Radioactive Waste Management

NDA Report no. NDA/RWM/146

Geological Disposal

Review of Alternative Radioactive Waste Management Options

March 2017

Radioactive Waste Management

NDA Report no. NDA/RWM/146

Geological Disposal

Review of Alternative Radioactive Waste Management Options

March 2017

Conditions of Publication

ISBN 978-1-84029-572-6.

Other Publications

If you would like to see other reports available from RWM and the NDA, a complete listing can be viewed at our website www.nda.gov.uk, or please write to us at the address below.

Feedback

Readers are invited to provide feedback on this report and on the means of improving the range of reports published. Feedback should be addressed to:

RWM Feedback
Radioactive Waste Management Limited
Building 587
Curie Avenue
Harwell Campus
Didcot
OX11 0RH
UK

email: rwmfeedback@nda.gov.uk

Abstract

The 2014 White Paper on Implementing Geological Disposal recognises that it is appropriate to investigate and remain aware of alternative options to geological disposal where there could be the potential to improve the overall management of higher activity radioactive wastes. This report forms part of RWM's ongoing commitment to periodically review developments in the area of alternative radioactive waste management options.

Executive Summary

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, which applies in England and Northern Ireland. Welsh Government policy is also for geological disposal for the long-term management of HAW.[1]

Government has identified the Nuclear Decommissioning Authority (NDA) as the organisation responsible for implementing its policy on managing higher activity radioactive waste. The NDA has, in turn, established Radioactive Waste Management Limited (RWM) to develop and implement a safe, sustainable and publicly acceptable approach to geological disposal.

The NDA has developed a strategy for integrated and optimised radioactive waste management across its estate. The need to develop radioactive waste storage plans and to investigate new technologies and solutions in radioactive waste management forms a key part of this strategy. Implementation of geological disposal is a long-term project and hence a flexible approach is needed. RWM supports the NDA by considering developments in radioactive waste management options. Keeping alternative options to geological disposal under review allows RWM to develop its technical programme to take developments in storage, disposal and waste treatment options into account. We work closely with our sister organisations overseas to share existing knowledge, experience and understanding in a cost effective manner.

Between 2003 and 2006, a wide range of options for how to deal with the UK's higher activity radioactive waste was considered, from indefinite storage on or below the surface through to disposal in ice sheets. This work was carried out by the independent Committee on Radioactive Waste Management (CoRWM) and involved extensive consultation with the public and expert groups.

In July 2006, CoRWM recommended that geological disposal, coupled with safe and secure interim storage, was the best available approach for the long-term management of the UK's legacy of higher activity radioactive wastes. CoRWM stated that the aim should be to progress disposal as soon as practicable, consistent with developing and maintaining public confidence.

As part of this approach, CoRWM also made the recommendation for continuing monitoring of developments in alternative management options, as part of ensuring flexibility in decision making, recognising the possibility of alternative or improved management options becoming available in the future. This report provides an update to previous reviews of developments in this area[2,3], and is intended to be an objective technical review of published literature.

The review reported here has been limited to alternatives to geological disposal that were short-listed by CoRWM, together with those options where CoRWM explicitly recommended ongoing review of developments. The review has not considered the status of wider options that were not short-listed by CoRWM (for example, indefinite storage, disposal in subduction zones, disposal at sea, disposal in ice sheets) as there has been no change in the basis for screening options, in particular the criteria that the option breaches internationally recognised treaties or laws.

---

[1] Scottish Government policy is that the long-term management of HAW should be in near-surface facilities.
[2] J Beswick, *Status of technology for deep borehole disposal*, EPS International, April 2008
[3] N Butler, *Literature Review of Partitioning and Transmutation*, Serco, February 2011

Two main types of alternative management options have therefore been reviewed:

- **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 options (although research and consideration of interim storage prior to waste disposal is the responsibility of the wider NDA and nuclear site operators), and
  - waste treatment techniques, including thermal treatment, enhanced encapsulation, and partitioning and transmutation (P&T).
- **Alternative disposal routes** 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) within a geological disposal facility. Such options include:
  - near-surface and intermediate depth disposal, and
  - deep borehole disposal.

A Geological Disposal Facility (GDF) will continue to be required for the disposal of radioactive waste as the alternatives to disposal in a GDF cannot practicably be applied to all components of the radioactive waste inventory, even if used in combination (for example, treatment or long-term storage are also employed).

For some wastes, alternative waste management options offer the opportunity to:

- reduce the inventory of radioactive waste requiring disposal in a GDF and/or
- alter the characteristics of the waste to facilitate easier management.

RWM is either closely monitoring international developments, or actively involved in pursuing all the opportunities identified in this report.

List of Contents

1 Introduction

1.1 Review of Alternative Radioactive Waste Management

UK Government policy is to manage the UK inventory of Higher Activity Waste (HAW)[4] through geological disposal[5], 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 [2]. Scottish Government policy is that the long-term management of HAW should be in near-surface facilities [3].

The 2014 White Paper recognises that it is appropriate to investigate and remain aware of alternative options to geological disposal where there could be the potential to improve the overall management of HAW. It states [1]:

> "…developments in alternative management options should be actively pursued through monitoring of, and participation in, national or international research and development programmes" (Paragraph 2.32).

This requirement stems from the UK Government Committee on Radioactive Waste Management's (CoRWM's) recommendation for continuing monitoring of developments in alternative management options, as part of ensuring flexibility in decision making, and keeping options open, recognising the possibility of alternative or improved management options becoming available in the future (CoRWM Recommendation 5) [4].

There is interest in the UK in alternative radioactive waste treatment and disposal options as part of optimising waste management, partly in response to Scottish Government policy, but also more widely to reduce constraints on nuclear site decommissioning activities that arise from the lack of waste management infrastructure such as a geological disposal facility (GDF). This is reflected in the Nuclear Decommissioning Authority's (NDA's) strategy [5; Pages 14 and 29].

Radioactive Waste Management (RWM) is a wholly owned subsidiary of the NDA, whose mission is to deliver a GDF and provide radioactive waste management solutions. RWM is committed to keeping alternative radioactive waste management options under review, in keeping with good practice for maintaining awareness of developments in the nuclear industry, and in support of UK Government policy, Scottish Government policy, and NDA strategy. RWM's strategic objective and programme plans for work in this area are summarised within its Science and Technology (S&T) Programme [6; Major Product SP6], which notes that periodic review of alternative management options will be carried out, and the findings published, to provide a basis for communicating developments with the UK Government, the NDA and with other stakeholders.

---

4 HAW comprises high-level waste (HLW), intermediate-level waste (ILW) and a small amount of low-level waste (LLW) that is not suitable for near-surface disposal, for example, at the LLW Repository in West Cumbria (LLWR) or the new LLW disposal facility at Dounreay. Also relevant are various nuclear materials not currently designated as wastes, such as spent fuel, uranium and plutonium.

5 Throughout this document, the terms "geological disposal" and "geological disposal facility" or "GDF" refer to a deep, mined facility (repository) for radioactive waste, consistent with their use in UK Government documents. These terms, as used, do not encompass alternative options such as deep borehole disposal.

This report forms part of RWM's ongoing commitment to periodically review developments in the area of alternative radioactive waste management options. It is provides an update to previous reviews of developments in this area that were performed in 2008 and 2011 [7,8].

1.2 Report Objectives

The objective of this report is to review recent developments in the published literature in the field of alternative radioactive waste management options, building on past reviews (for example, [4,7,8]).

1.3 Scope of the Review

The current reference approach for radioactive waste management in England, Wales and Northern Ireland is for disposal of all HAW in a GDF, together with any nuclear materials that come to be designated as wastes in future. Any management steps that reflect a departure from this reference approach can be considered as alternative radioactive waste management options. The distinct waste management policy in Scotland [3], compared to that in England, Wales and Northern Ireland, should be borne in mind when reading this review; specific implications are discussed where relevant throughout the report.

The review reported here has been limited to alternatives to geological disposal that were short-listed by CoRWM, together with those options where CoRWM explicitly recommended ongoing review of developments [4]. The review has not considered the status of wider options that were not short-listed by CoRWM (for example, indefinite storage, disposal in subduction zones, disposal at sea, disposal in ice sheets) as there has been no change in the basis for screening options, in particular the criteria that the option breaches internationally recognised treaties or laws and there is no foreseeable likelihood of change in the future.

Two main types of alternative management options have therefore been reviewed:

- 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.

The scope of this review covers all HAW, as well as nuclear materials that could come to be declared as HAW in future. This includes high-level waste (HLW), intermediate level waste (ILW) and a small amount of low-level waste (LLW)[6] that is not suitable for near-surface disposal, plus spent fuel, separated plutonium, highly enriched uranium (HEU) and depleted, natural and low enriched uranium (DNLEU). Box 1 summarises current assumptions about how these wastes and materials will be packaged for disposal.

[6] In the UK, LLW is defined as radioactive waste having a radioactive content not exceeding 4 gigabecquerels per tonne (GBq/te) of alpha or 12 GBq/te of beta/gamma activity. (Internationally, LLW is often defined as "radioactive waste suitable for near surface disposal").

Box 1. Reference and alternative waste packaging approaches

At the current, generic stage of its programme, RWM has defined a set of illustrative concepts for disposal of HAW in three host rocks (higher strength rock, lower strength sedimentary rock and evaporite). Some of the alternative waste management options discussed in this report consider waste packaging[7] approaches that differ from assumptions reflected in these disposal concepts. It is therefore important to be aware of current assumptions about waste packaging, so that there is a basis for understanding what constitutes an "alternative". A brief summary follows; more detailed information is available elsewhere (for example [9,10]).

High heat generating waste (HHGW), which includes vitrified HLW and any spent fuel, plutonium and HEU[8] declared as waste would be packaged in high integrity containers. Low heat generating waste (LHGW)[9], which includes ILW, LLW and any DNLEU declared as waste would be placed in stainless steel, iron or concrete containers. Much of the LLW and ILW is encapsulated in a cementitious grout, but polymer encapsulants are also used, to a lesser extent, and some LHGW is planned for disposal as unencapsulated waste (for example, when packaged in robust shielded containers). The use of a standard cement powder (CEM-I) blended with either ground granulated blast-furnace slag (GGBS) or pulverised fuel ash (PFA) is the baseline technology in the UK for cement encapsulation of LLW and ILW [12].

Previous studies on this topic have concluded that whilst alternative waste management options offer the opportunity to reduce the inventory of radioactive waste requiring geological disposal and/or could alter the characteristics of the waste to facilitate easier management, they are highly unlikely to render a GDF wholly unnecessary. This is for two reasons:

- Alternative steps in long-term management only have the effect of reducing the quantity of radioactive waste, altering its character and/or altering disposal timescales; they do not reduce the inventory of long-lived radionuclides to zero and disposal of the remaining waste would still be necessary.
- The available alternatives to disposal in a GDF cannot practicably be applied to all components of the HAW inventory, even if used in combination and if additional management steps (for example, treatment or long-term storage) are also employed.

These points are reflected in the 2014 White Paper, which states [1]:

> *"At the moment, no credible alternatives have emerged that would accommodate all of the categories of waste in the inventory for disposal. In any realistic future scenario, some form of GDF will remain necessary" (Paragraph 2.35).*

---

7 A waste package is defined by RWM as "The product of conditioning that includes the wasteform and any container(s) and internal barriers (for example; absorbing materials and liner), as prepared in accordance with requirements for handling, transport, storage and/or disposal" [Nuclear Decommissioning Authority, 2012b. Geological Disposal: Generic Waste Package Specification, NDA Report No. NDA/RWMD/067, March 2012].

8 HEU is designated as HHGW in the Derived Inventory for the purposes of grouping wastes and materials that would be disposed of in the same area of a GDF and using similar packaging approaches. However, it does not actually generate significant heat.

9 Although the term Low Heat Generating Waste is used, the majority of the waste this term encompasses produces no detectable heat.

This review considers developments in the field of alternative waste management.

1.4 Review Methodology

The approach followed in this review has been to identify and record recent developments in alternative waste management options in four topic areas, the first two being alternative steps in long-term radioactive waste management, and the second two being alternative disposal routes to a GDF:

- Long-term interim storage
- Waste treatment techniques
- Near-surface disposal
- Deep borehole disposal

For each topic area, the following information is provided:

- An overview of the alternative waste management option
- A summary of the maturity of the alternative waste management option
- A description of the alternative waste management option
- Current practice and recent developments in the field
- Consideration of the components of the UK HAW inventory and associated nuclear materials to which the alternative waste management option could potentially be applied
- An indication of the potential impact that applying the option could have on the UK inventory of HAW and (where relevant) nuclear materials and/or on the inventory consigned to a GDF

1.5 Structure of this Report

The rest of this report has the following structure:

- Section 2 reviews options for long-term interim storage of radioactive waste, prior to disposal
- Section 3 reviews the range of treatment options available to reduce the quantity and/or alter the characteristics of HAW to facilitate easier disposal
- Section 4 reviews near-surface disposal approaches based on current and planned activities in the UK and overseas
- Section 5 reviews the status of activities in support of deep borehole disposal
- Section 6 provides a synthesis of the key developments in the field of alternative radioactive waste management options and their relevance for RWM, and identifies work areas that RWM envisage monitoring more closely in future

2 Long-term Interim Storage Options

2.1 Introduction

Storage may be considered to be a facilitating step within various waste management strategies that are applicable to either unconditioned or conditioned waste, in order to achieve the goal of safe management. The storage period may vary and can include:

- Short duration storage (for example, periods of up to months of buffer storage to facilitate process throughput)
- Interim storage in a robust engineered facility with a design life of typically 100 years [13]
- Extended storage for more than a century, pending some other management strategy, or geological disposal

Short duration storage, interim storage, and an element of extended storage are already implemented or planned as essential parts of current national strategy for HAW management. The exact duration of such storage varies from waste stream to waste stream, depending on the schedule for waste emplacement operations in a GDF – current scheduling assumptions are set out in RWM's generic disposal facility design report [14]. HAW packages are placed in engineered stores, mainly at waste producers' sites, with the intention that they will be moved to a GDF when the GDF emplacement schedule permits, currently assumed to start around 2040 for LHGW, with first emplacement of HHGW in about 2075 [14].

In this review, "long-term interim storage", as an alternative waste management step, is therefore considered to be any storage beyond currently assumed timescales. Long-term interim storage constitutes an alternative management step that can be employed as part of a waste management lifecycle ending with disposal, either in a GDF, or in some alternative facility (for example, a near-surface disposal facility). Scottish policy states "There will be a need to ensure that storage facilities are capable of managing the waste in the long-term. Long-term does not mean indefinite storage but it may mean waste is stored for many decades" [3; Paragraph 2.04.24].

This review focuses on recently published studies on approaches to long-term interim storage that could be implemented to increase the flexibility of, or develop other alternatives to, geological disposal.

Long-term interim storage is potentially applicable to a wide variety of wastes in both a conditioned and unconditioned state. The discussion below is sub-divided so that various distinct sub-options are considered separately. These include:

- Long-term interim storage of spent fuel (SF) and HLW, including cask storage
- Decay storage of ILW and specific approaches to decay storage of ILW, such as in situ storage (for example, SAFESTORE)

2.2 Review of Long-term Interim Storage of HLW/SF

ALTERNATIVE: Long-term interim storage of HLW/SF
Overview of alternative waste management option
Storage of spent nuclear fuel or HLW is a proven technology that has been employed at numerous sites worldwide since the earliest days of the nuclear industry. It is an essential part of the nuclear fuel cycle, allowing the fuel time to cool prior to reprocessing or

ALTERNATIVE: Long-term interim storage of HLW/SF
disposal. Historically, such storage was predominantly achieved by placing fuel assemblies under water in storage ponds, at the reactor sites and at reprocessing sites. Consequently, considerable knowledge has been accumulated on the behaviour of fuel and its cladding during wet storage. Storage ponds are typically 12 m or more deep, with the bottom 4 m or so containing racks designed to hold fuel assemblies removed from the reactor. Delays in national geological disposal programmes have raised interest in the feasibility of extending spent fuel storage for many more decades. The existing storage capacity in ponds is not always sufficient or appropriate for extended fuel storage, so to create extra capacity, dry cask storage has been developed as a method of storing spent fuel that has already been cooled in a pond for at least one year and often as much as ten years [15]. By removing the older fuel from the pond, capacity is made available for new fuel assemblies. Fuel removed from wet storage may need to be dried before being stored in dry casks. Casks are typically sealed steel cylinders that contain the fuel surrounded by inert gas. The steel cylinder provides leak-tight containment of the spent fuel, which is surrounded by additional steel, concrete, or other material to provide radiation shielding to workers and members of the public. There are various dry storage cask system designs. With some designs, the steel cylinders containing the fuel are placed vertically in a concrete vault; other designs orient the cylinders horizontally [15]. The concrete vaults provide the radiation shielding. Other cask designs orient the steel cylinder vertically on a concrete pad at a dry cask storage site and use both metal and concrete outer cylinders for radiation shielding. Dry cask storage is used widely in the USA and also in other countries. The UK has only just completed construction of its first dry cask storage facility at Sizewell B [16]. However, the broader use of dry cask storage is being investigated by the NDA [17]. A further approach is to use dry vault storage. This typically involves storage of spent fuel assemblies or HLW in tubes or some other framework (rather than shielded casks) within a shielded building employing a passive heat transfer system. Although this approach has not been as popular as wet storage for spent fuel, it has been applied using a variety of dry vault storage technologies in Canada, France, Hungary, US and at the Magnox Wylfa power station in the UK. Dry storage facilities generally remove decay heat by passive cooling and have low operating costs. They also provide the advantage of incremental storage capacity expansion by allowing additional capacity to be constructed on an as-needed basis. The majority of dry storage facilities have been constructed at reactor sites [18].
Current maturity of alternative waste management option
Spent fuel (under either wet or dry conditions), and HLW storage (under dry conditions), are mature technologies and established practice worldwide. Even so, work on long-term storage has increased markedly in recent years, as exemplified by the International Atomic Energy Agency (IAEA) conferences held on the topic in 2010 and 2015 [19,20]. A review and assessment of the status of dry storage was completed in 2010 by the United States Nuclear Waste Technical Review Board (NWTRB) [21]. This was a comprehensive review of all publicly available documentation and contains many relevant references to recent technical studies. The Board identified several issues that should be looked at: • Understanding the ultimate mechanical cladding behaviour and fuel-cladding degradation mechanisms potentially active during extended dry storage

ALTERNATIVE: Long-term interim storage of HLW/SF

- Understanding and modelling the time-dependent conditions that affect ageing and degradation processes
- Modelling of age-related degradation of metal canisters, casks, and internal components during extended dry storage
- Inspection and monitoring of fuel and dry storage systems to verify the actual conditions and degradation behaviour over time
- Verification of the predicted mechanical performance of fuel after extended dry storage during cask and container handling, normal transportation operations, fuel removal from casks and containers, off-normal occurrences, and accident events
- Design and demonstration of dry-transfer fuel systems for removing fuel from casks and canisters following extended dry storage

UK-specific studies have also been carried out. For example in 2014, RWM (then RWMD) published a feasibility study that examined options for long-term storage of spent fuel, with a particular emphasis on options to manage the higher burn-up proposed for spent fuel in new nuclear power stations [22]. The study considered pond storage, as well as vault-based and cask-based dry storage approaches. It examined the potential advantages and disadvantages of different management lifecycles, and the impact that they could have on the optimal approach to implement geological disposal of spent fuel (including disposal concept design, required cooling time and hence, timescales for disposal). The report concluded that the use of multi-purpose storage, transport and disposal containers could reduce the need for handling spent fuel assemblies and avoid concerns about handling aged spent fuel. The study also concluded that judicious mixing of long-cooled and short-cooled spent fuel in disposal containers could potentially enable the required storage period for cooling of spent fuel prior to disposal to be reduced from the order of 140 years to 60 years.

Some existing cask designs, including an overpack, can weigh in excess of 130 tonnes and could not be handled within any geological disposal concepts potentially available to RWM. Such proprietary designs will also place constraints on their ability to be transported on the UK rail infrastructure. Hence, further work is being undertaken to investigate smaller cask designs better suited for the UK rail infrastructure and proposed GDF handling systems.

Description of alternative waste management option

The options for storing spent fuel can be categorised as follows:

1. Pools at reactors – with expanded capability being achievable by re-racking.
2. Storage pools in a building or underground cavern away from the reactor.
3. Dry storage casks on pads stored either outside, in a conventional building or in a hardened or bunkered building.
4. Dry storage vaults, above or below ground.

Pool storage as in Option (1) is standard at most reactors. Many countries have re-racked their pools as it became clear that no spent fuel disposal or centralised storage option was available or that reprocessing would not be implemented. Away-from-reactor pool storage as in Option (2) has been implemented, for example in a 30 m deep cavern in Sweden. This facility has already been expanded since its original construction and will be further expanded in the future. Dry storage in casks on pads as per Option (3) is being carried out at numerous reactor sites in the USA and Canada. Dry casks are emplaced in centralised storage buildings in Germany and in Switzerland. Dry storage in vaults – Option (4) – is

ALTERNATIVE: Long-term interim storage of HLW/SF
practiced for spent fuel in the UK (at the Wylfa nuclear power plant), Hungary and the USA, and for HLW in the Netherlands – and also at the commercial reprocessing plants in France, the UK and Japan [23]. A combination of the options discussed above can also be used. New reactor operators in the UK will ensure that there is sufficient storage capacity at the reactor for the whole operational lifetime (usually proposed to be a combination of pond and dry storage casks, as is currently used at Sizewell B). The most recent national review of long-term HAW policy was undertaken in the USA by a presidentially appointed Blue Ribbon Commission [24,25]. One of the spent fuel management options considered was extended storage. The Commission noted that "…*experience shows that storage – either at or away from the sites where the waste was generated – can be implemented safely and cost-effectively. Indeed, a longer period of time in storage offers a number of benefits because it allows the spent fuel to cool while keeping options for future actions open*". The Commission recommended that efforts be made to develop one or more consolidated storage facilities and also to prepare for the eventual large-scale transport of spent nuclear fuel and HLW to the facilities. However, it also urged prompt efforts to develop geological disposal facilities and recommended that "…*a program to establish consolidated storage must be accompanied by a parallel disposal program that is effective, focused, and making discernible progress in the eyes of key stakeholders and the public*". The recommendation for centralised long-term storage of spent fuel, pending the availability of a GDF, backs up previous USA policy on this matter, and is based on the following kinds of consideration: • Increasing lack of space in current on-site stores (given delays in implementation of disposal); • Uncertainty about the timescale over which such stores will need be maintained; • A sense that it could potentially be better (for example, in terms of security, safety and efficiency) to store spent fuel at fewer, more modern facilities, rather than in aging facilities at many different sites around the country. Balancing such factors is the potential need for double transport of waste and the risks and concerns associated with transport operations.
Status of current practices / recent developments
Currently, the most active developments relate to dry casks. The recent rise in interest in dry storage has led to the production of new guidance from the IAEA [26,27]. The major reactor accident at Fukushima in 2011 has also led to renewed discussion on the safety of large pool stores at reactor sites and to increased pressure on utilities to move spent fuel away from reactor sites, or into dry cask storage. However, the latest regulatory guidance in the UK allows for both wet and dry storage [28]. The first dry store in the UK (at Sizewell B), was completed in 2016, and will use the Holtec HI-STORM technology, employing vertical-loaded, double-walled canisters inside a carbon steel and concrete composite overpack. This is also being used in Spain and in a large central storage facility under construction at Chernobyl in Ukraine [29]. Other cask types are also available with different capacities, materials (concrete or metal) and configurations

ALTERNATIVE:	Long-term interim storage of HLW/SF

(vertical or horizontal), as shown in Table 2.1.

Table 2.1: Dry storage cask types [30].

Cask Design	Developer
Ductile cast iron cask with forged stainless steel lids (CASTOR®)	GNS
Massive or composite forged metal (carbon steel / stainless steel) cask	ES, Holtec, MHI, NAC, TNI
Stainless steel, steel and concrete cask (CONSTOR®)	GNS
Forged stainless steel transport cask & concrete overpack	ES, Holtec, NAC
Forged carbon steel transport cask & simple metal overpack	TNI
Forged carbon steel transport cask & concrete module	TNI
Forged carbon steel cask	TNI

Over time, the capacity of dry cask designs, in terms of the number of spent fuel elements and the total heat output that can be accommodated, have both increased significantly. Higher burn-up of spent fuel and shorter cooling times are now pushing the need for thermal capacity of storage casks beyond 40 kW [31]. The main developments that can be expected in the future are in methods that improve the heat transfer from the centre of the casks/canisters. To optimise self-shielding (and thus reduce the cask wall thickness), it is better to place the highest burn-up, shortest cooled spent fuel assemblies in the central positions of the cask and lower burn-up, longer cooled spent fuel assemblies in peripheral positions. However, if this is done, the temperature of the central fuel assemblies can exceed the limits set to ensure the long-term stability of the spent fuel pin cladding material. For high-burn-up fuel assemblies, this leads to a requirement for longer cooling times, to reduce the spent fuel heat output, or to a lower loading of spent fuel assemblies in a cask.

Centralised interim storage of spent fuel underground (in casks) has been considered by RWM as part of a novel scenario for accelerating the implementation of the UK geological disposal programme [32]. Indicative timelines discussed in that work suggest that this approach could enable the start of spent fuel emplacement (initially in an underground centralised store) at the site of a GDF to be brought forward from the current baseline assumption of 2075 to as early as 2033.

By preceding disposal with a period of extended storage, the heat output from most HHGW would drop significantly, enabling closer spacing of waste packages in a GDF (depending on the disposal concept), whilst still respecting the maximum permitted temperatures, as specified in RWM’s disposal system specification [10].

In 2016 RWM published a study that was focussed on further developing the understanding of thermal constraints associated with the disposal of HHGW [33]. As part of this work the methodology to perform thermal dimensioning analysis was developed. This methodology supports the identification of the parameters (for example; container spacing, waste container loading and emplacement time) that have the greatest influence

ALTERNATIVE: Long-term interim storage of HLW/SF
on temperature constraints. In general it was found that the optimum strategy for not exceeding temperature limits in a GDF was likely to involve adjusting several design parameters, rather than a single parameter by a significant amount.
Applicability to management of UK inventory of HAW and nuclear materials
The implementation of longer storage periods for spent fuel and HLW would have a direct impact on the design and operation of a GDF and any associated encapsulation facilities. This is illustrated in the following factors: *Waste package temperature and radiation levels:* These reduce for longer storage times, which would potentially ease handling and allow closer packing in a GDF (subject to concept and constructability). However, unless the HLW / spent fuel is repackaged then the original packaging may have deteriorated, which could provide additional challenges for the operation of a GDF. *Wasteform behaviour:* Degradation of the fuel matrix or cladding, or of the vitrified HLW matrix during long-term storage could, depending on the storage conditions, affect the source term in operational safety assessments. *Waste package type:* The move towards cask storage could lead to a change in waste packages proposed for disposal at a GDF. At present, most dry cask designs are developed for spent fuel transport and storage, rather than disposal, so existing casks might not be suitable for disposal, and spent fuel could require repackaging. *GDF management:* The availability of alternative storage capacity for spent fuel/HLW could provide operational flexibility at a GDF. This would be particularly true for waste in stores nearing the end of their design life, where there would be a need to balance arguments about the potential need to renovate / replace a store versus optimising the schedule of disposals to a GDF. Increased flexibility in the timescales on which waste is consigned to a GDF could potentially reduce disposal costs, by reducing the throughput / emplacement rate at a GDF.
Potential impact on UK inventory of HAW and nuclear materials
The volume of spent fuel and HLW requiring disposal would not change following extended storage, although the activity and heat output would reduce with continued long-term storage. As noted earlier, a recent study by RWM found that it was found that the optimum strategy for managing heat in a GDF was likely to involve adjusting several design parameters, rather than a single parameter by a significant amount (such as storage period) [33]. The UK inventory for geological disposal has a wide diversity of characteristics [9] and the study also found that the variability between the different waste types is sufficiently substantial that concept, design, and scheduling solutions should be tailored to particular waste types [33]. For cask storage of spent fuel, a key issue is the size and weight. Some existing cask designs, including an overpack, can weigh in excess of 130 tonnes and could not be handled within any geological disposal concepts potentially available to RWM. Such proprietary designs will also place constraints on their ability to be transported on the UK rail infrastructure. Hence, further work is being undertaken to investigate smaller cask designs better suited for the UK rail infrastructure and proposed GDF handling systems.

2.3 Review of Decay Storage of ILW

ALTERNATIVE:	**Decay Storage of ILW**
Overview of alternative waste management option	
Decay storage is the process of storing the waste (either before or after conditioning / packaging) for tens of years, while the shorter-lived radionuclides decay.	
Current maturity of alternative waste management option	
Many sites across the NDA estate have adequate storage capacity to accommodate decay-stored wastes if this strategy were to be adopted more widely, although the infrastructure to handle alternative package types and provide shielding may need to be adapted. Recent developments in diverting LLW away from disposal at the LLW Repository in West Cumbria (LLWR) means that the LLWR has sufficient capacity for the known volume and radiological content of LLW for the foreseeable future [5]. There are opportunities to send short-lived solid ILW, currently expected to be disposed of in a GDF, to the LLWR. Although there may be benefits of diverting decay-stored waste from GDF disposal to the LLWR, diversion in the other direction may be equally beneficial and may act to free up further near-surface disposal capacity. For example, some small volume waste streams having a high inventory of particular radionuclides, for which the capacity is limited at the LLWR, may be better suited to GDF disposal.	
Description of alternative waste management option	
The baseline ILW conditioning and packaging strategies adopted at nuclear licensed sites in the UK are based on the assumption that waste currently designated as ILW in the UK Radioactive Waste Inventory (UKRWI) [34] will still be ILW at the time of packaging, and that it remains the intention to dispose of it in a GDF, or manage it in near-surface facilities in the case of Scotland. Similarly, in developing national waste management strategy it has been generally assumed that the packaged waste will remain ILW at the time of disposal, but, as the timescale for availability of a GDF remains uncertain, attention is being increasingly given at a national level to the implications of radioactive decay for waste classification and disposal strategy. Some wastes, particularly those in which the main radionuclide constituents are relatively short-lived (for example, with a half-life less than ~30 years), will undergo a significant decrease in radioactivity, so that they could potentially become amenable to near-surface disposal at some point within the next 300 years. In addition, the 2009 regulatory guidance on near-surface disposal of radioactive waste provides for consideration of disposal of shorter-lived or less radiotoxic ILW at near-surface facilities, even without a period of decay storage to LLW prior to disposal [35; Paragraph 3.4.1]. As noted above, Scottish policy on radioactive waste management calls for long-term management of HAW in near-surface facilities, located as near to the site where the waste is produced as possible, and considers that up to 300 years is an acceptable period for institutional control [3]. In this respect, decay storage involving management of waste in surface facilities for up to 300 years would be consistent with Scottish policy.	

