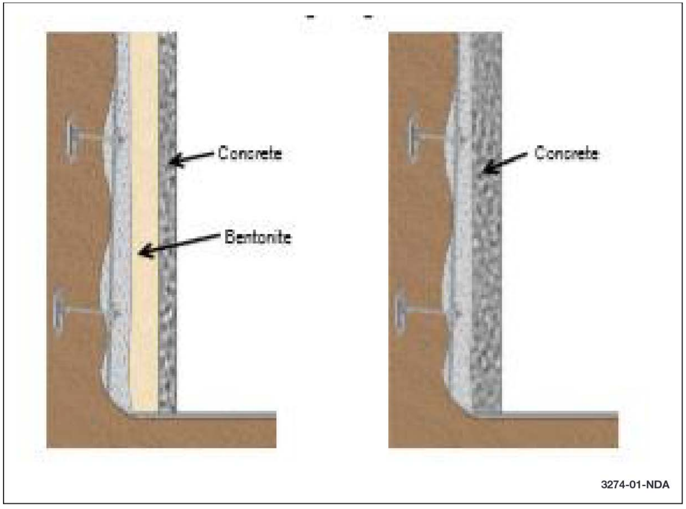
Long-term safety [A6.4]

- Post-closure performance will be determined by a combination of engineered and geological barriers. For LHGW, where neither very long-lived containers nor extremely durable wasteforms are specified, the geosphere barrier might be expected to play an increasingly important role compared to the EBS as the depth of disposal increases. This is because, in general, the groundwater travel times would be expected to be longer (allowing for more radioactive decay, sorption, and dispersion), and the flow rates in the vicinity of the disposal area would be lower (reducing the flux of radionuclides from the disposal facility).
- RWM's previous generic assessments have assumed LHGW would be disposed in vaults. At the level of detail appropriate for a preliminary analysis of conceptual designs, a vault and silo are very similar: the excavation volumes are broadly comparable, and only the orientation and aspect ratio differ. This may give rise to some differences in groundwater flow rates and flow directions through the excavations but these are expected to have relatively limited consequences for release rates.
- One differentiating feature of the existing silo-type repositories (which are all near surface), compared to RWM's illustrative designs for vaults in higher strength rock, is the reinforced concrete or bentonite liner that is intended to limit groundwater flow through the EBS and EDZ. A liner could also be included in a silo excavated at depths (as considered in previous silo designs by Nagra Kristallin Project [A6.5]), although scoping calculations carried out in [A6.4] indicate little post-closure performance benefit of a liner because safety is determined largely by the hydrogeological properties of the geosphere.

Silo Liners (or secondary engineered barrier structure)

Some (but not all) existing silo repositories include a secondary engineered barrier structure, usually of reinforced concrete, to provide an additional containment barrier, to restrict groundwater flow and radionuclide transport. This may be freestanding with an annular void between the rock and the concrete, or it may be built directly adjacent to the rock. Examples of these variations in these secondary engineered barrier structures are shown illustratively in Figure A6-2.

Figure A6-2: Examples of secondary engineered barrier structures (liners) in silos. Left: a freestanding concrete liner with the annular gap between the liner and the wall backfilled with bentonite. Right: a concrete liner constructed directly against the rock wall and its supports. Note that in some systems the barrier system also extends over the floor of the silo.



The primary purpose of a freestanding concrete liner may be to provide an additional containment barrier, to restrict groundwater flow and radionuclide transport. The purpose of a liner built adjacent to the rock wall may be either to provide additional containment, to provide structural stability for the excavation, or accommodate or resist rock movement. In some cases, the liner may be subdivided with internal walls to allow waste packages to be emplaced in specific zones (e.g. higher activity packages in the centre).

Operational and construction safety [A6.4]

Construction

The international precedence demonstrates that silos of a wide range of sizes and designs can be constructed and operated safely in suitable geological environments, but there are limits on the excavations:

- depth (below ground) is constrained by the mechanical strength of the rock but it is certainly possible to construct silos in higher strength rock or salt at the depths generally considered for geological disposal;
- diameters are typically in the range of 20 to 40 m, with the upper range constrained by the mechanical strength of the rock; and
- heights are typically a few multiples of the diameter, in the range of 45 to 70 m, with the height generally limited by operational issues (e.g. safe working heights) rather than geological conditions.

