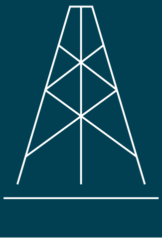
Deep Isolation and ERDO

Preliminary assessment of a Deep Isolation borehole repository as a disposal option for nuclear waste in the ERDO countries



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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 | Tokyo, Japan

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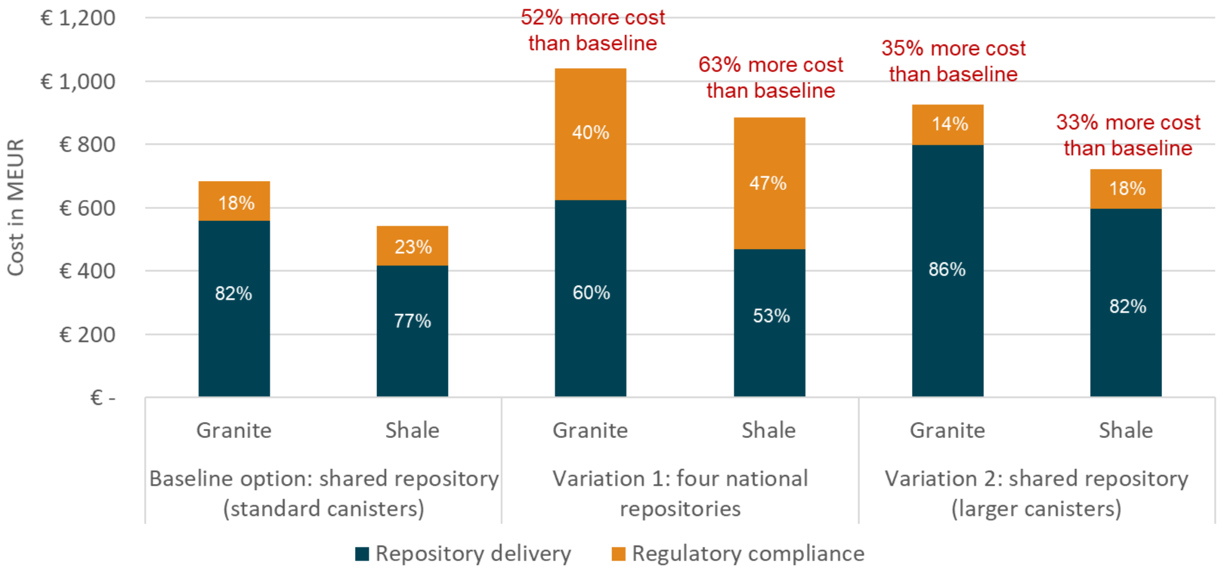
Executive summary

This paper presents an initial high-level assessment of the viability and costs of using Deep Isolation's deep borehole technology to dispose of radioactive waste from some of the former ERDO Working Group and 2021-established ERDO Association countries (Croatia, Denmark, Italy, the Netherlands, Norway, Poland and Slovenia). Key findings include:

- **Suitability**
    - 100% of the collective inventory of heat-generating High-Level Waste (HLW) across these countries is technically and commercially feasible for deep borehole disposal.
- **Costs**
    - Preliminary estimates, based on a high-level generic design for an integrated multi-national repository using horizontal boreholes, suggest that delivery of such a repository would cost between €418 million and €560 million. On top of this, we estimate that the costs of regulatory compliance (including site characterization, licensing and post-closure monitoring) might cost a further €124 million – although these estimates are considerably more uncertain.
    - This total cost range of €542 – 684 million represents a saving of half to two-thirds of the likely cost of disposal in a mined deep geological repository, based on ERDO's earlier assessment of such costs.
    - ERDO countries will still need to invest in disposal solutions for their Intermediate Level Wastes (ILW), through shallow land disposal facilities and/or mined repository disposal. However, by managing the heat-generating HLW at lower cost and at far greater depth in boreholes, the countries concerned have the opportunity to achieve significant reductions in the overall costs currently estimated in national radioactive waste management programmes.
- **Factors driving cost variance:**
    - Detailed costs will be dependent on the final inventory selected for borehole disposal, the specific geology of the selected disposal site(s), and the detailed repository design that is developed to meet stakeholder and regulatory needs in those circumstances. Our report considers a number of the factors and future decisions that might impact costs, with preliminary findings including:
        - ***Number of sites***: preliminary analysis suggests that disposing the heat-generating HLW in separate DBD repositories in each country would cost between €0.9 billion and €1.0 billion – over half as much again when compared with our baseline estimate for a multi-national repository.
        - ***Canister sizing***: our generic design assumes use of a standard canister (34 cm diameter) for most waste types, and a larger canister (47 cm diameter) for vitrified HLW. Previous planning assumptions by ERDO have assumed disposal of all waste in a one-size-fits-all large canister. Our preliminary analysis suggests this would add around one third to the costs of a Deep Isolation repository.
        - ***Borehole geometry***: our generic design assumes horizontal geometry, but vertical might be more appropriate for some combinations of site and inventory. This could drive up costs in some circumstances and reduce them in others. Our report presents analysis comparing costs of a 1.5-kilometre vertical disposal section with a 1.5-kilometre horizontal disposal section (both at the same location in a generic European geology) and finds that the former is 80% more expensive.
        - ***Rod consolidation***: our generic design assumes, for simplicity, that waste forms are placed directly in disposal canisters with no reconfiguration of fuel wherever possible. But there is scope to achieve significant packaging efficiencies by taking fuel rods out of their current spent fuel assemblies before placing in disposal canisters. Further (safety and other) analysis and demonstration is needed to validate this, but preliminary calculations based on published work by Sandia, MIT and others suggest that this might reduce ERDO's borehole disposal costs by over €145 million.

- For the first two of these factors, we have undertaken preliminary ERDO-wide analysis of the cost impact of varying our baseline assumptions, as shown below.



- **Wider benefits.** In addition to the potential cost savings, deep borehole disposal offers other significant benefits including:
  - **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.
  - **Speedier implementation:** Implementation times are much shorter than the many years required to construct a mined repository, and the modular nature of a borehole repository means that disposal operations can begin with as few as one borehole. This opens up potential for the ERDO countries to put their HLW beyond reach decades earlier than otherwise possible, creating significant non-proliferation benefits.
  - **Reduced financial risk.** The bulk of the costs for a borehole repository are based on off-the-shelf technologies that are deployed daily in the oil and gas sector. This reduces the risk of cost and delivery overruns when compared with the uncertainties surrounding a large, bespoke engineering project on the scale of a mined repository.

In conclusion, the report confirms ERDO's own assessment that DBD is a viable and cost-effective option for disposal of ERDO's high-heat generating waste. It makes recommendations for next steps, focused on a full-scale demonstrator facility that will support both elements of the dual-track approach - actions that will be beneficial for all ERDO members, regardless of whether future decisions are to invest in an integrated multinational repository or individual national repositories.

1. Introduction

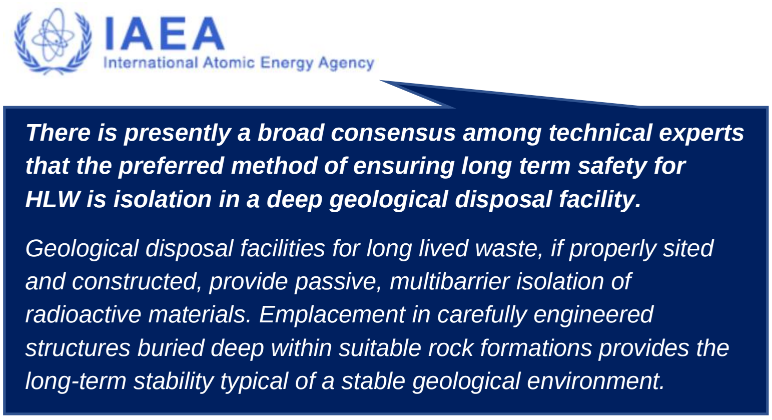
1.1 About this paper

This report has been commissioned from Deep Isolation EMEA Limited for Norwegian Nuclear Decommissioning (NND), on behalf of the ERDO Association (Association for Multinational Radioactive Waste Solutions). The purpose of this report is to provide an initial assessment of Deep Isolation's deep borehole solution for disposal of nuclear waste from the ERDO countries.

1.2 Context

There is global consensus – across governments, regulators, scientists and the nuclear industry – that the only safe solution for the long-term disposal of higher activity nuclear waste is through deep geological disposal (see Exhibit 1). That is, encasing the waste within multiple barriers and then burying it deep underground – with the earth's rocks themselves acting as the ultimate and best barrier.