ALTERNATIVE: Decay Storage of ILW

Figure 2.1: Hazard / risk reduction associated with Interim Safe Storage [36].

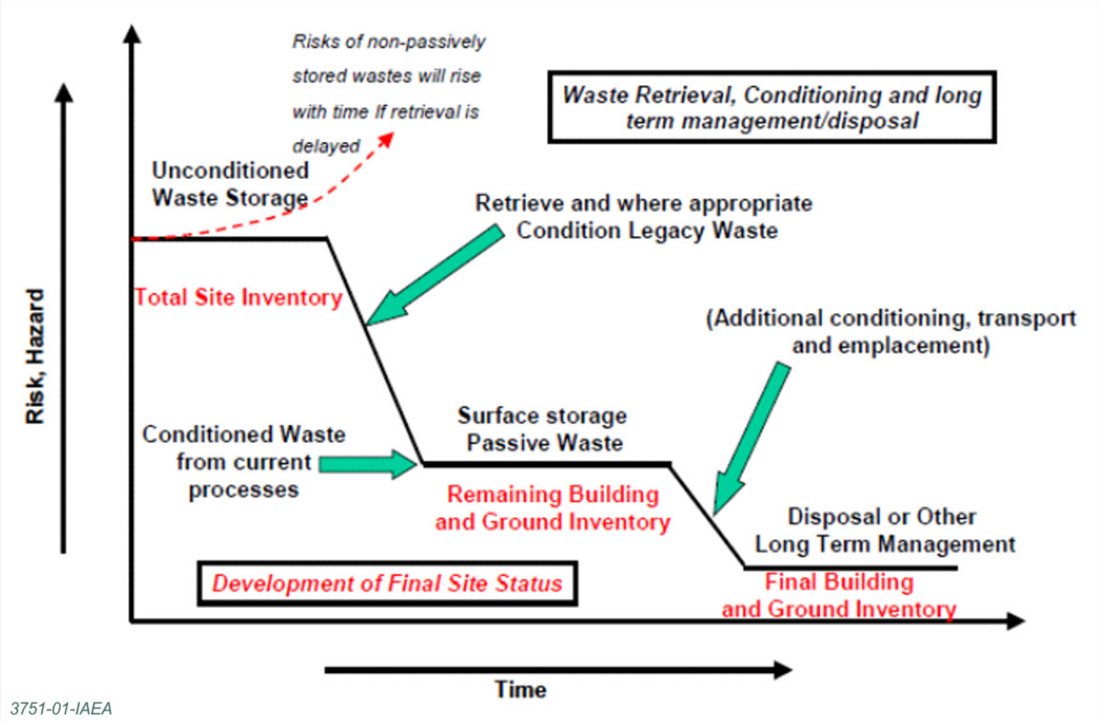


Figure 2.1 shows the hazard/risk levels associated with different phases of waste management. It is noted that handling operations associated with retrieval, conditioning, transport and emplacement of waste in a disposal facility would tend to increase hazards and/or risks (dose levels to workers) somewhat in the short term. This is not shown on Figure 2.1. Nevertheless, these operations would lead to much greater overall hazard and risk reductions in the longer term, as illustrated.

Extended *in situ* decay storage[10] of waste materials prior to conditioning and packaging, in order to allow activity to decay, is a feature of the Magnox SAFESTORE concept, in which shut down reactors are placed in a passive state and monitored and maintained for decades before dismantling and decommissioning is completed [5]. At the moment, this remains the baseline strategy for the fleet of Magnox reactors that are currently undergoing decommissioning with the dates for entry into Care and Maintenance currently ranging from 2019 to 2029. The SAFESTORE concept was implemented in 2010 for two Magnox reactors at the Berkeley site in the UK [37]. (The current baseline strategy may change, as a blanket strategy for all reactors in the Magnox fleet may not be appropriate. On behalf of the NDA, Magnox Limited are developing and evaluating credible options for the alternative timing of reactor dismantling, including assessing implications of the nuclear new build programme. They will focus first on those sites for which the benefits of early reactor dismantling are particularly evident, for example sites with a high land value or sites likely to yield the greatest learning for other sites [5]).

In situ storage seeks to take advantage of radioactive decay so that at the time of final site clearance, some 60-70 years into the future, the dose burden to workers will be

10 *In situ* decay storage refers to leaving the waste in place, rather than carrying out demolition, treatment and packaging of waste. With regard to Magnox decommissioning strategy it refers to leaving the reactor buildings and pressure vessels so that any radioactivity will decay in place until final site clearance.

ALTERNATIVE: Decay Storage of ILW
significantly reduced, primarily owing to decay of Co-60 (half-life of 5.27 years), which is a significant dose contributor in activated reactor pressure vessel and primary gas circuit steel. (The dose from any Cs-137 and Sr-90 in the waste would also be reduced by around a factor of 4). This approach is analogous to decay storage but does not involve placing the waste in packages and a dedicated store. It also does not involve any assumption that the wastes will be differently routed for disposal at the end of the SAFESTORE period – the baseline assumption is that ILW that has been subjected to SAFESTORE will go to a GDF for disposal. However, the possibility exists that, following the SAFESTORE period, such wastes could be diverted to near-surface disposal, and NDA-sponsored studies are underway to consider this opportunity in more detail. Work is also ongoing in the UK to evaluate the feasibility of extending *in situ* storage into *in situ* disposal for certain reactor building components, as part of further developing end state management strategies for UK nuclear licensed sites [38].
Status of current practices / recent developments
Initiatives are under way across the NDA estate to determine opportunities for management of boundary wastes. It is acknowledged in the NDA Strategy [5] that the boundary between different waste categories and associated routes needs careful management. Due to the nature of the wastes, geological disposal may be more appropriate for some LLW, while for some HAW (particularly those containing short-lived radionuclides), a more appropriate management route could be in a near-surface environment. The NDA will continue to sponsor studies investigating specific decay storage opportunities with the strategic aim of making best use of current and future assets [5]. For some waste streams (for example, the Ministry of Defence (MoD) resins held at Rosyth), benefit could potentially be gained through reclassification of ILW as LLW following decay storage of as little as a few years [39]. For others, many decades of decay storage would be needed to achieve the same result [40]. GE Healthcare currently uses decay storage on short (a few years) and long (several decades) timescales to manage some of its ILW and prepare it for eventual near-surface disposal. At the NDA's Magnox reactor sites, the baseline strategy is to defer reactor dismantling for around 85 years following shutdown. The NDA are currently questioning whether the baseline strategy is appropriate as a blanket strategy for all reactors in the Magnox fleet. On behalf of the NDA, Magnox Limited is developing and evaluating credible options for the alternative timing of reactor dismantling, including assessing implications of the nuclear new build programme [5]. Both Magnox and DSRL have considered decay storage of ILW as a management strategy for specific wastes streams. Magnox has previously advocated a decay storage strategy for its ILW desiccant but in 2013 this was changed to washing followed by incineration and disposal as low-activity waste (LAW), on the basis of an options appraisal [41]. The Chapelcross Magnox reactor site plans to store tritiated ILW in sealed containers (500-litre drums and Temporary Storage Vessel (TSV) overpacks) for 150 years until the waste can be disposed of as LLW [42]. DSRL has ~750 m^3 of tritiated steel ILW, mostly from the Prototype Fast Reactor (PFR). It is estimated that it will take 45 to 50 years for it to decay to LLW and DSRL proposes to decay store the waste in an unshielded ILW store, ungrouted, and subsequently dispose of it as LLW [43]. In addition, an integrated project team is considering opportunities for management of "problematic wastes" across the UK [5]. Problematic wastes are defined as wastes that are not suitable for treatment in existing processing plants, or plants currently planned at a detailed level [12]. Wastes can be considered problematic by virtue of their physical, chemical and/or radiological properties. It is possible that, for certain problematic HAW

ALTERNATIVE: Decay Storage of ILW
streams, decay storage may be identified as an appropriate management strategy, with resulting diversion of the waste to near-surface disposal.
Applicability to management of UK inventory of HAW and nuclear materials
An NDA strategic business case completed in 2014 presented credible options and evaluated the use of decay storage as a specific component of LLW/ILW boundary waste management, considering potential benefits to the NDA estate, and the case to change the current strategy and undertake coordinated activities [43]. The study recommended that decay storage management strategies should continue to be evaluated by waste producers at a tactical level, and considered for application to specific waste streams within each Radioactive Waste Management Case (RWMC) as it is developed. Decay storage management was also included as an approach in the NDA's recently issued guidance to industry on HAW storage [44].
Potential impact on UK inventory of HAW and nuclear materials
RWM recognises that there is uncertainty over the use of decay storage as part of future HAW management, and acknowledges that any changes in practice would affect the quantities reported in its Derived Inventory [9]. Uncertainties associated with the use of decay storage (and decontamination) are captured within the Derived Inventory: Alternative Scenarios report, as part of Scenario 12, which considers the potential impacts of excluding ILW / LLW boundary wastes that waste producers have identified as likely to be disposed of to LLWR [48]. Excluding these wastes results in a decrease of less than 1.2% in the ILW packaged volume 2013 Derived Inventory value [48]. Information from recent studies for RWM has helped to identify additional UK ILW waste streams that might be suitable for decay storage [40]. Based on the waste volumes currently in existence and scheduled to arise before 2113, wastes potentially amenable to decay storage have been estimated to comprise 38,070 m^3 or 13% of the 290,000 m^3 total ILW inventory by volume (based on the 2013 UKRWI and data from [40]). This volume includes 27,340 m^3 at Sellafield Limited, 8,640 m^3 at Magnox Limited, 1,500 m^3 at Dounreay, 370 m^3 at Harwell and 220 m^3 at the Culham Centre for Fusion Energy (CCFE) (that will in future be managed by Magnox at Harwell).

3 Higher Activity Waste Treatment Techniques

3.1 Introduction

A wide variety of treatment options is available for application to HAW as part of an optimised waste management lifecycle. Some of these have the potential to reduce the volume of waste that would subsequently require disposal. Some alter the characteristics of the wasteform to make it more amenable to safe long-term disposal, for example by altering its chemical form to one that is more long-lived, or by reducing its chemical reactivity and/or potential for gas generation. Altering the characteristics of the wasteform could help to facilitate re-routing of some HAW away from a GDF to near-surface or intermediate depth disposal facilities (see section 4).

Many treatment options are already implemented as part of current UK HAW management activities, in line with the NDA's HAW treatment framework [12], which considers waste encapsulation[11], thermal treatment, containerisation, decontamination, problematic wastes and decay storage. Some of these options can be regarded as already being part of the UK's baseline strategy for HAW management and are therefore not alternative treatment options, albeit the extent to which they will ultimately be employed across the UK inventory is currently uncertain. They are therefore not discussed in this review. Two such options include organic polymer encapsulation of ILW and decontamination techniques. Polymer encapsulation (as opposed to cement encapsulation, which is well-established) alters the characteristics of conditioned ILW, but does not significantly affect the conditioned waste volume requiring disposal, nor does it alter the required disposal route[12]. In contrast, application of decontamination techniques to HAW could enable concentration of much of the associated radioactivity into a relatively small volume, allowing the bulk of the waste volume to be diverted away from a GDF to near-surface disposal, re-use or even free release, in keeping with the waste management hierarchy. Both of these options have been the subject of recent studies to consider their applicability in a UK context [45,46].

The treatment options that are considered in this review have therefore been limited to three groups of options that are not already employed as part of UK HAW management (and can therefore be regarded as alternative treatment steps):

- Thermal treatment techniques, including joule-heated melting and vitrification, plasma melting and vitrification, and hot isostatic pressing (HIP).
- Enhanced cementitious grout encapsulation options that are applicable for some problematic wastes, (for example, alternatives to conventional formulations based on Ordinary Portland Cement).
- Partitioning and transmutation.

Associated discussion is captured in Sections 3.2, 3.3 and 3.4 respectively. Other potential treatment options targeted at specific wastes (for example, biological degradation of graphite) have been identified, but at present are at a very early stage of development, so are not considered in this review [47; Section 5].

RWM recognises that there is uncertainty over the choice of treatment and conditioning options that may be employed as part of future HAW management, and acknowledges that any changes in practice would affect the quantities reported in its Derived Inventory [9]. Uncertainties associated with the selection of different treatment and encapsulation

---

[11] Strictly speaking, encapsulation is a conditioning technique, not a treatment technique.
[12] The main driver for using organic polymer encapsulants is to employ them to condition waste streams that are not suitable for cement encapsulation, including wastes that contain significant quantities of reactive metals, radium-bearing wastes, and filters whose physical properties make adequate infiltration by a cement encapsulant difficult.

techniques are captured within the Derived Inventory: Alternative Scenarios report, as part of Scenario 10, which considers the potential impacts of alternative waste packaging assumptions [48].

3.2 Review of Thermal Treatment Techniques

This section considers emerging / developing thermal treatment techniques that have the potential to improve UK HAW management strategy. It focuses on the thermal treatment techniques that are actively being pursued in the UK. In the UK, work on thermal treatment has centred largely around vitrification, with various technology demonstrations funded by Sellafield Ltd. These include plasma-heated and joule-heated systems, the latter of which can be further subdivided into in-container vitrification (ICV), an example of which is the GeoMelt® system, and continuous vitrification, as in the Energy Solutions' joule-heated ceramic melter system intended for use at Hanford. A further, non vitrification, thermal treatment option is HIP, as developed for radioactive waste immobilisation by the Australian Nuclear Science and Technology Organisation (ANSTO), in which the waste is consolidated by the simultaneous application of heat and pressure. Each of these techniques is discussed under a separate sub heading below. It should be noted however, that a much broader suite of thermal treatment techniques is available and could potentially be applied as part of UK HAW management, including:

- Incineration, for example the SHIVA incineration process developed by CEA/AREVA in France.
- Other melting techniques, for example, cold crucible melting, as implemented for HLW vitrification at La Hague in France.
- Pyrolysis / steam reformation (for example, as developed by Studsvik and implemented in Sweden and the USA for the treatment of operational wastes).
- Gasification, gas conditioning and flue gas cleaning processes (for example, as developed by VTT in Finland, and as considered for application to graphite wastes [47]).

Vitrification of highly active liquid from spent fuel reprocessing to convert it into HLW is not discussed, since this is an established process that underpins the baseline inventory of UK radioactive wastes and is therefore not an alternative treatment option. For the same reason, the techniques considered here are those that show promise for application to HAW inventory components where there is no existing thermal treatment solution in use (hence, the exclusion of cold crucible melting, which is primarily relevant for HLW).

The NDA recognised in its HAW treatment framework [12] that recent thermal treatment initiatives are fragmented, and are being taken forward by different organisations to address differing requirements. They have considered a variety of technologies, which have been directed at treating a range of waste types. Some good progress has been made, but the impacts of this innovative technology have so far been limited. The NDA believes this can be addressed through greater overall coordination. It has assessed the requirements for a thermal treatment capability in the UK and concluded that there is a business case for the development of such a capability for treating ILW and other radioactive materials as appropriate. With this in mind, it has established an integrated project team (IPT) to enable the development of thermal treatment capability [5]. To facilitate Site Licence Company (SLC) delivery, and to complement future R&D, the NDA thermal IPT is being delivered by Sellafield Ltd, on behalf of the NDA (with representation from the National Nuclear Laboratory (NNL), SLCs, RWM, MoD and AWE). The aim is to establish a demonstration facility on the Sellafield site, regarded as a necessary enabler to the development of an operational full-scale thermal treatment capability.

ALTERNATIVE:	**Thermal Treatment Techniques**

Overview of alternative waste management option

Thermal treatment techniques involve the application of heat / energy to waste in order to produce a product suitable for ongoing storage and ultimately disposal. A range of thermal treatment technologies exist, each of which has particular features. Broadly however, they all offer similar overarching benefits and drawbacks. Potential benefits include [49]:

- *Volume reduction / increased waste loading*: The waste volume can be reduced relative to raw waste by removal of water, thermal degradation, oxidation of bulky organic wastes such as plutonium-contaminated material, and by melting waste components which can then fill void spaces. Furthermore, the mineralogy of the product can potentially be formulated so that the waste itself is an intimate part of the immobilising matrix. For example, the open structure of inorganic ion exchangers can be collapsed into a higher density mineral with little or no addition of other materials. The reduction in waste volume could facilitate an increase in waste package loading of thermally treated waste. This is potentially the most significant benefit of thermal treatment, since it would reduce the operational lifetime of the treatment / packaging plant as well as the number of waste packages requiring storage, transport and disposal. RWM has estimated that the use of thermal treatment techniques could result in decreases of up to ~5% in the packaged volume and ~8% in the number of disposal units [49].
- *Removal or reduction of reactivity in the product:* The product resulting from treatment at high temperatures would be relatively refractory and inert, through a combination of having oxidised during processing and/or having melted, which reduces the available surface area for subsequent reaction. This can enhance the disposability of the waste, by reducing the potential for detrimental interactions with other wastes / disposal system components. The resulting product typically has a relatively high durability and has a reduced potential for gas generation (since many gas-generating precursors will have reacted during treatment). The robust nature of the wasteform could potentially facilitate consideration of alternative disposal strategies for wastes at the boundary between ILW and LLW, by providing enhanced confidence in the long-term safety of waste diverted from a GDF to surface / near-surface disposal. This could be of particular relevance with regard to Scotland's policy of near-surface management of its HAW, but is also more widely relevant in the UK.
- *Destruction of organic material:* There are several advantages from the destruction of organic waste components prior to disposal. Soluble degradation products of materials such as cellulose have the potential to increase solubility of actinides in a GDF. Non-aqueous phase liquids, which could otherwise facilitate transport of a range of species away from a GDF would also be removed.

On the other hand several challenges need to be overcome through the development of the technology against specific waste feeds.

- *Radioelement volatility*: Tritium, carbon-14 and iodine-129 are difficult to contain during treatment unless closed system techniques such as HIP are used, and could result in secondary wastes, which would also require management and disposal. The extent of the challenge for other radioelements will depend on the operating temperature and on process-specific factors affecting the kinetics. For instance, reports of the fraction of caesium which is volatilised during vitrification vary from as low as 1% to over 30% [50,51,52]. (Incorporating volatile elements into the glass/ceramic matrix would be expected to improve the long-term safety of the

ALTERNATIVE: Thermal Treatment Techniques

waste - see *removal or reduction of reactivity in the product* above).

- *Process complexity:* Operation at high temperature introduces additional process complexity, so that innovative approaches are required to minimise in-cell components requiring maintenance.
- *Waste and waste product heterogeneity*: Complete reaction of the waste and incorporation of all waste components may not take place, particularly if the raw waste is heterogeneous and/or poorly characterised (as could be the case for legacy wastes managed via this technique).
- *Development of process envelopes:* With the exception of HLW vitrification at the Sellafield waste vitrification plant, there has not yet been sufficiently extensive R&D support to allow the development of process envelopes for thermal processes. This introduces a significant need for development of in-line process control, for instance for the measurement of temperature, mixing, composition and off-gas analysis.
- *Development of formulation envelopes:* The requirement to establish an acceptable compositional range for the waste product introduces a need for significant R&D on each candidate waste stream and for monitoring waste composition and controlling the formulation of additives. Formulation envelopes define an acceptable range and require compromise in waste loading. The claims for high waste loadings for thermal treatment processes therefore need to take account of these issues.
- *Control of fissile material and criticality safety:* A side effect of the good volume reduction / waste loading achievable via thermal treatment techniques is that they can lead to the concentration of fissile material, which could potentially have implications for criticality safety. Waste loading therefore needs to take account of safe fissile masses, not just the maximum loading that is technically achievable.
- *Wasteform compatibility with GDF disposal system:* There are potential issues with the compatibility of vitrified or partially vitrified wasteforms with the cementitious backfill employed within the reference disposal concepts for LHGW in a GDF [53]. Widespread implementation of thermal treatment could therefore require adoption of a revised disposal concept for some LHGW, possibly including separation of this waste from cement-encapsulated ILW to avoid the potential for detrimental interactions.

Continuous thermal treatment techniques tend to have a higher process throughput. However, techniques that involve batch processing provide for improved material inventory accountancy and criticality control.

To facilitate the evaluation of thermal treatment technologies an NDA-led IPT including Sellafield and NNL has been formed with the aim of demonstrating appropriate thermal treatment options for the immobilisation of UK radioactive wastes with the emphasis on the processing a range of feeds from doped surrogates to real wastes. The IPT is following a waste-led approach where technologies will be assessed against the properties of specific waste streams with the identification of suitable technologies. Choices will be made as to which technologies merit installation and exploitation at active pilot scale in NNL's rig hall facility in its Central Laboratory. The aim is to deliver technologies to the point at which they will be suitable for consideration in the design and build of full-scale plants by waste plant operators at Sellafield and across the UK.

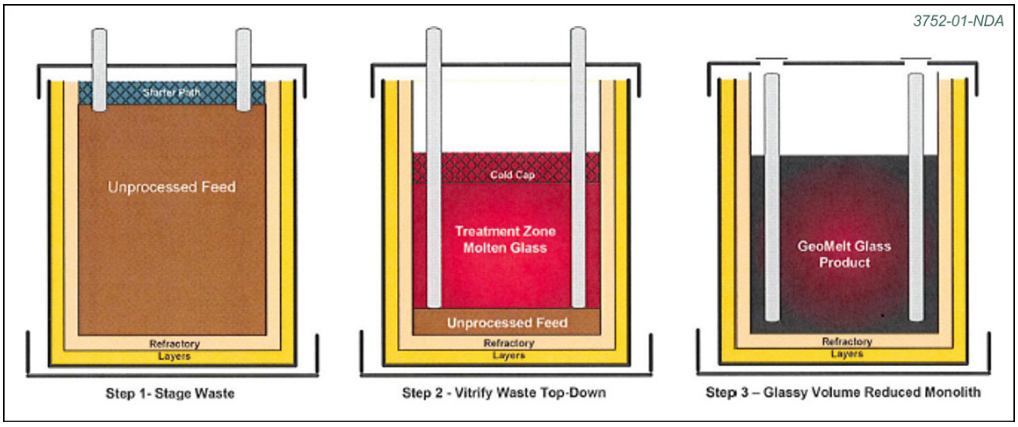
ALTERNATIVE: **Thermal Treatment Techniques**
Current maturity of alternative waste management option
The assessment of maturity of thermal treatment techniques is difficult to summarise as the maturity needs to be assessed for a combination of waste feeds and treatment technology. All the technologies mentioned have been demonstrated inactively. HIP technology has been demonstrated at laboratory scale within the UK. The ICV in NNL's Central Laboratory has undertaken active trials at the 500 kg scale on low active contaminated soils. Further trials are planned progressing from low active wastes with the potential to process ILW and alpha wastes with engineering modifications to provide containment and minimise dose. The system has also been considered for treating active asbestos in the UK [54]. The ICV facility is available for understanding the behaviour of radioactive species during vitrification and building up an understanding of the challenges which could be faced during the implementation of such a technology at full scale. Plasma treatment is an industrially-established technique used to treat ILW (for example, in Switzerland). In the UK, it has not yet become established industry practice, but several demonstrations on UK wastes have been carried out. A similar level of technical maturity applies to continuous joule-heated melter technologies, which have been successfully applied to treat radioactive waste in the USA, Germany and Belgium.
Description of alternative waste management option

<u>Joule-heated In-container Vitrification</u>

Joule-heated thermal treatment vitrifies hazardous and radioactive waste within a ceramic container (termed In-Container Vitrification, or ICV). The process gives rise to a stable and inert glass product.

The waste and glass formers are loaded into a cast refractory box (CRB) as in Figure 3.1 with a conductive "starter path" laid across the top. In the case of high throughput, International Standards Organisation (ISO) freight containers can be lined with refractory material and used. The melt is started by providing electrical power (via a number of graphite electrodes) across the starter path. The flow of current across the starter path creates heat, melting the material surrounding it. The electrical resistance of the molten material reduces, allowing it to support the flow of electrical current to sustain and continue the melting process. As the melt progresses (typically at temperatures of 1000-1800°C [51]) the electrodes are lowered further into the melt to allow the full contents of the CRB to melt.

Figure 3.1: ICV staged arrangement [51].



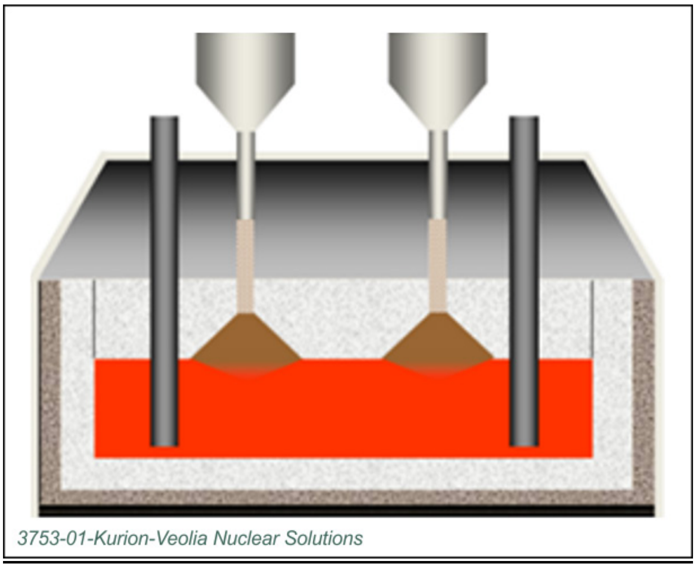
ALTERNATIVE: Thermal Treatment Techniques

Since the volume of material in the CRB will decrease as the melt progresses, a feed-while-melt system can be used to allow additional waste to be added to the melter while the melt is progressing (see Figure 3.2) thereby ensuring a full CRB of treated waste is produced. After the power is turned off the molten material cools, producing a durable glass monolith which immobilises radionuclides, heavy metals and any other non-volatiles. Small quantities of secondary wastes generated within the off-gas system (for example, particulate captured on filters) can be used as a feed in the next melt.

ICV provides a significant volume reduction (up to 80% for certain waste streams [55]) and co-immobilisation of wastes (due to certain wastes having excellent glass-forming properties). A further benefit of ICV is that no pouring of glass is required (unlike continuous joule-heated melting).

In terms of drawbacks, tritium, I-129 and C-14 are difficult to contain in the wasteform; they are however contained within the off-gas system described above. Improved retention of radionuclides is possible through optimisation of the operating temperature and use of glass-forming additives. ICV could be used to treat a wide range of LLW and ILW, including those which are particularly difficult to find a treatment for, such as asbestos-contaminated radioactive wastes [55] and other orphan wastes.

Figure 3.2: Illustration of the “feed while melt” System (from Kurion – Veolia Nuclear Solutions).



Continuous Joule-heated Melters

The joule-heated system is probably the most ubiquitous of melter systems and has been successfully operated on United States Department of Energy (DOE) sites for the vitrification of military wastes, as well as in Germany, Belgium and Russia [49]. It is also being developed for use at the Hanford site in treating both high activity and low activity waste streams.

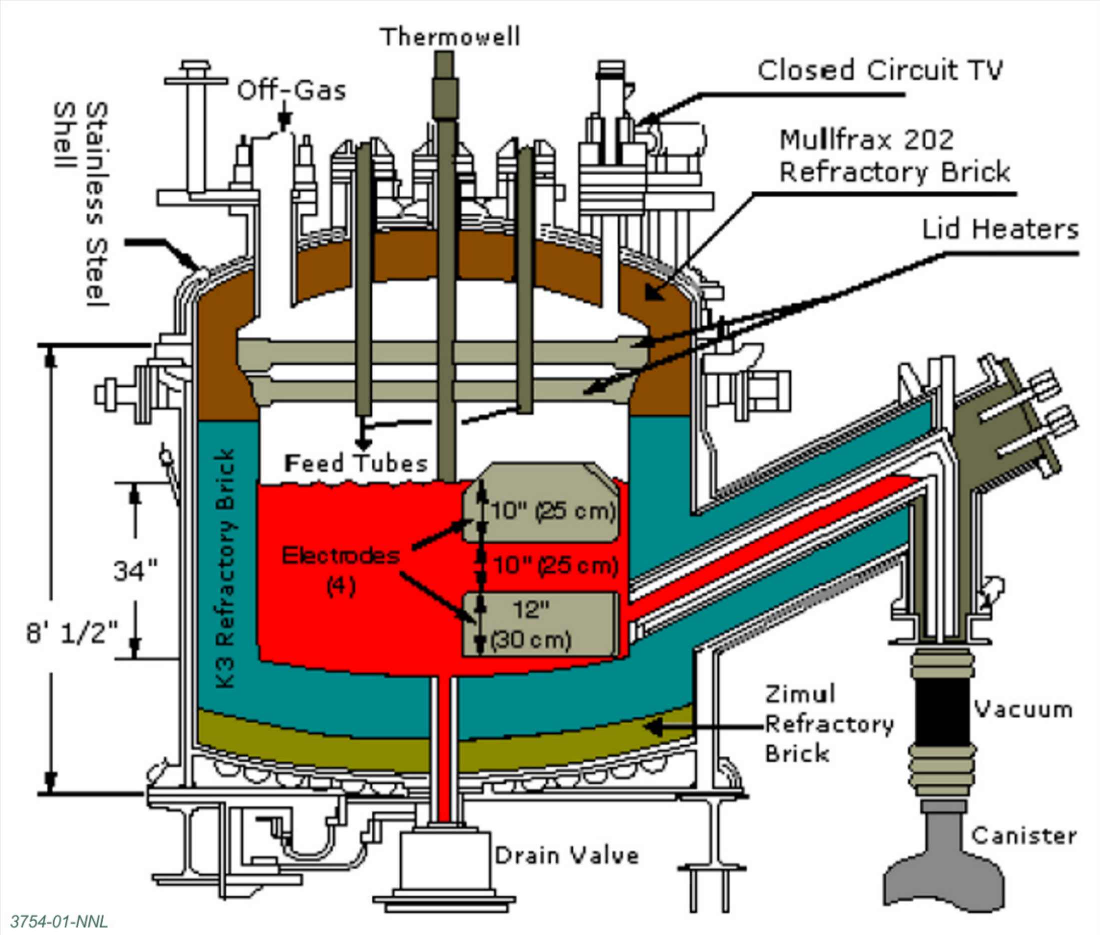
A typical example of a joule-heated ceramic melter is shown in Figure 3.3. The glass pool is heated by submerged electrodes. The waste and frit feeds are fed through the roof of the melter and bubblers can be used to augment mixing in the melter thus promoting reaction between feed and frit and contributing to a homogenous final product.