Experience from silo excavations shows they can be excavated faster than a similarly dimensioned vault. This is likely to save some costs for construction, although it is not likely to be the overall rate-limiting step for construction of the GDF, due to phasing of construction and operational activities.

Emplacement

Waste emplacement in a silo must be done using an overhead crane (whereas emplacement in a vault may be done with either a crane or a stacker truck, i.e. purpose-designed forklift). Wide diameter silos (e.g. SFR and Wolsong) use rotating bridge cranes to access all areas within the silo. Depending on the repository design, it is possible to use fewer cranes in a silo-type repository than for a vault. For example, the VLJ repository uses a single crane that can be moved between the LLW and ILW silos.

There are some uncertainties regarding operational safety issues for silos related to the height and geometry of the excavation (e.g. increased consequence from accidental drop of a waste package, and risks for workers from working at height). It is likely, however, that these risks can be mitigated by conventional engineering design and working procedures.

The differences in geometry and orientation between a silo and vault influence the probability and consequence of accidents. Most notably, the consequences of drops and falls are significantly greater for a silo. For example, the maximum drop height in a typical vault is around 10 m whereas in a silo it could be 60 m. On the other hand, transport distances may be less and, if necessary, engineering counter-measures could be introduced to reduce the probability or consequences of drops.

Package Stacking

Waste packages are emplaced in much higher stacks in silos than in vaults. For example, in the SFR, a maximum of 42 packages are stacked whereas, in the UK Unshielded-ILW vault design, the limit is 7. Stacking is important for silos because one of the key benefits of the disposal concept is a high useable disposal volume, and that requires a larger height: diameter ratio than vaults. Excavating tall silos in Higher Strength Rock is not a limiting factor on their size: the practical limit is the number of waste packages that can be stacked without the weight of the stack crushing the lowest package. Most UK LHGW will be packaged in 3 m^3 boxes and 500 l drums placed in stillages. These packages were not designed to be stacked more than 6 or 7 high. To adopt silos in the GDF, it would be necessary to 'layer' the silo in such a way as to reduce the loading on the lowest waste packages in a stack. For example, after a silo has been filled 6 packages high, all interstitial spaces could be backfilled and a new floor installed in the silo, before a second layer (6 packages tall) emplaced. Assuming 3 m^3 boxes (each with a height of 1.25 m) stacked 6 tall; a layer would be around 10 m tall allowing sufficient thickness of a dividing floor. If the silo has a useable height of around 50 m, this would 5 layers or 30 boxes vertically. This option has many advantages in terms of operational safety, but sacrifices ease of retrieval after the layer of grout has been emplaced.

Implementation approach

Flexibility with respect to host rock variability: There is proven experience of constructing silos in a range of rock types, both hard and soft. However, it becomes progressively more difficult to excavate wide diameter silos (than tunnels) in soft rocks or poor quality hard rock without the need for substantial reinforcements.

Flexibility with respect to waste type: Silo geometry is feasible for all LHGWs (at depth) although current UK packages would likely have to be adapted to allow high stacking, or layering of the waste packages with periodic backfilling could be considered.

Flexibility with respect to scheduling: A vault has inherently more flexibility than a silo for varying where each waste package is positioned (e.g. to place packages with higher dose rates in the centre). This is partly because the larger surface area in a horizontal vault provides more individual locations than a silo. Unless a silo has internal supporting walls, it must be filled layer by layer to ensure stability. However, the overall rate of waste emplacement is not expected to be substantially different between silos and vaults.

Retrievability options

Reversibility / package retrieval (before closure): Assuming waste packages are not backfilled during emplacement, it should be easier to retrieve a specific waste package from a vault than a silo using overhead crane, if needed. This is because, at most, only a few packages may need to be lifted out of the way to access any waste package in the short stacks in a vault, compared to the tall stacks in a silo. If a vault were filled using a stacker truck (i.e. the first package in would be the last package out), there may be less difference between the concepts.