Exhibit 1: Geologic disposal is the safe solution for high level nuclear waste



IAEA
International Atomic Energy Agency

There is presently a broad consensus among technical experts that the preferred method of ensuring long term safety for HLW is isolation in a deep geological disposal facility.

Geological disposal facilities for long lived waste, if properly sited and constructed, provide passive, multibarrier isolation of radioactive materials. Emplacement in carefully engineered structures buried deep within suitable rock formations provides the long-term stability typical of a stable geological environment.

Source: Status and Trends in Spent Fuel and Radioactive Waste Management, IAEA, 2018

However, one barrier hampering progress globally on this front is cost: the current model for deep geological disposal, which involves mining out massive underground repositories, is complex and expensive. Only a handful of countries have advanced and realistic plans for such massive engineering projects, and no such facility is operational anywhere in the world (although Finland expects to have an operational facility in the next few years).

Building on the work of the earlier ERDO Working Group, the ERDO Association has been established for European countries[1] to work together in assessing whether it is feasible and economical to build one or more shared geological repositories to dispose of their joint inventory of high-level waste. During 2021, NND has been leading a project within ERDO to study the suitability of deep borehole disposal (DBD) as an alternative and lower-cost solution for elements of that waste inventory. The project has developed a high-level generic concept, with estimated costs, as described in a paper being presented to IAEA in November 2021 [1]. This finds that:

- DBD is a technically feasible concept that could add to the range of technologies available for waste-management organizations
- Not all ERDO waste requiring geological disposal is of dimensions suitable for DBD, but the design of mined repositories could be simpler if the DBD-compatible wastes (which tend to have higher radiotoxicity and heat) were routed to DBD
- Inclusion of DBD in a national strategy could broaden the range of potentially suitable disposal sites
- The lower fixed costs and greater adaptability to small inventories could allow internationally collaborative efforts to shift focus from the pursuit of a shared mined repository to the

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[1] Currently Croatia, Denmark, Italy, the Netherlands, Norway Poland and Slovenia.

development of standardised development processes, designs, canisters, seals, equipment, and methods.

Against the background of these potential benefits from DBD, NND have asked Deep Isolation to undertake a preliminary study into the feasibility and costs of deploying Deep Isolation's DBD technology for ERDO waste.

1.3 About Deep Isolation

Deep Isolation is a leading innovator in nuclear waste storage and disposal. Launched in 2016, we offer a solution that avoids the need for expensive mined repositories that require human presence underground. Instead, our solution places corrosion-resistant canisters containing spent fuel in deep boreholes 1-5 kilometres underground. We construct these repositories using directional drilling technology within sedimentary, igneous or metamorphic host rocks – rocks that we can demonstrate have been isolated from the biosphere for a million years or more. Deep Isolation's solution is not a theoretical concept, but a practical solution backed by:

- Extensive scientific research on the long-term environmental safety performance [2-6]
- Around 40 patented inventions granted and in development
- Extensive supply-chain partnerships with leading companies from the global drilling and radioactive waste management sectors.

As part of our commitment to bring this innovative solution to markets around the world, in 2020 we established a European business, Deep Isolation EMEA Limited – which has led our work with NND and ERDO for this review.

1.4 Purpose and objectives of this study

The purpose of this study is:

To provide an initial assessment of Deep Isolation's deep borehole solution for disposal of nuclear waste from the ERDO countries

In fulfilling that purpose, the following five objectives are in scope for this initial study:

1. Evaluate what ERDO nuclear waste groups are suitable for disposal using Deep Isolation's solution
2. Develop outline reference architecture for a DI repository capable of disposing of these waste groups at single location
3. Develop high level cost estimates for DI repository (for generic granite/shale geologies)
4. Provide qualitative advice on the key factors that would drive cost variation
5. Set out recommendations on next steps

1.5 Structure of this report

The report is in the following main sections:

- Section 1 is this introduction.
- Section 2 gives an **overview of Deep Isolation's technical solution** for deep geological disposal of nuclear waste.
- Section 3 presents the results of our **Inventory analysis**, evaluating which ERDO nuclear waste groups are suitable for disposal using Deep Isolation's solution.
- Section 4 presents our proposed **Outline reference architecture** for the DI repository given the findings from Section 3 – and also highlights key areas in which this reference architecture differs from that currently being assumed within ERDO's preliminary work on DBD.
- Section 5 then presents our **High-level cost estimates** for implementation of the outline reference architecture at a single central site, and discusses the key considerations that would drive any variations on these estimates.
- Section 6 sets out our **Preliminary conclusions**
- Finally, Section 7 sets out **Recommendations and next steps** – our view on the further work, analysis and R&D that may inform further due diligence and future decisions by the ERDO group.

This main report is supported by four annexes:

- Annex A provides further **technical detail** on Deep Isolation's solution.
- Annex B presents **key data on each ERDO Waste Group**, and summarises our preliminary recommendations on the appropriate disposal concept for each group.
- Annex C underpins our cost estimates with more detail on the **relative costs and benefits of different borehole geometries.**
- Annex D contains the report's **bibliography** and a list of **abbreviations**.

2. Deep Isolation's technical solution

Deep Isolation's primary reference architecture places corrosion-resistant canisters containing nuclear waste in a long horizontal borehole 1-3 kilometres underground.

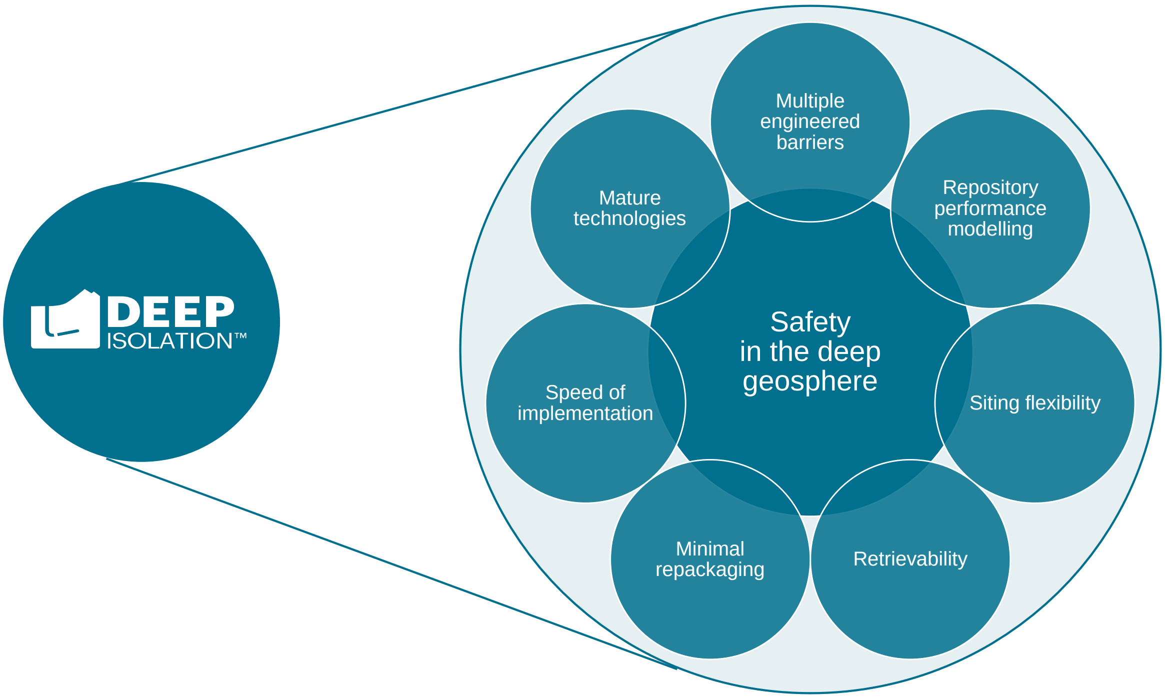
In some cases, given particularities of the inventory for disposal or the particular location identified for disposal, we might recommend a vertical or slanted borehole instead. In most cases, however, we believe a horizontal disposal zone is likely to offer the optimum approach. That is the case in our recommended reference model for an ERDO borehole repository - further details on the rationale for this are set out in Section 4 below.