The main technical challenge specific to continuous-pour joule-heating systems is the pouring system. High levels of noble metals can block bottom pouring systems. Airlift systems can mitigate this but have complexities of their own. Failure to remove noble

ALTERNATIVE: Thermal Treatment Techniques

metals from the system can result in build-up and potential shorting of the melter and reduced energy transfer to the melt. Bubbling systems are often used to enhance mixing and to prevent noble metals build up.

Figure 3.3: Schematic cross-section of a joule-heated ceramic melter [49].



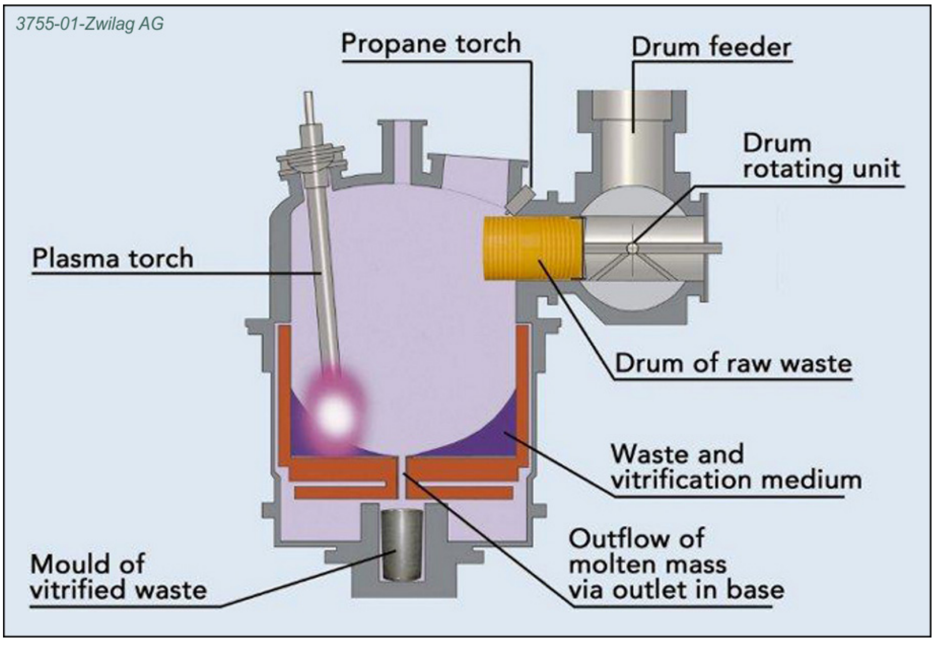
Plasma Melting

Plasma treatment systems have been deployed worldwide for the treatment of radioactive wastes (as well as being used extensively to treat municipal waste, with the benefit of not only passivating the hazardous materials, but also using the off-gas to produce electricity). The Zwilag plasma melter in Switzerland is an example of a plasma melting system which has been operating for a number of years for the treatment of LLW drums [49]. In the UK development has been carried out by Tetronics and Costain with earlier involvement of the NNL [56].

Plasma systems can be operated in either transferred (electrode to melt pool) or non-transferred (electrode to electrode) arc modes and can be designed to be batch or continuous operations. High temperatures are deployed in which organics are destroyed and wastes homogenised forming vitreous products such as glasses or slags with the addition of appropriate glass formers. A typical plasma melter set-up is shown in Figure 3.4. In this system, a water-cooled reaction chamber is used along with a transferred arc. As with other thermal treatment systems an off gas system is deployed to manage any volatiles that are given off. Frequently these can be reintroduced back into the plasma system.

ALTERNATIVE: Thermal Treatment Techniques

Figure 3.4: Plasma melter set-up (© Zwilag AG).



Hot Isostatic Pressing

HIP provides for consolidation of waste by the simultaneous application of elevated temperature and pressure [57]. The waste to be consolidated is contained in a specially designed stainless steel can, which is hermetically sealed. Specific advantages of HIP are:

- HIP is largely insensitive to the physical, electrical and thermal properties of the wasteform.
- HIP has been demonstrated at an operational level for radioactive wastes immobilised in glass ceramics.
- The consolidation process is totally contained, and therefore generates minimal secondary wastes, with no potential for volatile losses – these are incorporated into the waste matrix.
- The process is scale independent.

One specific disadvantage is the requirement for a certain degree of pre-processing to ensure the waste stream is compatible with the HIP process.

HIP has been demonstrated for the immobilisation of simulated plutonium residues on the Sellafield site, and is currently being developed for consolidation of Magnox sludge and immobilisation of surplus separated plutonium. It is applicable to other waste streams, for example clinoptilolite and other ion exchange materials. In the USA, HIP has been selected for the immobilisation of the Idaho calcines, and in Australia HIP is to be used for the immobilisation of waste from medical isotope production at the ANSTO.

The initial requirement is pre-treatment of the waste to ensure compatibility with HIP. If the waste is wet it will require drying, and potentially a higher temperature calcination stage. A small amount of additive may be required to assist the consolidation process, but depending on the waste stream, waste loadings (for ILW) can be close to 100%.

ALTERNATIVE: Thermal Treatment Techniques
The processed waste is then fed into a HIP can, which is designed to collapse into a regular cylinder. A pilot-scale HIP can is shown in Figure 3.5. In this example, the initial can is 28 cm high by 20 cm diameter and the final can is 20 cm high by 16 cm diameter. The HIP can enters the process with both end caps welded in position, and the can is filled through a 25 mm diameter tube, on which the final closure seal is made. The proposed batch size for the Idaho calcines is 900 kg which requires a HIP can 70 cm diameter by 150 cm high. Following consolidation the HIP can is suitable for storage and disposal. Over-packing may be required to facilitate subsequent handling operations.

Figure 3.5: Example of a HIP can before (right) and after (left) the HIP run [57].
The pre consolidation can on the right is approximately 30 cm high and 20 cm in diameter.

Status of current practices / recent developments
Joule-heated In-container Vitrification Kurion has teamed up with the NNL to install an ICV system in the Central Laboratory at Sellafield. This technology has previously been demonstrated on a range of Sellafield Ltd inactive surrogate wastes representative of Magnox sludge, plutonium-contaminated material (PCM), sand and clinoptilolite from the Sellafield Ion Exchange Effluent Plant (SIXEP), and ILW in skips [51]. The system has more recently been prepared for nuclear operations at NNL's Workington facility, including an inactive commissioning trial followed by an inactive soil melt. With the Workington activities complete the rig has now been installed in the NNL Central Laboratory [58] where an active melt has already taken place with a further active melt planned for demonstrating the vitrification of active soils and the potential for their vitrification with simulated ILW. The off-gas system being used for these trials also has the capacity to be used with larger-sized containers.

ALTERNATIVE: Thermal Treatment Techniques
<u>Continuous Joule-heated Melters</u> Sellafield Ltd engaged Energy Solutions to carry out a demonstration of the technology for the immobilisation of “pumpable” wastes [50]. Successful trials were carried out for the vitrification of separate feeds of sand/clinoptilolite and Magnox sludge. Glasses were formulated at crucible scale and pilot scale trials carried out giving product with 35 wt% waste loading in the case of Magnox sludge and 70 wt% waste loading in the case of sand/clinoptilolite. Performance data were obtained for the treatment of over 370 kg of wastes feed and the parameters obtained have allowed the vendors to demonstrate proof of concept. <u>Plasma Treatment</u> Plasma treatment has been developed for application to radioactive wastes at various locations worldwide. The Zwilag facility in Switzerland has been operating for a number of years in the processing of LLW in Switzerland and a European funded project is currently underway led by Belgoprocess, which is aimed at the installation of a facility in Bulgaria for the treatment of solid wastes [59]. In the UK, Tetronics with British Nuclear Fuels Ltd (BNFL) demonstrated the potential of using plasma techniques for the treatment of PCM [56]. This has been followed by the demonstration of plasma for the treatment of a range of ILW by Tetronics / Costain funded by an Innovate UK grant and through a demonstration for Sellafield Ltd. <u>Hot Isostatic Pressing</u> For the plutonium residues programme, the plan was for a glovebox-scale process for the immobilisation of approximately 500 kg of plutonium residues. Development was halted due to escalating programme costs, but could be taken forward in future. However the technology is being further explored as an option for the immobilisation of the UK separated plutonium stockpile under an NDA-funded programme which provides for active demonstration of the technology at the laboratory scale using UK plutonium oxide feeds. Within the UK, Georoc Ltd has demonstrated HIP at the 100 kg scale with non-integrated processing, and a demonstration pilot plant is being designed. An NDA-funded programme of work is intended to further develop the pilot plant for plutonium immobilisation by 2020. At ANSTO, the process has been demonstrated inactively at the required scale and a fully active plant is being designed with intent to build and commission it over the next two years. Recent progress with the Idaho calcines has been limited due to contractual issues, but HIP still remains a credible option. It is planned for all processed calcine to be ready for off-site transport by the end of 2035.
Applicability to management of UK inventory of HAW and nuclear materials
Over the past decade Sellafield Ltd has engaged providers of thermal treatment technologies with the aim of assessing the suitability of such technologies to the immobilisation of ILW on the Sellafield site. Kurion, Energy Solutions, Costain / Tetronics and Georoc Ltd have shown by practical demonstration that such technologies can process a range of wastes, including sludges, ion exchangers, PCM and decommissioning wastes into an immobilised form suitable for ongoing storage and disposal. Based on these trials the technology owners have provided conceptual designs showing how such a full-scale plant could be designed to treat examples of Sellafield Ltd waste streams. HIP has also been demonstrated for the immobilisation of simulants of plutonium residues

ALTERNATIVE: Thermal Treatment Techniques
stored on the Sellafield site and is now the basis of a programme of work funded by the NDA and carried out by NNL to demonstrate the feasibility of the immobilisation of the UK plutonium stockpile through active trials. HIP could provide an alternative management route for separated plutonium to the currently preferred option of reuse in MOX, CANDU or PRISM reactors [60].
Potential impact on UK inventory of HAW and nuclear materials
Thermal treatment systems have the potential to destroy organics, remove water, passivate reactive metals and greatly reduce the reactivity of the wasteform to be disposed, as well as significantly reducing the volume of packaged waste. The degree of volume reduction possible will depend on the extent to which thermal treatment is applied, as well as the characteristics of the individual waste streams treated in this way. By taking advantage of the good glass-forming properties of some wastes, co-immobilisation is possible, thus providing an even greater level of volume reduction over that already given through thermal treatment (by minimising the need to add glass formers or other conditioning agents). While these technologies have only been demonstrated for Sellafield Ltd wastes at pilot scale, concept designs offered by technology providers suggest that the processing of the volumes ILW required by the NDA estate are well within the capabilities of these melter systems. Each of the systems evaluated has strengths and weaknesses, with some more suitable for the treatment of large volumes of relatively homogenous wastes, and others more applicable to the batch treatment of more heterogeneous streams which may be expected from decommissioning activities. A number of thermal treatment technologies could play a role alongside encapsulation as part of the broader toolkit available to waste producers.

3.3 Review of Enhanced Encapsulation

ALTERNATIVE: Enhanced Encapsulation
Overview of alternative waste management option
The use of a standard cement powder (CEM-I) blended with either ground granulated blast-furnace slag (GGBS) or pulverised fuel ash (PFA) is the baseline technology in the UK for the encapsulation of LLW and ILW [61]. This approach has been used at the four operating encapsulation plants at Sellafield: • Magnox Encapsulation Plant (MEP) • Wastes Encapsulation Plant (WEP) • Waste Packaging and Encapsulation Plant • Waste Treatment Complex However for some problematic waste streams, notably reactive metals, these conventional grouts may not be the optimum solution; therefore, alternative enhanced grouting options may be required. This is an area that has been investigated by both the academic and technical communities in the UK, France and the USA in particular. The use of alternative "enhanced" grouts could allow existing encapsulation plants to treat

ALTERNATIVE: Enhanced Encapsulation
a wider range of wastes, using existing infrastructure, although development work would be required in order to increase the maturity of associated processes to an operational level. Further consideration of the use of alternative encapsulants to treat a broader range of HAW is planned as part of the NDA's HAW treatment framework [12]. Alternative encapsulants might also come to replace CEM-I -based cementitious grouts in the event of future shortages of GGBS or PFA, which originate from iron smelting and coal-fired power stations.
Current maturity of alternative waste management option
The physical and chemical properties of alternative enhanced cements have been assessed, principally at laboratory scale. Extensive further development work would be required to provide the data on longer-term behaviour required to demonstrate disposability of the encapsulation products and the engineering and plant data for operations. As with all alternative processing routes, this would involve a systematic development programme, comparable to the Product Evaluation Programmes that underpinned the development, design, commissioning and operation of the existing encapsulation plants.
Description of alternative waste management option
A number of alternative grouts have been investigated, typically at a small scale [62,63]. Specific grouts which have been assessed for radioactive waste encapsulation include: • Magnesium phosphate and calcium aluminate phosphate cements. • Calcium sulfoaluminate cements. • Calcium aluminate cements (also known as high alumina cements). • Geopolymers (inorganic materials that form long-range amorphous networks). These formulations could all be back-fitted into existing encapsulation plants with minimal modification to the processes. It should be noted that, as with the existing CEM-I -based processes, all of the alternative enhanced materials would require blending with filler materials such as GGBS or PFA in order to provide the properties required. These are mature formulations for use in the non-nuclear construction industry [64], with proven track records. However, they have not been applied for the encapsulation of radioactive waste in the UK.
Status of current practices / recent developments
Alternative enhanced grout development work has been performed by a number of countries, including the US, UK and France, to assess process development and the properties of the wasteforms produced. However, all of the work to date has been at small scale. Much of the development work has been targeted at their use for waste streams containing borates and zinc [65,66], which are known to retard conventional cement systems, but which the alternative cements are more tolerant of, allowing greater waste loadings to be achieved. The full range of alternative enhanced encapsulants has also been investigated in an IAEA coordinated research project [67]. Because of the lower pH of these cement systems [68], they are also applicable to the encapsulation of wastes such as aluminium cladding, whose corrosion rate increases at higher-pH values.

ALTERNATIVE: **Enhanced Encapsulation**
Applicability to management of UK inventory of HAW and nuclear materials
Alternative, enhanced cement encapsulants have applicability to some of the low-volume orphan wastes that may contain chemical constituents which retard the setting and strength development in conventional cements. The lower pH of these cement systems means that they may offer advantages for the treatment of aluminium-bearing waste streams, although it is noted that these are typically mixed-component waste streams, which will also contain Magnox, whose corrosion rate may be increased at a lower pH. An issue that would need to be considered is whether the addition of low-calcium, low-pH materials adversely affects RWM's generic long-term safety case for a GDF and, in particular, the dissolution rates associated with the high-pH backfill materials that may be used in the ILW disposal vaults.
Potential impact on UK inventory of HAW and nuclear materials
The use of this option may allow waste streams that are currently regarded as problematic due to their chemical composition to be conditioned using grout encapsulation technology. It may also allow higher waste loadings to be achieved, compared to the use of conventional grouting systems, but further development work would be required to assess this. However, given the relatively limited range of waste streams to which enhanced grouts might be applied to realise a benefit, and the fact that conditioning factors would be broadly comparable to those for conventional CEM-I -based grouts, it is not considered that they could significantly alter the volume of waste being consigned to a GDF. As reprocessing operations on the Sellafield site come to an end for the Thermal Oxide Reprocessing Plant (THORP) in 2018 and the Magnox reprocessing plant in 2020, the two encapsulation plants that process the ILW arising from reprocessing (WEP and MEP respectively) will be seeking new missions. One option would be the repurposing of these plants to allow them to treat other waste streams, potentially including problematic waste streams, using the alternative enhanced encapsulants. Because these plants are configured for the use of cementitious materials already, switching to the alternate cements could be a viable option, with minimal changes to plant processes. Clearly this decision would need to consider all aspects of the processing of other feed streams, most notably the import routes for the waste into each plant. It is noted that the use of enhanced encapsulants in new, and perhaps modular, treatment units might offer the advantage of a lower cost treatment route for smaller volumes of waste, which would otherwise require the development of tailored treatment processes. The use of alternative encapsulants would require assessment by RWM through its disposability assessment process to determine how these cements and their hydration products would interact with other materials in a GDF, in order to confirm their compatibility with the rest of the disposal system.

3.4 Review of Partitioning and Transmutation

ALTERNATIVE: Partitioning and Transmutation
Overview of alternative waste management option
P&T is a set of technologies that was originally suggested as an option to reduce long-lived actinides and fission products to stable isotopes. The concept of P&T is based on a combination of chemical engineering techniques that are used to partition (separate-out) long-lived nuclides from irradiated nuclear fuel and a source of neutrons, which is used to transmute (convert) these to shorter-lived and stable isotopes. The feasibility of this technology has not been demonstrated on an industrial scale and is only potentially applicable to a small number of radionuclides in spent fuel as part of a closed fuel cycle. Work in this area over the last five years has been focused on researching separation of actinides (Korea) and developing designs for advanced future fuel cycles (Belgium, France and Japan). Drivers for implementing P&T for radioactive waste management have included: • 'Cleaner' nuclear energy. • Increased sustainability and reduced waste disposal problem, by reducing the volume of radioactive waste and hence, reducing the size of the disposal facility required. • More control of the nuclear inventory and a reduction in the radiological risk. • Improved proliferation resistance. P&T is a multi-step process involving separation of radionuclides of interest, incorporation of these species into material to be irradiated, and the irradiation (transmutation) step itself. Implementation of P&T has a number of associated drawbacks, including: • The need to incorporate the radionuclides to be transmuted within reactor core fuel, or alternatively, to produce transmutation "targets", which has implications for worker safety, technical complexity of waste handling, generation of secondary wastes and processing costs. • The transmutation step is slow and requires long irradiation times and/or repeated irradiation cycles to achieve a satisfactory yield. Even then, the transmuted product would still contain some long-lived radionuclides and would have significant radioactivity for many hundreds or thousands of years (depending on the transmutation yield). Thus, P&T does not obviate the need for a GDF. • The low maturity of P&T would require major investment to progress it to the point of industrial application. • It would be preferable to adopt P&T when initiating a nuclear fuel cycle (rather than applying it to an established fuel cycle), since its use has implications for the choice of reactor design, fuel type and fuel processing facilities. Moreover, P&T can only be applied to unconditioned waste. For these reasons, P&T is more suited as a technique to be applied to radioactive wastes to be produced in the future. • P&T would need to be applied as part of a closed fuel cycle; the partitioning of species to be transmuted would most likely be performed as an additional step, or steps, during spent fuel reprocessing [69], and the irradiation step would require multiple recycles of the material through a reactor to have a significant impact on the inventory. The UK is moving towards an open fuel cycle with the imminent closure of both the Magnox and THORP reprocessing facilities [5; Page 14], so the

ALTERNATIVE: Partitioning and Transmutation
prospects for application of P&T to fuel cycle activities in the UK in the near future seem limited. A better interpretation of P&T might therefore be that it provides a technical range of alternatives for effective fuel cycle inventory management but it would always have to be used in conjunction with traditional waste management techniques such as vitrification, encapsulation and geological disposal.
Current maturity of alternative waste management option
P&T is far from an industrially mature technology. Overall, it is currently still at a laboratory-based level of maturity. Current estimates for pilot plant production for P&T are at least 5-10 years away, and have been in this position for several decades, given limited interest and investment in this field. Internationally, P&T schemes are only really being considered against future fuel cycles, not for the treatment of legacy wastes. On that basis, it is estimated that a fully mature industrial process would not be available for at least 20-30 years.
Description of alternative waste management option
It is difficult, if not impossible, to transmute fission products efficiently since they either have a very low probability of transmutation or isotopes of the same element are produced that have very long half-lives. Therefore, the goal of P&T is to reduce the radiotoxicity of long-lived radio-isotopes produced in reactors, such as the “minor” actinides Np, Am and Cm, to as low a level as possible (usually taken to be less than the activity of natural uranium) in as short a period as possible. Because the subsequent decay of transmuted waste can take many hundreds of years in even the most ideal case, geological disposal will still always be required. Both partitioning and transmutation would generate secondary wastes, with different physical, chemical and radiological characteristics to the original waste. The nature of these would vary depending on the processes being followed, but for partitioning, they are likely to be ILW and LLW streams similar to those produced in traditional spent fuel reprocessing. For transmutation, secondary wastes would be produced during the preparation of fuel or “targets” from the raw waste to be transmuted, and additional, unwanted, radionuclides could also be generated through the transmutation process itself. <u>Partitioning strategies and technologies</u> A common feature of all P&T fuel cycles is the need to remove fission products from the spent fuel and to recycle actinides so that they may be consumed by transmutation, thereby reducing the long-term radiotoxicity of the spent fuel or vitrified HLW produced from spent fuel reprocessing. Various separation processes have been proposed based on aqueous and pyrochemical processes. Aqueous processes use solvent extraction technology and are extensions of the Purex process which is used at THORP. The Purex process recovers U and Pu only for reuse, whereas P&T scenarios require the recovery of the minor actinides (Np, Am and Cm) as well. Modification of the Purex process to recover Np is feasible. However, the separation of Am and Cm is particularly challenging due to their chemical similarity to the rare earth elements (lanthanides) which are present in spent fuel in much greater mass. In general, two approaches are considered for the recovery of the minor actinides from spent fuel. In type (1) the minor actinides Am & Cm are recovered from the Purex raffinate in a form suitable for manufacture into heterogeneous targets for incineration in fast or ADS reactors/systems. In type (2) all of the transuranic elements are recovered together

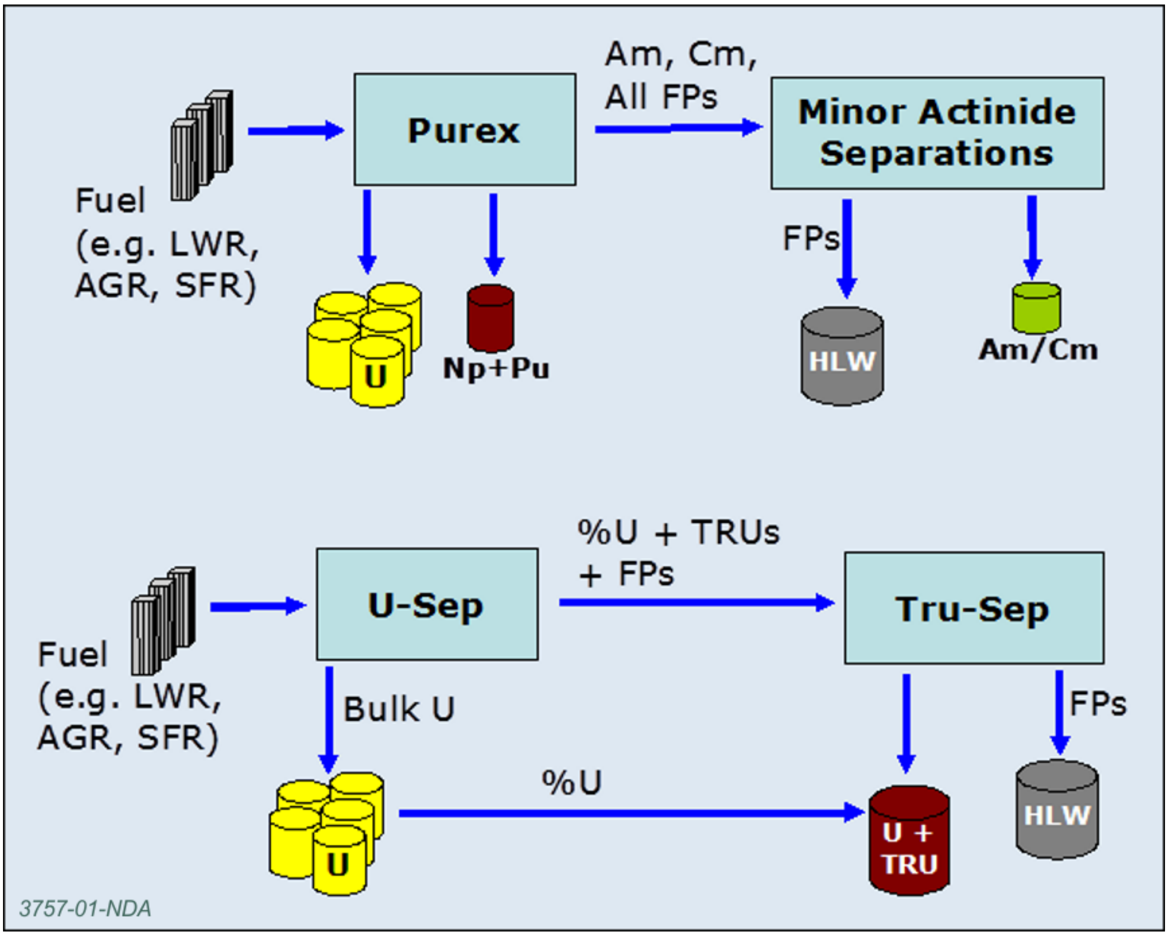
ALTERNATIVE:	Partitioning and Transmutation

for manufacture into homogeneous fuel for use in fast reactors. This is illustrated in Figure 3.6.

The development of processes to recover and separate minor actinides has been demonstrated at laboratory scale, however, there is considerable further development required to prove these processes at an industrial scale.

In addition to partitioning for transmutation, advances in separation processes have been made to recover and segregate some fission products (for example; Cs, Sr, Tc and I). Separation processes could potentially be used for some currently unconditioned wastes in the UK. Shorter-lived isotopes could then undergo medium-term decay storage (e.g. Cs, Sr for around 100 years) prior to disposal, which could facilitate re-routing of some waste components away from a GDF. Long-lived isotopes (for example; Tc and I) could be immobilised in a matrix with superior performance targeted at specific radionuclides, potentially providing a more robust post-closure safety case for a disposal facility. Whilst not strictly P&T, these advances still form part of the P&T collective as they serve to reduce the long-term impact of radioactive waste on the environment and, therefore, are expected to improve public perception of the sustainability of nuclear power.

Figure 3.6: Options for minor actinide recovery from spent fuel.



Pyrochemical processes are also under development and are seen as viable alternatives to aqueous processing technology. Compared to aqueous processes, pyrochemical processes are generally considered better suited for the treatment of high burn-up fuel such as those arising from fast reactors or for the recycle of targets from accelerator driven systems (ADS), rather than for the treatment of large tonnages of thermal oxide fuel. This

ALTERNATIVE:	Partitioning and Transmutation

is because the high specific heat and radiation output of these fuels can degrade the chemical species used in aqueous processes.

Physics of transmutation and transmutation approaches

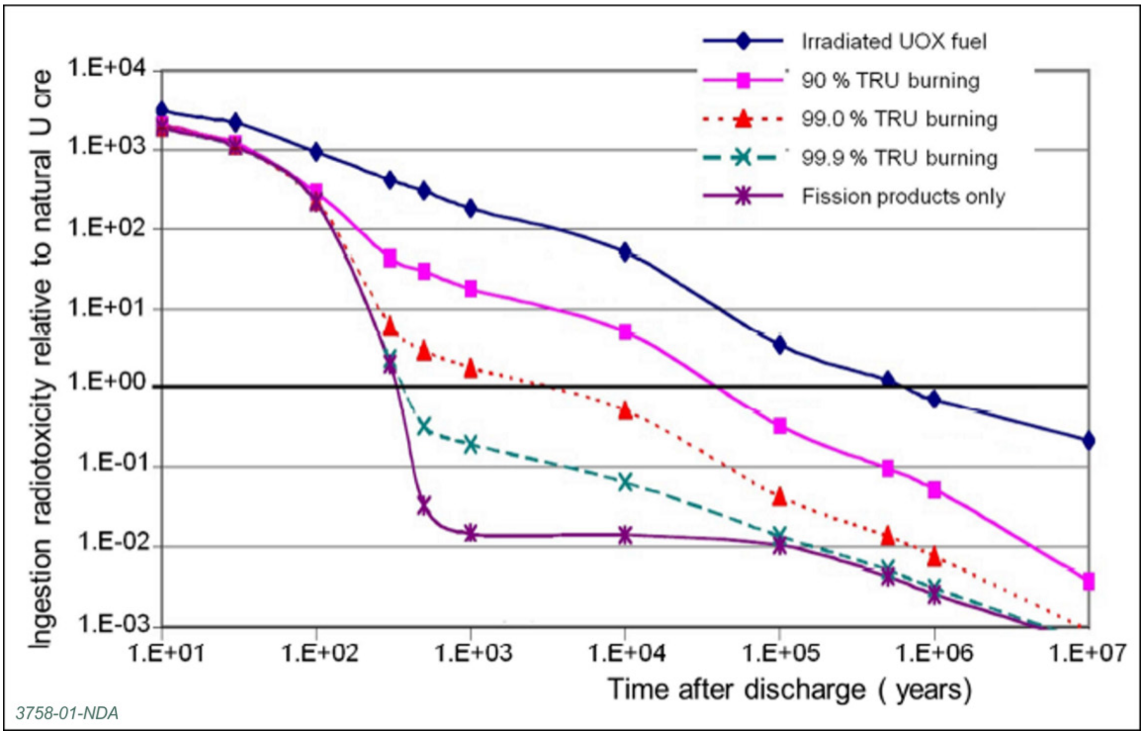
In a strong neutron flux field, as in a fast reactor or ADS (see later), actinides can be destroyed by fission or by neutron capture. In general, it is preferable to fission the actinides in the transmutation process rather than cause transmutation by neutron capture. This is because the resultant fission products tend to have shorter half-lives. Since the probability of fission compared to neutron capture increases with increasing neutron energy, and fast spectrum devices usually have much larger neutron fluxes, these tend to be the current preferred option. However if a sufficiently large neutron flux could be produced at thermal energies, as discussed below, this may be an alternative for efficient transmutation.

In either case, the objective is to transmute actinides to shorter-lived species that would contribute much less to long-term radiotoxicity. Two broad approaches have been proposed. *Homogeneous recycle* involves the incorporation of actinides in the main core fuel, which is most effective for Np. For other actinides (for example, Am and Cm), the *heterogeneous* approach is more effective, in which the actinides are loaded in separate "target" fuel assemblies. The main fuel assemblies provide a high neutron flux field to irradiate the target assemblies and destroy the minor actinides. Homogeneous recycle requires all of the fuel mass in the core to be fabricated remotely, which would be particularly difficult for Am and Cm because of their very intense gamma radiation fields. Np has a somewhat lower gamma radiation field which makes the homogeneous approach more feasible. Concentrating Am and Cm in heterogeneous targets is more practical because it implies a significantly smaller mass of highly active fuel to be fabricated. The complex, highly shielded fabrication facilities required to work with these intense gamma emitters could therefore be constructed on a smaller scale.

