DEEP ISOLATION™

Deep Isolation in the UK

Initial study to consider the suitability of elements of UK nuclear waste inventory for Deep Isolation's disposal solution

20 MARCH 2023

CONTACT

emea@deepisolation.com
+44 207 873 2309
deepisolation.com

EMEA OFFICE

1 Northumberland Avenue,
London WC2N 5BW, UK

LOCATIONS

Berkeley, CA, USA | Washington, DC, USA | London, UK | Seoul, Korea

Contents

NWS statement on Deep Isolation Report

Nuclear Waste Services (NWS) welcomes the report commissioned by the Nuclear Decommissioning Authority (NDA) from Deep Isolation on the suitability of Deep Isolation's storage and disposal solution for elements of the UK nuclear waste inventory.

NWS is responsible for the delivery of the UK's Geological Disposal Facility (GDF), as a safe endpoint for managing higher activity radioactive wastes. This involves working with communities to find a suitable site and a willing community to host a GDF. A GDF will be a highly engineered facility, which will safely isolate and contain radioactive wastes at a depth of 200 – 1,000 m.

In line with government policy, NDA and NWS continue to review new and emerging technologies which could have the potential to improve the long-term management of some of the UK's higher activity radioactive wastes. In this context, Deep Isolation have undertaken an initial assessment of their own work into the suitability of their directional borehole disposal technology, at a depth of 1,000 m or more.

NWS recognises that Deep Isolation has further developed aspects of deep borehole disposal implementation since our earlier consideration of the broad technology domain in 2016. With a focus on technical feasibility, our key conclusions in relation to the Deep Isolation study, in line with the company's own assessment, are that:

- Directional borehole disposal could not replace the need for development of a GDF in the UK, since it is not suited to the full diversity of the UK's waste inventory.
- A GDF will always be required, but directional borehole disposal could conceivably be considered in the future to dispose of some of the UK's high heat generating waste inventory for geological disposal (e.g. high level waste glass and spent fuel and nuclear materials if classified as waste).
- Further development of directional borehole technology is required to increase the maturity for potential application to the conceivable inventory, including consideration of operational and post closure safety.

In summary, NWS recognises the insight afforded by Deep Isolation's study and will continue to engage with such developments, while recognising that a GDF will still be required for the majority of the UK higher activity waste inventory, even when Deep Isolation's directional borehole technology is developed to sufficient maturity for potential implementation.

Executive summary

About this study: analysing an innovative disposal solution within the UK context

- This study has been commissioned from Deep Isolation EMEA Limited by NDA, as an initial assessment of the potential suitability of Deep Isolation's directional borehole technology for disposal of elements of the UK's Inventory for Geological Disposal.[1]

Our findings

- **Inventory Mapping:**
  - 63% by volume of the UK's Inventory for Geological Disposal (IGD) is intrinsically not compatible with borehole disposal.[2]
  - A further 26% can in principle be transferred to Deep Isolation disposal canisters for borehole disposal – but the existing plans for disposal in a mined repository are likely to be more cost-effective.
  - This leaves 11% of the IGD that, based on this preliminary study, is operationally and commercially suitable for disposal in a deep borehole repository. This comprises all the UK's high heat generating waste (HHGW) – accounting for 96% of NDA's forecast for radioactivity levels of the IGD in 2200.
- **Technical readiness**
  - Of the 11% of the IGD that we have identified as suitable for deep borehole disposal:
    - A little over four-fifths consists of legacy and new build spent fuels,[3] for which technical readiness is higher. Disposal can be implemented using mainly mature, 'off-the-shelf' technologies that are used on a daily basis in the nuclear and oil and gas sectors.
    - For the remaining fifth (HLW, HEU and plutonium residues not suitable for MOX fuel manufacture), further investigation of waste handling and/or drilling capabilities are necessary. Deep Isolation and its delivery partners are confident these can be delivered cost-effectively, but further work is needed to demonstrate this and to test our cost assumptions.
- **Costs:**
  - We have developed 15 scenarios, which show our estimated, unvalidated cost of disposing all the UK's HHGW and also selected sub-sets. These describe how costs vary across geological environments, and between single site and multi-site approaches.
  - The scenarios for disposing 100% of HHGW show estimated costs between £2.98 billion and £4.45 billion. More narrowly focused scenarios show that all the UK's Legacy Spent Fuel can be disposed of for £1 - 1.4 billion and all High-Level Waste for £256 – 288 million.
- **Conclusions:**
  - Borehole disposal cannot replace the UK's need for a mined Geological Disposal Facility (GDF). However, the wastes that are potentially disposable in deep boreholes account for all the heat and almost all the long-lasting radioactivity in the UK inventory.
  - Further work is needed to evaluate the impact of such an approach on the overall costs, benefits and risks of the UK's integrated waste management strategy.

Conclusions: additional research is needed to inform future decisions

The study concludes with Deep Isolation's recommendations to NDA including: a) undertaking more detailed business case work to assess the possible role for deep borehole disposal within NDA's integrated waste management strategy and b) engagement in international collaboration on deep borehole disposal demonstration.

---

[1] The Inventory for Geological Disposal 2018 [1] comprises higher activity wastes from the legacy nuclear power programme and up to 16GWe of new build; it assumes 95% of the UK plutonium inventory is dispositioned as irradiated MOX fuel (115 tonnes).

[2] Due to dimensions of either the waste form itself or of packaging from which it cannot be cost-effectively unpacked.

[3] Spent fuel and nuclear materials are not categorised as waste in the UK until its owner decides it has no further use; they are included in the Inventory for Geological Disposal for planning purposes.

;

1. Introduction

1.1 Context

The UK Government is committed to delivering deep geological disposal of nuclear waste, as set out in its December 2018 policy paper "Implementing geological disposal – working with communities" [2]. Geological disposal will be implemented by means of a mined Geological Disposal Facility (GDF), with a preference for delivery at a single site. A consent-based process of community engagement is currently underway to identify the site for such a repository[4], and an initial generic design for the GDF has been published [3]. The Nuclear Decommissioning Authority is accountable for delivery of this policy, working with its subsidiaries including Radioactive Waste Management (RWM), now operating as Nuclear Waste Services (NWS). Under this policy the NDA is also required to review options that have the potential to improve the long-term management of some of the UK's higher activity waste. As part of this obligation, the NDA decided in February 2020 to commission an initial assessment of the suitability of Deep Isolation's directional borehole disposal technology in a UK context. This report is the result.

1.2 Purpose and objectives of this study

The purpose of this study is to provide NDA with information that enables it to assess the potential suitability of Deep Isolation's directional borehole disposal solution for elements of the UK's nuclear waste inventory. In fulfilling that purpose, the following objectives are in scope:

1. To map Deep Isolation's solution against the UK Inventory for Geological Disposal
2. To map Deep Isolation's solution against three typical UK geologies
3. To assess the safety performance of Deep Isolation's solution in the context of the UK's generic safety case for geological disposal
4. To prepare high-level cost estimates for delivery of the solution in each of the three generic UK geologies.

Costs are assessed on a 'stand-alone' basis: i.e. looking at the implementation costs of a borehole repository, without at this stage seeking to quantify the impact on broader costs, financial and non-financial benefits and risk profiles that would arise if NDA were to incorporate deep borehole disposal into its integrated waste management strategy. Other important considerations that are out of scope for this preliminary study include: mapping out the licensing and permissioning pathways needed in the UK context; scoping the research and demonstration programme that might be required in the UK to support regulatory approval of the safety case for deep borehole disposal; and factoring these findings back into an overall business case.

2. Deep Isolation's technical solution

2.1 Overview

Deep Isolation's solution places corrosion-resistant canisters containing radioactive waste and spent fuel deep underground. It deploys widely-used directional-drilling technology to access stable and isolated host rocks, supported by site characterization techniques to ensure geologic isolation and patented canister technology to transport and manage fuel assemblies.

2.2 Repository design options

There are multiple borehole configurations that can be used to dispose of nuclear waste, including horizontal, vertical, and slanted. The optimal configuration and depth will depend on the available host-rock, waste type, and needs of the country and community hosting the repository.