Deep Isolation's solution brings together two important drivers of technological innovation and scientific advance that are now coming to maturity:

- **Drilling innovation.** Using proven directional drilling technology, horizontal boreholes can be drilled into sedimentary, igneous or metamorphic host rocks. The billion tons of rock between the surface and the buried waste (located in the horizontal section) provide both a permanent and natural barrier that exceeds human health and environmental impact standards by orders of magnitude – and which is supplemented in our solution with multiple engineered barriers.
- **Scientific advances in subsurface geophysical and geological analysis.** These enable us to locate suitable host rocks in a range of geological environments, and to demonstrate that they are low-permeability geologic formations that have remained stable and isolated from humans and the environment for millions of years.

Key features of Deep Isolation's technical solution are illustrated in Exhibit 2, and described in more detail at Annex A. The solution is supported by over 40 US and international patents granted and in development, covering: formation suitability; repository design; canister design; handling, emplacement and retrieval; and monitoring. Most support all borehole architectures; some are specific to horizontal or vertical architectures.

Exhibit 2: Key features of Deep Isolation's solution



3. Inventory analysis

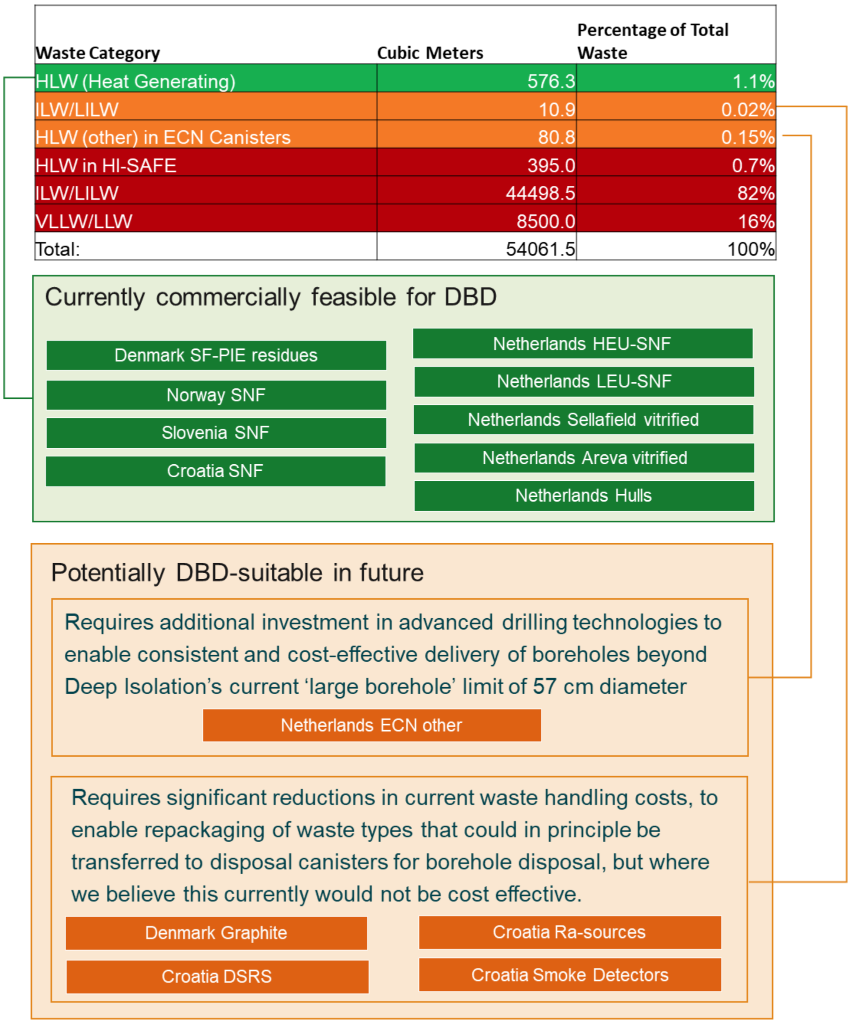
The project has reviewed the radioactive waste inventories of five countries participating in the ERDO borehole project: Croatia, Denmark, the Netherlands, Norway, and Slovenia. Inventory information was provided by the relevant national waste management organizations: Fund for financing the decommissioning of the Krško NPP(FUND), Danish Decommissioning, Centrale Organisatie Voor Radioactieve Afval (COVRA), Norweigan Nuclear Decommissioning (NND), and Agencija za radioaktivne odpadke (ARAO) respectively.

3.1 Wastes suitable for borehole disposal

Across these countries, the total inventory of radioactive waste for disposal represents 54,062 cubic meters.

As shown at Exhibit 3, we estimate that just over 576 cubic metres is suitable for borehole disposal - representing 100% of the heat-generating waste across these five inventories.

Exhibit 3: Overview of inventory suitability for DBD



Waste Category	Cubic Meters	Percentage of Total Waste
HLW (Heat Generating)	576.3	1.1%
ILW/LILW	10.9	0.02%
HLW (other) in ECN Canisters	80.8	0.15%
HLW in HI-SAFE	395.0	0.7%
ILW/LILW	44498.5	82%
VLLW/LLW	8500.0	16%
Total:	54061.5	100%

Currently commercially feasible for DBD

Denmark SF-PIE residues

Norway SNF

Slovenia SNF

Croatia SNF

Netherlands HEU-SNF

Netherlands LEU-SNF

Netherlands Sellafield vitrified

Netherlands Areva vitrified

Netherlands Hulls

Potentially DBD-suitable in future

Requires additional investment in advanced drilling technologies to enable consistent and cost-effective delivery of boreholes beyond Deep Isolation's current 'large borehole' limit of 57 cm diameter

Netherlands ECN other

Requires significant reductions in current waste handling costs, to enable repackaging of waste types that could in principle be transferred to disposal canisters for borehole disposal, but where we believe this currently would not be cost effective.

Denmark Graphite

Croatia Ra-sources

Croatia DSRS

Croatia Smoke Detectors

A further 92 cubic metres might be DBD-suitable in future, but this would require either:

- Additional investment in advanced drilling technologies to enable consistent and cost-effective delivery of deep boreholes beyond Deep Isolation's current 'large borehole' limit of 57 cm
- Significant reductions in current waste handling costs, to enable repackaging and/or restructuring of waste types that could in principle be transferred to disposal canisters for borehole disposal, but where we believe this currently would not be cost effective.

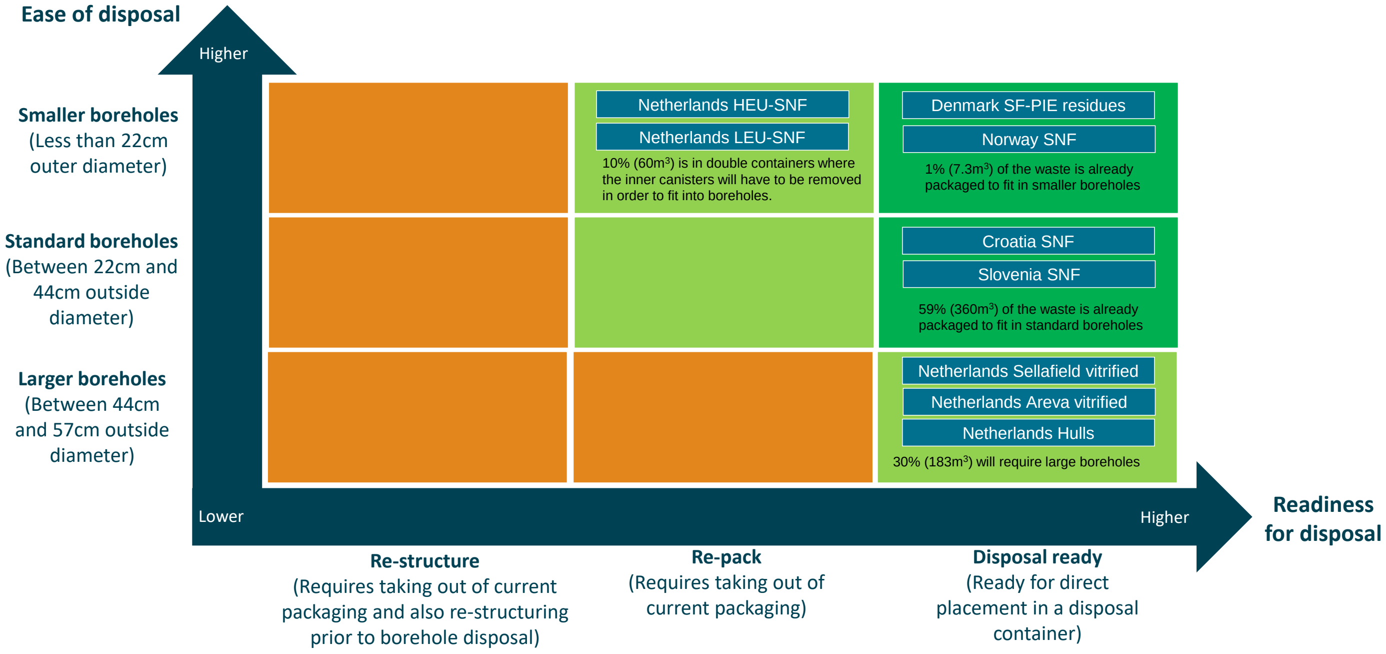
These findings were discussed with NND during the project. As a result, we agreed to focus further work in the assignment on the nine waste groups highlighted in green. This focus on HLW matches the conclusions that NND and ERDO had made during their own work on DBD.