With both homogeneous and heterogeneous approaches, the fission and neutron capture cross-sections would be relatively small and the transmutation rates low. In a fast neutron spectrum, actinide fission and capture cross-sections are quite small, so despite the very high absolute neutron flux, reactions rates are relatively low and typically only a small fraction of the actinides would have reacted during several years' core residence time. Because of this, most advanced P&T fuel cycle scenarios assume that minor actinides would be recycled through the core several times. In thermal neutron spectra the cross-sections are higher, but the absolute thermal fluxes are lower and again the fractional transmutation is low. Higher transmutation fractions could be achieved by using moderated targets in fast reactors. The fast neutron flux would be thermalised by a local moderator, such as zirconium hydride (ZrH), resulting in extremely high thermal fluxes (an order of magnitude higher than achievable in a thermal reactor). By this means, overall transmutation fractions approaching 90% would be achievable, although a significant proportion of this fraction would be achieved via neutron capture, so may still result in relatively long-lived radionuclides as transmutation products. It can be seen from Figure 3.7 that even a transmutation fraction of 90 % still has only a relatively limited impact on the radiotoxicity of spent fuel.

ALTERNATIVE: **Partitioning and Transmutation**

Figure 3.7: Impact of the total transmutation yield on the radiotoxicity of irradiated uranium oxide fuel. The pink line gives the radiotoxicity with 90 % of the transuranics (TRU – Np, Am, Cm and Pu) transmuted (from [70], adapted from [71]). Radiotoxicity is calculated relative to 5 tons of natural uranium ore, to account for enrichment.



A high transmutation fraction is desirable because it avoids the need to recycle the minor actinides several times in actinide target fuels. Moreover, for a transmutation factor "ε", the mass of actinides active in the fuel cycle scales inversely with ε and for safety it is highly preferable to minimise the active inventory. Furthermore, in a phase-out scenario where fission reactors are eventually replaced by other technology, it would be necessary to carefully manage this end-of-life actinide inventory and clearly this would be much easier if the transmutation factor was high.

ADS refers to reactors that could be operated in a sub-critical condition with a neutron multiplication factor of between 0.95 and 0.98. To maintain a steady-state flux and power, it would be necessary to use a spallation neutron source driven by a proton beam from an accelerator. The power output would be governed directly by the beam power and could be switched off simply by tripping the accelerator beam. In ADS, the sub-critical core would provide between 20 and 50 times multiplication of the spallation source, so that the vast majority of neutrons in the system would come from fissions. Sub-critical systems could therefore be correctly regarded as being similar to critical systems in terms of neutron flux and actinide transmutation.

In all the critical reactors considered to date, there are quite severe restrictions on the mass of actinides that could be loaded before the core characteristics become unacceptable for safe operation. It is claimed that sub-critical systems would be safer than critical systems and while this is debateable, there are grounds to believe that they may be able to accommodate a higher actinide loading than critical reactors. Overall, the relative performance of sub-critical and critical systems is a complex issue that has not yet been fully resolved.

ALTERNATIVE:	**Partitioning and Transmutation**
Status of current practices / recent developments	

As discussed above, the initial concept of P&T was to process radioactive waste in such a way as to remove the need for a GDF with only a limited period of surface storage required. However work since the 1980s has shown that this idealised view is not tenable and that a GDF will always be required.

A review of P&T was carried out for RWM in 2011 [8]. Since then, there has been an incremental increase in the work associated with P&T rather than breakthrough results.

As an indication of the recent work in the last five years or so, it is convenient to separate the technical work into that associated with partitioning and transmutation.

The continuing R&D into P&T during this period has been encapsulated in two major conferences in 2012 [72] and 2014 [73] sponsored by the Nuclear Energy Agency (NEA), together with several workshops (referenced below).

<u>Partitioning</u>

In the last five years, there has been continued laboratory-based work mainly on the separation of actinides from spent fuel. This work has been based in two areas: aqueous separation and pyrochemical separation (for example, see [73] and references therein). This work has mainly involved the investigation of specific reactions for Am and Np extraction.

Pyrochemical separation involves using electrochemical techniques to dissolve reactor fuel and extract various nuclides. The technique was developed by Argonne National Laboratory (ANL) in the USA during the 1960s. Institutions in Russia and South Korea, as well as ANL, are in the process of developing this technique further. In South Korea, for example, with USA assistance through the International Nuclear Energy Research Initiative (I-NERI) program, KAERI (Korean Atomic Energy Research Institute) built the Advanced Spent Fuel Conditioning Process Facility (ACPF). This led to KAERI's Pyro-process Integrated Inactive Demonstration Facility (PRIDE), which began testing operations in 2012. Demonstration work is proceeding to 2016, as effectively the first stage of a Korea Advanced Pyroprocessing Facility (KAPF) to start experimentally in 2016 and become a commercial-scale demonstration plant in 2025 [74].

<u>Transmutation</u>

There has been no major construction work on transmutation facilities. There has been, however, significant design work associated with several proposed major facilities.

MYRHHA

The Belgian facility MYRHHA (Multi-purpose hybrid research reactor for high-tech applications) was originally planned as a test bed for an ADS which involved a proton accelerator producing spallation neutrons to transmute minor actinides contained in fuel cooled by a lead bismuth eutectic. Since then its design has evolved to include a wider range of capabilities as a material research reactor. It is currently planned to be operational by 2026.

There are several facilities, either operational or in the design stage, which support the overall design of MYRHHA especially in the area of coolant research [75].

J-PARC TEF/TEP

The Japanese are proposing to build two facilities at the Japanese Proton Accelerator Complex (J-PARC) which will investigate an ADS (Transmutation Experimental Facility-T) and also the lead bismuth eutectic coolant (Transmutation Experimental Facility-P). J-

ALTERNATIVE: Partitioning and Transmutation
PARC has entered into a cooperative agreement with MYRHHA to share data obtained through their work. Currently the two Japanese facilities are due to begin operation around 2018 and 2022 respectively [76]. *ASTRID* A dedicated research programme, the Advanced Sodium Technological Reactor for Industrial Demonstration (ASTRID) programme, was launched by the CEA in 2010. Its aims were essentially twofold: the design of a Generation-IV sodium-cooled demonstrator (both reactor and related fuel cycle facilities) and a minor actinide transmuter. It is currently planned to be operated from around 2025. There are many industrial and international collaborators, together with support from several European Commission-funded projects [77].
Applicability to management of UK inventory of HAW and nuclear materials
P&T is primarily relevant for the management of radionuclides present in spent fuel and HLW produced from spent fuel reprocessing. As currently envisaged, P&T would only be applicable to actinide and minor actinide (Np, Am, Cm) in these wastes / materials. Fission products and other waste streams are not considered susceptible to this technology mainly because of the extreme difficulty in transmuting the material. Much of the UK's HLW has already been conditioned into a vitrified wasteform. There are very limited benefits to be gained from reworking this product and there would be significant associated disadvantages (for example, in terms of worker dose, costs and secondary wastes). Current UK reprocessing facilities are not suitable for partitioning the minor actinides of interest for transmutation. Moreover, as noted previously, the UK is moving to an open fuel cycle with the imminent closure of both the Magnox and THORP reprocessing facilities [5]. Implementation of any form of P&T would require a reversal of this policy since P&T implicitly implies reprocessing [69]. Even if such a change were made, P&T could only serve to reduce the inventory of minor actinides such as Np, Am and Cm, albeit that these species might be present at greater levels in the higher burn-up fuel cycles under consideration as part of new nuclear build proposals in the UK.
Potential impact on UK inventory of HAW and nuclear materials
With the current low technical maturity of P&T and its applicability mainly to a closed fuel cycle, the prospects for implementation of P&T in the UK in the near future seem limited. Nevertheless, given the continued international interest in P&T, RWM will continue to monitor developments in the field of P&T as part of its overall periodic review of alternative waste management options. One potential impact of actinide and minor actinide P&T would be to reduce the long-term (>500 years) heat production in a GDF. As noted by a recent OECD-NEA task force, which reviewed the impacts that P&T could have on geological disposal, this could potentially allow an increase in the packing density of waste and help to reduce the size of disposal areas in a GDF, leading to a reduction in construction costs [78; Table 3.4 and Section 4.4]. However, since the major heat production in the first 500 years or so would result from fission products (which would not be consumed in the P&T schemes being considered), the ability to take full advantage of this would require interim storage until this heat production has decayed. This would clearly add additional costs to the overall waste management process and it is far from obvious that this would produce an overall reduction in combined storage and disposal costs (let alone the huge costs of actually developing and implementing the necessary P&T technologies). There would also be an impact on the security of fission product storage for this period. The implementation of

ALTERNATIVE:	Partitioning and Transmutation
decay storage is discussed in Section 2. A careful distinction needs to be made between the total radiotoxic inventory of a GDF and the radiotoxicity that is potentially released from a GDF through, for example, groundwater flow. The largest part of the total radiotoxicity in the inventory for geological disposal is due to actinides. However, long-term safety cases typically show that the activity which could be released from a GDF, at least in the first million years after disposal, is dominated by long-lived fission products which, as noted above, are difficult to transmute, as well as radionuclides produced from the activation of impurities present in the initial composition of the nuclear fuel. Examples include chlorine-36 and iodine-129. This means that transmutation could have only a limited impact on the species that dominate the activity released from a GDF via the groundwater pathway. On the other hand, doses from a human intrusion scenario, such as drilling a borehole into a GDF, could be significantly reduced by P&T. There could also be a reduced risk of the accumulation of fissile material in the GDF leading to a criticality event [8]. It should be noted that the human intrusion scenario and a criticality event are considered as low probability scenarios in the generic disposal system safety case for a GDF for UK HAW.	

4 Near-surface and Intermediate Depth Disposal

4.1 Introduction

The environment agencies' guidance on requirements for authorisation of radioactive waste disposal (the GRA) distinguishes between two broad types of disposal facility for radioactive waste [35,79]. It defines *geological disposal* as a long-term management option involving the disposal of radioactive waste in an engineered underground facility, where the geology (rock structure) provides a barrier against escape of radioactivity and where the depth, taken in the particular geological context, substantially protects the waste from disturbances arising at the surface [79; Paragraph 3.3.1]. *Near-surface* disposal facilities are defined as those located at the surface of the ground, or at depths down to several tens of metres below the surface [35; Paragraph 3.3.1]. The type and extent of the engineered barriers will depend on the waste and the location. The near-surface GRA explicitly identifies the potential for disposal of shorter-lived or less radiotoxic ILW at such facilities [35; Paragraph 3.4.1].[6]

The definitions of both types of facility note that they could be entirely on land or could be constructed under the seabed but accessed from land. In the case of geological disposal, the geosphere is expected to provide isolation and stability as a result of the depth of the facility, and will comprise an important component of the safety concept over much longer timescales than is feasible for near-surface facilities (where external processes such as climate change would be expected to have greater impacts on shorter timescales).

The types of disposal facilities considered in this section include those that would be classed as near-surface disposal facilities and as geological disposal facilities based on the above definitions, but in the latter case, at a shallower depth than is normally considered for a GDF in the UK (for example, 30-200 m below the surface)[13]. The term *intermediate depth disposal* is used to distinguish the latter in this report. Both types of Near-Surface and Intermediate Depth (NSID) facilities could potentially be implemented in the UK on a separate site, or above the level of a GDF and accessed by the same access ramps/shafts as the main facility (for example, as proposed for a proportion of the ILW inventory in RWM's review of options for accelerating implementation of geological disposal [32]). This review also identifies recent work that is considering the disposability of HAW at the LLWR.

Scottish Government policy does not specify what a disposal facility should look like or how it should be constructed [3]. In the rest of the UK, Government policy is for geological disposal as the permanent solution for HAW management in England and Wales [1]. Here, NSID disposal is an alternative to disposal in a GDF that is potentially applicable to short-lived and/or lower-activity ILW, graphite wastes and/or DNLEU, depending on whether a safety case can be made for disposal of associated inventories. Significant quantities of these wastes and materials already exist, for example, arising from nuclear power plant operations. Further large quantities are expected as a result of reactor decommissioning activities, ongoing enrichment activities, and potentially new nuclear build. Current stocks and future arisings are reflected in the UKRWI [27] and in RWM's Derived Inventory [7]. NSID disposal of each of the waste and material types identified above is discussed later in this section.

In addition to engineered waste disposal facilities, near-surface disposal also encompasses disposal within existing structures, voids and bunds and the in situ disposal of radioactive waste, with or without engineered closure. These alternative options are all aimed at allowing optimisation of waste disposal at decommissioning nuclear sites and have been considered in recent guidance developed by the environment agencies [31]. This guidance

[13] There is no explicit depth range specified in the geological disposal GRA [79], but CoRWM [80] indicates that a depth of more than 200 m constitutes a GDF.

on requirements for release of nuclear sites from radioactive substances regulation (the GRR) has been issued as a consultation draft and is currently under trial at three sites across the UK (Dounreay, Winfrith and Trawsfynydd). The GRR provides dose and risk criteria for a site that are similar to the criteria for a dedicated disposal facility set out in the GRA [28]. These criteria apply after the period of radioactive substances regulation and the GRR recognises that a period of restricted use is likely to be important in controlling potential doses and risks to the public in the period prior to this. Decay and other attenuation processes during the period of restricted use, with exposure prevented by the application of institutional controls, mean that there is a potential for significant amounts of short-lived radioactive waste to be disposed of in these types of facility. An example would be tritiated reactor bioshield concrete either left in situ (for that material below ground level) or used to infill voids in below-ground structures.

4.2 Review of Near-surface and Intermediate Depth Disposal

ALTERNATIVE: Near-surface and Intermediate Depth (NSID) Disposal

Overview of alternative waste management option

Potential drivers for NSID disposal

Potential benefits of NSID disposal for HAW are outlined below. Given the wide range of disposal concepts, designs and siting options encompassed in the broad category of NSID disposal, the points below may be more or less applicable for different specific examples and, in some cases, may not be achievable.

Construction cost: There is an expectation that NSID disposal concepts would offer cost savings relative to deeper options because of the reduction in underground excavation. In practice, this will depend on a number of factors, including :

- the scale of excavation required (which depends on the disposal concept)
- the cost of storage (and decay storage) facilities
- the expected duration of facility operation, and any periods of intermittent operation
- the extent of structural support required (which depends on the disposal concept and site characteristics at the depth of interest)
- for a new NSID disposal facility, whether it is associated with another SLC site or constructed separately

In all cases, the relative costs of different disposal routes should be considered, and it should be borne in mind that the costs associated with construction of a GDF will, in any case, be necessary, since a GDF will be needed for managing wastes not suitable for NSID disposal.

Accelerated emplacement opportunity: NSID disposal could potentially be implemented earlier than the current scheduling assumptions for GDF disposal, owing to simpler excavation and construction. Consequently, there is potential to accelerate the removal of liabilities from nuclear licensed sites, as well as to significantly reduce upstream costs associated with ongoing interim storage of wastes. It should be noted that all new disposal facilities would be subject to finding a suitable site and the uncertain timescales for the siting process.

Optimising use of a site of limited extent: The potential for multi-level disposal at a single site has been investigated by several waste management programmes (for example [82,83]). These studies have usually considered siting several disposal panels or arrays of vaults at GDF depth in the same host rock, stacked one above another and separated

ALTERNATIVE: **Near-surface and Intermediate Depth (NSID) Disposal**
vertically by some tens of metres. However, NSID disposal would allow the option of using shallower formations overlying the GDF host rock (or shallower regions of the same host rock) much more widely separated by depth. *Minimising use of resources and environmental impact:* Depending on the disposal concept, NSID disposal could offer the opportunity to use simplified engineered structures and to reduce the amount of excavation compared to a GDF. As with construction costs, the potential benefit would need to be evaluated in terms of relative differences, compared to the resource use and environmental impact of excavating and constructing vaults at GDF depth. *Flexibility (for example; for scheduling, operations):* Disposal of wastes identified as suitable for a NSID facility could potentially be scheduled separately from the wastes assigned to a GDF (assuming the NSID and GDF facilities have different access routes). This, in turn, could reduce constraints associated with the capacity of underground transfer facilities for a GDF, since less construction and backfill materials and waste would need to be transported from/to GDF depth. *Enhanced retrievability:* The ability to retrieve waste after backfilling of disposal areas is potentially easier for disposal carried out directly from the surface (as in a surface trench or silo), compared to a deeper facility accessed by a shaft or drift. Conversely this is a factor that limits the role that NSID disposal may play in relation to material that is currently subject to safeguards. *Improved construction and/or operational safety:* Disposal concepts operated from the surface may avoid construction and operation hazards associated with working underground, where a safe environment requires provision of power, lighting, ventilation and drainage as well as measures to prevent rock fall. <u>Potential drawbacks and disadvantages</u> The feasibility of implementing NSID disposal of UK HAW will depend on the radionuclide inventory, half-life, long-term radiotoxicity and chemotoxicity of specific waste streams and the risk that these characteristics pose when considered against site-specific factors such as the location, design and geology in the vicinity of a disposal facility, noting that it may not be cost effective to develop a NSID disposal route if the size of the inventory of wastes suitable for such disposal is small. The feasibility of NSID disposal depends on the ability to make a safety case for disposing of a particular inventory, taking account of all these factors. Near-surface disposal (located at the surface of the ground, or at depths down to several tens of metres below the surface) in particular is only potentially applicable to a portion of the inventory currently destined for disposal in a GDF. Segregation of suitable wastes could incur additional costs and operational hazards, which would be considered in waste management treatment decisions [84]. Siting of new NSID facilities would need to consider the effects of climate change and coastal erosion over appropriate timescales. This may be important where disposal at existing nuclear sites is being considered. It may be more difficult to make a long-term safety case for NSID disposal of some HAW, in particular because there is a greater risk that a near-surface disposal facility could be significantly disrupted (for example; by inadvertent future human intrusion, by erosion at coastal sites or during a future glaciation). Groundwater and gas migration pathways to the accessible environment are also likely to be shorter than those from a GDF, such that impacts of radionuclides such as carbon-14 and radon may be enhanced. These risks are typically reduced with increasing depth of disposal, such that a facility at a few tens of metres below the surface would largely preclude large-scale human intrusion but could still

ALTERNATIVE: Near-surface and Intermediate Depth (NSID) Disposal
be disrupted by erosion over one or more glacial cycles. A deeper facility (for example, 100-200 m deep) would be below the depth affected by anything other than small-scale human intrusion (such as boreholes) and would be at reduced risk of disruption due to large-scale natural processes such as glaciation. Further consequences of the absence or reduction of a geological barrier in near-surface disposal include difficulties in meeting environmental criteria for non-radiological contaminants. For instance, some metal contaminants may have increased solubility under near-surface (oxidising) conditions and concentrations in shallow groundwaters may be higher due to the shorter geosphere pathway and the reduced retardation effect of sorption processes. Solid contaminants such as asbestos would also need to be considered in an assessment of the disruption of near-surface facilities closer to the surface, however landfill disposal of stable, non-reactive, hazardous waste is standard practice for conventional waste.
Current maturity of alternative waste management option
NSID disposal is a mature option for management of short-lived ILW, with significant UK and overseas experience (in the case of short-lived ILW disposal). There are operational facilities at all depths between the surface and greater than 100 m for disposal of LLW and ILW.
Description of alternative waste management option
Potential NSID disposal concepts range from simple surface facilities to more highly engineered facilities at depth, with a variety of concepts possible at any depth in a candidate site. Example disposal concepts include: 1. Surface mounds above the water table. 2. Disposal in simple surface facilities (for example, in lined trenches or vaults) below the water table between 0 and 30 m underground. 3. Silos or shafts between 0 and 200 m underground operated from the surface. 4. Silos operated from underground, sited below land or beneath the sea. 5. Vault at a few tens of metres depth, sited below land or beneath the sea. 6. GDF-like concept implemented between 100 and 200 m, sited below land or beneath the sea. These generic disposal concepts are each described, with examples, below. <u>(1) Surface mounds above the water table</u> Key Features: • Waste in one or more concrete vaults is formed into a monolith with use of backfill material. • The whole facility is mounded over, with variety of barriers to water ingress to maintain unsaturated conditions. • The position above the water table keeps the waste dry and reduces the rate of degradation of barriers. • Institutional control may be required for a period of time (up to 300 years, depending on the inventory). • The location of such facilities needs to consider the effects of climate change and landscape evolution (for example, coastal erosion) over the long term.

ALTERNATIVE:	Near-surface and Intermediate Depth (NSID) Disposal

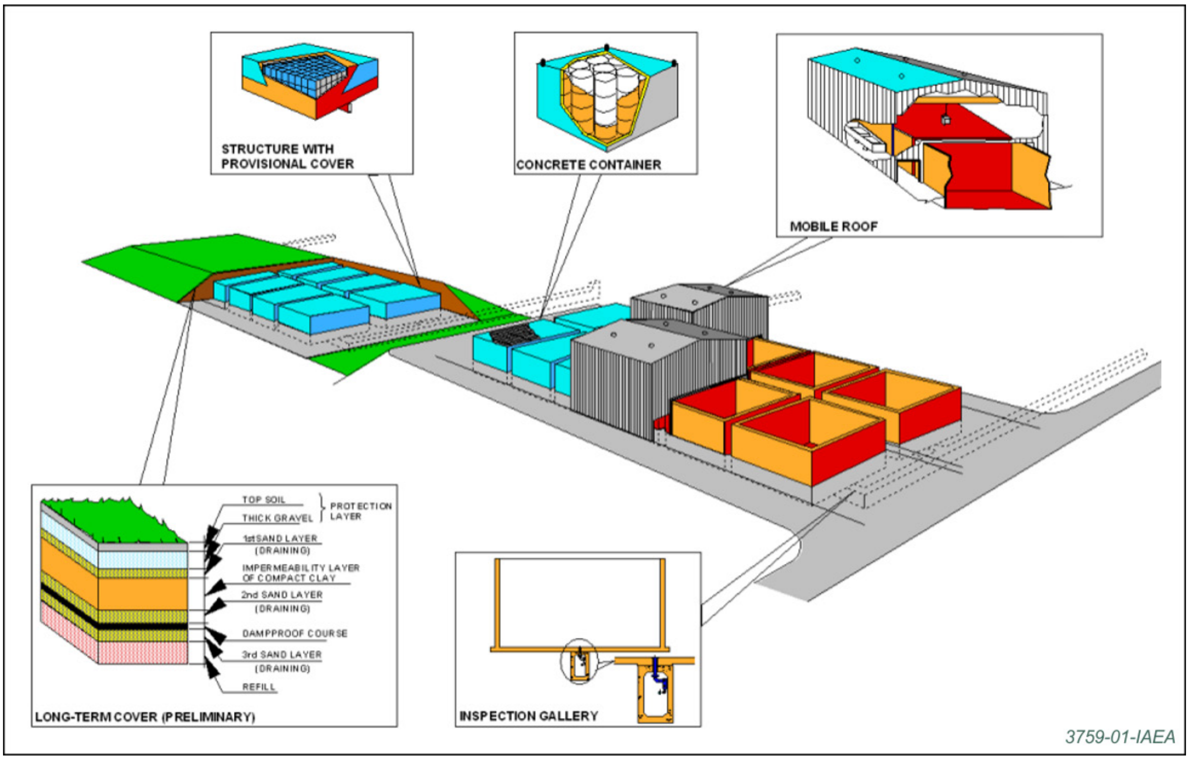
Examples:

- Vault 8, Vault 9 and planned future vaults at the LLWR.
- Centre de l'Aube, France (for L/ILW).
- El Cabril facility in Spain (for L/ILW).
- Proposed Category A facility, Dessel, Belgium (for short-lived L/ILW).

Waste Control Specialists site at Andrews, Texas, USA (for depleted uranium) [85].

Figure 4.1 shows a schematic of the El Cabril facility for LLW and ILW. Cement-encapsulated containerised waste (the 'disposal unit') is emplaced within concrete disposal cells which are covered by a mobile roof during operations. On completion of a cell, the void space between the disposal units is filled with gravel and a cover slab installed. When a set of cells is filled, an engineered cap composed of a number of different materials designed to reduce the potential for rainwater ingress to the cells is constructed enclosing the whole disposal volume.

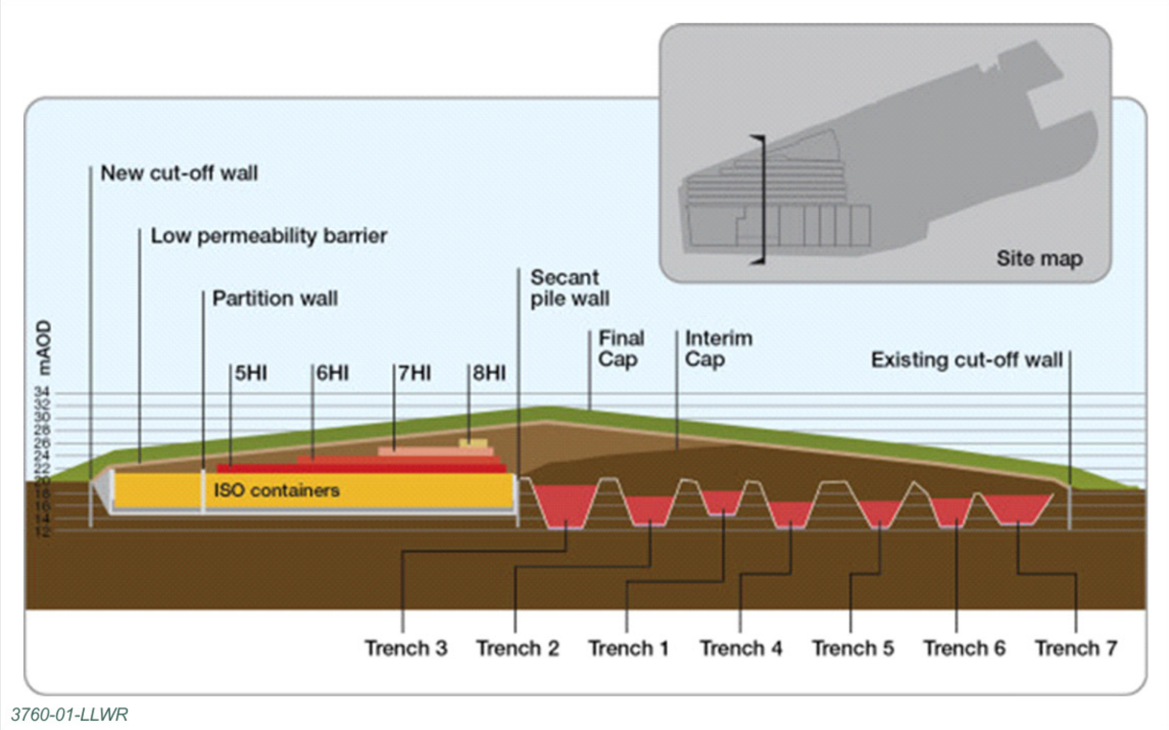
Figure 4.1: Schematic layout of disposal areas for LLW and short-lived ILW at the El Cabril disposal facility in Spain (from [36]).



The LLWR has a similar engineered concept for disposal of LLW in the UK (see cross section in Figure 4.2 below). For current disposals (Vaults 8 and 9) compacted LLW is emplaced in steel ISO containers, with void space within the container filled with a cementitious grout. Containers are stacked in a concrete-lined vault above the water table. A permanent cap is planned to be built over the vault disposals and also previous disposals to adjacent trenches. Containers will be stacked higher in the centre of the cap to maximise the volume of disposed LLW. The cap serves to reduce the infiltration of water into the wastes and to maintain unsaturated conditions for several hundred years. A planning application was submitted in October 2015 for phased construction of the LLWR to include two further vaults and the final cap (planning approval for the vaults was secured in July 2016). The final cap will be emplaced initially over an interim cap over the trenches and over the existing vaults and then progressively over future vault disposals.

ALTERNATIVE: Near-surface and Intermediate Depth (NSID) Disposal

Figure 4.2: Cross-section of the LLWR showing disposal trenches (right) and vaults (left) (from [86]).



<u>(2) Disposal at the surface below the water table</u>

Key Features:

- The waste will become saturated with time, but engineered barriers aim to prevent or reduce water flow through the waste.
- The depth of the facility is sufficient to make the surface environment safe after a period of institutional control that allows decay of shorter-lived radionuclides.
- Shallow trenches may be mounded over, for example the current interim cap over legacy disposal trenches at the LLWR, rather than being filled to ground level.

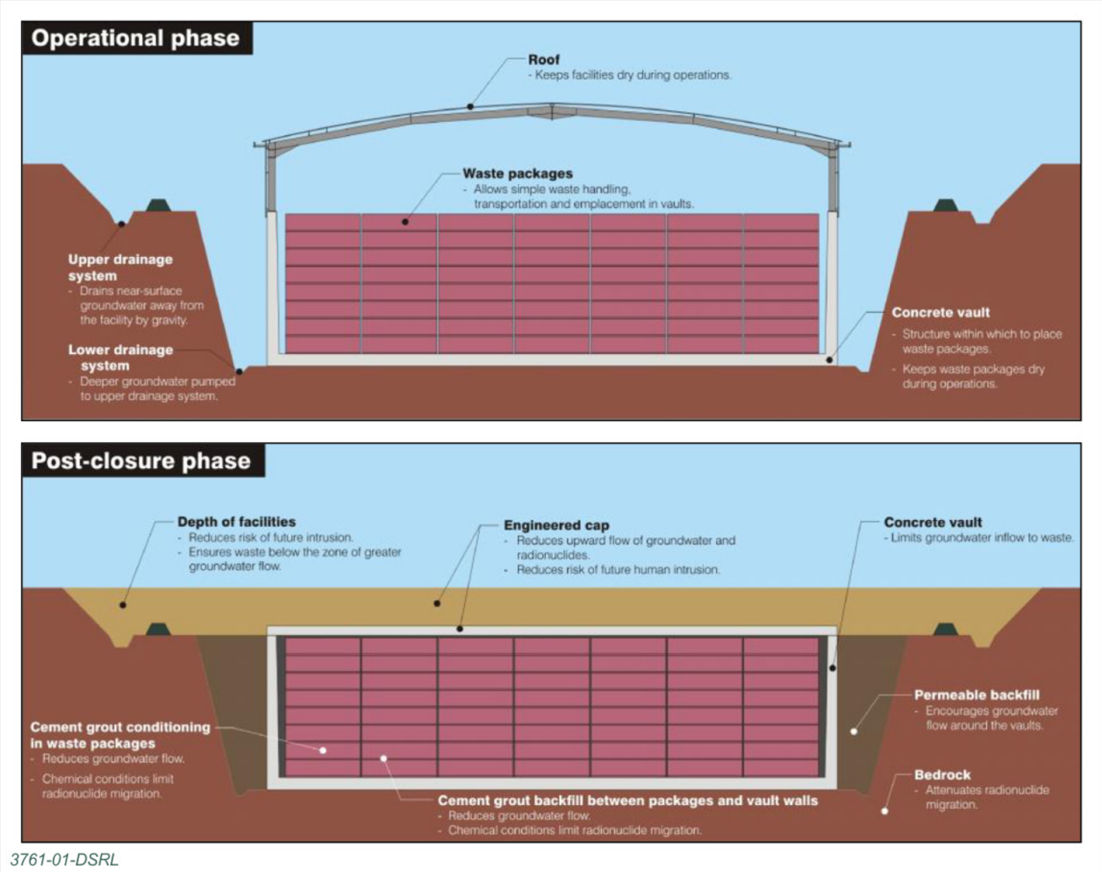
Examples:

- Dounreay New Low-Level Waste Facilities (NLLWF), Scotland.
- Rokkasho LLW facility, Aomori Prefecture, Japan.