Unique to Deep Isolation, the deep horizontal borehole design capitalizes on the drilling advancements made in the oil and gas industry that make borehole disposal siting options even more flexible. In horizontal repositories (see Exhibit 2), a vertical access hole is drilled and cased from the surface to a point a few hundred meters above the target repository horizon. A smaller-diameter hole is drilled and cased from that point in a gradual curve (less than 8° per 30 metres) until it has created a horizontal shaft. The radius of the curvature is large

[4] [1] Chapter six sets out the final Working with Communities policy, and how NWS will work in partnership with communities to identify a suitable site for a GDF.

enough to allow for emplacement of waste canisters up to 5 meters long. From the bottom of the curved section, the disposal section is drilled and cased for a distance of a few hundred to a few thousand meters. The waste is emplaced in Duplex stainless-steel corrosion-resistant canisters, then lowered down the borehole, typically to a depth of 1 km or more, and placed end-to-end in the encased horizontal section of the borehole.

2.3 Demonstrating geological isolation

The performance of a nuclear waste repository is measured by the radiation exposure risk to humans and the environment. To improve confidence in site characterization and thus long-term safety, Deep Isolation offers a patented method to measure the isolation of stagnant pore fluids in the vicinity of a potential repository. Demonstrating long-term performance and safety involves heat and fluid transport modelling of the subsurface combined with risk-informed assumptions about the likely features, events and processes that could affect the safety of the repository. Initial safety calculation models (see Section 5 for more details) conclude that the isolation and large rock volume present in deep horizontal or vertical borehole disposal are effective in minimizing the potential radiological exposure to humans and the surface environment.

2.4 Engineered barrier components

Corrosion-resistant canisters

One component of the engineered barrier system is a long-term durable canister specifically designed to hold spent nuclear fuel assemblies or other high-level radioactive waste (see Exhibit 1 below). Thermodynamic modelling suggests canisters made of highly corrosion-resistant alloys are likely to be stable in the reducing chloride environments found at depth and provide an engineered barrier expected to last for thousands of years [4], after which time the thermal effects created by the spent nuclear fuel will have dissipated and many radionuclides will have decayed.

Exhibit 1: A Typical Waste Canister

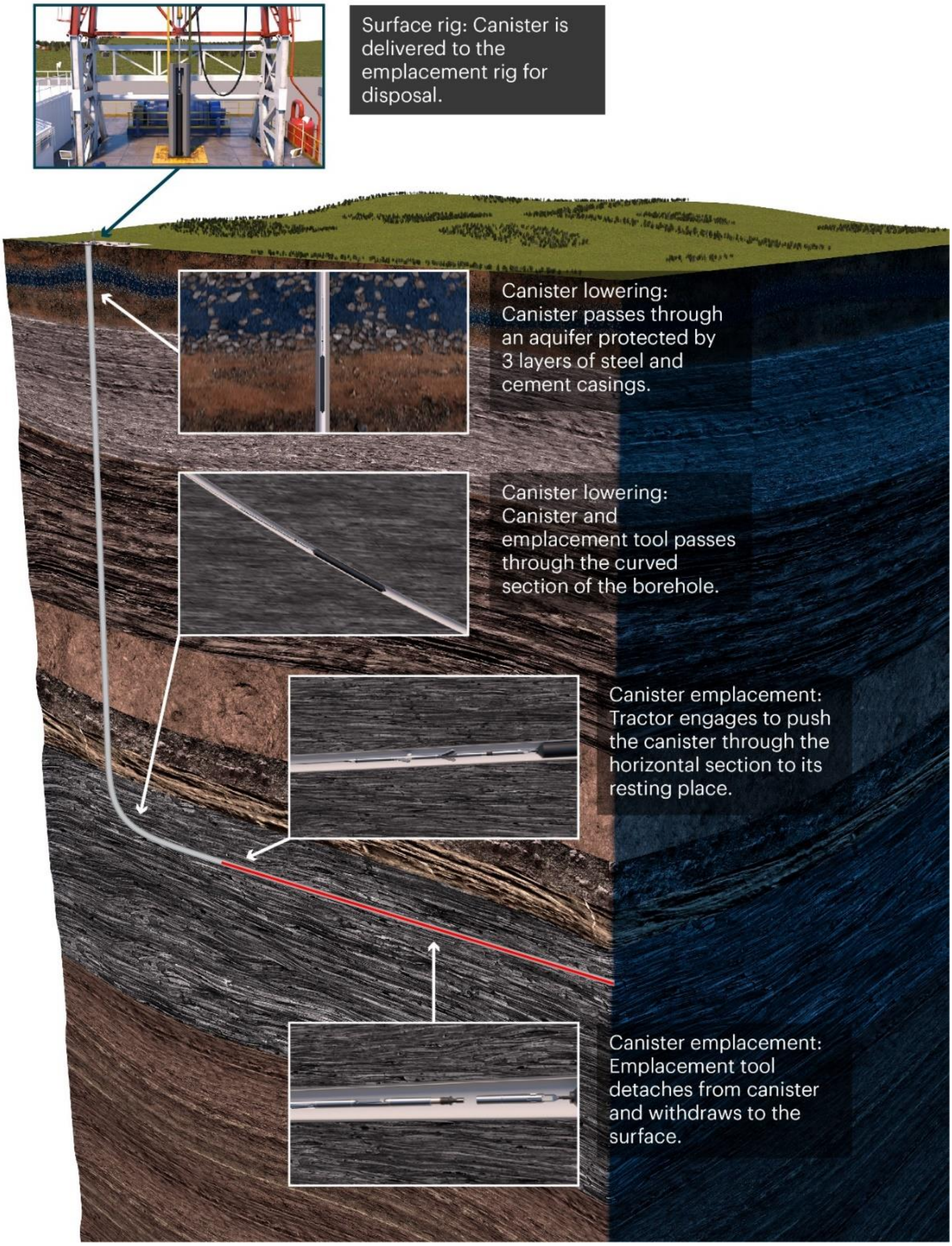
(Upper left shows the canister cross section when holding a spent nuclear fuel assembly. Upper right shows the end cap. Bottom shows how the assembly fits inside the canister)

Deep Isolation and its nuclear engineering partner, NAC International, are working in 2023 with the UK's Nuclear Advanced Manufacturing Research Centre to undertake a 'design for manufacturing' review of our current engineering designs, aimed at enabling cost-effective manufacture at scale in partnership with the UK's hi-tech manufacturing sector.

Casings, backfills and seals

Cemented steel casing provides stability to the borehole, and a borehole liner ensures a smooth conduit for canister emplacement and retrieval. After emplacement of the canisters, the disposal section access casing is removed, and the section is plugged by filling the upper portion of the borehole with sealing materials that may include a combination of bentonite clays, cements, asphaltic compounds, and various rock forms. The backfilled and sealed portion of the borehole is more than a kilometre in length and provides a robust barrier to radionuclide mobility and transport in all types of borehole disposal.

Exhibit 2: Emplacement in a horizontal deep borehole



Placing and retrieving

Placement and retrieval methods for borehole equipment are highly developed and are commonly performed using wireline with a tractor, coiled tubing, or drill-pipe methods. Methods to prevent and release stuck canisters during emplacement have been assessed and developed and are not expected to challenge the operational safety of the repository. Regulations in some countries (but not the UK) may require that high-level waste disposed of in a deep geologic facility be retrievable. In the drilling industry, retrieval of objects from deep boreholes is routine, including uncooperative retrieval.

Siting flexibility

Deep borehole disposal expands the range of potential locations for siting a geological repository - enabling a choice between drilling vertically down into the deep crystalline basement, or using directional drilling techniques to create borehole repositories in appropriate geological formations that are now accessible within a greater subsurface geological volume.

3. Inventory mapping

This section examines the extent to which deep borehole disposal is suited to the UK's inventory for geologic disposal.

3.1 Data sources

The UK's nuclear legacy goes back to the very start of the worldwide nuclear industry. It represents one of the largest environmental remediation programmes in Europe and has given rise to one of the most heterogeneous inventories of nuclear waste held by any country.