3.2 Potential models for borehole disposal

Annex B provides more detail on the dimensions and current packaging status of the nine ERDO waste groups that are suitable for borehole disposal. As illustrated in Exhibit 4, they vary across two key dimensions that are important for repository design:

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.

Exhibit 4: ERDO HLW mapped against ease and readiness for disposal using Deep Isolation's solution



	Re-structure (Requires taking out of current packaging and also re-structuring prior to borehole disposal)	**Re-pack** (Requires taking out of current packaging)	**Disposal ready** (Ready for direct placement in a disposal container)
Smaller boreholes (Less than 22cm outer diameter)		Netherlands HEU-SNF Netherlands LEU-SNF 10% ($60m^3$) is in double containers where the inner canisters will have to be removed in order to fit into boreholes.	Denmark SF-PIE residues Norway SNF 1% ($7.3m^3$) of the waste is already packaged to fit in smaller boreholes
Standard boreholes (Between 22cm and 44cm outside diameter)			Croatia SNF Slovenia SNF 59% ($360m^3$) of the waste is already packaged to fit in standard boreholes
Larger boreholes (Between 44cm and 57cm outside diameter)			Netherlands Sellafield vitrified Netherlands Areva vitrified Netherlands Hulls 30% ($183m^3$) will require large boreholes

90% by volume of this HLW inventory for borehole disposal is "disposal ready": in the sense that, the existing waste form is already of a diameter suitable for encapsulation within a borehole disposal canister without any other re-packaging or re-structuring[2].

The HLW inventory varies in terms of the boreholes that would be required:

- 59% by volume is suitable for Deep Isolation's "standard" borehole, which is sized for PWR assemblies of the sort contained in the Croatian and Slovenian SNF inventory
- 30% (all from the Netherlands) will require larger boreholes
- 11% could potentially be disposed of in smaller diameter canisters and boreholes.

Our recommendations for the optimal mix of disposal methods across these wastes are discussed in Section 4.

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[2] Note that further work will be needed following this preliminary assessment to ascertain whether any additional disposition investments are needed ahead of placing the waste forms in disposal canisters. For example, we understand that the Danish waste is poorly characterized, mixed with small amounts of other wastes, and in containers that may contain voids. Overall, our view is that a simple and safe way forward is likely to be direct emplacement in disposal canisters, but further work including canister design, gas generation and heat transfer analysis is needed to verify this.

4. Outline reference architecture

4.1 Design assumptions

A Deep Isolation repository follows the seven design principles recommended by IAEA in its guidance [7] on the design of radioactive waste repositories:

a) Use of a requirements-driven design basis
b) Design based on the multiple-barrier safety concept (combining, in the case of a Deep Isolation repository, multiple redundant engineered barriers with very high levels of passive safety from the depth and geometry of the repository)
c) Use of safe, reliable, available and maintainable technology
d) Iterative development and optimization of the design
e) Maintenance of design integrity
f) Production of a transparent and auditable design
g) Incorporation of nuclear safeguards and security integrated design.

A gated process of iterative engineering design is used to do this, for which the starting point is Deep Isolation's generic 'Concept of Operations' (COOP). Given the limited time and scope available for this preliminary study, we have not undertaken the detailed engagement with ERDO stakeholders needed to develop and document a full set of stakeholder requirements and a Conceptual Design for an ERDO repository. However, we have discussed with NND during the project a set of high-level design assumptions for an ERDO repository, as shown at Exhibit 5.

Exhibit 5: Design assumptions underpinning our preliminary architecture for an ERDO repository

Design parameter	Design assumptions
Fuel type and geometry	The repository should be capable of disposing the fuel types and dimensions shown at Annex B
Number of sites	A single shared borehole repository disposing of all suitable ERDO waste at one site
Waste encapsulation and transport	Waste is encapsulated off-site into borehole disposal canisters, which are sealed and then placed in industry-standard casks for safe transportation and storage - arriving at the repository in a form that requires minimal handling, modifications and processing prior to disposal. Waste encapsulation is managed with minimum re-packaging to simplify the process. That is so waste forms that can be placed directly within disposal canisters with no re-configuration of rods, even if re-packaging would allow more efficient use of each disposal canister. (For example, spent fuel assemblies are placed directly within disposal canisters, rather than being disassembled to encapsulate more fuel rods in each canister.)
Fuel characteristics and heat load	For a pressurized water reactor (PWR) assembly, 60 GW-d/kg burnup and minimum cooling time of 30 years (630 watts) with canister spacing of 1 m. Reduced cooling periods are expected to be feasible, but subject to additional analysis.
Intermediate on-site storage	Not all canisters transported to the disposal site will necessarily meet the fuel condition requirement and thus intermediate storage of the fuel at the disposal site would be required.
Canister sizing	Waste shall be inserted into standardized disposal canisters to avoid the need for bespoke canister development. This means use of Deep Isolation's standard canister (34 cm outside diameter, 5 m length) or, for larger waste forms, our large canister (47 cm outside diameter, 5 m length).
Canister emplacement	The repository is assumed to have six wells operating at the same time and emplacing 250 canisters per year per well (equivalent to an average of one canister per day, five days per week for 50 weeks per year) – so a total of 1,500 canisters per year.
Canister retrieval	Retrieval prior to closure is considered as an off-normal requirement. After repository closure, not within the design basis.

Design parameter	Design assumptions
Repository configuration	Horizontal boreholes spaced at least 30 metres apart, each with a total vertical depth of 1.5 kilometres and 1.5-kilometre disposal sections, and with disposal canisters spaced 1 metre apart. The 30 metre spacing is deemed a lower limit and feasible from a drilling perspective, but long-term performance considerations may expand that distance if space minimization is not a primary objective.
Geology	The repository should be capable of being sited in a wide range of geological environments. These must include the two generic geologies used for costing purposes in Section 5: granite and shale.
Post-closure monitoring period	50 years.

It is worth noting that these design assumptions broadly parallel those used in ERDO's existing reference model for DBD, except in three respects:

1. The ERDO reference model was developed principally in relation to Norway, with NND technical specialists developing a concept for the Norwegian inventory and geology and then using the result as a reference concept for the ERDO project.
2. The ERDO reference model assumes a vertical borehole (while noting that refinement of the canister design, the waste inventory, and adaption to site-specific geological conditions could lead to a conclusion that a horizontal borehole is preferable).
3. The ERDO reference model assumes a 'one-size-fits-all' disposal canister - and hence borehole diameter – that is based around the largest waste form (vitrified HLW), even though 70% of ERDO's HLW for borehole disposal would fit in smaller canisters.

Deep Isolation's view is that a vertical (or slanted) borehole design is indeed likely to be optimal for Norway (given its very small inventory and its extensive granitic geology even at shallow depths). But we recommend use of a horizontal assumption in the preliminary architecture for an ERDO repository. This is because horizontal geometry is likely to give the optimum balance of performance and cost considerations for a repository capable of disposing all relevant ERDO waste in a wide range of potential geologies, as discussed at Annex C. Ultimate decisions on this will be informed by site-specific considerations, and the cost implications of assuming vertical or horizontal geometry are discussed at Section 5.3 below.

On canister sizing, we believe that use of a 'one-size-fits-all' large canister will add cost and risk to ERDO's disposal programme. Instead, we assume use of standard boreholes for all waste types except those where the dimensions of the waste form require a large borehole - even if packaging efficiencies suggest that use of larger boreholes might reduce total cost[3]. The assumed disposal concept that flows from this assumption for each of the waste groups is as described at Exhibit 6.

Exhibit 6: Disposal model assumed for each ERDO HLW waste group

Waste Groups	Recommended disposal concept
Denmark SF-PIE residues, Norway SNF, **Croatia & Slovenia SNF**	**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 34 cm outside diameter and approximately 5 m length. • We will drill a standard diameter borehole with disposal zone diameter of 44 cm, and to a depth of 1-3 kilometres. (The exact depth will depend on the preliminary modelling of the specific waste form and contents with the specific site geology and other factors – for costing purposes, we assume 1.5 kilometres.) • We would then emplace the canisters in the borehole.