Figure 4.3 shows schematically the Dounreay NLLWF during operations and in the post-closure phase, after closure and capping. The red rectangles illustrate individual cement-grouted LLW containers arranged in the vaults in eight-high stacks.

ALTERNATIVE:	Near-surface and Intermediate Depth (NSID) Disposal

Figure 4.3: Cross-section of the NLLWF at Dounreay in Scotland (from [87]).



The two vaults constructed in Phase One are for different LLW streams. The “Demolition LLW” vault is for waste at the low end of the radioactivity scale for LLW (the upper activity limits for this vault are 10 MBq/te alpha activity or 400 MBq/te beta/gamma activity), which requires less engineered handling and disposal procedures. This is mainly lightly contaminated rubble from demolition of buildings on the Dounreay site. The “LLW vault” is for all of the rest of the LLW, which requires more engineered packaging to be safely handled, and for which different disposal procedures have been developed.

When the vaults are full, they will be closed and any remaining excavated voids filled in. The roofs will be removed and the tops capped over with engineered materials, and the area restored as closely as possible to its original setting.

<u>(3) Silo or shaft operated from the surface</u>

Key Features:

- Increased depth potentially allows greater isolation from the surface environment and reduces the possibility of large-scale excavation of the waste (assuming that the silo is not filled with waste close to the top).
- Large operating heights for emplacement compared to trenches or vaults could raise concerns, as during early times (maximum drop) only very robust containers

ALTERNATIVE: Near-surface and Intermediate Depth (NSID) Disposal

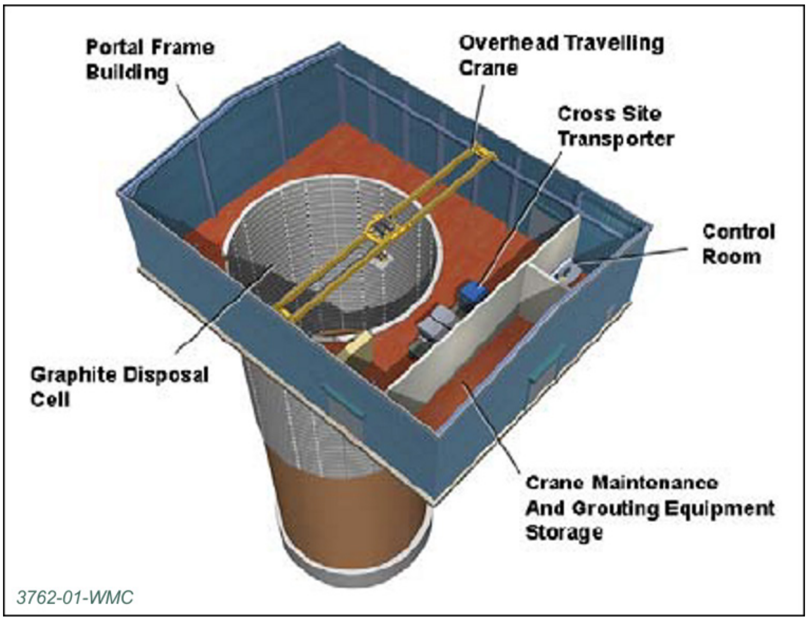
would survive a drop intact. Potential effects of incidents must be mitigated in other ways.

Examples:

- Hunterston Pathfinder concept, Scotland (solid ILW).

Figure 4. shows details of the operation of the Hunterston Pathfinder concept for graphite waste disposal (from [88]).

Figure 4.4: Operation of the Hunterston Pathfinder concept for solid ILW disposal.



The silo would be constructed from the surface with concrete segment walls forming part of the multi-barrier containment along with a substantial reinforced concrete base slab. Cement-encapsulated waste in boxes would be stacked in the silo with the remaining gaps grouted to create a monolith within the disposal cell.

The portion of the silo above the cap would be backfilled to the surface, ensuring that the waste would be located tens of metres below the present ground level and that extensive inadvertent human intrusion would be difficult. The surface of the silo would be mounded to encourage run-off and reduce rainwater ingress. The potential site was close to the coast with discharge paths to the marine environment.

(4) Silo accessed from underground

Key Features:

- Accessing silos from underground, rather than directly from the surface, increases the potential isolation of the wastes from the surface environment.
- Such facilities may be more costly to build and operate than surface shafts due to the greater underground infrastructure required.
- The underground silos potentially benefit from a more stable and favourable geological environment than surface-operated silos.
- Such silos could be sited below land or beneath the sea.

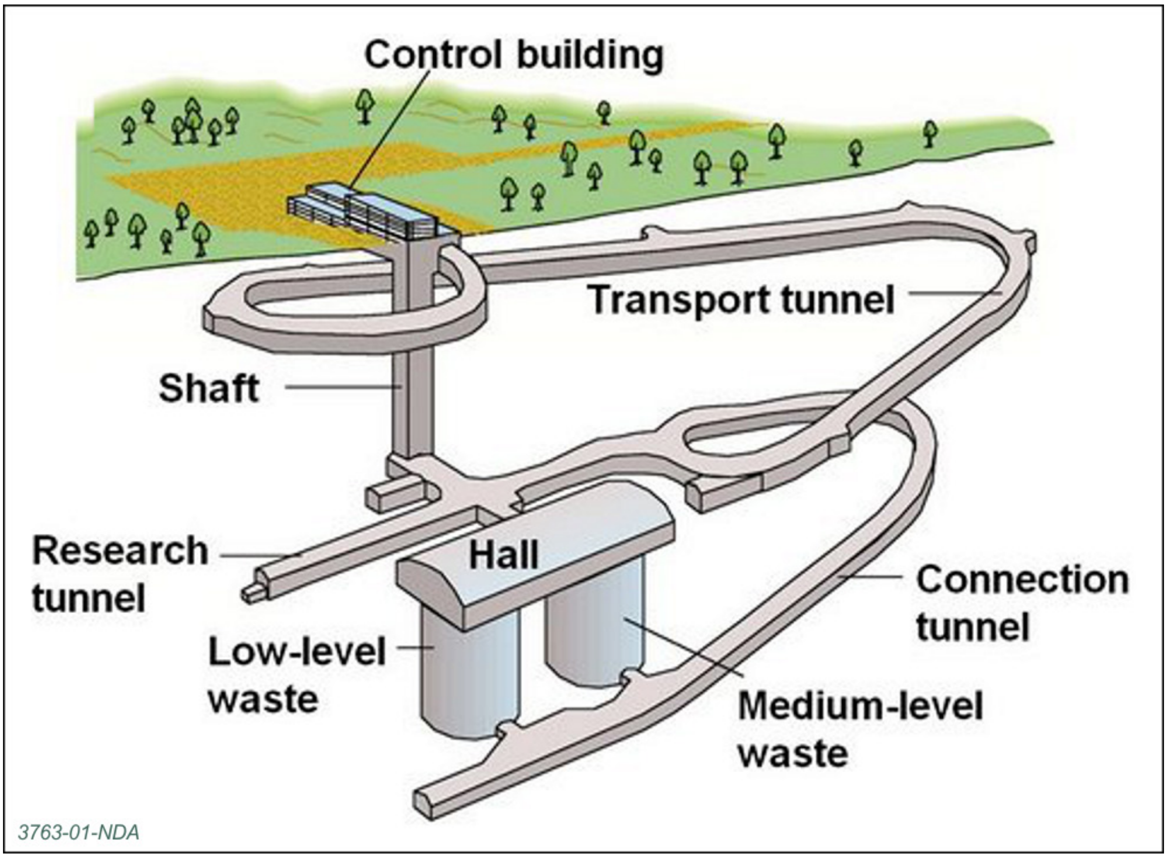
ALTERNATIVE:	Near-surface and Intermediate Depth (NSID) Disposal

Examples:

- VLJ L/ILW facility, Olkiluoto, Finland.
- Wolseong L/ILW silo facility at Gyeongju, South Korea.
- SFR ILW Silo, Forsmark, Sweden.

Figure 4.5 shows schematically the VLJ silos for L/ILW operating waste from the TVO nuclear power stations at Olkiluoto. The silos are operated from an access drift from the surface buildings. The waste in concrete boxes is delivered by radiation-protected vehicles to the loading hall at a depth of 60 m below ground. The silos are accessed from the floor of the loading hall and extend to a depth of 100 m below the surface. One silo is used for operational LLW in drums, sixteen of which are placed in concrete boxes stacked within the silo. The other silo is for ILW, much of which is ion exchange resin encapsulated in bitumen within steel drums, also emplaced using concrete boxes.

Figure 4.5: Schematic layout of the VLJ facility for disposal of operating wastes from the Olkiluoto nuclear power plant in Finland (from Posiva website).



(5) Vault at a few tens of metres depth

Key Features:

- Such vault facilities are similar in many respects to the underground silos, but with vault and wasteform designs more closely derived from GDF disposal concepts.
- The vaults could be sited below land or beneath the sea.

ALTERNATIVE: Near-surface and Intermediate Depth (NSID) Disposal

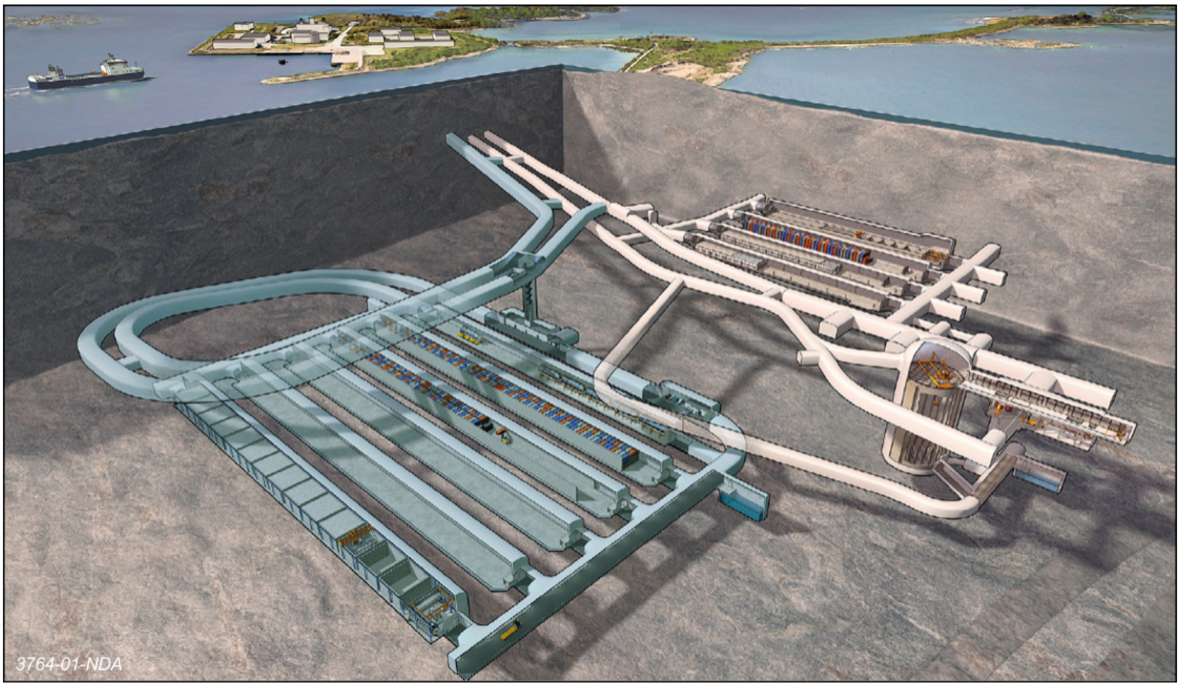
Example:

- SFR L/ILW vault facility, Forsmark, Sweden.

Figure 4.6 illustrates the SFR facility in Sweden [89] – the white structures are already operating facilities (comprising four vaults and also a silo for longer-lived and higher-activity wastes), while the grey structures are the SFR extension (see Example 6) for which a construction license application has been submitted.

The operating vaults are at a depth of approximately 60 m below the floor of the Baltic Sea and are each slightly different in design and accept different waste types. For example, in the "1BMA" vault, ILW in steel drums or larger steel or concrete containers is placed in open sections in a large concrete channel constructed within the vault. As the sections of the channel are filled, a concrete lid is installed. Voids between the waste packages may be left open or backfilled with grout. However the space between the concrete channel and the rock walls will be filled with sand to create a hydraulic cage. In contrast, the "1BLA" vault is used for LLW in ISO containers (10-foot or 20-foot standard shipping containers) that are stacked, three containers high and two to a row, on the floor of the vault. There are presently no plans for any backfill in the 1BLA vault. Closure will involve only casting of concrete plugs in both ends of the vault.

Figure 4.6: Schematic layout of the SFR disposal facility in Sweden, including the existing facility, in white, and the planned extension, in grey (from [89]).



(6) GDF-like concept implemented at a depth of between 100 and 200 m

Key Features:

- Intermediate depth geological disposal results in the disposal of radioactive waste below the depth at which some forms of inadvertent human intrusion could occur. Depending on its location, an intermediate depth facility could be isolated from changes to the surface environment (for example, from the effects of glaciation) for the long periods required for higher-activity wastes to decay to insignificance.

ALTERNATIVE: Near-surface and Intermediate Depth (NSID) Disposal

Examples include:

- SFR L/ILW facility extension, Forsmark, Sweden.
- Loviisa VLJ, Hästholmen, Finland (L/ILW).
- Rokkasho L1 (ILW) facility, Aomori Prefecture, Japan.

The SFR extension, shown in grey in Figure 4.6, will be constructed at a depth of approximately 120 - 140 m below the floor of the Baltic Sea. As with the existing facility, the five new vaults will be of different designs to accept different waste types. Four of the new vaults are of the same type as 1BLA with LLW in ISO containers, with a further single vault for ILW in a BMA-type disposal vault.

Status of current practices / recent developments

In the last four to five years, the following developments in NSID disposal facilities have taken place:

- The IAEA has published a Safety Standard which provides an introduction to near-surface disposal and also the requirements of a safety assessment for such a facility [90]. The IAEA is currently developing draft guidance on the disposal of ILW.
- Construction of, and first waste emplacement in, the NLLWF at Dounreay, noting that this is currently intended for LLW only [87].
- Submission of a safety case for disposal of Category A wastes (short-lived L/ILW) at Dessel in Belgium by ONDRAF/NIRAS (2013) [91].
- License application for the SFR extension in Sweden (2014).
- Opening of the Wolseong L/ILW silo facility, South Korea (2015).
- Conceptual designs and safety case developed for near-surface on-site silo disposal facility for ILW at Hunterston A (this project has not been taken forward by the NDA).

In support of NDA strategy for the management of HAW, RWM is working closely with LLW Repository Ltd to consider opportunities for the management of waste according to the most appropriate disposal route, using a risk-based approach [13,92,93,94]. Currently, LLW meeting specific waste acceptance criteria is consigned to the LLWR. However, the division between LLW and HAW is not clear cut, partly because of the nature of radioactive waste: radioactive decay will reduce the activity associated with many waste streams over time. As discussed in Section 2.2, wastes currently defined as ILW but containing short-lived radionuclides or low levels of contamination close to the LLW/ILW boundary may become LLW before geological disposal is implemented, or after some defined period of long-term storage. Such “boundary wastes”, therefore, may also be suitable for near-surface disposal.

A number of other European countries operate facilities for surface disposal (for example Centre de l’Aube, France; El Cabril, Spain) or near-surface disposal (for example SFR, Sweden; VLJ, Finland) of wastes that would be classified as short-lived ILW in the UK. Typical short-lived ILW disposed of in these facilities includes operational wastes from water reactors such as ion exchange resins used to remove short-lived fission and activation products from cooling water. The UK, with its legacy of gas reactors, does not have an extensive inventory of such wastes, although the three reactor types currently under consideration for new nuclear build in the UK are all water reactors.

ALTERNATIVE: Near-surface and Intermediate Depth (NSID) Disposal
LLW Repository Ltd has developed guidance on decision making for waste close to the LLW/ILW boundary [95], and has recently commissioned studies on the management of short-lived ILW and boundary wastes using near-surface disposal. This work supported development of NDA's strategic position [43] for wastes for which decay storage may be appropriate (for example, boundary wastes). The NDA is also committed to supporting Scottish Government in delivering its Implementation Strategy for the long-term management of HAW. RWM will review its current Letter of Compliance process in support of the development of near-surface disposal concepts for wastes arising in Scotland.[5] The scope of HAW that might be amenable to on-site *in situ* disposal or disposal within existing structures, voids and bunds at decommissioning sites – in accord with recently published draft guidance on requirements for release of nuclear sites from radioactive substances regulation [38] – is currently uncertain. Such disposal options, which would need to be authorised, have the potential to remove some wastes arising from final site clearance from the HAW inventory that is currently intended for geological disposal. The amount of HAW arising from decommissioning is dependent upon the configuration and operation of the nuclear site prior to decommissioning.
Applicability to management of UK inventory of HAW and nuclear materials
NSID disposal has been considered in the UK in recent years for the following components of the UK HAW and nuclear materials inventory: • Short-lived ILW and other wastes close to the LLW/ILW boundary – at shallow depths [40,92]. • Magnox core graphite, and operational graphite – at intermediate depths [88,96]. • DNLEU – at intermediate depths [80]. Intermediate-depth concepts could be applicable to other components of the HAW inventory as well, but there has been no detailed consideration of this to date. Individual waste streams may be more or less suitable for NSID disposal, depending on their physical and chemical characteristics - activity concentration is not the only factor affecting their disposability (for example, see LLWR waste acceptance criteria [97]). Waste streams with, for example, significant quantities of stable heavy metals (which give rise to a hazard because of their chemotoxicity) may need to be specifically considered. A recent study conducted on behalf of RWM to identify boundary wastes suitable for near-surface disposal [40] considered the presence and quantity of the following materials in determining the suitability of waste streams: • Asbestos. • Corrosive metals. • Heavy metals. • Reactive metals. • Toxic materials. • Explosive materials. • Materials that could affect the retention of radionuclides, such as organics, ion-exchange materials, complexing and chelating agents. An NDA report on the long-term management of UK reactor core graphite in 2013

ALTERNATIVE:	Near-surface and Intermediate Depth (NSID) Disposal

concluded that it was not currently considered credible to directly dispose of reactor graphite to either the LLWR or to other radioactive waste permitted landfill sites [96].

Consideration of the UK inventory of graphite under the upstream optioneering programme [40] suggested that the whole of this waste group would have decayed to activity levels consistent with LLW by 2138. Although the content of carbon-14 would result in activities above the current authorised limit for disposal of these wastes to LLWR, it does not foreclose the option of disposal in alternative NSID facilities, such as might be developed in conjunction with a GDF. Treatment of graphite to remove the majority of the carbon-14 (for separate disposal) could facilitate near-surface disposal of the bulk material.

An assessment of the feasibility of NSID disposal of all or part of the UK DNLEU inventory [80] identified a number of issues that suggest intermediate depth disposal would be preferred over near-surface disposal (at shallow depth) for this material. In particular, the very long half-life of uranium-238 (the main radioactive constituent of DNLEU), and the in-growth of associated daughters, presents problems in making a robust long-term safety case for near-surface disposal of DNLEU because of the risk of eventual large-scale disruption of near-surface facilities through natural processes or human intrusion. The radiological hazard associated with the material does not decay significantly with time (in fact, radiotoxicity rises as short-lived daughters ingrow). Furthermore, although the activity level associated with the material itself is relatively low (most of the DNLEU inventory is categorised as Low Specific Activity (LSA-1) [98]), the chemotoxicity of uranium may also need to be taken into account in determining environmental impact under near-surface conditions. In addition, small parts of this inventory may also present concerns due to their enrichment or their chemical form, and disposal at a GDF may continue to be the favoured option for these inventory components. Nevertheless, disposal of the majority of the DNLEU at intermediate depths is regarded as feasible in principle, but is strongly dependent on site-specific conditions. Such disposal concepts offer most opportunities if earlier emplacement of DNLEU can be achieved by development of a simpler, purpose-built disposal area, and DNLEU disposal operations do not delay disposal of other wastes at a GDF, or if a restricted host rock volume limits disposal of the entire inventory at GDF depth. The most significant potential cost savings arise if development of such an intermediate-depth facility were to allow the currently assumed DNLEU disposal schedule to be significantly advanced, thus reducing costs associated with storage.

Near-surface disposal is not applicable to HLW and spent fuel because these wastes / materials need to be isolated over a timescale that cannot be assured at such depths. The radioactivity levels associated with HLW and spent fuel mean that anticipated doses arising from their disposal in near-surface facilities are unlikely to be acceptable

Potential impact on UK inventory of HAW and nuclear materials

As discussed above, as a minimum, there is potential for near-surface disposal at shallow depths to divert a proportion of the short-lived ILW from geological disposal and for intermediate-depth disposal to divert a substantial portion of the remaining HAW inventory, including graphite wastes and DNLEU (intermediate-depth disposal of other materials has not yet been investigated in detail). Estimates of the volume of wastes that could be diverted from a GDF are inherently uncertain as these figures require assumptions about the way in which the wastes are conditioned and packaged, which may be different depending on the disposal route and assumptions about waste package requirements. Thus, the volume of waste diverted from a GDF may not be the same as the volume of the same waste diverted to an NSID facility. The volumes given below should therefore be treated as only indicative of the magnitude of minimum volumes of waste involved.

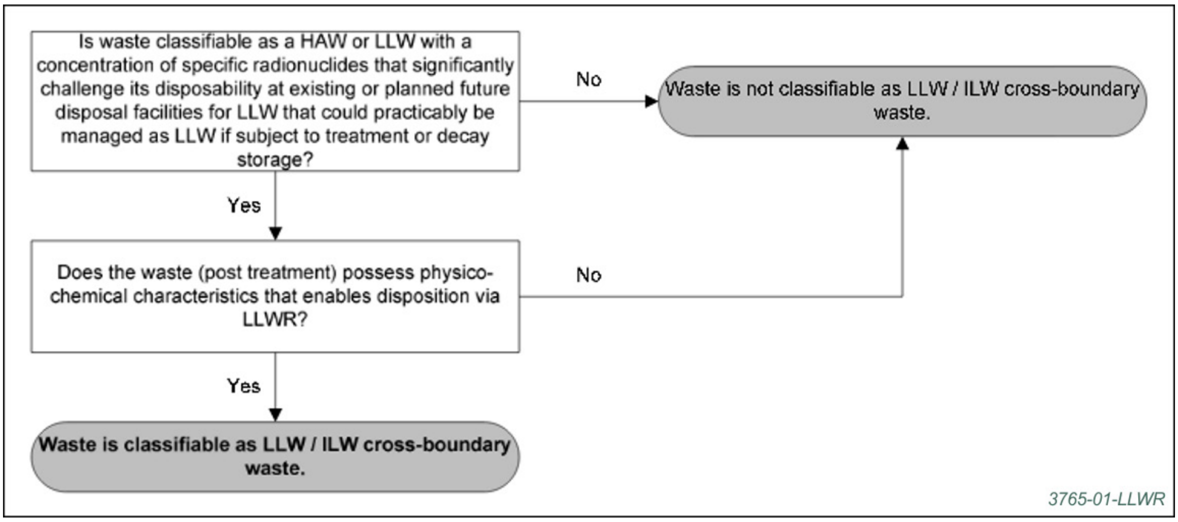
An RWM study [92] identified up to 45,000 m^3 (stored volume) of ILW that will decay to

ALTERNATIVE:	Near-surface and Intermediate Depth (NSID) Disposal

LLW within 300 years, with 88 waste groups, approximately 24,000 m^3, being short-listed as candidates for further consideration. LLW Repository Ltd is currently considering this inventory further as part of ongoing studies on short-lived ILW and boundary wastes. LLW Repository Ltd [95] has defined criteria for boundary wastes, and a review of LLW and ILW in the 2010 UKRWI identified approximately 156,000 m^3 (conditioned volume) of cross-boundary waste – see Figure 4.7. This volume is expected to be an upper estimate compared to the more conservative assumptions used in the RWM study [92].

Large volumes of operational and core graphite (66,000 te or approximately 80,000 m^3 packaged volume) [88,96] might also be suitable for diversion to NSID disposal facilities, depending on the ability to make a safety case for disposal of a specific inventory at a particular site. The feasibility of NSID disposal at around 30m depth has been considered in some detail for the case of operational graphite wastes arising at Hunterston, North Ayrshire [88], and is considered to be consistent with the policy of the Scottish Government [3]. A preliminary assessment for core graphite was also undertaken.

Figure 4.7: Test criteria for determination of boundary waste as defined by LLW Repository Ltd (from [95]).



A significant portion of the inventory of DNLEU may be suitable for routing away from a GDF. The total mass of civil DNLEU concerned is 170,000 tU [9]. The feasibility of NSID disposal of the DNLEU inventory was considered by the uranium Integrated Project Team, using a number of concepts for NSID facilities for disposal of this waste. The study considered the disposal of the waste in the form of unconditioned uranium oxide powders in the existing and planned storage containers (mainly steel “DV-70” containers). The total volume of the DNLEU inventory in the form of storage containers is approximately 95,000 m^3 [81]. Intermediate-depth facilities may be preferred compared to shallower depths for these materials because of their extremely long half-life and because of the potential radiological impact that would be associated with large-scale disruption of a disposal facility containing this material. Low enriched uranium and some miscellaneous DNLEU may be less suitable for NSID, owing to levels of enrichment and/or chemical form, but these comprise only a tiny fraction of the total UK DNLEU inventory (<2%).

The potentially large volumes of ILW and/or DNLEU that could be diverted to NSID facilities could significantly reduce throughput requirements at reception facilities and access drifts / shafts of a GDF and/or scheduling constraints on waste emplacement operations. The current schedule for GDF operations envisages emplacement of legacy LLW/SILW/UILW in the period 2040 to 2105 followed by new-build ILW and DNLEU.

ALTERNATIVE: Near-surface and Intermediate Depth (NSID) Disposal
Accelerating the emplacement of legacy ILW could result in significant cost savings from surface stores not refurbished or replaced, since a large proportion of this waste will have arisen before 2040 (although it would also be necessary to take into account the impact of discounting and reduced time for radioactive decay). Cost savings could also accrue from earlier disposal of the DNLEU, should it be declared a waste on timescales to facilitate this, as demonstrated by the uranium IPT[14] [80,99]. All of these wastes and materials will have arisen before 2040 and will require surface stores to be refurbished or replaced in the period between the present and when they are disposed.

[14] It is noted that recent changes to RWM's assumptions about how DNLEU would be packaged for disposal at a GDF (and handled during emplacement) in any case help to alleviate scheduling constraints associated with transferring this material through an inlet cell into the unshielded ILW disposal area (which was previously assumed to be required).

5 Deep Borehole Disposal

5.1 Introduction

Deep Borehole Disposal (DBD) has been suggested as an alternative disposal route for managing high activity, moderate volume components of radioactive waste inventories. It would entail the emplacement of waste packages in the lower portions of small diameter boreholes (< 26 inch diameter) drilled 4 to 5 km from the surface into crystalline basement rock.

Deep borehole concepts have been investigated (but not implemented) in several countries since the 1980's: United States [24,116,117], Sweden [133], Denmark [100], Germany [106] and South Korea [134]. Deep borehole disposal is not a proven technology and there remains considerable uncertainty over the feasibility of aspects of deep borehole disposal. Issues, such as waste package handling and retrieval, mitigation against accident scenarios (for example, dropped packages or stuck packages), as well as techniques for construction and eventual sealing would need to be addressed. Hence, the claimed potential advantages of DBD are not sufficiently underpinned to establish whether it offers any overall benefit as part of the UK's HAW strategy.

There is renewed interest in deep borehole disposal in the US for specific waste types, and in order to determine whether deep borehole disposal is feasible for sealed sources, field work is required. This has led to a 5 year programme of work planned in the US to investigate whether boreholes of 17 inch diameter can be drilled and dummy waste containers emplaced reliably.