The key reference document we have used to gain information on that inventory is Inventory for Geological Disposal [1] (henceforth referred to as the IGD). This gives details of all the nuclear waste that the UK expects to dispose of in its planned GDF, grouped into 12 major waste groups. It is to be noted that the IGD specifies disposition of 95% of the UK plutonium inventory as irradiated MOX fuel (115 tonnes) and 5% immobilised in a titanate ceramic pucks encapsulated by borosilicate glass – the can-in-canister concept (5.75 tonnes, unsuitable for MOX manufacture). We also reviewed two key supporting documents: the "Proof Method" report [5] that was published alongside the IGD, giving detail on the methodology and assumptions used in its creation; and "Geological Disposal Waste packages and the assessment of their disposability" [6].

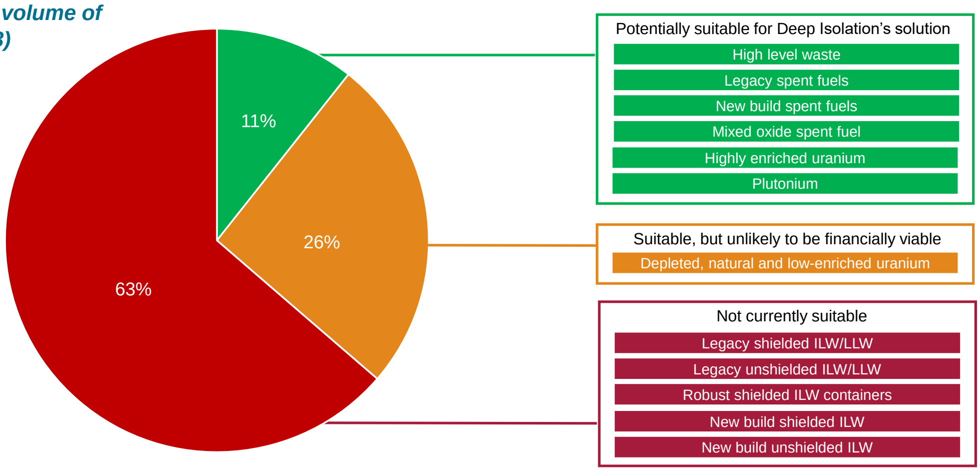
3.2 Overview of findings

Summary: 11% by packaged volume of the IGD is dimensionally suitable for borehole disposal, meaning this technology could never replace a GDF in the UK. However, given the nature of these waste groups, there may be benefits for using deep borehole disposal for some parts of the inventory in an integrated "GDF Plus" strategy.

In total, as illustrated at Exhibit 3, we estimate that 63% by packaged volume of the IGD is currently not suitable for Deep Isolation's solution. This consists of IGD Waste Groups 1 – 6 (Legacy shielded ILW/LLW, Legacy unshielded ILW/LLW, Robust shielded ILW containers, New build shielded ILW, and New build unshielded ILW). These waste groups are too large for borehole disposal and, based on our discussions with NDA, we believe that it would currently be impossible or prohibitively costly to re-pack these waste groups[5].

[5] We note that some of the innovative technologies that NDA is currently exploring, such as thermal treatment, may result in volume reductions and structural changes which may in future make some waste streams within these groups compatible with borehole disposal. However, we have not sought to quantify this potential future opportunity within this project.

Exhibit 3: Packaged volume of waste in the IGD (m3)



The remaining 37% of the IGD that is compatible with borehole disposal falls into two groups.

The biggest group by volume is depleted, natural and low-enriched uranium (DNLEU). This is, or will in the future be, stored as oxide powder and could in principle be transferred to disposal canisters for borehole disposal. However, even if using large disposal canisters within large diameter boreholes, the large volumes involved would require over 600 boreholes within a Deep Isolation repository and take decades to emplace. Our advice is therefore that it will be more cost-effective for NDA to continue to dispose of DNLEU within large-volume disposal packaging inside a mined GDF, as currently planned.

The second group (representing 11% of the IGD) consists of Waste Groups 7-12 - where our preliminary conclusion is that borehole disposal is both suitable and financially cost-effective. These account for all the UK's high heat generating waste groups[6] and, as illustrated below, for 96% of forecast activity levels in 2200.

Exhibit 4: Comparison of the fraction of the activity (at 2200) and volume associated with each waste group in the UK Inventory for Geologic Disposal [1] [7]

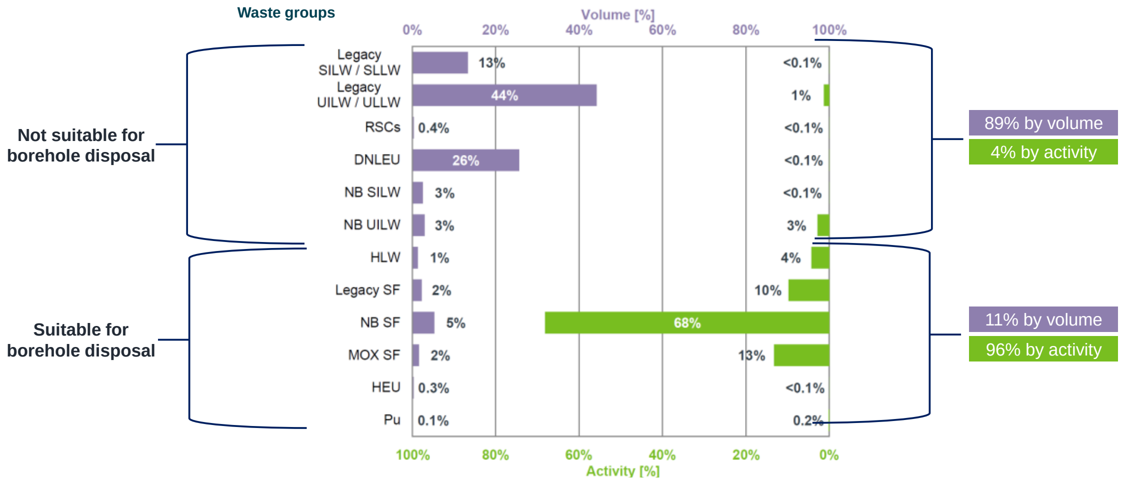
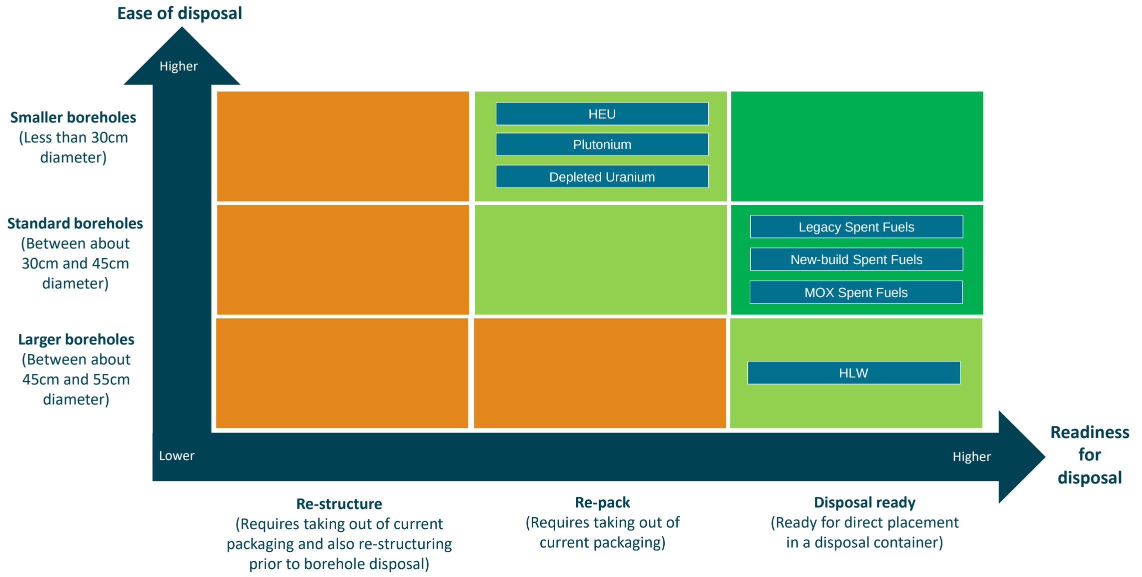


Exhibit 5 shows how these borehole-suitable waste groups vary against two drivers of cost and delivery time for borehole disposal:

1. **Ease of disposal:** the smaller the waste form, the quicker and less expensive it is to drill the appropriate borehole.
2. **Readiness for disposal:** the more re-packing and restructuring that is needed, the more cost and time is added to the process.