Maturity of technology

For near surface disposal, existing and operating silo repositories exist with technology options that could be easily transferred and adopted for use in a UK silo for LHGW (short-lived wastes only) as part of the GDF. Likewise, at depth and in a sufficiently strong hard rock environment, similar silo designs for all LHGW are conceivable. Assessing constraints on transfer of experience from elsewhere is inherently constrained by the host rock environment.

Knowledge Gaps

To-date, only international silo options have been reviewed to understand the broad benefits and constraints (compared with vault concepts) for the disposal of LHGW in a UK GDF. RWM has previously considered a conceptual design for silos where the disposal height was constrained by existing package specifications [A6.6]. However, as discussed in [A6.4], larger silos provide proportionately greater benefits in terms of the amount of useable disposal space and efficiency, and should be explored.

Further consideration of the silo disposal concept would require a number of engineering solutions to be developed:

- packages are currently designed to withstand a load of up to 6 packages on top – silos could contain stacks that are 30 to 40 packages high;
- the operating height in a silo could be as much as 60 m but current specifications assume a maximum drop height of 11 m [A6.7]; and
- the retrievability of waste packages - if it is necessary to incrementally backfill waste packages in a silo (e.g. with cement in layers), this may make retrieval much more difficult as structural cement would be required.

A number of uncertainties have been identified in [A6.4]. Most notably these uncertainties are related to the comparative volumes of excavated rock and the impact on construction costs when comparing silos with vaults for UK LHGW.

Environmental impact

A large diameter silo makes more efficient use of excavated volume than a similarly dimensioned vault, so less rock may need to be excavated for silos (compared with vaults). However, this benefit may be offset by the need to excavate a second construction tunnel for silos. Although this second tunnel may be needed in any case to separate movements of waste packages from removal of rock spoil during phased construction of the GDF.

Life cycle costs

At this stage, no attempt has been made to quantify the life-cycle costs of including silos for LHGWs as an integral part of the UK GDF designs. Many factors will affect costs (and excavated volumes), but in practical terms the most important will be:

- the maximum diameter for the silo excavation (dependent on the rock strength);
- the maximum height for the operational section of silo (dependent on the ability to stack waste packages);
- the emplacement method and backfilling strategy;
- the ventilation requirements;
- the length of the construction tunnels needed for silo excavations; and
- the geometry and structure of required liners and any other support structures.

International concept developments 2008-2016

Slovenia – the proposed repository at the Vrbina – Krško site would consist of silos constructed below the groundwater level in low permeable strata at a depth of approximately 15 m to 50 m below the surface [A6.8].

Sweden and Finland - Examples of operational shallow disposal facilities (a hundred metres or so depth) include the SFR facility in Sweden [A6.2, A6.9] and the VLJ facilities (Olkiluoto VLJ and Loviisa VLJ are at depths of 60-95m and 110m respectively) in Finland [A6.1, A6.10].

UK - The 2011 Graphite Pathfinder Project was established by NDA at Hunterston A and tasked with establishing the feasibility of a silo for around 2000m^3 of solid ILW, extending from the surface to a depth of 58m. A preliminary Environmental Safety Case was reported for the application to dispose of such wastes in a near surface facility [A6.11].

South Korea- Wolsong intermediate depth disposal facility - constructed between 2006 and 2014, and currently operational [A6.12].

Summary

The international precedence in silos demonstrates that silos can be constructed and operated safely in suitable geological environments, but there are limits on the excavations. The work to-date explores international precedence in the use of silos for radioactive waste disposal and for other non-nuclear activities.

Further consideration of silos for the disposal of LHGW is only beneficial for the volume efficient, wide diameter designs that can be excavated in higher strength rock. There are no known examples of wide diameter silos excavated in low-strength sedimentary rocks, although construction technology is advancing rapidly. There are examples of wide diameter silos in salt but these are usually constructed using solution mining (e.g. for gas storage) and their long-term stability and ability to resist plastic deformation is dependent on site-specific host rock conditions.