5.2 Review of Deep Borehole Disposal

ALTERNATIVE:	**Deep Borehole Disposal**
Overview of alternative waste management option	
The main issues to be considered for DBD include: *Long-term safety:* DBD would provide an order of magnitude increase in the thickness of the geological barrier compared to a GDF (typically 200-1000 m below the surface). At 4-5 km depth, hydrogeological processes are thought to be slow or static, with very low hydraulic conductivities / permeabilities, as well as high salinity gradients (resulting in density stratified groundwater). Typically there are fewer natural processes driving groundwater movement than at shallower depths. These factors could provide greater isolation of the waste from surface induced perturbations, as well as greater containment, effectively preventing radionuclides from returning to the surface environment over the periods required to render long-lived radionuclides safe. *Technical maturity:* DBD of radioactive waste is of low technical maturity, has never been implemented, and field testing of the concept has also not been achieved. The individual steps that would be involved in implementing DBD (borehole drilling; installation of casing; characterisation; consolidation of waste; package emplacement; and borehole sealing) have all been the subject of extensive desk-based R&D, and for some, there is significant transferable experience from related industries, such as the oil and gas industry. However, the feasibility of their integrated application to radioactive waste disposal has not been demonstrated. Proof of the concept as feasible would be essential before it could be implemented as part of the UK's HAW management strategy. *Potential for mal-operations / accidents during waste package emplacement:* The transport of multiple waste packages to depths of several thousand metres, in boreholes with only limited clearance surrounding the packages, gives rise to the risk of packages becoming	

ALTERNATIVE: Deep Borehole Disposal
stuck during transfer and emplacement. Also, failure of the emplacement equipment could result in packages being dropped significant distances. Man access to the borehole would not be possible, so quality control (for example, to verify correct package emplacement positions) would be limited to indirect methods (for example, use of cameras / sensors), employed in a confined space. Retrieval / dislodging of stuck packages would be limited to remote techniques such as "fishing" (discussed later). In the worst case, failed emplacement operations could result in waste packages needing to be abandoned at depths other than that planned for disposal and/or packages being breached. The possibility for stuck/dropped waste packages could hamper the ability to make a safety case for DBD, so clear mitigation strategies would be needed. *Consolidation and/or repackaging of waste:* For materials such as spent fuel, it would be preferable to consider consolidating fuel pins / pellets (rather than packing whole fuel elements) to improve packing efficiency. The additional operations required could have significant implications for worker safety, environmental impacts, generation of secondary wastes and costs. *Retrievability:* Retrieving waste packages after they have been emplaced in a borehole at 4-5 km depth would be technically challenging, owing to the limited accessibility of packages (only the top package in a borehole would be immediately available) as well as the risk of packages becoming stuck or being dropped while being returned to the surface. Once a borehole had been sealed, retrieval would present significant technical and safety challenges. Whether there is a requirement for retrievability, over and above the requirement to be able to reliably emplace and recover from mal-operations, would need to be established. It is, however, worth noting that there could also be benefits associated with the challenge of waste package retrieval (for example, enhanced confidence in putting fissile material permanently beyond reach). *Uncertainty over site characteristics:* Deep basement rock can have considerable variability in chemical and physical properties and there are few well-characterised deep boreholes. Adequate characterisation for the purposes of DBD would require application of a range of techniques deep underground in a confined space. It would therefore be technically challenging to obtain the necessary information to ensure that assumptions about the favourable conditions expected to be present in deep boreholes can be confirmed. *Speed of implementation:* If proven to be technically feasible, regulatory approval gained and a suitable disposal site found, it might be possible to implement DBD relatively quickly. Studies have estimated that it would take a little over four years to drill, case, fill and seal a 5 km borehole [7,101] (although as yet, this has not been demonstrated). It is currently assumed that a GDF would not receive the first containers of HLW until at least 2075 [32] (although there is potential to bring this forward by some 35 years as some HLW has been cooling for decades). It is also potentially possible if DBD were available to dispose of the UK's HLW, that first emplacement could be brought forward by the same margin. If a deep borehole could be constructed, filled and sealed more quickly than a GDF, this could enhance the secure management of fissile material, by putting it beyond reach. Of course, DBD faces the same challenges as other forms of disposal in terms of identifying suitable sites where there is local support for disposal, and this can have a significant impact on timescales for implementing disposal. *Disposal costs:* In terms of technical implementation, DBD has been claimed to be potentially more cost effective than geological disposal for particular waste streams. For example, a cost comparison has been made with SKB's KBS-3V concept for the geological disposal of spent fuel. Using SKB's figures, DBD has been estimated to be a factor of five less expensive per tonne of spent fuel [102; Pages 155-156]. However, as with

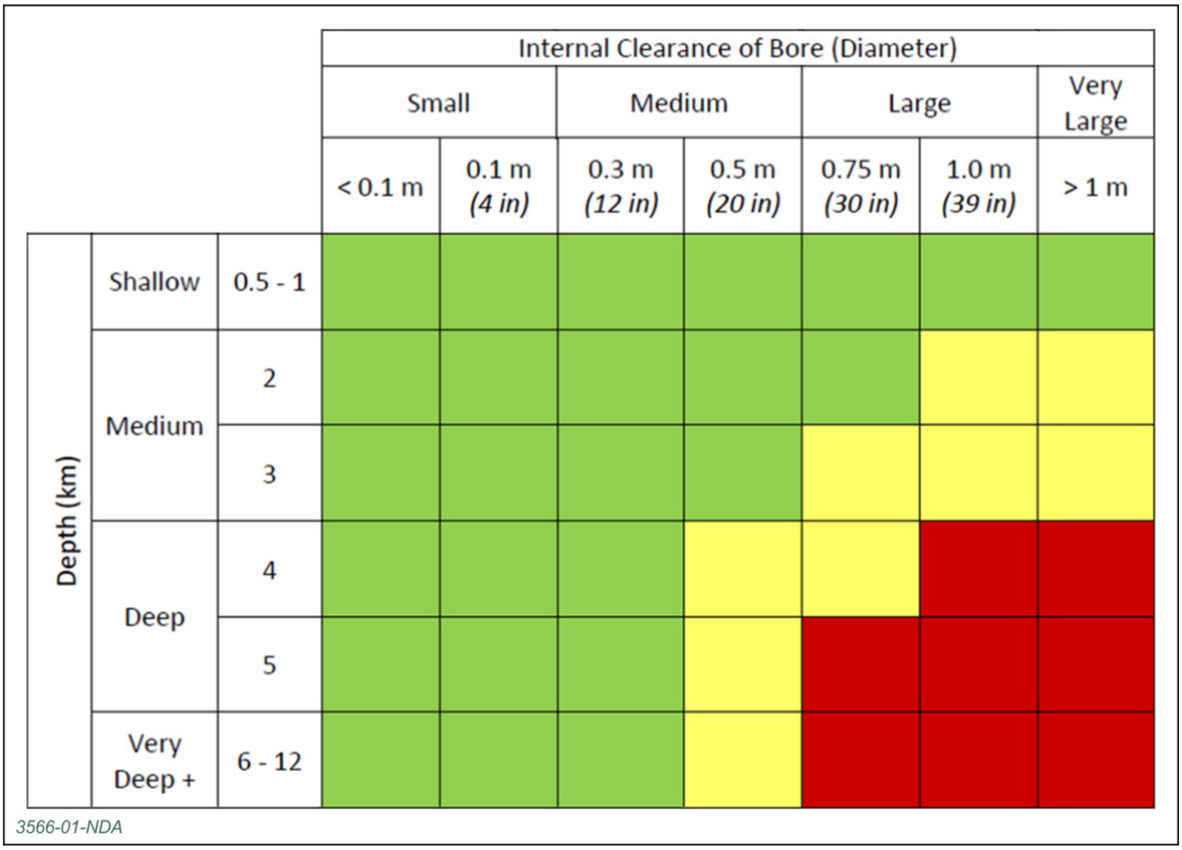
ALTERNATIVE: Deep Borehole Disposal
implementation timescales, discussed above, a large proportion of the costs of disposal are associated with siting, characterisation, stakeholder engagement and licensing. Such factors could dominate overall disposal costs. (It is also noted that the cost comparison above assumes that the use of DBD as an alternative disposal route would avoid the need to construct a GDF. This assumption does not apply in the UK, where a GDF is planned for disposal of all HAW. Cost differentials in this context would be between the cost of DBD versus the cost associated with those components of the GDF that were no longer required (for example, the vaults/tunnels associated with specific inventory components) – the wider GDF infrastructure would still be needed.) *Siting:* It has been claimed by some proponents of this technology that the increased isolation of waste and reduced environmental impact (both spatially and temporally) of DBD could possibly make this a more publicly acceptable disposal option than a GDF, thereby helping to ease the problem of finding a disposal site (although as described later in this report the recent experience in the USA suggests that siting an actual DBD facility for real wastes faces common issues to siting a GDF, and could be just as challenging). The boreholes themselves could be constructed on or close to the sites of nuclear facilities if the geology were found to be suitable. Such an approach would minimise the need for transportation of radioactive waste, thereby reducing associated safety risks and disturbances.
Current maturity of alternative waste management option
The basic technology for DBD exists in the drilling and nuclear industries, but requires demonstration through field tests to bring its technical maturity closer to the point of implementation for higher activity radioactive wastes. Understanding of the processes and interactions between disposal system components (for example, the features, events and processes (FEPs) applicable for safety assessment) is currently immature for DBD. For vitrified HLW, it remains to be demonstrated that holes of the width required can be drilled to depths of 4-5 km. For spent fuel, the basic technology for handling individual fuel rods exists, but would need developing for this specific application. The sealing and support matrix formulation requires development, both on a laboratory scale and in field scale trials – research is currently underway towards this end at the University of Sheffield. For plutonium, R&D that is being undertaken on wasteform fabrication may also be applicable to DBD. Other areas that would benefit from further effort include the development of an improved consensus within the DBD community concerning the safety functions that need to be provided by different components of the disposal system. In particular, the degree of emphasis to be placed on engineered barriers over the long-term, including the need, or otherwise, for a sealing and support matrix in the disposal zone is unclear - a complex engineered barrier system may not be necessary or desirable, noting that this complicates the overall disposal concept and its implementation (which is already challenging), and that the most important barrier associated with DBD is the host rock and overlying geology at the disposal site. Further development of the safety case for DBD during both the operational and post-closure phases would also be required, building on recently completed work by Sandia National Laboratory (SNL) [121]. Making a pre-closure (operational) safety case and post-closure safety case would be challenging for DBD; a pre-closure safety case is arguably more challenging, given the need to demonstrate that the waste would be safely handled and managed in the event of all conceivable emplacement difficulties.

ALTERNATIVE: Deep Borehole Disposal
Description of alternative waste management option

Basic DBD concept

DBD would involve sinking a vertical hole to a depth of at least 4 km below the surface into the crystalline basement. The hole would then be lined with steel casing to maintain its integrity and facilitate emplacement of waste packages, which would fill the hole below a depth of around 3 km - the disposal zone (DZ). The casing would be perforated in the DZ to allow wellbore pressure equalisation, as well as to enable sealing and support matrices to flow between the annuli and to reduce weight. The diameter of the hole would be largest near to the surface, but would become narrower in the DZ, where it could vary from 21.6 cm to 66 cm depending on the waste packages being disposed of [101]. Figure 5.1 illustrates how these diameters compare with the current state-of-the-art regarding the depth and diameter of boreholes that are considered feasible to drill. Waste packages would be lowered into the borehole, either individually or in strings using drill pipe, wireline or coiled tubing [101,103].

Figure 5.1: State-of-the-art of borehole deployment (in 2015) as a function of depth and diameter (adapted from [104], which draws on [7]). Depths and diameters shaded green are feasible using current technology, provided that geological conditions are favourable (boreholes have been drilled across this range); those shaded yellow could be feasible with modest tool and process development; those shaded red would require substantial development to achieve and are considered impractical in the foreseeable future.



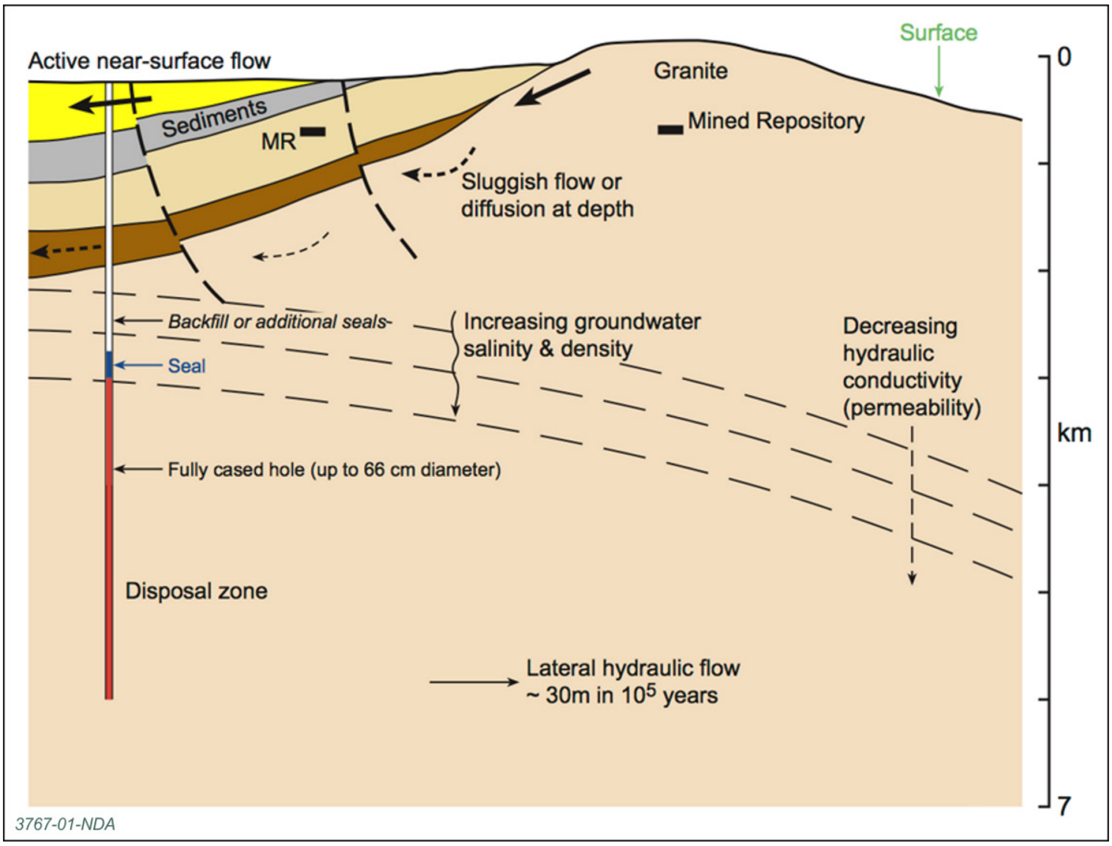
The spacing of waste disposal intervals at sites with multiple boreholes must meet thermal management requirements for disposal. When drilling a borehole, deviation of the borehole from its designed trajectory must be controlled such that the distance between any two boreholes is greater than 50 m at a bottom depth of 5,000 m [105]. Modelling has shown

ALTERNATIVE: Deep Borehole Disposal

the thermal interference between disposal boreholes is relatively small for spacing of greater than 50 m [105]. Drilling of multiple boreholes in an array must preclude the possibility of intercepting another borehole in which waste has already been emplaced. A ground-level borehole separation distance of between 100 and 200m has been suggested to provide adequate borehole separation at disposal depths [140].

DBD is a multi-barrier concept, where engineered barriers, including the wasteform, container, borehole seals (and potentially backfilling materials), would contribute to operational and long-term safety. However, considerable emphasis is placed on the geological barrier, with the thickness of rock providing isolation and containment. At the disposal depths considered for DBD, bulk hydraulic conductivities for intrarock fluid flow are expected to be extremely low, while upwards movement of potentially contaminated groundwaters would be likely to be further constrained by a density stratification caused by a salinity gradient, leading to isolation of deep water from near-surface waters that might have prevailed for millions of years (see Figure 5.2). Moreover, the impact of any seismic activity would be greatly reduced at increased depth.

Figure 5.2: Schematic diagram of basic DBD concept compared with a GDF (termed "mined repository" here).



Given the static, stable nature of the undisturbed natural environment, the most important contributions of engineered barriers to long-term safety are expected to be:

- To stop the borehole itself and the surrounding excavation damaged zone (EDZ), (sometimes known as the disturbed rock zone or DRZ), from becoming a preferential pathway for groundwater movement and contaminant transport.
- To contain radioactivity during the thermal phase associated with any heat-generating wastes, when convection driven by the heat output from the waste could

ALTERNATIVE:	Deep Borehole Disposal

temporarily drive enhanced upward groundwater movement.

Waste Package Emplacement

Coiled tubing deployment has developed rapidly over the last decade to a point where it is routinely used in holes to depths well in excess of the 4-5 km required by DBD. Deployment speeds are relatively fast: 2,000-3,000 m/h is achievable, though safe, practical speeds are likely to be less [101]. Coiled tubing offers technical advantages over both drill pipe and wireline emplacement techniques and is significantly less costly to implement than drill pipe emplacement, since it avoids the need for a large surface rig (which is required for drill pipe emplacement). Moreover, with coiled tubing, when lowering packages downhole, a greater degree of control may be obtained than wireline, though less than that for drill pipe emplacement.

The possibility of some packages becoming stuck in a borehole due to friction between the package and borehole casing would need to be considered. Possible options to mitigate this risk could include the use of continuous and smooth borehole casing, running a calliper or sensor ahead of each package during deployment to detect deformations or constrictions in the casing that might cause jamming, or fitting sacrificial centring fins to the waste containers which could be designed to come away without damage to the container if a package did get stuck and had to be pulled back up.

Several of the conventional strategies for dealing with downhole obstacles in the event of a blockage, such as drilling through the obstruction or forcing the container down the borehole could not be used when emplacing radioactive waste packages. Therefore, if packages became stuck during emplacement, retrieval methods known as “fishing” would be used. The technology and expertise for fishing is widely available and extensively used within the oil and gas industry [106; Page 189], although their application for waste package retrieval has not been tested.

Sealing and Support Matrices in the DZ

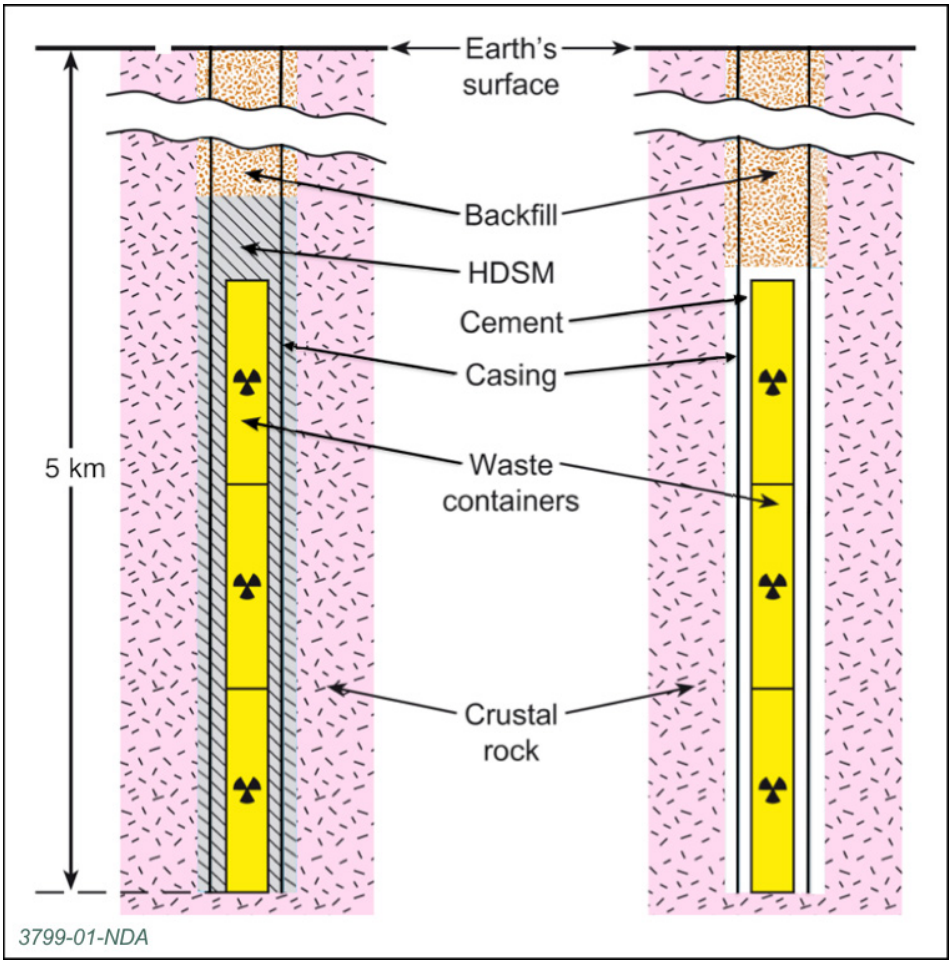
Once the waste packages had been emplaced in the DZ, the annuli between them and the casing and between the casing and the borehole wall would be filled with fresh water, brine or drilling/deployment mud depending on the exact DBD scheme. Such materials would be emplaced using conventional borehole drilling techniques. The choice between such filling materials would primarily be guided by the density of drilling fluid required to maintain wellbore stabilisation and drilling performance, so would not be specifically targeted to enhance long-term safety (although the fluid composition could potentially be tailored and/or varied with depth, to promote waste package longevity, or to encourage a quick return to “undisturbed” downhole conditions). As an alternative, some DBD proponents, such as Sheffield University’s DBD research group, advocate filling these spaces with a sealing and support matrix (SSM) instead. The primary function of an SSM would be to prevent the access of groundwater to the casing and disposal containers for as long as possible, thereby delaying any corrosion and helping to limit the release of any gaseous corrosion products or released radionuclides back to the surface. Corrosion could be further mitigated by application of a copper coating on the waste containers. A secondary function of a SSM would be to prevent the waste containers from being squashed by providing mechanical support against the hydrostatic pressure in the DZ and axial load stresses from the overlying waste containers, especially during the period before the borehole above is sealed. Two main SSMs are being actively developed: a High Density Support Matrix (HDSM) [107] and a high-temperature cementitious grout [108] (see Figure 5.3); these are discussed further below.

Whilst the use of an SSM as an engineered barrier would be potentially beneficial, it would increase the complexity of the deep borehole disposal concept. It would be difficult, if not

ALTERNATIVE: Deep Borehole Disposal

impossible, to demonstrate contiguous emplacement of the SSM in the small annuli between the waste packages, casing and borehole wall, particularly for cementitious SSMs.

Figure 5.3: Schematic diagram of DBD illustrating use of different SSMs [135].



HDSM

This is the currently preferred SSM by researchers. It is composed of a lead-tin alloy deployed as a fine shot, the size of which enables the filling material to penetrate into small spaces in the annuli. Radiogenic heating from the waste would quickly cause the shot to melt, and it would then flow, much like mercury, filling smaller void spaces. An alloy close to the eutectic composition would begin to melt at around 190˚C at the pressures found at the bottom of the DZ. This temperature could be tuned by varying the alloying metals and their mixing ratio. After the thermal pulse had subsided, the molten metal would cool and eventually re-solidify, forming an impermeable column of metal seal [135,119].

Research work on HDSM is being actively pursued at the laboratory scale, but this would need to be extended to a larger scale, and eventually to field trials to demonstrate feasibility. The concept is currently unproven and it is noted that, depending on site-specific conditions (for example, local fracturing of the rock), there could be potential for molten HDSM material to migrate away from a disposal borehole. HDSM could be especially beneficial in a DBD disposal scheme for spent fuel (see later). It is noted that tin and lead are both chemotoxic, so their inclusion in disposal concepts would require careful consideration to ensure there would be no associated detrimental impact (for example,

ALTERNATIVE: Deep Borehole Disposal

potential for contamination of aquifers). An alternative to tin would also be preferable on cost grounds.

Cementitious Grout

For some waste packages, for example unconsolidated and older spent fuel, small waste inventories and/or non-heat-generating wastes, radiogenic heating may not be sufficient to give complete melting of HDSM in the annuli. In these cases, the use of a special cementitious grout would be a possible alternative. Application of cementitious grouts in DBD would be challenging in view of the adverse conditions found downhole (aggressive saline environment, elevated temperature and pressure) which give rise to a reduction in the thickening and setting time and would influence the phase composition of the hardened cement phase with knock-on effects on its durability and mechanical strength. Temperature has a far greater influence than pressure and research has therefore focused on finding a cement formulation with a delayed thickening and setting at elevated temperature. Formulations have been developed based on class-G oil well cement plus an organic additive (for example, sodium gluconate [108] or polycarboxylate superplasticiser [109]). The correct amount of additive has been determined which not only maintains grout fluidity (important for emplacement), but also delays the onset of thickening at temperatures up to 140°C for a time of 4 hours or more (the estimated practical one-way trip time for emplacement of a waste package using coiled tubing). It has been found that these new cementing systems set within 24 hours. Noting the potential for organic materials to enhance radionuclide mobility, current research is focused on finding non-organic additives which yield grouts with similar properties to those with the organic additives, as well as evaluating different emplacement methods (cement in first followed by waste package or *vice versa*).

As noted above, emplacement of cementitious SSMs is a considerable challenge, particularly with regard to ensuring a complete annulus fill while working “blind” downhole with no way of confirming success.

Sealing of the Borehole

SSMs would need to be designed to provide sealing of the annulus within the DZ. However, regardless of whether SSMs are used, a permanent (or at least long-lasting[15]) sealing of the borehole above the DZ that also seals or isolates the EDZ would be required to ensure complete isolation of the waste packages. As noted earlier, ensuring that the borehole itself cannot become a preferential pathway for radionuclide migration would be crucial to underpin the isolation of radioactive waste. A number of sealing options exist including cement, concrete, bentonite clays, asphalt, and swell packers (of which there is extensive experience to draw upon from the oil, gas and geothermal industries). Alternative, emerging technologies developed specifically for DBD include the use of the thermite reaction to create oxide/ceramic plugs [110] and rock welding [111].

Rock welding would operate as follows: (1) a section of borehole casing would be removed close to where the seal will be situated, well above the DZ to ensure no detrimental impacts on the waste; (2) crushed host rock would be emplaced in the hole; (3) a sacrificial heating device would be lowered into the crushed rock with power supplied from the surface through an umbilical cord inside coiled tubing; (4) more crushed rock would be emplaced to completely bury the heater; (5) a pressure seal would be set above the crushed rock; and (6) heat from the electrical elements would raise the temperature of the

[15] Arguably, boreholes may only need to be sealed for a few hundred years (until the thermal phase has passed and static conditions are restored) to enable a satisfactory long-term safety case to be made.

ALTERNATIVE: Deep Borehole Disposal
rock above its solidus for a set period before power reduces leaving the rock magma to slowly cool and recrystallise, forming a permanent seal which extend beyond the annulus through the EDZ (thereby eliminating it in the vicinity of the rock weld and removing it as a continuous pathway to the surface). However, it should be noted that the temperatures that would be involved in rock welding (typically ~800°C) would create thermal and other disturbances in the host rock overlying the DZ that would be potentially far more intense and extend over greater distances than those associated with the thermal phase of the waste itself. Of all the sealing methods, rock welding would be the only one potentially able to eliminate the EDZ. While the underlying science of melting and recrystallisation has long been understood generically for granite [112,113], the exact relationships would need to be refined for any specific host rock involved (but they would be only slightly different in detail, for example, in the exact percentage of melting at any temperature). The process would need to be scaled up and demonstrated under the pressure and temperature conditions of DBD, and heaters and engineering for downhole implementation have yet to be developed. RWM is currently funding a three-year project to develop generic approaches to seal boreholes drilled as part of site investigations at a potential GDF site [114]. This work relates to site investigation boreholes, rather than disposal boreholes, and considers narrow diameter boreholes drilled at shallower depths than are relevant for DBD. Nevertheless, the outputs of the project may provide useful insights into approaches that could be used to seal deeper, larger diameter boreholes drilled for DBD.
Status of current practices / recent developments
<u>Status of DBD in the UK</u> In the UK, RWM has taken the position of maintaining a watching brief over DBD, as recommended by CoRWM [4]. Conceptual development of DBD and underpinning R&D is therefore largely confined to university research groups. The DBD research group at the University of Sheffield hosted a conference devoted to DBD in June 2016. This was attended by scientists and engineers from several countries, including France, Germany, South Korea, Sweden, Switzerland, the UK and the USA, as well as international bodies such as the IAEA. An outcome from this meeting was the production of a position statement by the panel members and represents their views rather than a consensus opinion of the meeting participants [115]. It was recognised that a mature safety case needs to be developed and technology demonstrated as feasible in order to underpin the consideration for this option as part of a country specific national strategy. The techniques and expertise for field tests and safety case development are already available in the radioactive waste management industry and elsewhere, and work is underway in the USA that aims to progress developments in both of these areas. <u>Status of DBD in the USA</u> Following the termination of federal funding for the Yucca Mountain programme, the Obama administration established a Blue Ribbon Commission to review the future of nuclear power in the USA, including disposal. Amongst other conclusions and recommendations, its 2012 report stated "…*the Commission has identified deep boreholes as a potentially promising technology for geologic disposal that could increase the flexibility of the overall waste management system and therefore merited further research, development and demonstration*" [24]. In response to this, the DOE funded Sandia National Laboratories (SNL) to prepare a roadmap for the research, development and practical demonstration of the concept. A DOE assessment of options recommended DBD for smaller DOE-managed wasteforms such as Cs and Sr capsules at Hanford [116]. The

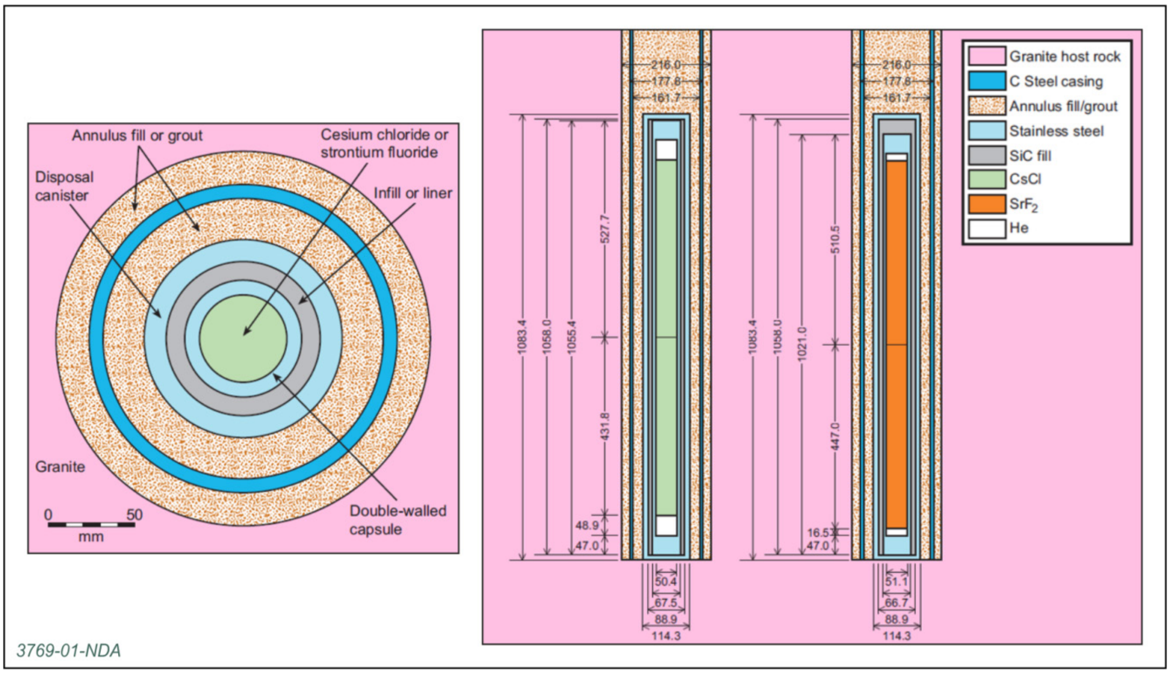
ALTERNATIVE:	**Deep Borehole Disposal**

DOE and SNL also established plans for a Deep Borehole Field Test (DBFT) [117]. Both are discussed below.