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[3] For example, we are assuming that four of the Norwegian spent fuel assemblies (11 cm diameter) will be disposed of in each standard disposal canister, whereas potentially around 40 might be disposed of in a large canister. We have assumed standard sizing wherever possible to ensure a conservative and low-risk approach to our cost model (given that the standard canister is further through the design and validation process than our large canister).

Netherlands vitrified HLW (both AREVA La Hague and Sellafield), Netherlands Hulls	**Larger-bore, direct disposal** • The vitrified HLW canisters would be placed into a disposal canister. The vitrified glass would not be removed from the HLW canister in which it is currently stored. • The Netherlands Hulls would be placed into a disposal canister. This would ensure that they have the right attachments for disposal and provide an additional barrier. • For these waste groups, we would manage as described in Standard Disposal, except using larger canisters and boreholes: – Disposal canister: 47 cm outside diameter – Borehole: 57 cm outside diameter.
Netherlands HEU-SNF; **Netherlands LEU-SNF**	**Standard-bore disposal with re-pack** • Individual HEU and LEU SNF fuel elements are currently aggregated into larger canisters. To allow for borehole disposal, these individual SNF fuel elements would have to be repackaged into a disposal canister that would fit the borehole. • For this waste group, once received at the repository in disposal canisters we would manage as described in Standard Disposal.

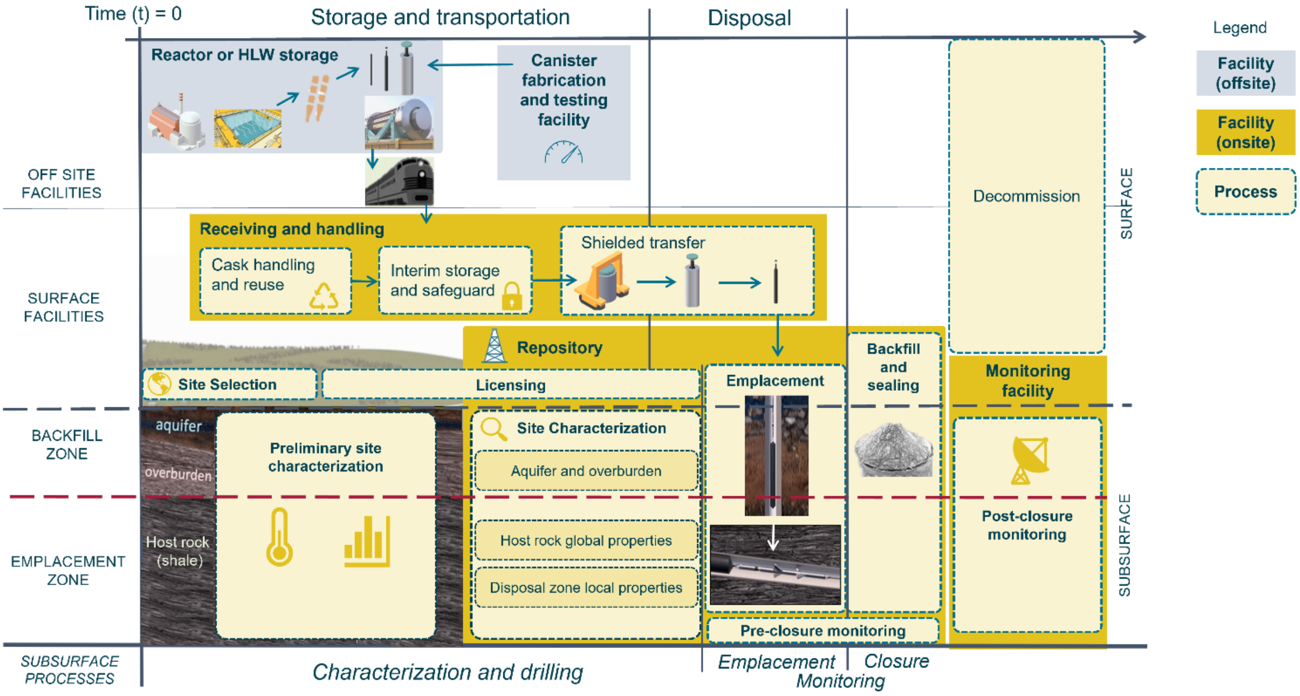
4.2 Concept of Operations for an ERDO Repository

Exhibit 7 defines the key ***functions*** of a deep borehole repository for the ERDO HLW inventory, and the ***form*** in which those are assumed to be delivered in our preliminary architecture for that repository. Exhibit 8 then summarizes these functions and form graphically. Both Exhibits are drawn from Deep Isolation's generic Concept of Operations, tailored to reflect the ERDO-specific design assumptions set out at Section 4.1 above.

Exhibit 7: Key functions within the Concept of Operations for an ERDO Repository

1. Offsite facilities	**a. At reactor storage** **i.** *Function*: Provide adequate cooling, shielding, and security to high level waste (HLW), such as spent nuclear fuel, vitrified waste, etc. **ii.** *Form*: Wet storage and dry storage cask facilities **b. Transportation** **i.** *Function*: Transfer fuel from waste origin (e.g., reactor site) to disposal site **ii.** *Form*: Transportation casks and rail or truck transporters **c. Canister fabrication and testing** **i.** *Function*: Build and test canisters to meet specifications necessary to ensure safety during emplacement, disposal, and monitoring periods **ii.** *Form*: A factory and testing facility, capable of processing techniques and controlling and measuring thermal, mechanical, and chemical conditions
2. Onsite facilities	**a. Receiving and handling** **i.** *Function 1*: Transfer fuel from transportation casks into intermediate storage casks **ii.** *Function 2:* Transfer fuel from transportation or intermediate storage casks into waste canisters **iii.** *Function 3:* Provide secure conditions for storage casks. **iv.** *Function 4*: Reuse, recycle, or dispose of unused storage transportation casks **v.** *Form*: Fuel handling, measurement, storage, and transportation equipment **b. Repository** **i.** *Function 1*: Identify and preliminarily screen disposal site **ii.** *Function 2*: Execute detailed site characterization **iii.** *Function 3*: Adhere to license requirements of the repository **iv.** *Function 4:* Accomplish the drilling process **v.** *Function 5:* Accomplish waste handling and repository closure processes. **vi.** *Function 6:* Initiate pre-closure monitoring processes **vii.** *Form*: Facility capable of drilling, inserting waste canisters, testing and monitoring devices, and sealing materials into host rock and overburden **c. Monitoring** **i.** *Function:* Accomplish the post-closure monitoring process **ii.** *Form:* A facility with measurement and information transmission capabilities

Exhibit 8: Concept of Operations for an ERDO repository



4.3 Physical dimensions of an ERDO repository

Based on the assumptions about inventory, canister sizing and borehole configuration set out at Exhibit 5 above, the key physical requirements for an ERDO HLW borehole repository are estimated as follows:

- 2,486 standard canisters and 360 large canisters
- 12 standard and 2 large boreholes
- A total sub-surface area of 0.87 km^2
- A total surface area of 0.01 km^2.

5. High-level cost estimates

In this section, we set out high-level estimates for the costs of planning, constructing and operating the on-site facilities and functions contained within the Concept of Operations described at Section 4.

5.1 Methodology and assumptions

We have estimated costs for a Deep Isolation repository in line with the design assumptions at Exhibit 5 above. 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 – and then to monitor the repository over a 50 year period. Out of scope for this assessment are: the costs of off-site storage, encapsulation in disposal canisters and transportation to the repository; and any payments to the community and/or landowners in respect of eg compensation for limited land use.

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

Cost area	Costs included within our estimates
Siting and licensing	• 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	• Canister materials, manufacturing and licensing • 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 • 50 years of post-closure monitoring

We used the inventory data summarised at Annex B to inform our analysis. Changes in the inventory or other assumptions described in this section may make a material difference in the cost of disposal estimates.

Within the scope of this initial preliminary study, we have not mapped out regulatory pathways for implementation of a repository within the ERDO countries and have not undertaken bottom-up costing for such implementation. Rather, we have based our preliminary cost estimates on a baseline study[4] 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. As in that study, the ERDO repository is assumed to be sited at a nuclear power plant with existing infrastructure.