[6] Plutonium and HEU do not generate significant amounts of heat. However, in this report we follow NDA's practice (in the Inventory for Geological Disposal) of including both of these within the High Heat Generating Waste category, on the grounds that they have "high fissile activity …. with similar disposal requirements"
[7] Data taken from [1], plus overlaid analysis by Deep Isolation.

Exhibit 5: UK nuclear waste mapped against ease and readiness for disposal using Deep Isolation's solution



4. Geological assessment

The UK's generic safety case for geological disposal [7] concludes that a GDF can be safely constructed in three illustrative geological environment types prevalent in the UK:

- **Lower strength sedimentary rock:** This category refers to fine-grained, sedimentary rocks with a high content of clay minerals and, thereby, a low permeability. Such rocks are mechanically weak, so that open fractures cannot be sustained. The transport of any mobile species through such sedimentary rocks would be dominated by diffusion.
- **Higher strength rock:** This category refers to igneous, metamorphic or older sedimentary rocks. These have low permeabilities and matrix porosities, with the majority of any groundwater movement being confined to fractures within the rock mass. The transport of any mobile species through the rock would be dominated by advection through the fractures.
- **Evaporite:** This category refers to rocks formed following the evaporation of ancient seas and lakes, which often contain bodies of halite. Halite provides a dry environment; it is weak and creeps such that open fractures cannot be sustained. Transport of mobile species through the rock would be by diffusion through any brine that might be present in regions of interconnected pore space, although such connectivity is unlikely to exist over significant distance in halite.

In principle, these three environments can also provide both safe and workable geological environments for a Deep Isolation repository:

- **Safety:** The qualitative and quantitative evidence for this safety is summarized in Section 5 below. As with a mined GDF, a more detailed and site-specific assessment of geological suitability would need to be undertaken in respect of any proposed location for a Deep Isolation repository. Any such site will need to be characterised in detail, enabling site specific hydrologic and geologic conditions to inform repository design and a fully developed safety case.
- **Practical workability:** Technical aspects relating to drilling and completion vary across these different geologies. LSSR is the geological environment in which the drilling industry has originally developed its expertise, and where much can be accomplished rapidly and in the near term. Evaporites and HSR each present additional challenge in terms of characterising the site as appropriate for a repository and then the construction process itself. In summary, we and our technical advisor on drilling (Schlumberger, the world's largest provider of oilfield services) are confident of our ability to deliver deep horizontal or vertical boreholes in these different environments, but costs will be higher in evaporite and higher still in HSR. There will also be a need to deploy less mature technologies, not yet subject to 'off the shelf' pricing. Our modelling [8] also suggests that a range of sealing options for the boreholes across these different geologies could meet safety objectives. These issues are addressed in further detail in Section 6, when we look at the cost implications of operating in the three environments.

It is also worth noting that not only can directional borehole repositories in principle be constructed in each of the UK's three generic geological environments, but they can also in principle be constructed in complex geologies formed from mixtures of these. This is because safety with deep borehole disposal is delivered by the depth and hydrologic properties of the geosphere; the detailed structure of the rock plays an important but secondary role [9].   As discussed in the following section, the greater depth also increases passive isolation from the surface, in principle supporting both lower peak doses and later arrival times of peak dose at the surface.

5. Safety assessment

5.1 Generic safety assessment for Deep Isolation's solution - overview

Deep borehole disposal, and the transportation and operational processes needed to support it, have been subject to far less intensive research and demonstration than mined repositories – which, globally, have benefitted from billions of pounds worth of research investment by governments. At this stage, therefore, the safety case for Deep Isolation's solution is necessarily less mature and well-evidenced than for a GDF.

Against that context, we have not sought within the limited scope of this study to demonstrate that Deep Isolation's solution will meet the safety requirements set by UK regulators. Rather, we have focused on assessing the extent to which available evidence suggests that – with further research, demonstration and documentation of evidence – it is likely to be able to meet those requirements. The results of this assessment are summarised in Exhibit 6 on the following page.

Exhibit 6: Summary assessment of the safety of a Deep Isolation repository in a range of geological environments

Key:

- Evidence suggests that Deep Isolation's solution is likely to be able to meet UK safety requirements.
- There is no reason to believe that Deep Isolation's solution could not meet UK safety requirements, but evidence for this has not yet been sufficiently documented.
- New research and analysis are needed to determine whether or not Deep Isolation's could meet UK safety requirements.
- Evidence suggests that Deep Isolation's solution is unlikely to be able to meet UK safety requirements.
- + Also offers potential additional safety benefits.

Components of the generic Disposal System Safety Case		Geological environments		
		LSSR	HSR	Evaporite
The Transport Safety Case	Transport Safety strategy, principles and approach			
	Safety of the transport package			
	Safety of the transport system			
The Operational Safety Case	Site selection and characterisation			
	Construction and non-radiological assessment	+	+	+
	Normal operations safety assessment			
	Accident safety assessment			
	Criticality safety assessment			
The Post-closure Environmental Safety Case	Safety concept			
	Maintenance of the engineered barrier system functions			
	Post-closure safety			
	Gas generation and migration			
	Natural events and climate change	+	+	+
	Site characterisation			
	Understanding of long-term evolution			
	Human intrusion	+	+	+
	Passive safety	+		+
	Multiple safety functions			

Four key themes emerge from this initial assessment:

1. **In terms of post-closure radiological safety over the very long term, a deep borehole repository is likely to meet UK safety requirements.** This is the area where we have focused our scientific investment, and the peer-reviewed analysis we have published suggests that Deep Isolation's solution will deliver levels of post-closure safety that are orders of magnitude higher than those required by UK regulation.

2. **Greater uncertainties exist in the crystalline basement (HSR) area** –where we are in an earlier phase of our modelling of such geology[8]. (These uncertainties are reflected in the "amber" assessment given to some components above.)

3. **We have as yet gathered and documented relatively little evidence on safety performance in a number of areas relating to transportation and operations.** Our approach to managing these issues is summarised in Sections 5.2 and 5.3 below. We see no reason to believe that this approach will not be capable of meeting UK regulatory requirements, because it draws on established practices in the nuclear

[8] So far we have published analysis of the long-term safety performance of an HSR repository that consists of multiple, parallel boreholes drilled vertically into crystalline bedrock, each accommodating 200 canisters containing a single fuel assembly from a pressurized water reactor, in a waste emplacement section between a depth of 1.5 and 3 km. (See [10]) We have also undertaken preliminary analysis of a horizontal borehole repository in crystalline basement at a disposal depth of 1.5 km – we have shared results of this with NDA, but they have not yet been finalized for publication.

handling industry. But further work will be needed to document and validate the generic safety case in these areas (which are shaded in yellow in Exhibit 6).

4. **In some areas, Deep Isolation's solution offers potential additional safety benefits beyond those assumed in the UK's generic safety case for geological disposal.** These are highlighted with a green plus sign at Exhibit 6:

   - **In terms of post-closure safety**, the extra depth of a Deep Isolation repository means that it by definition delivers additional safety benefits in areas such as safety from natural events, safety from human intrusion and passive safety.
   - **In terms of conventional safety**, deep borehole disposal eliminates a range of key risks associated with building and operating mined repositories that require human presence underground.

The qualitative and quantitative evidence that supports this summary assessment is reviewed below for each of the three lifecycle phases of the gDSSC.