Hanford Capsules

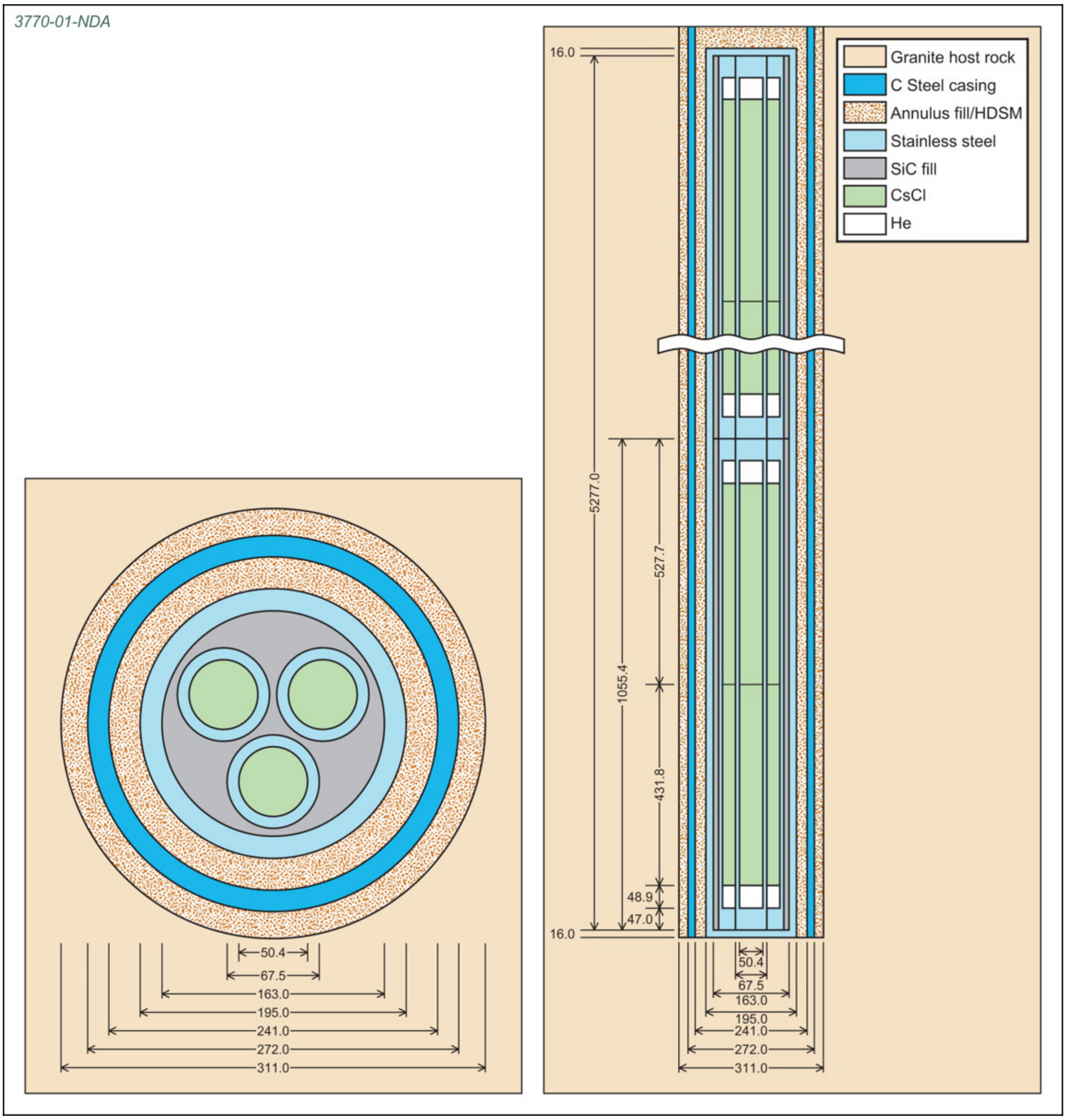
The United States DOE is considering DBD for the disposal of 1936 capsules containing halides of Cs-137 and Sr-90 currently in wet storage at Hanford; these capsules presently account for around one third of the total activity at this site. The small, double-walled capsules vary in length between 0.51 and 0.53 m, with an outer diameter of 6.7 cm. Approximately two-thirds of the capsules contain CsCl with the remainder holding SrF_2. Both Cs-137 and Sr-90 have relatively short half-lives (30.02 and 28.79 years, respectively) so the associated activity will decay relatively quickly. However, all of the caesium capsules also contain small amounts of Cs-135, which has a half-life of 2.3 million years and requires management on much longer timescales. A conceptual model for disposing of the entire inventory in a single borehole has recently been put forward [118]. Travis and Gibb [137] originally proposed emplacing pairs of capsules (placed axially end-to-end) in a larger stainless steel container, in-filled with silicon carbide to provide thermal conductance and mechanical support. They considered a disposal concept in which a borehole with a 21.6 cm (8.5 in) diameter would be drilled to a depth of 4-5 km and cased, with the DZ occupying the lowest 1 km of the hole. More recently, the same authors proposed a revised concept in which each overpack would contain 30 capsules [119]. The advantage of this greater density of capsules is that the length of the DZ is much shorter, and therefore the borehole need not be drilled as deep. Alternatively, for the same depth of borehole, the top of the DZ could be more remote from the surface, thus increasing the geological barrier. The containers for this purpose have an outer diameter of 19.5 cm and would require a borehole with a diameter of 31.1 cm (12.5 in), still well within the capabilities of existing drilling technology [101] and less than the diameter of the main borehole in the planned DBFT. The two disposal concepts are illustrated in Figure 5.4 and Figure 5.5.

Figure 5.4: Transverse and longitudinal cross sections of the original DBD concept for packaging pairs of CsCl / SrF2 capsules in stainless steel containers [137].



ALTERNATIVE: Deep Borehole Disposal

Figure 5.5: Transverse and longitudinal cross sections of the "triples" DBD concept for disposal of CsCl capsules. The longitudinal cross section is viewed from a point just inside the front of the container [119].



SNL has developed a safety assessment for the disposal of the Cs and Sr capsules in a single deep borehole [120]. Both pre-closure and post-closure safety were considered. Pre-closure safety used event tree analysis and considered the possibility of packages becoming stuck, tools being dropped downhole, and similar events. The post-closure safety assessment employed a multiphase flow and transport computer code to evaluate vertical transport through borehole seals and to determine surface doses. Preliminary results suggest minimal radionuclide releases beyond the DZ and zero dose at the biosphere during the ten million year assessment period.

Deep Borehole Field Test

The DOE and SNL have established plans for a Deep Borehole Field Test (DBFT) [117], which will entail the drilling of a 21.6 cm (8.5 in) diameter characterisation borehole, and a

ALTERNATIVE: Deep Borehole Disposal

43.2 cm (17 in) demonstration borehole, both to a depth of 5 km. The smaller hole will be used to characterise the lithology, structural geology, groundwater geochemistry and other downhole properties, with a view to testing the suitability of various techniques for site characterisation. The larger borehole will be drilled following successful completion of the characterisation borehole and will enable further characterisation but its main purpose is to test the engineering (drilling, casing and emplacement and retrieval of packages, demonstration of pre-closure and post-closure safety) associated with DBD. It is noted that the borehole diameters planned for testing within the DBFT are smaller than those anticipated to be required for disposal of some UK HAW.

The DBFT is planned to have a 5-year duration and has a budget of $80M [103,121,122]. A site for the DBFT was identified in Pierce County, in North Dakota, in early 2016. However, following public meetings, the DOE was informed that it must cease consideration of the DBFT in Pierce County in March 2016, owing to local community concerns [123]. A second suitable site in Spink County, South Dakota, was proposed in April 2016, but this has also been rejected by the local population [124]. In August 2016, the DOE put out a request for proposal for new sites [125]. As a result of this request for proposal, four candidate sites and test teams have been identified and contracts have been awarded by DOE. Each contract team is conducting community outreach and completing the necessary regulatory permits. If more than one team obtains community acceptance and approval to advance to the drilling and testing phase, DOE will conduct a down selection based on geologic site characteristics and the technical quality of a contractors drilling and testing plan.

There are any number of sites throughout the USA that satisfy the site suitability technical guidelines defined for the DBFT, but difficulties finding a suitable site have been predominantly to do with societal acceptance and, in particular, concerns that the test site would subsequently be used for radioactive waste disposal. This experience suggests that siting an actual DBD facility for real wastes faces common issues to siting a GDF, and could be just as challenging.

Nuclear Waste Technical Review Board International Workshop

The United States NWTRB held an international workshop on DBD of radioactive waste in Washington DC, in October 2015. The findings of the NWTRB have been published [126]. Many of the issues highlighted by the NWTRB were specific to the USA and/or to conducting the planned DBFT. However, more widely relevant recommendations were also made, including the need for a comprehensive risk analysis covering all aspects of drilling and emplacement of waste containers, and an analysis of the safety benefits of using a more robust wasteform and/or container within DBD disposal concepts, as part of developing associated safety cases. The review board was also concerned about the feasibility of obtaining adequate data to underpin the safety case for DBD.

<u>Status of DBD in Sweden</u>

Sweden has considered DBD as an alternative management option to a GDF for disposal of spent fuel. A number of studies were commissioned by the Swedish Nuclear Fuel and Waste Management Company (SKB) in the late 1980s, including the work of Juhlin and Sandstedt [127]. These informed SKB's Project Alternative Systems Study (PASS), in which SKB compared its own Very Deep Hole (VDH) concept with several mined repository systems including KBS-3 [128]. VDH was ranked last in all three detailed comparisons undertaken in the study (of technology, long-term performance and safety, and costs) and consequently came last in the overall ranking. The PASS concluded that the long-term safety of VDH was potentially as good as that of a GDF, but would be more difficult to demonstrate, and placed an emphasis on only one barrier, the geosphere, about

ALTERNATIVE:	**Deep Borehole Disposal**

which knowledge was limited at relevant depths in Sweden. SKB's position was that it would take at least 30 years of development and huge financial investment to bring the technology for VDH to a comparable level of maturity as that for the KBS-3 disposal concept.

More recent comparisons between DBD and disposal of spent fuel using the KBS-3 method have also been carried out (for example [129]). The overall conclusion of this work was that there was no basis in 2010 to suggest that a switch to planning for disposal in deep boreholes would result in a safer final disposal of the spent nuclear fuel than is offered by the KBS-3 method. The report also concluded that the KBS-3 method provides a final disposal of the spent nuclear fuel that can be controlled and verified at every step, while this is not possible in the case of disposal in deep boreholes. The retrievability of the waste was also a key issue for Sweden (as noted earlier, retrieval of waste from DBD would present significant technical and safety challenges).

SKB has continued to commission research into DBD in parallel with development and planning for implementation of the KBS-3V disposal concept in Sweden. Recent studies have included consideration of the radiological consequences of accidents during disposal of spent fuel in a deep borehole [130], a review of geoscientific data of relevance to DBD in crystalline rock [131], and development of a conceptual model for gas generation and transport associated with DBD of spent fuel [132].

In its 2013 Research, Development and Demonstration (RD&D) Report [133; Section 28.2], SKB stands by its assessment from previous RD&D programmes: that disposal in deep boreholes is not a realistic method for final disposal of spent fuel. SKB notes that it nevertheless intends to continue to monitor developments in the areas of drilling and disposal in deep boreholes, and to make use of any results from drilling programmes in Sweden that could be of relevance to the deep boreholes concept.

<u>Status of DBD in other countries</u>

The German parliament has taken the view that the country must develop the *safest* possible GDFs, and there has been a significant amount of debate about what "safest" means. A working group has been established to review the technical and scientific challenges and determine a site for a geological disposal. A scientific workshop was held in Berlin, in April 2015, the output of which was supportive of further investigations into DBD [106]. In South Korea, a feasibility study was launched in 2013-2014 for the preliminary evaluation of the geo-environmental characteristics of deep geological formations. This study had a budget of US$ 45,000. A second study was initiated in 2015-2016 with three times the previous budget, but this included a feasibility study into establishing the use of DBD for spent fuel in South Korea. The potential use of DBD as an alternative to disposal in a GDF is included in the National Basic Plan for HLW management in South Korea [134].

Applicability to management of UK inventory of HAW and nuclear materials

DBD would not be appropriate for the disposal of large volumes of LHGW. DBD would only be applicable to the disposal of wastes that are suitable for packaging in containers that would fit within a borehole, such as vitrified HLW and spent fuel, including high burn-up spent fuel from new nuclear build. For example:

- Vitrified HLW from UK reprocessing - would require boreholes with a diameter of 61-66 cm depending on the overpack [9,103].
- Spent-fuel - would require a range of waste packages tailored to spent fuel arising from different reactor types, including spent mixed oxide (MOX) fuel [137]. For

ALTERNATIVE: **Deep Borehole Disposal**
example, pressurised water reactor (PWR) fuel rods – removed from assemblies and consolidated in stainless steel containers for improved packing efficiency – it has been claimed would require boreholes 56 cm in diameter [135]. Alternatively, complete PWR assemblies would need approximately one third of the packing efficiency using the same borehole diameter. • Plutonium – schemes have been suggested for plutonium either by fabricating a low specification MOX and treating it as waste, or by creating MOX fuel to be burned in future licensed Generation III/IV reactors, followed by disposal [101] and also plutonium converted to a ceramic wasteform via HIP or in a wasteform comprising recrystallised granite [136]. Small volume, high hazard problematic waste streams may also be compatible with a tailored DBD concept. For example, in the USA, a single borehole, with a 31 cm diameter in the disposal zone, could accommodate the entire Hanford Cs/Sr halide capsule inventory [137].
Potential impact on UK inventory of HAW and nuclear materials
As DBD would not be appropriate for the disposal of large volumes of LHGW, it would not obviate the need for a GDF in the UK. The technology would need to be demonstrated as feasible before any of the potential claims could be established as offering any overall significant benefits to an UK HAW strategy. If the technology for DBD could demonstrated on an appropriate timescale disposal of applicable waste types via DBD has the potential to bring forward its disposal [32]. At a high level some scoping studies have been performed on the packaging needed and number of deep boreholes required. <u>Vitrified HLW</u> The 2013 UKRWI estimates there will be 1,080 m^3 of HLW [9], mainly from spent fuel reprocessing (with an allowance made for the volume reductions arising from vitrification of untreated waste). A large quantity of vitrified HLW is already packaged in containers with an outer diameter of 43 cm. If DBD were used as the disposal option, it has been previously estimated that the entire inventory of HLW would require eight boreholes [140]. A borehole outer diameter of 66 cm would be wide enough to take containers up to an outer diameter of 45 cm, enabling the use of overpacks were these to be deemed necessary. A borehole diameter of 66 cm at a depth of 4-5 km is at the limit of what is currently considered to be realisable in the foreseeable future, as indicated in Figure 5.1 (a 66 cm diameter borehole has been drilled and cased to a depth of 3.8 km [104,138]). Numerical modelling work suggests that the maximum temperature calculated along a horizontal radius measured from the centre of a waste container would be only a few degrees above ambient at a distance of around 25 m (based on data in [139]; Figure 4). <u>Spent Fuel</u> Although many DBD schemes could potentially accommodate complete used PWR and boiling water reactor (BWR) fuel assemblies, it would be more efficient to remove the fuel rods from the assemblies and consolidate them in waste containers. The technology for handling individual fuel rods already exists in many reactor fuel ponds and could be modified for the purpose of consolidated disposal. Fuel rods would need to be removed from the assembly in the fuel ponds and then either be (a) placed in a disposal container and sent to the packaging facility or (b) put in some sort of flask for transport to the packaging facility where they would be put into the disposal container. In both cases the container would then require to be heated slowly to ~330°C to drive off any remaining

ALTERNATIVE:	Deep Borehole Disposal

moisture before the voids were filled with molten lead. The container would then be sealed and cooled. Consolidated spent fuel packages would have densities of between 8,500 and 10,000 kg/m^3 – only slightly higher than the density of the HDSM described earlier, allowing these packages to gently sink through the molten HDSM and giving superior structural support once re-solidified (although central positioning of the containers within the surrounding HDSM could be difficult to control). Modelling work suggest that young, hot, spent fuel be disposed of in DBD without deleterious effects on the engineered barriers, but that higher heat output is advantageous from the point of view of using HDSM as an SSM [135].

Earlier scoping studies by Nirex estimate that approximately 13 deep boreholes would be required to dispose of the UK's legacy spent fuel [140].

<u>Plutonium</u>

Plutonium is included in the inventory for geological disposal, but is not currently classified as waste but could be at some point in the future, if it is deemed to have no further use. In December 2011, the UK Government set out its preferred policy for the long-term management of plutonium – that it should be reused in the form of mixed oxide fuel. However, only when the UK Government is confident that this could be implemented safely, securely and in a way that offers value for money, will it be in a position to proceed [1]. DBD would be capable of disposing of spent MOX for the same reasons as discussed under the section 'Spent Fuel'. As part of supporting Government in its development of policy for the management of plutonium the NDA have also considered the option of immobilising plutonium using Hot Isostatic Pressing (HIP) prior to geological disposal. This wasteform could also be potentially compatible with DBD. There has also been academic research on the development of granitic wasteform [136].

Earlier scoping studies by Nirex, based on plutonium immobilised as a ceramic, estimate that approximately 11 deep boreholes would be required to dispose of the UK's stocks of separated plutonium [140].

6 Synthesis and Conclusions

Four alternative radioactive waste management options have been considered in this review: two alternative steps in long-term radioactive waste management (long-term interim storage and HAW treatment), which could alter the nature and/or reduce the quantity of waste requiring geological disposal; and two alternative disposal routes (near-surface/ intermediate depth disposal, and deep borehole disposal), which could divert waste away from a GDF.

It was noted at the start of this document, in Section 1.3, that a recurring conclusion from previous reviews of alternative waste management options was that no alternative, or combination of alternatives, would completely obviate the need for a GDF. Nothing has been found in this review that challenges or alters this conclusion. The various alternative waste management options considered in this review could each potentially be applied to one or more components of the UK HAW inventory. However, a GDF will continue to be required for disposal of some HAW inventory constituents. In particular, it is difficult to envisage an acceptable alternative disposal route to a GDF for long-lived ILW.

RWM has contributed to the evaluation of some of the alternative waste management options for application to UK HAW over recent years, with a view to determining the impact of such options on a GDF and potential benefits for the whole waste management lifecycle, including:

- Work to investigate the potential advantages and disadvantages of centralising storage of ILW in the UK (in contrast to the current strategy of interim storage at each former reactor site) [22]
- Evaluation of opportunities to improve waste management practices for ILW and LLW [99], including:
    - Identification of an inventory of waste potentially suitable for diversion away from geological disposal based on activity levels, constituent radionuclides and other waste characteristics [41]
    - Evaluation of the potential for application of existing policy and guidance regarding the management of radioactive waste by safety case argument, rather than by waste classification [13]
    - Identification of opportunities for alternative disposal routes for wastes at the boundary between ILW and LLW [101]
- Work to evaluate the feasibility of NSID disposal of specific HAW and nuclear material inventory components such as graphite and DNLEU [80]
- Development of an integrated evaluation of how NSID disposal of ILW, underground storage of spent fuel (combined with staged licensing of disposal), and deep borehole disposal of vitrified HLW, could help to accelerate the implementation of geological disposal in the UK [32]

RWM is also participating as a stakeholder in other initiatives been led by the NDA and SLCs, including work to evaluate the feasibility of disposing of short-lived ILW at the LLWR, near-surface disposability of boundary wastes and the development of thermal treatment technologies for application to UK HAW (the latter as part of the NDA’s integrated project team on thermal treatment).

Key findings for each of the options reviewed in this report are summarised below.

6.1 Long-term Interim Storage

As an alternative management step, long-term interim storage constitutes an extension to practices that are already an essential part of national strategy for HAW management, beyond currently assumed timescales, in order to realise some additional benefit. As such, technologies for implementing long-term interim storage are proven and already in widespread use, so are available for implementation when required. In general, long-term interim storage can be advantageous because it does not foreclose future treatment or disposal options, and it allows additional time for radioactive decay. Notwithstanding the potential benefits, long-term interim storage requires the continuation of active management and institutional control of storage facilities, as well as replacement of these facilities (and potentially waste packaging) when they reach the end of their design life. This commits future generations to ensure safe long-term waste management, with associated implications for worker safety, secondary waste generation and costs. These issues become more acute the longer the storage continues, hence indefinite storage without a final disposal route is not considered ethically acceptable.

The key findings of the review of advances in the technology in recent years are:

- <u>Long-term interim storage of HLW/SF</u> – Delays in national geological disposal programmes and/or limited capacity for wet storage of SF in ponds has raised interest in storage of HLW and/or SF in dry casks. In some cases these casks have been proposed for multiple purposes – storage, transport and geological disposal. UK specific studies have been carried out to investigate the feasibility of geological disposal of these alternative disposal containers. The approach offers the potential benefit of reducing the handling of spent fuel assemblies and storage period required prior to disposal through judicious mixing of fuel of different ages. Further work is being undertaken to investigate smaller MPC designs better suited for the UK rail infrastructure and proposed GDF handling systems. The UK has just completed construction of its first dry cask storage facility at Sizewell B [16] and the broader use of dry cask storage is being investigated by the NDA [17]. Dry vault storage of spent fuel is in operation at Wylfa power station.
- <u>Decay storage of ILW</u> – Decay storage of ILW has been identified as an opportunity that could potentially result in significant reductions in the inventory requiring geological disposal (for example, through short-lived ILW being identified as suitable for disposal in LLWR). Decay storage of some ILW at a tactical level is already being practiced by some waste owners in the UK. RWM, the NDA and LLW Repository Ltd have all shown considerable interest in recent years in opportunities to employ decay storage in the UK, as evidenced by the NDA's decay storage strategy paper [39], work carried out under the upstream options programme (for example, [41,99]) and ongoing studies to consider the disposability of short-lived ILW and boundary wastes to the LLWR. Regulatory guidance also provides for disposal of short-lived ILW at near-surface facilities, even without a period of decay storage prior to disposal [35]. As the benefits of decay storage will be highly waste stream, timing and context specific opportunities for decay storage are being considered on a case by case basis by waste owners.

As well as long-term interim storage, recent work has also considered centralised storage. Such an approach would consolidate waste / material at a small number of modern facilities, and may provide increased efficiency of arrangements for long-term storage over timescales of decades or centuries, as well as enabling the waste / material to be removed from nuclear power plant sites at an earlier date [22].

Ultimately, the implications of long-term interim storage as an alternative management step for UK HAW depend on the extent to which it is implemented and the timescales over which it is applied, but will never remove the need for some form of permanent disposal of HAW, including a GDF. It is noted that extended long-term interim storage will have to be implemented in the UK until such time as a GDF or other disposal route becomes available. This is a key factor underpinning much of the recent interest by SLCs in opportunities to realise a benefit from extended long-term interim storage. RWM will continue to work with the NDA and SLCs to identify the role that long-term interim storage could play in the overall lifecycle management of radioactive waste management. Ongoing, collaborative work to consider the management of problematic wastes as part of an integrated project on this topic has identified the potential application of decay storage as part of finding effective waste management solutions for such wastes and possible re-routing waste away from a GDF.

6.2 HAW Treatment

A wide variety of options are available for the treatment and conditioning of HAW, as identified in the NDA's HAW treatment framework [12]. The extent to which these can be considered as "alternative" management options (at least in the UK) depends largely on whether they are considered within current waste management strategies at UK nuclear sites and within SLCs' integrated waste management strategies (for example [42]), as well as whether they are factored assumptions for packaging of future waste arisings within the inventory for geological disposal [9]. Treatment and conditioning plans are continually being reviewed and refined, such that technologies which might be considered as alternatives at present may soon be integrated into baseline strategy. In order to bound the scope of this review, decontamination treatment techniques, along with encapsulation in conventional cements or polymers are considered to be part of current baseline practices for UK HAW and were not reviewed. Thermal treatment techniques, "enhanced" cement encapsulation in tailored grout formulations, as well as P&T, are considered to be alternative treatment steps and have been reviewed.

Implementation of additional treatment steps could help to facilitate re-routing of some HAW away from a GDF to a near-surface or intermediate depth disposal facility. Some techniques (for example, decontamination) would concentrate radioactivity into a relatively small volume, allowing the bulk of the waste volume to be diverted away from a GDF. Other techniques, such as thermal treatment or "enhanced" encapsulation could produce more robust / inert wasteforms that provide a greater degree of containment compared to conventional cement-grouted wasteforms and, hence, could provide enhanced confidence in the long-term safety of radioactive waste disposal, even at shallower depths. Consequently, there is a strong synergy between HAW treatment and near-surface/ intermediate depth disposability.

- <u>Thermal treatment</u> – Many thermal treatment techniques are available at varying levels of maturity, from small test plants to full scale active plants already used to treat radioactive waste. Of these, several are receiving particular attention for application to UK wastes, including joule-heated melting and vitrification (both continuous and batch processes), plasma melting and vitrification, and HIP. Thermal treatment offers significant potential benefits for disposability, by significantly reducing the solid volume of waste as well as its chemical reactivity. A key mechanism to develop thermal treatment capabilities and their application to UK HAW is the NDA-led thermal treatment IPT, which aims to establish a demonstration facility on the Sellafield site. RWM will continue to participate in this IPT and maintain awareness of the status of developments in this field.
- <u>Alternative encapsulants</u> - Alternative or "enhanced" cement formulations for waste encapsulation offer tailored alternatives that may be better suited for the encapsulation of certain problematic wastes that could react detrimentally with conventional CEM-I -based grouts (for example, by retarding setting and strength development or through enhanced corrosion of reactive metals at high-pH). The main benefit of such formulations is their improved compatibility with the raw waste; little volume reduction compared to more conventional formulations is anticipated. Generally, these formulations are novel, and would require extensive further development before they could be implemented for conditioning waste. Since the most appropriate enhancements are likely to be waste stream specific, any further

development work would be led by SLCs as appropriate, focusing on specific problematic wastes. In parallel, as recognised in the science and technology plan, RWM could consider the potential impacts of alternative encapsulants on other materials expected to be present in a GDF and on the disposal system safety case [6].

- Partitioning and Transmutation - Whilst P&T offers the possibility to reduce the radiotoxicity, neutron output and decay heat associated with spent fuel and HLW, some long-lived radionuclides are practically impossible to transmute, so P&T does not obviate the need for geological disposal of HAW. P&T could conceivably help to reduce the inventory of certain radionuclides that might be more prevalent in higher burnup closed fuel cycles associated with spent fuel from new nuclear build (for example; Np, Am and Cm). R&D into P&T over the last few years has continued to contribute incremental increases in understanding, rather than breakthrough developments in the readiness of the technology for application. P&T remains a far from industrially mature technology and would require substantial further R&D and investment to implement. These conclusions are consistent with how P&T is viewed in other countries with mature nuclear power and radioactive waste management programmes (for example, France [141]) and with the views of the International Association for Environmentally Safe Disposal of Radioactive Material (EDRAM) [142]. Nevertheless, given the continued international interest in P&T, RWM will continue to monitor developments in the field of P&T as part of its overall periodic review of alternative waste management options.

RWM recognises that there is uncertainty over the choice of treatment and conditioning options that may be employed as part of future HAW management, and acknowledges that any changes in practice would affect the inventory of HAW requiring geological disposal. Uncertainties associated with the selection of treatment and encapsulation techniques are captured within the Derived Inventory: Alternative Scenarios report [48]. This report also captures scenarios of potential relevance to long-term storage (for example, Scenario 12, which remove boundary wastes from the inventory consigned to a GDF) and to near-surface disposal (for example, Scenario 11, which removes graphite wastes from the 2013 Derived Inventory).

6.3 Near-surface and Intermediate Depth Disposal

Near-surface and intermediate depth (NSID) disposal encompasses a wide range of disposal concepts, ranging from open trenches dug from the surface, through surface-accessed and drift-accessed silos, to facilities that resemble a GDF but at a shallower depth. Examples of all of these types of facility are currently in operation around the world and accept wastes including operational ILW, short-lived ILW and DNLEU (Depleted, Natural and Low Enriched Uranium). In addition, draft guidance recently published by the UK environment agencies [38] explicitly covers the basis for implementing a wider range of opportunities for on-site, near-surface disposal, including options for in situ disposal of certain ILW (for example, large, activated components such as reactor concrete base plates) and for disposal of decommissioning wastes in existing structures (for example, sub-surface ponds). Clearly therefore, NSID disposal represents a feasible alternative disposal route that could potentially be applied for managing some of the UK's inventory of HAW currently destined for a GDF. The concepts are potentially quicker, simpler, and less costly to implement, without significantly affecting safety. However, the way that some UK wastes are stored may challenge implementation (for example, the ability to segregate short-lived ILW from other inventory components).

The potential benefits that this route could contribute to enhanced integrated waste management is acknowledged in the NDA's strategy and significant work to realise associated opportunities has been undertaken in the last few years, including work commissioned as part of RWM's upstream options / HAW strategy programme. As part of this NDA strategy, further work is currently ongoing, including studies on short-lived ILW and boundary waste disposal, and an integrated project on near-surface disposal.

RWM will continue to engage with the NDA, LLW Repository Ltd and the SLCs on this topic, to support the realisation of opportunities for more optimal routing of HAW to appropriate disposal facilities.

6.4 Deep Borehole Disposal

DBD is a suggested alternative disposal option to a GDF [115]. Although there is considerable experience with the use of deep boreholes in the hydrocarbon industry, there has, as yet, been no "proof of concept" for this radioactive waste management option as a whole (for example; demonstration of borehole excavation to required depths and diameters, installation of casing, package emplacement / retrieval and sealing at an appropriate scale). Until this is achieved, DBD exists as a management option on paper only. This underlines the importance of successfully completing demonstrators such as the deep borehole field testing (DBFT) in the USA in order to better understand the feasibility of this suggested approach.

The main advantage of DBD is typically put forward as the improved long term isolation and containment of the waste that, conceptually, should result from disposal at depths of more than 3km (based on a much thicker geological barrier, with the potential absence of features that could drive radionuclide transfer to the surface environment). There are additional drivers to consider DBD for disposal of some specific waste groups (although none of these has been demonstrated in practice), most notably:

- The potential for accelerated disposal of certain waste streams, such as vitrified HLW and small volume, problematic wastes, accompanied by hazard reduction on nuclear licensed sites and potentially accelerated final site clearance. This possibility arises because deep boreholes are expected to be simpler and quicker to construct than a GDF, so could facilitate earlier, or modular, disposal of waste, either at a waste producer site, at a GDF site (in parallel with construction of the GDF itself) or at one or more additional sites.
- More secure disposal of fissile material, including separated plutonium, arising from the greater depth of disposal, challenges retrieving waste packages from such depths and shorter timescale for sealing and closing a borehole compared to a GDF.
- The limited significance of heat generation from HHGW, including HLW, legacy spent fuel, high burn-up spent fuel from new nuclear build, and MOX on the configuration of deep boreholes, such that the footprint for DBD of such wastes could potentially be far smaller than that required for disposal of the same waste volume in a GDF.