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 used a standard-sized canister and shale

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[4] For a summary of this US case study, please see Section 3.3 of Deep Isolation: An introduction for policy-makers around the world, May 2019. USD costs have been converted into Euros in this report at an exchange rate of $1 = €0.84119586. This represents (the average exchange rate in the 12 months to 25 November 2021. (source:, www.ofx.com).

geology as our baseline cost, with granitic geology assumed as 70% higher for drilling and well closure costs. We then assumed 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 that will need to be updated for circumstances of any specific implementation.

5.2 Cost results

A summary of our high-level cost estimate for an ERDO borehole repository is shown at Exhibit 10.

Exhibit 10: Estimated lifecycle costs for an integrated ERDO HLW borehole repository

Life-cycle stage	Cost category	Cost in a generic granite geology (MEUR)	Cost in a generic shale geology (MEUR)
Siting and licensing	Regulatory compliance	89.1	89.1
Construction	Repository delivery	329.7	200.1
Operations	Repository delivery	199.6	199.6
Repository closure	Repository delivery	30.7	18.0
Post-closure monitoring	Regulatory compliance	34.9	34.9
Total		**683.9**	**541.7**

As already discussed, these costs are high-level illustrative estimates, and actual costs will vary depending on site specific information and other factors. That said, it is worth noting that different elements of our cost estimates are subject to different levels of uncertainty:

- **Our estimates for repository delivery** (which includes all technical work to construct, operate and close the repository) reflect extensive engagement with multiple drilling and nuclear waste management partners in our supply chain. The bulk of the costs for a borehole repository are based on off-the-shelf technologies, reducing the risk of cost and delivery overruns when compared with the major civil engineering challenge that is represented by a mined repository. This means that:
    - Our cost estimates for standard boreholes come with a high degree of confidence, because directional drilling is a daily occurrence in the oil and gas sector and the design utilizes off-the-shelf products priced from major drilling service providers.
    - For the larger diameter boreholes needed to dispose of vitrified HLW canisters (requiring 57 cm outside diameter in the disposal section), there is confidence about feasibility but less certainty on time and 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 construction cost estimates for larger boreholes in granite would benefit from further 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 shale[5]. We have used this as the basis for our cost estimates in this scenario, but recommend further research and demonstration would be helpful to test and validate this (see Section 7).

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[5] 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 granitic rock types compared to shale and other low-strength sedimentary formations.

- **Our estimates for regulatory compliance** are more uncertain. Looking only at the initial **siting and licensing costs**, our estimate (at €89 million) is 41% higher than the comparable figure (€63 million) in the reference cost model being developed by ERDO. Both are uncertain, because no deep borehole repository has yet been taken through a full site characterization and licensing process. For **post-closure monitoring**, we have estimated annual costs of €698 thousand over a fifty year period – again, the period and requirements here remain highly uncertain.

5.3 Key drivers of potential cost variation

It is also important to note that our cost estimates are informed by the design assumptions documented at Section 4.1. Changes to any of these could have a significant impact on overall costs. That said, we believe it may be helpful to comment on four design assumptions in particular which could have significant implications for ERDO:

- Number of sites
- Borehole geometry
- Waste encapsulation
- Canister sizing.

Please note that in our commentary below we have used some evidence-based 'rules of thumb' to estimate the potential scale of cost variation that might flow from changing these assumptions, but this is for illustrative purposes only. Significant further design and planning work would be needed to develop detailed quantification.

5.3.1 Number of sites

Our reference model assumes integrated disposal of all ERDO HLW at a single borehole disposal site. But borehole technology inherently supports non-centralized disposal models – enabling, for example, each ERDO country to manage its own disposal site whilst pooling other common costs, in terms of safety case development, demonstration, encapsulation facilities and so on.

To inform ERDO's consideration of this issue, we have undertaken some initial analysis of the cost of implementing separate borehole repositories for the different inventories. All other design assumptions remained as set out in Exhibit 5, except that we tailored the disposal section of our standard borehole to reflect the very small disposal zones needed by some of these countries.

The results of this are set out below, and show a total cost of €0.9 billion and €1.0 billion for shale and granite respectively – over half as much again when compared with our estimates for an integrated repository.

Exhibit 11: Lifecycle costs of four[6] individual repositories

Life-cycle stage	Cost category	Cost in a generic granite geology (MEUR)	Cost in a generic shale geology (MEUR)
Siting and licensing	Regulatory compliance	276.8	276.8
Construction	Repository delivery	386.8	246.3
Operations	Repository delivery	202.0	202.0

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[6] That is: a Danish repository, a Netherlands repository, a Norwegian repository and a combined Slovenia/Croatian repository for spent fuel from the Krško power plant.

Repository closure	Repository delivery	36.8	20.4
Post-closure monitoring	Regulatory compliance	139.5	139.5
Total		**1042.0**	**885.2**

The additional cost is driven by the need to replicate a number of fixed costs in the repository development process. Operational costs to emplace the waste are the same in both the “multi-national repository” and “multiple national repositories” scenarios, but the former limits capital expenditure to one site only, and also sees economies of scale in the siting, licensing and closure processes. Note that in the latter scenario we have assumed that one of the repositories will go through a siting and licensing process ahead of the others, and that the subsequent repositories will reap significant economies in the safety case development and licensing processes (totalling a 47% saving on “Siting and licensing” compared with the first implementation). However, these economies of scale do not fully offset the extra costs of taking multiple sites rather than just one through a licensing process.

5.3.2 Borehole geometry

Our reference model assumes horizontal geometry for the disposal section of boreholes. Actual decisions on this will be dependent on geological conditions at a specific disposal site and stakeholder priorities across the range of relative benefits that different geometries can offer. A high-level view of some of the key considerations and relative benefits is presented at Annex C.

In terms of cost implications, a vertical borehole tends to be more cost-effective for small inventories requiring a very short disposal zone in a single borehole. For longer disposal sections, horizontal disposal tends to offer the optimal mix of cost and performance benefits. This is because costs tend to increase at a faster rate as a borehole goes deeper vertically, while the costs of extending horizontally tend to increase on a more linear basis. This is driven by the way that:

- Very deep vertical holes tend to penetrate multiple formations and cross multiple geological barriers – which increases the cost and complexity of drilling and requires investment in additional casing strings (and hence significantly wider borehole diameter at the surface).
- Disposal sections in deep vertical holes will typically be in crystalline basement, which involves significantly more expensive drilling than in suitable rock formations accessible at less great depths for horizontal repositories.

Annex B presents analysis of these effects undertaken by Deep Isolation and our principal drilling advisor, Schlumberger, in a generic geological environment (which is designed to be typical of many European locations, reflecting Central European basins, geological history and available geoscience data density). This analysis compares the cost of creating a 1.5 km vertical disposal section in crystalline basement with a 1.5 km horizontal disposal section in a sandstone formation (sealed by a layer of shale) offering strong isolation at less depth, and finds that the former is 80% more costly.

5.3.3 Canister sizing

As discussed in Section 4, our reference model assumes use of Deep Isolation’s standard canister (34 cm outside diameter, 5 m length) or, for larger waste forms such as vitrified HLW, our large canister (47 cm outside diameter, 5 m length). This compares with the current ERDO reference model, which assumes that all wastes will be disposed of in a large, universal canister sized for vitrified HLW.

In Exhibit 12 on next page, we provide an initial estimate of the implications of shifting from our reference model to a large disposal canister for all waste forms. This shows that total costs increase to €723 million - €926 million, compared with costs for our reference model of €542 million - €684 million. That represents a 33% increase in costs in shale geology, and a 35% increase in granitic geology.

Exhibit 12: Estimated lifecycle costs for an integrated ERDO HLW borehole repository, with all waste forms in large disposal canisters

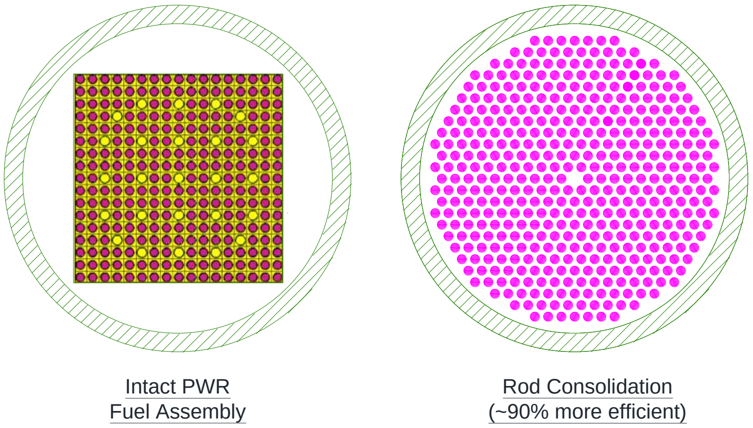
Life-cycle stage	Cost category	Cost in a generic granite geology (MEUR)	Cost in a generic shale geology (MEUR)
Siting and licensing	Regulatory compliance	91.0	91.0
Construction	Repository delivery	567.9	382.3
Operations	Repository delivery	187.9	187.9
Repository closure	Repository delivery	43.9	25.8
Post-closure monitoring	Regulatory compliance	35.7	35.7
Total		**926.3**	**722.7**

5.3.3 Rod consolidation

For reasons of simplicity, and to limit the amount of R&D needed for implementation of the repository, our reference model assumes minimum re-packaging. However, there is potential for significant further cost reduction through fuel rod consolidation, specifically in relation to the Croatian, Slovenian and Norwegian spent reactor fuels in rod bundle form.