Initial scoping calculations suggest the post-closure safety performance of silos and vaults, at the depths associated with geological disposal, is likely to be very similar with only minor differences in the flux and direction of groundwater movement.

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Appendix B – RWM Illustrative Designs

As no site has yet been identified for the GDF, the host geological environment is not known. RWM has investigated a wide range of disposal concepts considered by waste management organisations around the world. From these, a smaller number of illustrative disposal concepts have been defined for three host rocks appropriate to the UK, for the purpose of the current design and assessment work and as the basis for the generic DSSC.

The illustrative disposal concepts utilise the most appropriate engineered barriers, materials and facility layouts for each host rock.

The main role of the illustrative disposal concepts is to:

- provide the basis of assessment for the generic DSSC
- support the Disposability Assessment process

Through the iterative development of the disposal system, the illustrative disposal concepts also enable RWM to further develop its understanding of the requirements for the disposal system, develop and prioritise its research programme and underpin analysis of the potential cost of geological disposal.

The illustrative disposal concepts have been developed solely for these purposes. It is not the intention to select any of these concepts, instead when the geological environment for the GDF is known, appropriate concepts will be developed specific to that setting and the wastes to be disposed of, based on the developing knowledge of the site and the understanding of the full range of concepts under consideration. At this stage, no disposal concepts have been ruled out.

RWM's illustrative disposal concepts are based on selected disposal concepts developed by waste management organisations across the world, as listed in Table B1.

Table B1 Disposal concepts selected as the basis for RWM's illustrative disposal concepts

Host Rock	**Disposal Concept (Developer, Country)**	
	LHGW	**HHGW**
Higher strength rock[1]	UK LHGW Concept (RWM, UK)	KBS-3V Concept (SKB, Sweden)
Lower strength sedimentary rock[2]	Opalinus Clay Concept (Nagra, Switzerland)	Opalinus Clay Concept (Nagra, Switzerland)
Evaporite rock[3]	WIPP Bedded Salt Concept (US DOE, USA)	Gorleben Salt Dome Concept (DBE Technology, Germany)

Notes:

1. Higher strength rock – the UK LHGW concept and SKB's KBS-3V disposal concept for spent fuel were selected because of the availability of information on these concepts for the UK context.
2. Lower-strength sedimentary rock – the Opalinus Clay concepts were selected following an NEA review [2]. However, it should be noted that there is similarly extensive information available for the French (Andra) concepts (for Callovo-Oxfordian Clay), which have also been accorded strong endorsement from international peer review. Although the Swiss