With regard to implementation timescales, it is noted that identifying an acceptable site for DBD would be a key challenge (as for siting a GDF or any other radioactive waste disposal facility), and this could dominate implementation timescales, potentially far outweighing any benefit associated with quicker construction. The difficulties encountered in finding a site at which to conduct the DBFT highlight how challenging siting can be, even when no radioactive waste disposal is involved.

Implementing DBD would not obviate the need for a GDF, since it is unsuitable for disposal of some portions of the UK HAW inventory, most notably the large volumes of LHGW.

A number of concerns relating to the technical feasibility of implementation of DBD have historically been raised, including the feasibility of:

- Drilling boreholes of the necessary length and diameter.

- Waste package emplacement.
- Waste package retrievability, if required (noting that a lack of retrievability could also be an advantage for some wastes, provided safe package emplacement can be assured).
- Sealing disposal boreholes adequately so that they do not provide a preferential pathway for groundwater migration / contaminant transport.
- Adequately characterising the deep geological environment.

These areas have been the subject of desk-based research and some advances have been made in recent years (for example, in the fields of downhole emplacement methods; formulations for sealing and support matrices; options for borehole sealing; packaging designs for specific wastes; and development of pre-closure and post-closure safety assessments for DBD). These developments have helped to address some concerns about DBD, at least so far as is possible using desk-based studies. However, full-scale demonstration of each of the steps that would be involved in DBD would be necessary in order to determine whether concerns over feasibility could be addressed. RWM will continue to monitor developments in this field.

References

[1] Department of Energy and Climate Change, *Implementing Geological Disposal: A Framework for the long-term management of higher activity radioactive waste*, URN 14D/235, July 2014.

[2] Welsh Government, *Welsh Government Policy on the Management and Disposal of Higher Activity Radioactive Waste*, WG23160, ISBN 978 1 4734 3615 2, December 2015.

[3] Scottish Government, *Scotland's Higher Activity Radioactive Waste Policy 2011*, The Scottish Government, Edinburgh 2011, ISBN: 978-0-7559-9892-0, DPPAS 11098, 2011.

[4] Committee on Radioactive Waste Management, *Managing our Radioactive Waste Safely: CoRWM's Recommendations to Government*, CoRWM Final Report, Document 700, July 2006.

[5] Nuclear Decommissioning Authority, *Strategy: Effective from April 2016*, SG/2016/53, March 2016.

[6] Radioactive Waste Management, *Geological Disposal: Science and Technology Programme*, NDA/RWM/112, Version 3, May 2016.

[7] J Beswick, *Status of technology for deep borehole disposal*, EPS International, April 2008.

[8] N Butler, *Literature Review of Partitioning and Transmutation*, Serco, February 2011.

[9] Nuclear Decommissioning Authority, *Geological Disposal: The 2013 Derived Inventory*, NDA Report no. NDA/RWM/120, July 2015.

[10] Radioactive Waste Management, *Geological Disposal: Disposal System Specification Part B – Technical Specification*, Version 1.0 (Provisional), March 2016.

[11] Nuclear Decommissioning Authority, 2012b. *Geological Disposal: Generic Waste Package Specification*, NDA Report No. NDA/RWMD/067, March 2012.

[12] Nuclear Decommissioning Authority, *Higher Activity Waste Treatment Framework*, 23792960, October 2015.

[13] Nuclear Decommissioning Authority, *Higher Activity Waste Strategy,* May 2016

[14] Radioactive Waste Management, *Geological Disposal: Generic Disposal Facility Designs*, Version 3.0 (Provisional), July 2016.

[15] United States Nuclear Regulatory Commission, *Backgrounder on Dry Cask Storage of Spent Nuclear Fuel*, 301.415.8200, September 2015.

[16] World Nuclear News, *EDF Energy completes 'dry fuel store' at Sizewell B*, World Nuclear News website article, published 05 April 2016, accessed July 2016.

[17] Committee on Radioactive Waste Management, *Note on a Meeting with NDA on Spent Fuel and Nuclear Materials*, CoRWM doc. 3227, 20 March 2015.

[18] International Atomic Energy Agency, *Survey of wet and dry spent fuel storage*, IAEA-TECDOC-1100, July 1999.

[19] International Atomic Energy Agency, *Management of Spent Fuel from Nuclear Power Reactors*, *Proceedings of an International Conference 31 May-4 June 2010, Vienna, Austria*, April 2015.

[20] International Atomic Energy Agency, *International Conference on Management of Spent Fuel from Nuclear Power Reactors,* 15 – 19 June 2015, http://www-pub.iaea.org/iaeameetings/46528/International-Conference-on-Management-of-Spent-Fuel-from-Nuclear-Power-Reactors-An-Integrated-Approach-to-the-Back-End-of-the-Fuel-Cycle

[21] United States Nuclear Waste Technical Review Board: *Evaluation of the Technical Basis for Extended Dry Storage and Transportation of Used Nuclear Fuel*, December 2010.

[22] Nuclear Decommissioning Authority, *Geological Disposal: Feasibility studies exploring options for storage, transport and disposal of spent fuel from potential new nuclear power stations*, NDA Report no. NDA/RWMD/060/Rev1, January 2014.

[23] International Atomic Energy Agency, *Storage and Disposal of Spent Fuel and High Level Radioactive Waste*, Information Document for 50th General Conference, 2006.

[24] Blue Ribbon Commission on America's Nuclear Future, *Report to the Secretary of Energy*, Blue Ribbon Commission on America's Nuclear Future, January 2012.

[25] Blue Ribbon Commission on America's Nuclear Future, *Transportation and Storage Subcommittee Report to the Full Commission*, Updated Report, Blue Ribbon Commission on America's Nuclear Future, Washington, DC, January 2012.

[26] International Atomic Energy Agency, *Selection of Away-From-Reactor Facilities for Spent Fuel Storage – A Guidebook*, TECDOC 1558, 2007.

[27] International Atomic Energy Agency, *Operation and Maintenance of Spent Fuel Storage and Transportation Casks/Containers*, TECDOC 1532, 2007.

[28] Office for Nuclear Regulation, *Safety Aspects Specific to Storage of Spent Nuclear Fuel*, Nuclear Safety Technical Assessment Guide, NS-TAST-GD-081 Revision 2, March 2016.

[29] Holtec International, *Commencement of Inactive Commissioning for the HI-STORM ISFSI at EDF Energy's Sizewell B*, Holtec Highlights, HH 30.13 published August 19, 2015.

[30] T.W. Hicks, T.D. Baldwin, I. Hill, S. Watson, M.J. White, *The Feasibility of using Multi-purpose Containers for the Geological Disposal of Spent Fuel and High Level Radioactive Wast*e, GSL Report to RWMD, 1107-1, Version 1, November 2011.

[31] A.S. Hanson, *Used Nuclear Fuel – What will we do with it?* AREVA NC Inc. Presentation September 11, 2006, accessed online August 2016.

[32] Radioactive Waste Management, *Geological Disposal: Review of options for accelerating implementation of the Geological Disposal programme*, NDA Report NDA/RWMD/083, December 2011.

[33] Radioactive Waste Management, *High Heat Generating Wastes Project – Final report*, NDA/RWM/136, March 2016

[34] Nuclear Decommissioning Authority and Department of Energy and Climate Change, *Radioactive Wastes in the UK: A Summary of the 2013 Inventory*, URN 14D039, NDA/ST/STY (14) 0006, February 2014.

[35] Environment Agency, Northern Ireland Environment Agency and Scottish Environment Protection Agency, *Near-surface disposal facilities on land for solid radioactive wastes: Guidance on Requirements for Authorisation*, 2009.

[36] International Atomic Energy Agency, *Radioactive Waste Management: Status and Trends – Issue #3*, IAEA/WMDB/ST/3, August 2003.

[37] Magnox Ltd, *Berkeley Reactors into Safestore*, website article published 16 December 2010, accessed July 2016.

[38] Scottish Environment Protection Agency, the Environment Agency and Natural Resources Wales, *Guidance on Requirements for Release of Nuclear Sites from Radioactive Substances Regulation (GRR)*, Consultation Document, February 2016.

[39] Areva RMC, *Support for NDA RWMD GDF Programme Upstream Optioneering: Optimised Management of Orphan Wastes*, R12 – 152 (A) Issue 2, January 2013.

[40] AMEC, *Upstream Optioneering: ILW/LLW Opportunities: Preparation of an inventory of waste potentially suitable for diversion from geological disposal,* Report for RWM No. 201139-AA-0001/001 Issue 3, June 2015, LL23948891.

[41] Nuclear Decommissioning Authority, *An Overview of NDA Higher Activity Waste*, 23366104, November 2015.

[42] Magnox Limited, *Magnox Limited – Integrated Decommissioning and Waste Management Strategy*, May 2016.

[43] Nuclear Decommissioning Authority, *Decay Storage Management: Credible Options (Gate A)*. Doc Ref: SMS/TS/D1-HAW-6/001/C, Issue 1, LL22473690, December 2014.

[44] Nuclear Decommissioning Authority, *Industry Guidance: Interim Storage of Higher Activity Waste Packages – Integrated Approach*, Issue 3, June 2016.

[45] Radioactive Waste Management, *Geological Disposal: Guidance on the use of organic polymers for the packaging of low heat generating wastes*, WPSGD no. WPS/901/02, April 2015.

[46] E.J. Harvey, *Record of RWM Decontaminants Expert Workshop: Steventon House Hotel 29 September 2014*, GSL Report to RWM 1448-1, Version 2, February 2015.

[47] International Atomic Energy Agency, *Processing of Irradiated Graphite to Meet Acceptance Criteria for Waste Disposal, Results of a Coordinated Research Project*, IAEA TECDOC 1790, May 2016.

[48] Radioactive Waste Management, *Geological Disposal: The 2013 Derived Inventory: Alternative Scenarios*. NDA Report NDA/RWM/125, 2016.

[49] M. Angus, N. Gribble and C. Scales, *Thermal Processes for Immobilising Intermediate Wastes, NNL Position Paper*, NNL, 2016.

[50] K.S. Matlack, W.K. Kot, H. Gan, I.L. Pegg, G.A. Diener, and B.W. Bowan II, *Sellafield Thermal Treatment Trials Using Advanced Joule Heated Ceramic Melter Technology*, Paper 10110 in Proceedings of Waste Management 2010 Conference, 7-11 March 2010, Phoenix, Arizona, USA.

[51] K. Witwer, E. Dysland, M. James, C. Mounsey, *Thermal Treatment of UK Intermediate and Low Level Radioactive Waste: A Demonstration of the GeoMelt Process Towards Treatment of Sellafield Waste,* Paper 10507 in Proceedings of Waste Management 2010 Conference, Phoenix, Arizona, USA 7-11 March 2010.

[52] K. Witwer, S. Woosley, B. Campbell, M. Wong, J. Hill, *GeoMelt® ICV™ Treatment of Sellafield Pond Solids Waste*, Paper 13414 in Proceedings of Waste Management 2013 Conference, Phoenix, Arizona, USA 24-28 February 2013.

[53] S. Swanton, *Geological disposal of silicon-rich vitrified ILW products in a cement-based engineered barrier system: addressing key uncertainties*, presentation to IGD-TP 6th Exchange Forum, London, 4 November 2015, accessed online September 2016.

[54] Low-Level Waste Repository Limited, *LAW Asbestos and Asbestos Containing Waste Gate B (Preferred Options) Study*, 2016.

[55] K.G. Finucane, L.E. Thompson, T. Abuku, H. Nakauchi, *Treatment of Asbestos Wastes using the Geomelt® Vitrification Process*, Proceedings of Waste Management 2008 Conference, Phoenix, 2008.

[56] D. Deegan and C. Scales, *The Role of Tetronics Plasma Vitrification Technology in the Management and Conditioning of Nuclear Waste*, Paper ICEM2007-7271 in Proceedings of the 11th International Conference on Environmental Remediation and Radioactive Waste Management (ICEM), September 2-6, 2007, Brussels, Belgium, pp 1179-1187.

[57] E.R. Maddrell, *Hot isostatically pressed wasteforms for future nuclear fuel cycles*, Chem. Eng. Res. and Des., 91 (4) pp. 735-741, 2013.

[58] National Nuclear Laboratory, *NNL and Kurion Complete Initial Commissioning of GeoMelt® Vitrification System Prior to Deployment at NNL's Central Laboratory, Sellafield*, website article, November 2015, accessed September 2016.

[59] J. Deckers, *The Innovative Plasma Tilting Furnace for Industrial Treatment of Radioactive Waste*, Paper 14420 in Proceedings of Waste Management 2014 Conference, March 2-6, 2014, Phoenix, Arizona, USA.

[60] Nuclear Decommissioning Authority, *Progress on approaches to the management of separated plutonium, Position Paper*, SMS/TS/B1-PLUT/002/A, LL 21100718, January 2014.

[61] E.J. Butcher, R. Caldwell, H. Godfrey, M. Hayes and E. Miller, *Development and Implementation of Technology for the Treatment and Encapsulation of Operational Intermediate Level Waste*, Proceedings of ICEM '03 The 9th International Conference on Radioactive Waste Management and Environmental Remediation, Oxford, September 21 – 25, 2003,.

[62] Commissariat à l'énergie atomique et aux énergies alternatives, *Nuclear Waste Conditioning*, CEA e-den, A Nuclear Energy Monograph, Vernaz E. (Ed.), 2009.

[63] P.D. Swift, *The Development of Calcium Aluminate Phosphate Cement for Radioactive Waste Encapsulation*, A thesis presented for the degree of Doctor of Philosophy, Department of Materials Science and Engineering, Faculty of Engineering, The University of Sheffield, October 2013.

[64] Z. Yang, J. Brown Huddleston and W. Seger, *Performance evaluation of rapid-set pre-packaged cementitious materials for rehabilitation of surface distress of concrete transportation structures*, PCI Journal March–April 2016.

[65] S. Berger, C. Cau Dit Coumes, P. Le Bescop, D. Damidot, *Stabilization of ZnCl2-containing wastes using calcium sulfoaluminate cement: cement hydration, strength development and volume stability*, J. Hazard Mater. 2011 Oct 30;194:256-67. doi: 10.1016/j.jhazmat.2011.07.095. Epub 2011 Aug 5.

[66] Q. Zhou, N.B. Milestone and M. Hayes, *Towards Using Calcium Sulfoaluminate Cements for Nuclear Waste Immobilisation*, Proceedings of Stabilisation/Solidification Treatment and Remediation, Advances in S/S for Waste and Contaminated Land, Cambridge, 12-13 April 2005.

[67] International Atomic Energy Agency, *The Behaviours of Cementitious Materials in Long Term Storage and Disposal of Radioactive Waste: Results of a Coordinated Research Project*, IAEA TECDOC 1701, 2013.

[68] M. Hayes and I.H. Godfrey, *Development of the use of alternative cements for the treatment of intermediate level waste*, Proceedings of Waste Management Conference, February 25 – March 1 2007, Tucson, Arizona, USA.

[69] National Nuclear Laboratory, *Position Paper on Minor Actinide Transmutation,* accessed 2016.

[70] ONDRAF/NIRAS, *The impact of transmutation on the long-term management of category B&C wastes*, D. Boulanger, 2012-0782-GB (rev. 1), April 2012.

[71] Los Alamos National Laboratory, *Reduction of the Radiotoxicity of Spent Nuclear Fuel Using a Two-Tiered System Comprising Light Water Reactors and Accelerator-Driven Systems*, H.R. Trellue, Thesis report, LA-14052-T, June 2003.

[72] Nuclear Energy Agency, *Actinide and Fission Product Partitioning and Transmutation*, Twelfth Information Exchange Meeting, Prague, Czech Republic, 24-27 September 2012.

[73] Nuclear Energy Agency, *Actinide and Fission Product Partitioning and Transmutation*, Thirteenth Information Exchange Meeting, Seoul, Republic of Korea, 23-26 September 2014.

[74] Korea Atomic Energy Research Institute, *Status of R&D Activities on Pyroprocessing Technology at KAERI*, Presentation to SACSESS International Workshop, Warsaw, 22-24 April 2015.

[75] SCK·CEN, *R&D carried out in support to the MYRRHA Project*, Presentation to ESNII Biennial Conference, Brussels, 17-19 March 2015.

[76] T. Sasa, *Design of J-PARC Transmutation Experimental Facility*, Progress in Nuclear Energy 82, 64-68, 2015.

[77] Commissariat à l'énergie atomique et aux énergies alternatives, *Status of the ASTRID Project*, Presentation to ESNII Biennial conference, Brussels, 17-19 March 2015.

[78] Nuclear Energy Agency, *Potential benefits and impact of advanced fuel cycles with actinide partitioning and transmutation*, NEA No. 6894, ISBN 978-92-64-99165-1, 2011.

[79] Environment Agency and Northern Ireland Environment Agency, *Geological disposal facilities on land for solid radioactive wastes: Guidance on Requirements for Authorisation*, 2009.

[80] Committee on Radioactive Waste Management, *Geological disposal of higher activity radioactive wastes*, CoRWM Document 2550, 2009.

[81] R. Wilmot, S. Doudou, J. Kent, F. Neall and S. Wickham, *Integrated Project Team on Uranium: Phase 2 [Task ASS-3]: Feasibility of Nearer-Surface Disposal of DNLEU*, GSL Report to RWM, 1207-ASS-3-1, Version 2.1, July 2016.

[82] Swiss National Cooperative for the Disposal of Radioactive Waste, *Kristallin-I Conclusions from the regional investigation programme for siting a HLW repository in the crystalline basement of Northern Switzerland,* Nagra NTB 93-09E [Fig 7.2], May 1994.

[83] Nuclear Waste Management Organization of Japan, *Development of repository concepts for volunteer siting environments,* NUMO Technical Report NUMO-TR-04-03, August 2004.

[84] NDA, *The NDA Value Framework*, version 1.2, January 2016

[85] Texas Commission on Environmental Quality, 2015. *Radioactive Material License R04100 for Waste Control Specialists, Andrews, Texas*. December 2015.

[86] Low Level Waste Repository Ltd, *The 2011 Environmental Safety Case: Environmental Safety Case – Main Report*, LLWR/ESC/R(11)10016, May 2011.

[87] Dounreay Site Restoration Limited, *New Low Level Waste Facilities Phase One Vaults Project Summary*, October 2014, accessed online July 2016.

[88] A. Meehan, P. Sibley, A. Johnson, J. Lightfoot and D. Jackson, *On-Site, Near Surface Disposal of Graphite Wastes in the UK* – 11271. Proceedings of Waste Management Conference, Phoenix, February 27 – March 3, 2011.

[89] Svensk Kärnbränslehantering, *Extending the SFR,* SKB Fact Sheet, June 2015. Accessed online July 2016.

[90] International Atomic Energy Agency, *Near Surface Disposal Facilities for Radioactive Waste,* IAEA Safety Standards Series No. SSG-29, Report No. STI/PUB/1637, LL24192197, March 2014.

[91] ONDRAF-NIRAS, *The Safety Case: A milestone for the safe surface disposal of the Belgian Category A waste at Dessel*, 2012.

[92] Radioactive Waste Management, *Upstream Optioneering: Summary of LLW/ILW Opportunities*, NDA Report no. NDA/RWM/134, July 2015.

[93] AMEC, *Upstream Optioneering: ILW/LLW Opportunities: Management of Waste by Safety Case rather than Classification*, Report No. 201139-AA-0002/001, Issue 2, July 2015.

[94] AMEC, *Upstream Optioneering: ILW/LLW Opportunities: Identification of potential opportunities for ILW/LLW boundary wastes introduced by changing disposal route*, Report No. 201139-AA-0004/001 Issue 1, May 2014.

[95] Low Level Waste Repository Ltd, *Guidance on decision making for management of wastes close to the LLW and ILW categorisation boundary that could potentially cross the LLW boundary,* Report No. NWP/REP/016, Issue 2, February 2013.

[96] Nuclear Decommissioning Authority, *Higher Activity Waste: The Long-term Management of Reactor Core Graphite – Credible Options (Gate A)*, SMS/TS/D1-HAW-6/002/A, Doc ID: 21083563, September 2013.

[97] A. Laker, *LLWR Waste Acceptance Criteria - Overview*, WSC-WAC-OVR, Version 3.0, April 2012.

[98] J. Kent, F. Neall and J. Newton, *Geological Disposal: Summary of the factors affecting the disposability of unirradiated depleted uranium tails and Magnox depleted uranium.* RWM Report NDA/RWM/145, October 2016.

[99] F. Neall, *Integrated Project Team on Uranium: Phase 2: Preferred disposal concept options for depleted, natural and low enriched uranium*, Report 1207-DCD-5 Version 2.1, September 2016.

[100] Elsam/Elkraft, *Disposal of High-level Waste from Nuclear Power Plants in Denmark; Salt Dome Investigations*, 5 vols, ELSAM Frederica, Denmark and ELKRAFT Baler, Denmark,1981.

[101] A.J. Beswick, F.G.F. Gibb and K.P. Travis, *Deep borehole disposal of nuclear waste: engineering challenges,* Energy, 167, pp 47-66, 2014.

[102] United States Nuclear Waste Technical Review Board, *International Technical Workshop on Deep Borehole Disposal of Radioactive Waste*, Transcript of Workshop held on 20 October 2015, accessed online August 2016.

[103] American Nuclear Society, *Field Test to Evaluate Deep Borehole Disposal*, Radwaste Solutions, 23 (1), pp 30-39, 2016.

[104] A. Sowder, R. McCullum, V. Kindfuller, *Why Demonstration of a Deep Borehole Disposal Concept Matters to the Nuclear Industry*, Proceedings of the 15th International High-Level Radioactive Waste Management (IHLRWM) Conference, Charleston, SC, April 12-16, 2015.

[105] Arnold, B.W. et al, *Reference Design and Operations for Deep Borehole Disposal of High-Level Radioactive Waste,* SAND2011-6749, October 2011.

[106] Gesellschaft für Anlagen und Reaktorsicherheit (GRS) GmbH, *Proceedings of the Workshop "Final Disposal in Deep Boreholes Using Multiple Geological Barriers: Digging Deeper for Safety*" June 2015, Berlin, GRS-405, ISBN 978-3-944161-87-7, March 2016.

[107] F.G.F. Gibb, N.A. McTaggart, K.P. Travis, D. Burley and K.W. Hesketh, *High-density support matrices: Key to the deep borehole disposal of spent nuclear fuel*, Journal of Nuclear Materials, 374, pp 370-377, 2008.

[108] N.C. Collier, N.B. Milestone, K.P. Travis and F.G.F. Gibb, *The effect of organic retarders on grout thickening and setting during deep borehole disposal of high-level radioactive waste*, *Progress in Nuclear Energy*, 90, pp 19-26, 2016.

[109] N.C. Collier, K.P. Travis, F.G.F. Gibb, N.B. Milestone, *Cementitious Grouts for Disposal of Nuclear Wasteforms in Deep Boreholes*, Proceedings of the 15th International High-level Radioactive Waste Management (IHLRWM) Conference 2015, Charleston, SC, April 12-16 2015, pp 394-400.

[110] W. Lowry, S. Dunn, K. Coates, A. Duguid and K. Wohletz, *High performance ceramic plugs for borehole sealing*, Proceedings of the 15th International High-level Radioactive Waste Management (IHLRWM) Conference, Charleston, SC, April 12-16, 2015, pp 407-413.

[111] F.G.F. Gibb and K.P. Travis, *Sealing deep borehole disposals of radioactive waste by "rock welding"*, Proceedings of the 15th International High-level Radioactive Waste Management (IHLRWM) Conference, Charleston, SC, April 12-16, 2015, pp 401-406.

[112] P.G. Attrill and F.G.F. Gibb, *Partial melting and recrystallization of granite and their application to deep disposal of radioactive waste Part 1 – Rationale and partial melting,* Lithos, 67 (1-2) pp 103-117, 2000.

[113] P.G. Attrill and F.G.F. Gibb, *Partial melting and recrystallization of granite and their application to deep disposal of radioactive waste Part 2 – Recrystallization*, Lithos*,* 67 (1-2) pp 119-133, 2003

[114] Amec Foster Wheeler, Bedrock Geosciences, Clay Technology, Nagra, Quintessa, Schlumberger and Galson Sciences Ltd, *Sealing Site Investigation Boreholes: Phase 2. Annual Report for 2014/2015*, Report 202580/001 Issue A for RWM, January 2016.

[115] University of Sheffield, *Post-meeting Provisional Position Statement*, *International Meeting On Deep Borehole Disposal of High-Level Radioactive Waste 13th-15th June 2016, The University of Sheffield, UK,* July 2016.

[116] United States Department of Energy, *Assessment of Disposal Options for DOE-Managed High-Level Radioactive Waste and Spent Nuclear Fuel*. October 2014, U.S. Department of Energy, Washington, DC, 2014.

[117] Sandia National Laboratories, *Project Plan: Deep Borehole Field Test*. FCRD-UFD-2014-000592, Rev. 0, SAND2014-18559R. United States Department of Energy, Office of Used Nuclear Fuel Disposition, Washington, DC, 2014.

[118] B.W. Arnold, P.V. Brady, M. Sutton, K.P. Travis, R. MacKinnon F.G.F. Gibb and H. Greenberg, "*Deep Borehole Disposal Research: Geological Data Evaluation, Alternative Wasteforms, and Borehole Seals*, SAND2014-17430R, Albuquerque, NM, Sandia National Laboratories, 2014.

[119] K.P. Travis and F.G.F. Gibb, *Cleaning up Hanford: A Deep Borehole Disposal Concept for the Cs/Sr Capsules*, Proceedings of Waste Management 2016 Conference, Phoenix, March 6-10, 2016.

[120] G. Freeze, E. Stein, K. Kuhlman, G. Hammond, and J. Frederick, *Safety Case for Deep Borehole Disposal of Cs/Sr Capsules*, SAND2016-5350C, Presentation at International Meeting on Deep Borehole Disposal of HLW University of Sheffield, UK, 13-15 June 2016.

[121] R.J. MacKinnon, *Overview of the Deep Borehole Field Test*, Presentation to US Nuclear Waste Technical Review Board Briefing Meeting, Albuquerque, NM, 16 July 2015.

[122] B.W. Arnold, P. Brady, S. Altman, P. Vaughn, D. Nielson, J. Lee, F. Gibb, P. Mariner, K. Travis, W. Halsey, J. Beswick, and J. Tillman, *Deep Borehole Disposal Research: Demonstration Site Selection Guidelines, Borehole Seals Design, and RD&D Needs.* SAND2013-9490P, FCRD-USED-2013-000409. U.S. Department of Energy, Office of Used Nuclear Fuel Disposition, Washington, DC, 2013.

[123] W. Cornwall, *This time, it's North Dakota that sinks an experiment related to burying nuclear waste*, Science Magazine, DOI: 10.1126/science.aaf9820, March 2016, accessed online September 2016.

[124] S.D. Redfield, *Borehole Backers Abandon Spink County After Local Opposition*, Keloland Television website, June 2016, accessed online September 2016.

[125] United States Department of Energy, *A--RFP for Deep Borehole Field Test: Characterization Borehole Investigations*, Solicitation Number: DE-SOL-0010181, August 2016, accessed online September 2016.

[126] United States Nuclear Waste Technical Review Board, *Technical Evaluation of the U.S. Department of Energy Deep Borehole Disposal Research and Development Program*, A Report to the U.S. Congress and the Secretary of Energy, January 2016.

[127] Svensk Kärnbränslehantering, *Storage of nuclear waste in very deep boreholes: Feasibility study and assessment of economic potential*, SKB Technical Report TR-89-39 by C. Juhlin and H. Sandstedt, December 1989.

[128] Svensk Kärnbränslehantering, *Project on Alternative Systems Study (PASS) Final Report*, SKB Technical Report TR-93-04, October 1992.

[129] Svensk Kärnbränslehantering, *Jämförelse mellan KBS-3-metoden och deponering i djupa borrhål för slutligt omhändertagande av använt kärnbränsle*, SKB Report R-10-13 by B. Grundfelt, 2010 (In Swedish).

[130] Svensk Kärnbränslehantering, *Radiological consequences of accidents during disposal of spent nuclear fuel in a deep borehole*, SKB Report P-13-13 by B. Grundfelt, July 2013.

[131] Svensk Kärnbränslehantering, *Review of geoscientific data of relevance to disposal of spent nuclear fuel in deep boreholes in crystalline rock*, SKB Report P-13-12 by N. Marsic and B. Grundfelt, September 2013.

[132] Svensk Kärnbränslehantering, *The deep borehole concept: A conceptual model for gas generation and gas transport*, SKB Report P-13-11 by B. Grundfelt and J. Crawford, May 2014.

[133] Svensk Kärnbränslehantering, *RD&D Programme 2013: Programme for research, development and demonstration of methods for the management and disposal of nuclear waste*, SKB Technical Report TR-13-18, September 2013.

[134] K. Jungmin, *Update: Potential for Deep Borehole Disposal of Nuclear Wastes in ROK*, NAPSNet Special Reports, July 2014.

[135] F.G.F. Gibb, K.P. Travis and K.W. Hesketh, *Deep borehole disposal of higher burn up spent nuclear fuels*, Min. Mag., 76, pp 3003-3017, 2012.

[136] F.G.F. Gibb, K.J. Taylor and B.E. Burakov, *The 'granite encapsulation' route to the safe disposal of Pu and other actinides*, Journal of Nuclear Materials, 374, pp 364-369, 2008.

[137] K.P. Travis and F.G.F. Gibb, *Deep geological boreholes: A suitable disposal route for the Hanford Cs/Sr capsules?* Proceedings of the 15th International High-level Radioactive Waste Management (IHLRWM) Conference, Charleston, SC, April 12-16, 2015, pp 115-121.

[138] R.D. Pejac and E.P. Fontenot, *Design, testing and planning considerations for a 20 in record casing string*. SPE Drilling Engineering. June 1988: 187-194.

[139] F.G.F. Gibb, K.P. Travis, N.A. McTaggart, D. Burley and K.W. Hesketh, *Modelling temperature distribution around very deep borehole disposals of HLW,* Nuclear Technology, 163, (1), pp 62-73, July 2008.

[140] Nirex, *Summary Note for CoRWM on Distribution of Cost, Effort and Employment Profile for the Deep Borehole Disposal Option*, October 2005, LL21534992.

[141] Agence Nationale pour la Gestion des Déchets Radioactifs, *Position Paper on Reversibility, January 2016,* 577 VA, DICOD/16-0058, March 2016.

[142] International Association for Environmentally Safe Disposal of Radioactive Material (EDRAM), *EDRAM Views on the impact of partitioning and transmutation on the long-term management of radioactive waste*, website accessed September 2016.

Certificate No LRQ 4008580

Radioactive Waste Management Limited
Building 587
Curie Avenue
Harwell Oxford
Didcot
Oxfordshire OX11 0RH

t +44 (0)1925 802820
f +44 (0)1925 802932
w www.nda.gov.uk/rwm