Exhibit 13 illustrates the potential for rod consolidation to enable each disposal canister to dispose of almost twice as many fuel rods – reducing by nearly half the required number of disposal canisters and boreholes.

Exhibit 13: Illustrative potential packaging efficiencies from fuel rod consolidation



Applied to the ERDO inventory, such a rod consolidation programme would:

- reduce the total number of disposal canisters required from 2,846 to 1,766

- reduce the number of boreholes required from 14 to 9
- resulting in a saving in repository delivery costs of approximately €193 million and €145 million for granite and shale respectively.

That saving would of course be off-set to some extent by the additional capital expenditure and operational costs involved in rod consolidation. Deep Isolation is still working with our partners to define the detailed processes and costs involved, so have not included this opportunity in any of our published case studies on borehole cost. That said, our current findings – together with published analysis by Sandia, MIT and others – suggest that this would be a cost-effective option for a disposal programme of the scale of the ERDO inventory.

For example, a 2010 study by MIT [8], drawing together evidence and analysis from previous studies by the Electric Power Research Institute [9] and the Department of Energy's Prototypical Rod Consolidation Project [10] concludes that the rod consolidation costs needed to support a single-borehole repository would be approximately $12.50/kg HM (€ 10.8/kg HM).

Further work would be needed to develop costs geared to the scale of ERDO's inventory. The larger scale of operations required for ERDO might permit fixed costs of rod consolidation to be spread over more waste packages, potentially resulting in a lower cost per tonne. However, for illustrative purposes we have simply applied MIT's $12.50/kg HM estimate to relevant waste groups in the ERDO inventory – and this suggests a potential rod consolidation cost of €9.7 million, and hence a net reduction in the overall cost of disposal of €183 million and €136 million for granite and shale respectively.

6. Preliminary conclusions

Deep Isolation believes that ERDO is right to see deep borehole disposal – whether via an integrated multi-national facility or via individual national disposal programmes – as a viable and potentially attractive option.

This is because:

1. **DBD offers significant cost savings over disposal in a mined repository.** The costs in our reference concept for ERDO as described in Section 5.2 represent an average cost per tonne for the relevant inventories of around €302k per tonne of Heavy Metal (tHM) in shale and €381k per tHM in granite. These represent a cost saving of, respectively, 65% and 56% when compared with ERDO estimates of the cost of disposing similar wastes in a mined repository[7].
2. **Borehole disposal of the heat-generating HLW will yield significant savings across the total disposal budgets of the ERDO countries.** As shown at Exhibit 3, we estimate that just over 1% by volume is suitable for borehole disposal. This represents 100% of the heat-generating waste across the ERDO inventories. This means that the ERDO countries will still require one or more mined repositories to manage bulky ILW and non-heat-generating HLW that is unsuitable for borehole disposal. But by managing the heat-generating HLW at lower cost and at far greater depth in boreholes, the ERDO countries can see significant overall cost savings. This is because such wastes are a disproportionately high driver of cost within a mined repository, requiring:
    - greater spacing between packages (to avoid over-heating)

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[7] Our comparison here is with the typical cost per tonne of around $1 million USD (or 0.86 MEUR) for spent fuel in mined repositories identified in "The Costs of Geological Disposal", Neil Chapman, ERDO-WG / Arius Association, 18th December 2018 (presentation to IFNEC IFNEC-RNFSWG Workshop on Approaches to Financing a Multinational Repository – Challenges and Alternate Approaches).

- greater depth of construction (compared to shallow land burial for certain low-level waste)
- and a more complex engineered barrier system (EBS) than a repository built only to deal ILW.

And by co-locating boreholes with a mined repository, there is scope for significant savings and economies of scale in terms of site selection, site characterization and surface facilities.

3. **As well as cost reductions, borehole disposal also offers significant additional potential benefits to ERDO countries.** Other benefits that need quantifying in a full business case, and are beyond the scope of this preliminary study, include:

    - **Putting ERDO's HLW safely and permanently beyond reach decades more quickly than possible with a mined repository.** A phased approach can be taken to construction and operation of a DBD repository, beginning with as few as one borehole. And implementation times are much shorter than the many years required to construct a mined repository.
    - **Avoiding the operating expense of interim storage.** The faster disposal times with deep boreholes could enable ERDO's national waste management organizations to avoid additional capex and many years of expenditure on storage.
    - **Reduced financial risk.** The bulk of the costs for a borehole repository are based on off-the-shelf technologies that are deployed daily in the oil and gas sector. This reduces the risk of cost and delivery overruns when compared with the uncertainties surrounding a large, bespoke engineering project on the scale of a mined repository.
    - **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.
    - **A significant export opportunity for Europe's high-tech manufacturing sector.** By becoming early adopters of borehole disposal technology, the ERDO nations would be well placed to develop a significant manufacturing advantage in the infrastructure and consumables needed to support this (for example, manufacture of disposal canisters).

7. Recommendations and next steps

This report has set out initial high-level assumptions for the conceptual design of a deep borehole repository for all ERDO heat-generating high-level radioactive waste, along with preliminary cost estimates.

Further work is also needed to develop the detailed roadmap, engineering design, business case and safety case for such a repository. Last year, a group of waste management practitioners and borehole experts, under the aegis of the International Framework on Nuclear Energy Cooperation (https://www.ifnec.org), estimated around ten years to first licensed disposal[8].

Deep Isolation is ready to work with ERDO to develop the detailed plans for doing this, and to co-invest in order to bring timescales forward through public-private partnership.

The first step in Deep Isolation's roadmap for evaluating, planning and delivering deep borehole disposal is a Foundation Study – a collaborative engagement between Deep Isolation and our client that is aligned with the IAEA's recommended "Design Principles and Approaches for Radioactive Waste Repositories" [7]. Some key elements of a Foundation Study were addressed in this

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[8] Understanding Deep Borehole Disposal Technology in the context of Spent Fuel and High-Level Radioactive Waste Disposal, IFNEC webinar, December 2020

preliminary and limited scope report, but we recommend ERDO consider extending this to cover other important parts of the Foundation Study process including, for example:

- **Cost model:** Expanding our initial assessment to cover broader factors such as storage, waste encapsulation, and transportation, refining our US baseline costs for the ERDO market and regulatory requirements, plus a more detailed feasibility and cost-benefit analysis of rod consolidation in the context of ERDO countries
- **Safety calculations:** A more detailed assessment of ERDO's HLW inventory in terms of safety relevant parameters (e.g., heat generation, chemical form, degradation rate in repository conditions) and completion of generic safety calculations (including the operational and post-closure phases). Ultimately this would support more detailed options appraisal and confirmation of the reference architecture.
- **Geological readiness and site selection criteria:** A preliminary assessment of potential locations for borehole repositories in ERDO countries, combined with more refined estimates for site characterization costs and criteria.
- **Regulatory mapping:** Analysis of regulatory and licensing pathways
- **Societal research:** Quantitative and qualitative research into how citizens and communities in ERDO countries view different potential options for storage, transportation and disposal of radioactive waste (including deep borehole disposal, and its relative advantages and disadvantages compared with other approaches).

In addition to such further **planning and analysis**, we recommend that priority should be given to **practical research and demonstration steps** that support both elements of the dual-track approach: i.e., ones that will be beneficial for all ERDO members, regardless of whether future decisions will be to invest in an integrated multinational repository or individual national repositories.

Deep Isolation is currently conducting research with regulators, policy-makers and waste management practitioners internationally, to establish an evidence-based view of how the international radioactive waste management community understands and prioritizes the challenges that need to be addressed ahead of the first licensed disposal of spent fuel and HLW in deep boreholes. Preliminary findings from our first wave of research (with participants from sixteen countries, including five ERDO members) were presented at IAEA's conference in radioactive waste management in Vienna in November 2021.