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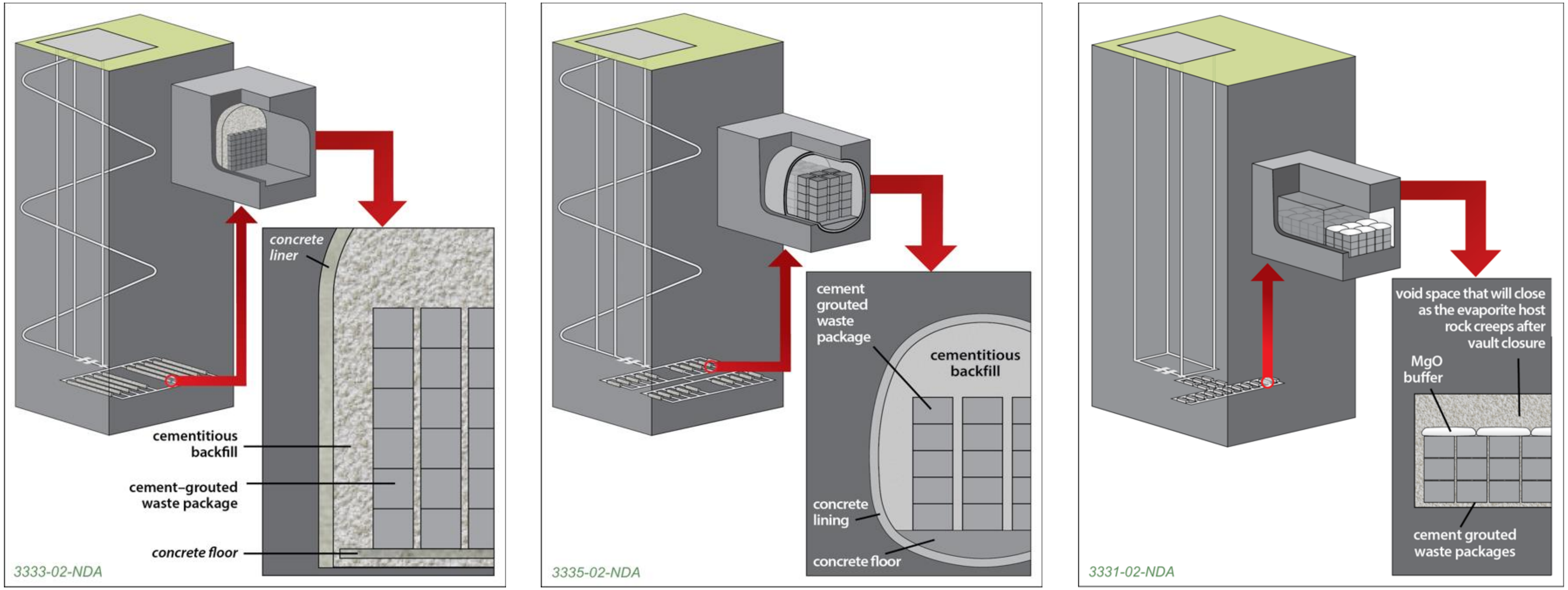
[2] Nuclear Energy Agency, Safety of Disposal of Spent Fuel, HLW and Long-Lived ILW in Switzerland – An International Peer Review of the Post-Closure Radiological Safety Assessment for Disposal in the Opalinus Clay of the Zurcher Weinland, NEA, Paris, 2004.

concepts are used as the basis of the illustrative disposal concepts, information is also drawn from the French programme and from the Belgian HLW/spent fuel supercontainer concept based on disposal of HHGW in Boom Clay.

3. Evaporite rock – the concept for the disposal of transuranic wastes (long-lived ILW) in a bedded salt host rock at the Waste Isolation Pilot Plant (WIPP) in New Mexico was selected because of the wealth of information available from this licensed facility. The concept for disposal of HHGW in a salt dome host rock developed by DBE Technology in Germany was also selected because of the level of concept information available.

The concepts in Table B1 form the basis of RWM’s illustrative disposal concepts for both LHGW and HHGW, for each of the three generic host rocks considered within the generic DSSC. The overlying rock type is also relevant to post-closure safety, and would influence decisions on access routes, although it does not affect the illustrative disposal concepts themselves. The six illustrative disposal concepts, that is for the 3 generic host rocks and 2 waste categories, are illustrated in the figures below for LHGW and HHGW respectively, and are described in more detail in Table B2 and Table B3 respectively. The illustrations show shafts and a drift in some cases for context, although these are access details that are not part of the concepts. All of these concepts are based on a multi-barrier approach.

Figure B1 Schematic of illustrative disposal concepts for low heat generating waste