5.2 Transport safety

Deep Isolation's approach to ensuring the safe transport of radioactive materials is through compliance with the regulatory regime set out in the IAEA Transport Regulations and consequential national legislation. These are based on the fundamental principle that transported radioactive material should be packaged adequately to protect persons, property and the environment from all the effects of ionising radiation during the transport of radioactive material, even under accident conditions and with minimal reliance on operational controls.

Deep Isolation's solution supports three models for transportation of nuclear waste:

1. **No transport**
   For use when the selected disposal site is co-located with a site where waste is currently produced or stored, this method has the most robust transportation safety case, as it removes all offsite transportation requirements.

2. **Transport 'as is'**
   If the disposal location is not co-located with the current site of waste generation or storage, off-site transportation of the waste will be needed. One potential option can be to transport the waste in the same packaging as planned by NWS for a mined repository, and then to re-package the waste into Deep Isolation disposal canisters at the disposal site. In this method, the safety case is identical to that provided in the UK's generic Transport Safety Case. [11]

3. **Transport in a disposal canister**
   In this method, waste is placed into a Deep Isolation disposal canister at its current location, then placed within a transportation cask that is authorised to contain one or more Deep Isolation disposal canisters. An example would be use of the MAGNATRAN® Transport Cask designed by Deep Isolation's partner NAC International and licensed by the US Nuclear Regulatory Commission (NRC) to transport Multipurpose Canisters (MPC) containing numerous spent fuel assemblies. To support this mission, the MAGNATRAN® Transport Cask internals would need to be modified to accommodate multiple smaller Deep Isolation disposal canisters instead of a single large MPC and to undergo licensing in the UK.

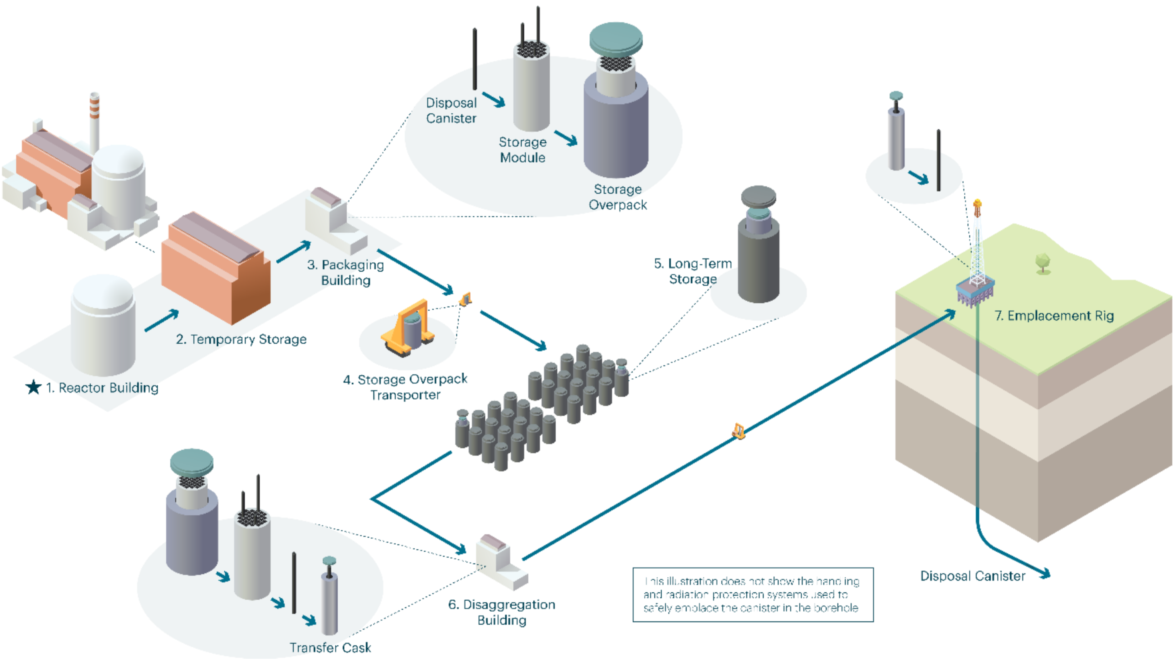
In all three of the above models, it is the transport packaging used that performs the safety and security functions for transportation, provides radiation shielding and provides the enveloping transportation acceptance criteria. The Deep Isolation canisters themselves would not be relied on for transportation safety.

Our assessment is therefore that transportation safety for a Deep Isolation repository is likely to be similar to the transportation safety modelled by NWS – or better in the case of no public transportation. Further work is needed to model, document and validate this in detail.

5.3 Operational safety

A high-level overview of our operational process is illustrated at Exhibit 7 on the following page.

Exhibit 7: overview of nuclear waste disposal process



Key preliminary conclusions are:

- The conventional fault groups that are the most significant in terms of potential for harm during the construction and operation of Deep Isolation repository are also risks for a GDF:
  - Structural collapses underground of the borehole or portion thereof
  - Working with loads at height
  - Transport accidents
  - Criticality
- A Deep Isolation repository solution can provide credible hazard management strategies to reduce risks to workers and the public from these and other hazards - strategies will be based on technology and experience available now that deliver both above ground and below ground safety.
- The key potential hazards that are unique to borehole disposal are dropped and stuck canisters. Deep Isolation's preliminary event tree analysis shows that all event sequences leading to stuck canisters (outside the disposal zone) have a frequency $<10^{-4}$/yr. Even if the canister fails and conservative transport assumptions are made, UK Safety Assessment Principles (SAPs) would be satisfied. Sandia National Laboratories' assessments [12] similarly do not consider stuck canisters within near/surface or aquifer regions, presumably because of the very low likelihood. Canisters stuck within the disposal zone would not have adverse safety impacts as the repository would already have been licensed to contain a larger amount of waste (i.e., source term).
- Deep Isolation's solution (by its nature as a drilled rather than constructed repository) eliminates or significantly reduces a range of key risks. These include:
  - **Structural collapses underground – specifically rockfalls.** The collapse of the borehole remains a risk to be managed but potential for harm is much lower since no humans will be underground.
  - **Fire and explosions (in particular in the underground environment).** The underground environment of a Deep Isolation repository will be wet, so fires and explosions are unlikely.
  - **Flooding (in particular in the underground environment).** A Deep Isolation repository is already flooded[9] so no additional flooding of the repository is possible.
  - **Air quality underground.** No humans will be underground, so this is not a safety factor for a Deep Isolation repository.

[9] Except in an evaporite environment.

- Further work is needed to model, document and validate our operational safety procedures in detail, and Deep Isolation continues to invest in this.

5.4 Post-closure environmental safety

Long-term post-closure safety for a Deep Isolation repository is built around the core concept that the retentive properties of rock (HSR, LSSR, evaporite) together with great depth (typically 1-3 km) provide intrinsic long-term passive safety.

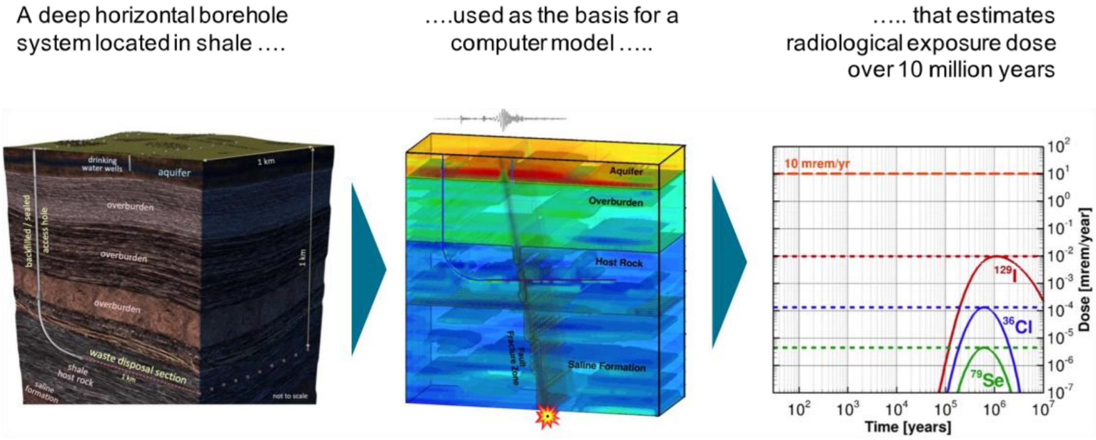
In this model, engineered barriers (canisters, fuel waste forms, buffers, etc.) are designed to perform both initial emplacement and long-term safety functions which delay release of radionuclides into the geosphere. Elements of the Deep Isolation Engineered Barrier System (EBS) are projected to last for millennia: canisters >40,000 years [4], vitrified HHGW >20,000 years [13], ceramic UO_2 fuel >200,000 years [14], [15]. However, reliance on engineered barriers is not requisite for the safety of a properly sited, constructed and sealed Deep Isolation repository. The fundamental protection and isolation from the surface biosphere derive from the depth and characteristics of the host rock formations overlying it.