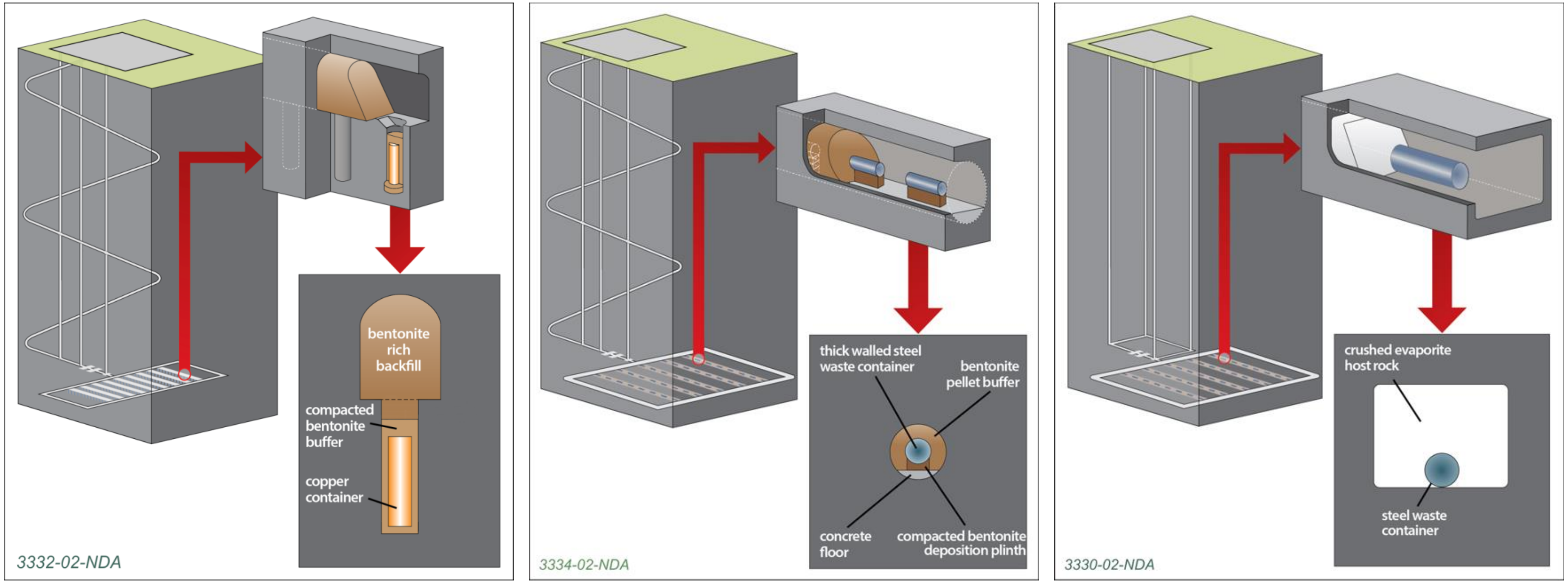


Higher Strength Rock

Lower Strength Sedimentary Rock

Evaporite Rock

Figure B2 Schematic of illustrative disposal concepts for high heat generating waste



Higher Strength Rock

Lower Strength Sedimentary Rock

Evaporite Rock

Table B2: Description of illustrative disposal concepts for low-heat generating waste

Attribute	Higher strength rock	Lower strength sedimentary rock	Evaporite rock
Source example	UK ILW/LLW Concept – NDA, UK	Opalinus Clay Concept – Nagra, Switzerland	WIPP Bedded Salt Concept – US-DOE, USA
Waste groups	Suitable for LHGW in the UK inventory.	Suitable for most LHGW in the UK inventory.	Suitable for most LHGW in the UK inventory.
UK geological Environment	Higher strength host rock overlain by sedimentary sequence that provides significant (tens of thousands of years) groundwater travel time.	Lower strength sedimentary host rock in which the permeability is sufficiently low that solute transport is by diffusion. There will be a cover sequence but its nature is not specified, or important to the definition of the disposal concept.	Evaporite host rock. There will be a cover sequence but its nature is not specified, or important to the definition of the disposal concept beyond it protecting the evaporite from low salinity groundwater.
Components	Large horseshoe-shaped vaults (eg 16 m × 16 m × 300 m). A lining may be installed to prevent rockfall and water ingress. Such support, as required, is provided by rock bolting, mesh and shotcrete. Cement grouted waste in standardised vented stainless steel containers. High pH, high porosity and permeability cementitious backfill (Nirex Reference Vault Backfill – NRVB) surrounding waste packages. Emplaced as part of closure engineering. Crushed host rock mass backfill. Low permeability seals/plugs.	Oval-shaped vaults (for example 9.5 m (width) × 11.5 m (height) × 100 m). A lining may be installed to prevent rockfall and water ingress. Such support, as required, is provided by rock bolting, mesh and shotcrete. Cement grouted waste in standardised vented stainless steel containers. High pH, high porosity and permeability cementitious backfill surrounding waste packages. Backfill has some structural strength to resist creep of the host rock. Emplaced as soon as each vault has been filled. Crushed host rock mass backfill. Low permeability seals/plugs.	Rectangular-shaped vaults (eg 10 m (width) × 5.5 m (height) × 100 m), which are unlined. Cement grouted waste in standardised vented stainless steel containers. Sacks of MgO are placed on top of each waste stack to absorb CO_2 and water and buffer pH. Remaining void space left open. Vault closed as soon as it has been filled. Crushed host rock mass backfill. Low permeability seals/plugs. Underground access is by shaft.

Attribute	Higher strength rock	Lower strength sedimentary rock	Evaporite rock
Waste handling and emplacement	Unshielded packages transported underground within transport container. Remote emplacement of unshielded ILW waste packages by crane. Shielded ILW/LLW waste packages emplaced by stacker truck (with shielded cab). Standardised containers to facilitate handling and stacking. Vaults open at both ends during operational period facilitating ventilation.	Unshielded packages transported underground within transport container. Remote emplacement of unshielded ILW waste packages by crane. Shielded ILW/LLW waste packages emplaced by stacker truck (with shielded cab). Standardised containers to facilitate handling and stacking. Vaults open at both ends during operational period facilitating ventilation.	Unshielded packages transported underground within transport container. Remote emplacement of unshielded ILW waste packages by stacker truck. Manual emplacement of shielded ILW/LLW waste packages by stacker truck (with shielded cab). Standardised containers to facilitate handling and stacking. Vaults open at both ends during operational period facilitating ventilation.
Operational considerations	Achieving a uniform distribution of backfill around the waste packages may present challenges, especially if the operation is carried out many decades after the equipment was installed. Delayed backfilling has associated maintenance requirements to ensure environmental conditions are maintained for decades after vaults have been filled; prevention of rockfalls etc. Continued ventilation requirements – packages are vented and so radioactive and potentially flammable/explosive gases are released during the operational period.	Excavation support systems are needed. “Early” backfilling is required for stabilisation of the rock.	“Early” backfilling is required for stabilisation of the rock.

Attribute	Higher strength rock	Lower strength sedimentary rock	Evaporite rock
Post-closure safety concept	Backfill is designed to condition the groundwater to a high pH for timescales of a million years or more and thereby provide a chemical barrier to release of radionuclides. High pH conditions reduce the solubility and mobility of certain key radionuclides such as actinides. Low permeability host rock ensures very slow migration in groundwater.	Backfill is designed to condition the groundwater to a high pH for timescales of a million years or more and thereby provide a chemical barrier to release of radionuclides. High pH conditions reduce the solubility and mobility of certain key radionuclides such as actinides. Low permeability host rock ensures very slow migration in groundwater.	Host rock creeps and completely encapsulates waste packages. Dry environment means that there is no transport via the groundwater pathway.
Monitoring of waste packages and retrievability (ie the reverse of emplacement prior to backfilling)	Crane emplacement would allow selective retrieval prior to backfilling. However, cranes would need to be maintained for 100 years. Potential for monitoring either through inspection of selected (retrieved) waste packages or remotely, for example inspection by camera.	Backfilling immediately after the vault has been filled limits the potential for retrievability and monitoring. However, the access tunnels will be fully lined and kept open until GDF closure.	Closing the vaults immediately after they have been filled limits the potential for retrievability and monitoring. However, the access tunnels will be kept open until GDF closure, although creep may be an issue.
Technical maturity	This concept has been developed in the UK and is used as a reference for disposability assessments. Extensive research and development has been carried out but no site-specific safety case has yet been developed.	This concept is an adaptation of the opalinus clay concept for disposal of long lived ILW developed by Nagra. It was selected because a review by the Organisation for Economic Co-operation and Development (OECD) Nuclear Energy Agency regarded the Nagra assessment of the concept as state of the art with respect to the level of knowledge available.	This concept is an adaptation of the WIPP disposal concept for transuranic wastes, which is an operating facility.