Deep Isolation's published modelling and safety calculations [16] (based on disposal of spent fuel assemblies in a horizontal borehole repository in generic shale host rock) support a robust safety case with inherent passive safety. Furthermore, the calculations suggest that the overall safety goal of isolating the waste from the accessible environment is inherently supported by the properties of the geosphere, the depth of the repository, and the attributes of its configuration. Long-term confinement of radionuclides in the stable waste matrix and long migration times allow for radioactive decay to occur, considerably reducing the activity of radionuclides potentially being released to the accessible environment and prior to reaching a receptor at the surface.

Key findings from this published analysis [16] include the following:

- The repository experiences a thermal period that is relatively short and small in magnitude. The host rock temperature rises less than 45 °C above its initial value and then returns to within ~25°C of its initial temperatures within 100 years. The canister is expected to maintain containment function during this short thermal period.
- The thermally induced advective flow into the vertical section can be shown to be an insignificant transport mechanism. Without significant advection, diffusion (which is not primarily driven by the effects of heat) from the disposal zone is the primary transport mechanism for radionuclides).
- The estimated maximum annual dose is low: approximately 0.1 microsieverts per year - which is 1,000 times smaller than a regulatory dose standard of 100 microsieverts per year. In terms of risk, the dose standard itself is more than 10 times less than the total annual natural background radiation dose that a member of the public receives (~1-3.5 microsieverts per year).
- This dose estimate is robust to changes in key assumptions and uncertainties in the model parameters.
- For example, the analysis models the impact of early canister failure - and even instant release of the entire radiological budget of the repository into the geosphere at day one. This shows that peak doses remain both very late arriving (1-3 million years) and very low. This in effect provides a confirmation of the role of the geosphere in long term safety. Most radionuclides are immobilized by sorption on rock surfaces.

Exhibit 8: calculating radiological safety of Deep Isolation's solution



Please note that the calculations and safety considerations summarised here are necessarily generic. That is, they do not derive from a specific geographic location or geological site. As with the UK's gDSSC, the safety case for deep borehole disposal will be developed further in the context of selection of a specific disposal site which can then be characterised in detail. Detailed modelling based upon site specific hydrologic and geologic conditions will inform repository design and a fully developed safety case.

Please also note that the calculations presented here relate to lower-strength sedimentary rock. Deep Isolation has recently completed a performance assessment for a generic HSR repository with a disposal zone from 1.5 - 3 km in crystalline rock. The calculation accounts for mechanism of diffusion and advection through fractured rock with a vertically long correlation structure. The results show that despite the assumed long-range connectivity of the fracture network and permeability at the top of the disposal zone (>10^{-17} m^2), the safety of HSR rock is comparable to that in sedimentary rock and transport remains limited by diffusion.

6. High-level cost estimates

6.1 Introduction

We developed high-level costings for 15 potential scenarios, covering centralised and split-location repositories in each of the three rock types within which Deep Isolation's solution could be deployed within the UK. The first six scenarios cover all the High Heat Generating Waste described in the Inventory for Geological Disposal; the second six look at disposal of legacy spent fuel only; and the final three look at the implications of focusing only on an individual waste stream at a single location – using HLW as an example.

6.2 Scope of cost assessment

For each scenario, we prepared estimated costs for a Deep Isolation repository or repositories capable of safely disposing of all the UKs high heat generating waste. The costs are undiscounted lifetime costs, covering all activities needed to plan, site, construct, operate and close the repository, as itemised in Exhibit 9 below.

Exhibit 9: lifecycle costs that are in scope for this assessment

Cost area	Costs included within our estimates
Siting	• Community engagement • Site characterization • Exploratory hole • Third party technical review • Licensing costs
Construction	• Drilling costs • Transfer casks and equipment • Other on-site capex (well-head shielding etc) • Borehole casing
Operations	• On-site transportation • Unloading and transfer operations • Emplacement • General site management • Safety – radiation and occupational • Security • Quality assurance
Repository closure	• Sealing the repository • Establishing post-closure monitoring processes

Costs are assessed on a 'stand-alone' basis: i.e. looking at the implementation costs of a borehole repository, without at this stage seeking to quantifying the impact on broader costs, financial and non-financial benefits and risk profiles that would arise if NDA were to incorporate deep borehole disposal into its integrated waste management strategy. Other important considerations that are out of scope for this preliminary study include: mapping out the licensing and permissioning pathways needed in the UK context; scoping the research and demonstration programme that might be required in the UK to support regulatory approval of the safety case for deep borehole disposal; and factoring these findings back into an overall business case.

6.3 Methodology and assumptions

We assumed a configuration for the repository based on a 1.5 km total vertical depth, curving to form a 1.5 km horizontal disposal section.

We used a standard-sized canister and LSSR as our baseline cost. Based on drilling cost estimates for higher strength rock and lower strength rock, we extrapolated the costs for drilling and well closure costs across each rock type. We then assumed a smaller sized borehole would cost 50% less and a large borehole would cost 50% more. This assumption will vary depending on site specific information and other factors – so our cost estimates should be seen as high-level illustrations.

Nevertheless, our estimates reflect extensive engagement with multiple drilling experts. This means that:

- Our cost estimates for small and standard boreholes come with a very high degree of confidence, because directional drilling of this nature is a daily occurrence in the oil and gas sector and features off-the-shelf products and pricing.
- For larger diameter boreholes (of around 45 cm to 60 cm diameter), there is confidence about feasibility but less certainty on cost. While industry has extensive experience of drilling such boreholes, this would be a more bespoke activity, where costs relate to the specific activity and geology of each site.
- In particular, our cost estimates for larger boreholes in Higher Strength Rock would benefit from testing and demonstration. Our principal technical advisor on drilling (Schlumberger, the world's largest provider of oilfield services) advises us that drilling costs in such a scenario will be 2.5 times higher than our costs for a standard borehole in LSSR[10]. We have used this as the basis for our cost estimates in this scenario, but recommend that further work would be helpful to test and validate this.

In our generic cost modelling, we assumed three generic conceptual cases with uniform rock composition from the surface to a disposal zone with a standard minimum depth of 1.5 km. Costs will reduce if shallower disposal depths are deemed sufficient and variability in drilling costs from to rock heterogeneity with depth are expected to be bounded by considering the most expensive drilling scenario (i.e., higher strength rock).

It is also worth noting that across the fifteen scenarios we have studied, 74-98% of costs are accounted for by the repository delivery process (that is, all the technical work to construct, operate and close the repository). The remaining 2-26% represent our estimates for the cost of regulatory compliance (that is, the work on site characterization and licensing)[11]. These latter estimates are significantly more uncertain than the former, because:

- no deep borehole repository has yet been taken through a full site characterization and licensing process
- this preliminary study has not addressed the licensing pathways and timescales required in a UK context.

In assessing repository delivery costs, we have assumed across the scenarios that we will always use standard boreholes for all waste forms, except high level waste, even if packaging efficiencies suggest that use of larger boreholes might reduce total cost. Canister costs are assumed to vary by size of canister and drilling costs by rock type and size, but all other costs are held constant per unit of costing.

We have modelled different combinations of canister and borehole diameters for those waste groups that can potentially use more than one disposal model. The most cost-effective repository model for each waste group is shown at Exhibit 10 below.

Exhibit 10: disposal model assumed for each IGD Waste Group

Waste Groups	Deep Isolation's disposal concept
AGR spent fuel, PFR legacy spent fuel, Magnox, legacy spent fuel, New-build spent fuels, MOX spent fuel	**Standard-bore, direct disposal** • For these waste groups, the fuel assemblies that hold the waste can be placed without modification directly within a standard Deep Isolation canister, of 34cm outside diameter and about 5m length. • Note that existing plans to repackage AGR fuel through a rod consolidation process can also be accommodated in this concept.

[10] The higher costs are a function of more drilling time due to the increase in the volume of rock removed for the drillhole for larger sizes and the time it takes to drill through the non-LSSR rock types.

[11] Work to map out licensing pathways and regulatory requirements for the UK was out of scope for this preliminary study at NDA's request. We have therefore based our preliminary cost estimates on a baseline study by Deep Isolation and Bechtel in 2019 of the costs of siting a 220 borehole repository in the US, disposing one tenth of the total U.S. commercial SNF inventory in 2075. For a summary of this US case study, please see Section 3.3 of [17]

	• We would drill a standard diameter borehole of diameter 44cm, and to a depth of 1-3 km. (The exact depth will depend on the preliminary modelling of the specific waste form and contents with the specific site geology and other factors.) • We would then emplace the canisters in the borehole.
High level waste	**Larger-bore, direct disposal** • The HLW canister would be placed into a disposal canister. The vitrified glass would not be removed from the HLW canister in which it is currently stored. • For this waste group, we would manage as described in Standard Disposal, except using larger canisters and boreholes: – Disposal canister: 47cm outside diameter, each containing three HLW canisters – Borehole: 57cm outside diameter.
HEU and Plutonium	**Standard-bore disposal with re-pack** • These waste groups are currently stored in a variety of forms. In principle, they could go in any size disposal canister. Our recommendation is that using standard or larger canisters will give packaging and handling efficiencies that, for the UK's volumes of waste, will more than offset the extra costs of increased canister and drilling costs compared with using small bore. • In the first twelve scenarios, we assume that standard canisters and boreholes are used for this waste, to give increased levels of certainty. • NDA's strategic objective is to put the UK's plutonium beyond reach [18]. Further work is required to determine the acceptable conditioning and packaging requirements to achieve the objective of beyond reach, and compatibility with Deep Isolation's disposal canister. For this waste group, we would manage as described in Standard Disposal.

Costs were then determined for a single site in a single rock type that deployed both standard and large canister sizes. As in the NDA's own GDF cost methodology [19], we assumed that the disposal canister costs are incurred by the waste encapsulation facility and are the responsibility of the waste owner, and also excluded the costs of transportation to the disposal facility on the same grounds. The single site was assumed to have six wells operating at once and emplacing 250 canisters per year per well or 1,500 canisters per year for the single site[12].

We then determined the costs for two sites. In order to maintain comparability between rock types, we assumed the two sites were in the same rock type. The emplacement rate maintained at 250 canisters per year per well but doubled due to the two sites, with 3,000 canisters emplaced per year. In all cases, we have assumed that NDA's site operating businesses do not face any constraints in matching our emplacement rates with equivalent export rates of waste from their sites. However, it is recognised that constraints of Sellafield site operations in waste would bound achievable waste package dispatch and emplacement rates.

6.4 Results – all HHGW

In all six scenarios, the High Heat Generating Waste being disposed of accounts for 11% of the total packaged waste volume currently destined for the GDF.

Key points emerging from our cost analysis are:

- The full lifecycle undiscounted cost of disposing all the UK's High Heat Generating Waste lies in a range of £2.98 billion to £4.45 billion, depending on the scenario chosen.
- LSSR provides the most cost-effective disposal environment, followed by evaporite and HSR
- The two-site option is slightly more cost-effective than the single site option in all three geological environments. This is driven by increased operational efficiency (in effect, we can dispose of waste at twice the pace), which more than offsets the extra costs of additional siting and licensing requirements

6.5 Results – legacy Spent Fuel only

We looked at six scenarios for disposal of the UK's legacy SF[13] (which represents 28% by conditioned volume of total HHGW in the IGD

[12] We assumed that one canister per day and disposal operations were five days per week for 50 weeks per year. The actual disposal rate can be varied based on number of wells and other factors to meet the receipt rates expected.
[13] This analysis covers legacy AGR SF, legacy Magnox SF and legacy PFR SF.

Key points emerging from our cost analysis are:

- The full lifecycle undiscounted cost of disposing all legacy spent fuel lies in a range of £1.02 billion to £1.41 billion, depending on the scenario chosen.
- Unit costs are 56% - 63% lower than those found in the 'all-HHGW' scenarios, reflecting the highly cost-effective fit between these waste forms and a standard horizontal borehole repository.
- As in the 'all-HHGW' scenarios, LSSR provides the most cost-effective disposal environment, followed by evaporite and HSR.
- However, unlike in the 'all-HHGW' scenarios, the one site option is now more cost-effective than two sites. This reflects the lower volumes, which can be managed more rapidly at a single site and so do not justify the extra capex required by an additional site.

6.6 Results – HLW only

Finally we looked at the cost of disposing of a single waste stream at a single site, using HLW as an example.

The UK's HLW represents (with a conditioned volume of 1,500 m^3) just 12% of the total volume of HHGW being disposed of in the six scenarios costed at Section 6.4. All this waste could be disposed of in 3-4 larger-diameter boreholes, for a cost of between £0.26 billion and £0.29 billion depending on geology.

7. Conclusions

The findings of this preliminary study are that deep borehole disposal cannot replace the UK's need for a mined GDF, but that it nevertheless may have a helpful role to play in the disposal of the UK's nuclear waste inventory, with potential to enable significant savings in the overall cost of disposal. Further study is needed to provide a fuller evidence base and to refine the preliminary cost estimates presented in this report. Deep Isolation's recommendations to NDA include:

1. Building on this preliminary assessment by undertaking more detailed work on the business case for use of deep borehole disposal within the NDA's integrated waste management strategy
2. Engaging with international collaboration in relation to demonstration of deep borehole disposal.

Further details on each area are set out below.

7.1 Business case development

Important issues that were excluded from the scope of this preliminary study at NDA's request include: regulatory and licensing pathways for implementation of deep borehole disposal in the UK; consideration of how the technology might be integrated with existing plans for the GDF; delivery planning.

These issues should now be considered by NDA within a more detailed analysis of the business case for deep borehole disposal within its integrated waste management strategy.

While the modularity of boreholes opens many possibilities, in practice we see two main options for using deep borehole disposal to take cost, time and risk out of the overall disposal programme for the UK:

- A hybrid facility, in which NWS's current GDF design is optimised to include deep borehole disposal for one or more waste streams that would benefit from the increased levels of passive safety offered by deeper isolation from the biosphere, and where this would enable cost savings across the facility as a whole.
- A GDF sited and constructed as currently planned, but with some particularly difficult waste types left in Sellafield for disposal in boreholes - removing the need for inter-community transportation and bringing significant safety, security and safeguards benefits.