Table B3 Description of illustrative disposal concepts for high-heat generating waste

Attribute	Higher strength rock	Lower strength sedimentary rock	Evaporite rock
Source example	KBS-3V Concept – SKB, Sweden	Opalinus Clay Concept – Nagra, Switzerland	Gorleben Salt Dome Concept – DBE-Technology, Germany
Waste groups	Suitable for a wide range of HHGW, although the very long container lifetime provided by copper container may not be optimal for some wastes (eg HLW) which do not need to be contained for such a long period. Alternatives to copper will be considered.	Suitable for all types of HHGW	Suitable for all types of HHGW
UK geological environment	Higher strength host rock overlain by sedimentary sequence that provides significant (tens of thousands of years) groundwater travel time.	Lower strength sedimentary host rock in which the permeability is sufficiently low that solute transport is by diffusion. There will be a cover sequence but its nature is not specified, or important to the definition of the disposal concept.	Evaporite host rock. There will be a cover sequence but its nature is not specified, or important to the definition of the disposal concept beyond it protecting the evaporite from low salinity groundwater.
Components	1.5 m diameter borehole approximately 8–10 m deep drilled vertically from the floor of the horseshoe shaped deposition tunnel. Borehole designed to take single waste package and buffer. Copper container with cast iron insert to provide mechanical strength. Compacted bentonite buffer. Bentonite-dominated deposition tunnel backfill. Crushed rock mass backfill in access tunnels. Low permeability sealing system.	2.5 m diameter unlined horizontal tunnel with a concrete floor, nominally 800 metres in length. Thick-walled carbon steel container. Pelleted bentonite buffer, although compacted bentonite pedestal used to support waste package. Crushed host rock mass backfill. Sealing system.	Rectangular (4.5 m wide by 3.5 m high) unlined horizontal tunnel, nominally 800 metres in length. Thick-walled carbon steel container. Crushed host rock buffer. Crushed host rock mass backfill. Sealing system.

Attribute	Higher strength rock	Lower strength sedimentary rock	Evaporite rock
Waste handling and emplacement	Waste package transported underground in re-usable transport container and then emplaced remotely. Robust sealed waste package prevents releases during operations.	Waste package transported underground in re-usable transport container and then emplaced remotely. Robust sealed waste package prevents releases during operations.	Waste package transported underground in re-usable transport container and then emplaced remotely. Robust sealed waste package prevents releases during operations.
Operational considerations		Excavation support systems are needed.	Excavation support systems are needed.
Post-closure safety concept	A very long container lifetime ensuring no release for hundreds of thousands of years. Combination of protection provided by the buffer and choice of container material ensures extremely long container lifetime.	Waste container protected by buffer provides containment during the thermal period, and is expected to remain intact for tens of thousands of years. Long term containment is dominantly provided by low permeability host rock, which ensures that solute transport is dominated by diffusion.	Evaporite host rock will creep and compact the buffer resulting in complete encapsulation of the waste packages in a dry environment. Dry environment will limit corrosion of the thick-walled waste container so the container is likely to remain intact for hundreds of thousands of years.
Monitoring of waste packages and retrievability	Tunnel backfill must be emplaced as soon as possible after buffer emplacement so potential for monitoring and reversability limited. Concept allows for retrievability.	Buffer is emplaced at the same time as waste packages so potential for monitoring and reversability limited. Concept allows for retrievability.	Buffer is emplaced at the same time as waste packages so potential for monitoring and reversability limited. Concept allows for retrievability.
Technical maturity	The Swedish KBS-3V concept is an example of this concept. A site-specific safety case has been submitted for regulatory review but certain aspects of the concept are still subject to development for a UK geological environment.	Similar concept currently being developed by Nagra. Extensive research, including work in underground research laboratories, although rate of progress is modest owing to a site not yet having been selected in Switzerland.	This concept was adapted from the concept for disposal of HLW and spent fuel in a salt dome host rock developed by DBE Technology; it was selected due to the level of concept information available.

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