In terms of which waste groups might be most appropriate for such a hybrid model, further joint work is needed on the business case for different options:

- In this preliminary study, Deep Isolation has at NDA's request provided cost estimates for disposal of all the HHGW. Deep Isolation believes that this "all HHGW" option is worth exploring further – because it has the potential for transformational impact on the costs and timescales of the decommissioning programme.
- However, our assessment is that the optimum approach for the UK is most likely to be deployment of deep boreholes as a niche technology, addressing some very specific business case subsets of the IGD. Examples of such targeted business cases that we recommend for further exploration include:

- **Plutonium:** The NDA is working with the UK government to identify and implement a disposition solution that puts the UK's plutonium beyond reach. This could be via reuse as mixed oxide fuel (MOX) or immobilisation in a form suitable for geological disposal. We recommend that this work should include consideration of deep borehole disposal as the disposal route in the latter option – which has the potential to offer significant cost and time savings. One borehole could dispose of all the plutonium currently earmarked for the GDF (i.e. the 5% of the plutonium inventory not suitable for MOX fuel manufacture).
- **HLW:** All the vitrified HLW currently stored at Sellafield could be disposed of in three to four boreholes. NWS does not plan to put any of this into the GDF until 2075 at the earliest. There could be real benefit in emplacing this material in boreholes as soon as practicable after the GDF site has been selected.
- **Exotic Fuels** currently being brought into the IGD and out of scope of the preliminary study.
- **Defence Fuels** such as spent fuel from submarine reactors. These were also excluded from the scope of our preliminary study but are potentially suitable for borehole disposal.

7.3 International collaboration

In parallel with the above activities, we highlight the investment by other national waste management organizations to support demonstration of the technology and strengthen the empirical evidence that underpins the safety case. Within publications and conferences, there has been a convincing articulation of the need for a deep borehole disposal demonstration project, including from experts at Sandia National Laboratory (SNL), CSIRO [20], University of Sheffield [21] in the UK, GRS in Germany [22], and the Electric Power Research Institute [23] in the United States. SNL has estimated a US demonstration program (including drilling of a full scale and depth borehole) to require a budget of $75 million [24].

Recent research [25] by Deep Isolation across waste management organizations, national policymakers and regulator found that 4 out of 5 of these stakeholders are keen to see increased international collaboration on deep borehole disposal, with priorities including in particular an end-to-end demonstration of an operational borehole repository. Deep Isolation is committed to working with all international stakeholders to support and co-invest in such collaboration. In December 2022, a new non-profit organization – the Deep Borehole Demonstration Center - was established to take this forward, funded on a multi-national, public-private-partnership basis[14].

[14] https://www.deepisolation.com/press/deep-borehole-demonstration-center-announced-with-launch-executive-director-ted-garrish/

References

[1] "Inventory for Geological Disposal: Main Report," DSSC/403/02, Oct. 2018. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/835814/Inventory_for_geological_disposal_a.pdf

[2] "Implementing Geological Disposal - Working with Communities," BEIS, Dec. 2018. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/766643/Implementing_Geological_Disposal_-_Working_with_Communities.pdf

[3] "Geological Disposal: Generic Disposal Facility Design," Radioactive Waste Management, DSSC/412/01, Dec. 2016. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/635113/NDA_Report_no_DSSC-412-01_-_Geological_Disposal_-_Generic_Disposal_Facility_Designs.pdf

[4] J. Payer, S. Finsterle, J. Apps, and R. A. Muller, "Corrosion Performance of Engineered Barrier System in Deep Horizontal Drillholes," *Energies*, 2019, [Online]. Available: https://www.researchgate.net/publication/332559094_Corrosion_Performance_of_Engineered_Barrier_System_in_Deep_Horizontal_Drillholes/link/5cbdb5a4a6fdcc1d49a634fb/download

[5] RWM, "Inventory for Geological Disposal: Method Report," DSSC/405/01, Oct. 2018. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/835815/Inventory_for_geological_disposal_Proof_Method_report_a.pdf

[6] "Geological Disposal: Waste Packages and the assessment of their disposability," DSSC/441/01, Dec. 2016.

[7] "Geological Disposal: Overview of the generic Disposal System Safety Case," Radioactive Waste Management, DSSC/101/01, Dec. 2016. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/634857/NDA_Report_no_DSSC-101-01_-_Geological_Disposal_-_Overview_of_the_generic_Disposal_System_Safety_Case.pdf

[8] S. Finsterle, C. Cooper, R. A. Muller, J. Grimsich, and J. Apps, "Sealing of a Deep Horizontal Borehole Repository for Nuclear Waste," *Energies*, vol. 14, no. 1, p. 91, 2021.

[9] G. Bracke, F. Charlier, A. Liebscher, F. Schilling, and T. Röckel, "Does Deep Borehole Disposal of HLRW has a Chance in Germany?," *Atw Atomwirtsch*, vol. 62, p. 46, Jan. 2017.

[10] S. Finsterle, R. A. Muller, J. Grimsich, E. A. Bates, and J. Midgley, "Post-Closure Safety Analysis of Nuclear Waste Disposal in Deep Vertical Boreholes," *Energies*, vol. 14, no. 19, 2021, doi: 10.3390/en14196356.

[11] "Geological Disposal: Generic Transport Safety Case - Main Report," Radioactive Waste Management, DSSC/201/01, Dec. 2016. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/634885/NDA_Report_no_DSSC-201-01_-_Geological_Disposal_-_Generic_Transport_Safety_Case_-_Main_Report.pdf

[12] G. A. Freeze, E. Stein, and P. V. Brady, "Post-Closure Performance Assessment for Deep Borehole Disposal of Cs/Sr Capsules," *Energies*, vol. 12, no. 10, 2019.

[13] D. Clayton *et al.*, "Generic Disposal System Modeling-Fiscal Year 2011 Progress Report," Sandia National Laboratories, FCRD-USED-2011-000184, Aug. 2011.

[14] É. Y. Vernaz, "Estimating the lifetime of R7T7 glass in various media," *Comptes Rendus Physique*, vol. 3, no. 7–8, pp. 813–825, 2002.

[15] Posiva Oy, "Safety Case for the Disposal of Spent Nuclear Fuel at Olkiluoto," POSIVA 2012-12, Dec. 2012. [Online]. Available: https://inis.iaea.org/collection/NCLCollectionStore/_Public/44/091/44091445.pdf

[16] S. Finsterle, R. A. Muller, J. Grimsich, J. Apps, and R. Baltzer, "Post-Closure Safety Calculations for the Disposal of Spent Nuclear Fuel in a Generic Horizontal Drillhole Repository," *Energies*, vol. 13, no. 10, 2020, doi: 10.3390/en13102599.

[17] C. Parker, "Deep Isolation: An introduction for policy-makers around the world," Deep Isolation, White paper, Sep. 2021. [Online]. Available: https://www.deepisolation.com/wp-content/uploads/2020/05/DeepIsolation-IntroWhitePaper-international-policy-makers.pdf

[18] "Cleaning up the UK's earliest nuclear sites, caring for people and the environment," Nuclear Decommissioning Authority (NDA), Mar. 2021. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/973438/NDA_Strategy_2021_A.pdf

[19] "Geological Disposal: Steps towards implementation," Nuclear Decommissioning Authority (NDA), NDA/RWMD/013, Mar. 2010.

[20] G. Freeze, D. Sassani, P. V. Brady, E. Hardin, and D. Mallants, "The Need for a Borehole Disposal Field Test for Operations and Emplacement," in *WM 2021*, Phoenix, Arizona, Mar. 2021.

[21] F. Gibb and J. Beswick, "A deep borehole disposal solution for the UK's high-level radioactive waste," ISSN 1751-4223, Feb. 2022. [Online]. Available: https://www.icevirtuallibrary.com/doi/10.1680/jener.21.00015

[22] G. Bracke, W. Kudla, and T. Rosenzweig, "Status of Deep Borehole Disposal of High-Level Radioactive Waste in Germany," *Energies*, vol. 12, no. 13, p. 2580, 2019.

[23] A. Sowder, R. McCullum, and V. Kindfuller, “Why demonstration of a deep borehole disposal concept matters to the nuclear industry,” presented at the Proceedings of the International High-Level Radioactive Waste Management Conference, 2015.
[24] B. W. Arnold *et al.*, “Research, development, and demonstration roadmap for deep borehole disposal,” *SAND2012− 8527P. Albuquerque, NM: Sandia National Laboratories*, 2012.
[25] C. Parker, F. Brundish, B. Madru, J. Mathieson, and N. Chapman, “Implementing Deep Borehole Disposal: Study of International Stakeholder Views from Regulatory, Policy & WMO Communities,” in *WM2022*, Phoenix Arizona, Mar. 2022.