Informed by those findings, our core recommendation is that ERDO's priorities in taking this work forward should focus on shared investment by ERDO members to develop a non-radioactive DBD demonstration facility.

The clear consensus of participants in our international opinion research is that the technologies needed for deep borehole disposal are mature, and that the key requirement now is to demonstrate them all on an integrated basis at scale. 82% of respondents cite lack of such a demonstration facility as the single largest challenge for borehole disposal, and 78% are in favour of collaboration by national waste management organizations in joint projects to accelerate DBD implementation.

While further work is needed to scope out the roadmap for such a demonstrator, in broad terms we see this as a three-phase process:

1. **Collaboration with Deep Isolation to develop a Generic Design for a full-scale DBD demonstrator**. This should include:
    - All the outputs specified by IAEA[9] as appropriate for such a design stage:
        - Generic layout

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[9] See recommended outputs for a geological repository Conceptual Design on p24 of IAEA's "Design Principles and Approaches for Radioactive Waste Repositories" [7]

  - Generic Product Breakdown Structure (PBS)
  - Preliminary tentative budget[10]
  - Tentative programme development plan
  - Identification of main design risks and opportunities

- Plus a recommended commercial and business model for the demonstrator, including scope for:
  - cost-sharing with non-ERDO countries
  - leveraging private-sector investment
  - securing future revenue streams for ERDO members from commercialization of the intellectual property co-created in such a facility.

2. **Siting, development and operation of the demonstrator facility**, in accordance with the programme plan and business model developed in step 1.
3. **Use of learnings from the demonstrator to develop a standardized 'DBD licensing toolkit'** of methodologies for use in managing a siting and licensing process. This would help address what stakeholders in our IAEA-published research see as the clear potential for economies of scale in the licensing process for DBD that are not feasible in the case of mined repositories. Such learnings could then be taken forward either individually by ERDO members, or as part of a multinational repository.

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[10] We understand ERDO has developed an initial internal estimate of €97 million for a deep borehole demonstrator. Deep Isolation and our supply chain partners believe that an effective end-to-end demonstration could be delivered for less than this, and would be delighted to work with ERDO on a more detailed scope and budget. Note that our reference cost estimate at Exhibit 10 does not include costs of a demonstrator. However, if the site for a demonstrator facility was subsequently developed as a disposal site, there would be an opportunity to reduce our estimated €89 million siting and licensing cost estimate for the operational repository.

Annex A: Key features of Deep Isolation's solution

Key features of Deep Isolation's technical solution are illustrated in Exhibit A1, and described in more detail at Exhibits A2-A9.

Exhibit A1: Key features of Deep Isolation's solution

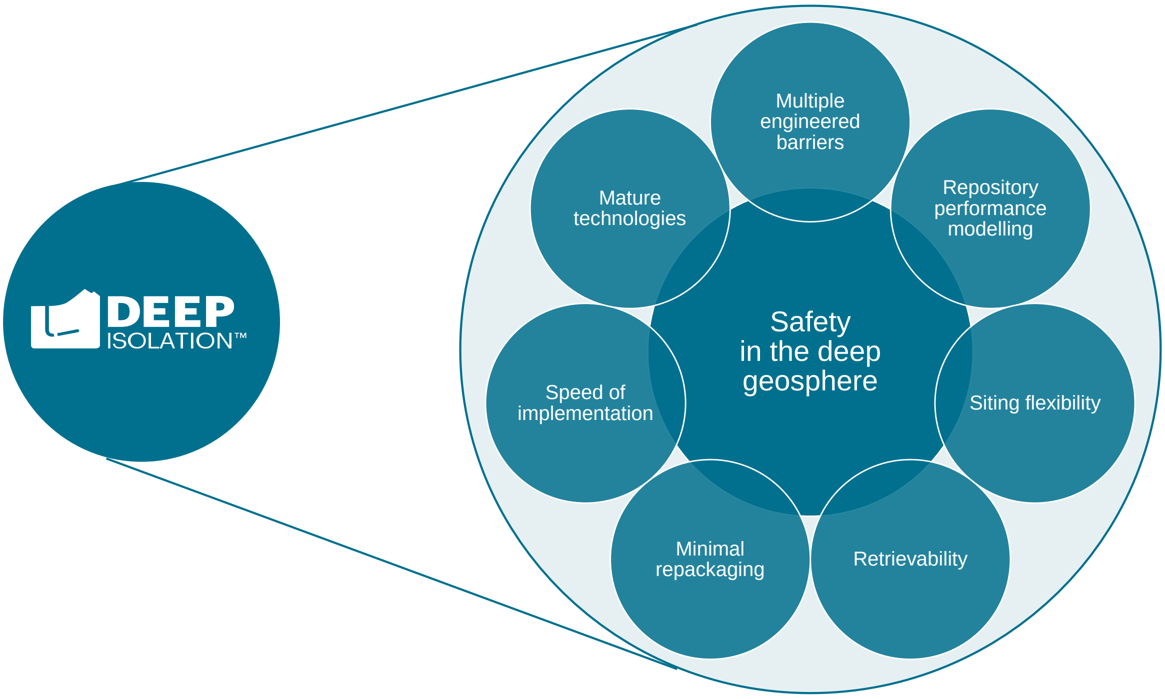

Exhibit A2: Safety in the deep geosphere

Disposal of waste in deep isolated geologic formations provides a safe, secure and permanent solution. It offers:

- **Safety in depth:** The 1-3 km depth of disposal offers protection from the long-term effects of climate change and other natural processes that may adversely affect repository integrity. Increased depth also reduces risks associated with inadvertent and potentially malicious forms of human intrusion.
- **Reducing conditions:** The reducing (low oxygen) environment at depth supports the long-term integrity and function of the engineered barrier system. Reducing conditions inhibit both canister and casing corrosion and also slow the degradation of waste forms like vitrified HLW and uranium dioxide (UO_2) spent fuel. This slows the release of radionuclides into the geosphere.
- **Sorption and transport:** The inherent absorbing and hydrologic properties of many rock formations limit the mobility of most radionuclides. In appropriately sited repositories, the combination of sorption, long travel paths through the geosphere to the surface (1-3 kilometres), and slow, often diffusion-limited migration of mobile radionuclides (e.g., ^{129}I, ^{36}Cl, ^{79}Se) contributes to low peak doses at the surface. In our modelling, typical peak doses in the human accessible biosphere are orders of magnitude lower than the limits considered safe by regulators. Most radioactive waste either decays away underground within the engineered barrier system (waste form and canister) or during the long migration from the disposal section to the accessible environment is locked permanently in the geosphere.
- **Future safety demonstrated by past performance:** An array of isotopic markers in the deep geosphere can provide critical information on:
  - The relative isolation of the geologic environment from surface waters
  - The long term (>1 million years) mobility of safety relevant radionuclides through the rock formation
  - Formation-scale average permeabilities relevant to repository design and modelling.

These isotopic systems include a broad range of stable and unstable isotopes, importantly ^{36}Cl, ^{4}He, ^{81}Kr and a range of additional noble gases. Used in combination, these different lines of isotopic evidence can be developed into a compelling case for the past isolation of repository host rock formations and their potential as repository sites. The information stored in isotopic systems provides insight into the integrated performance of the deep hydrogeologic system and its response to long-term and large-scale forcing events (climate change, seismicity). A deep hydrologic system that has maintained isolation for the past million to tens of millions of years is likely to provide isolation and stability for a repository over safety relevant time periods in the future [11]-[14].

Exhibit A3: Mature technologies

We deliver this deep geologic safety by leveraging mature technologies widely used across the oil and gas sector and that we have integrated and enhanced with our own patented innovations. In particular:

- **Directional drilling:** Advances in directional drilling technology have made deep horizontal boreholes reliable and relatively inexpensive to develop. In the US in the period 2007-2018, more than 120,000 horizontal wells have been drilled, with typical depths of 0.5 to 3 kilometres, and lengths of 4 kilometres or more.[11] Most of these wells were constructed using small (< 25 cm) diameter casings; however, there are many examples of larger diameter extended-reach well bores in offshore environments, such as the Gulf of Mexico and the Cook inlet area of Alaska, where they are more appropriate for resource extraction. Studies by our partners show that large deep horizontal boreholes (45 cm) are feasible in appropriate host rock formations using 'off the shelf' drilling and casing technologies[12]. Industry specialists expect that speciality 57 cm casing for horizontal boreholes will be available shortly.
- **Site characterization:** A diverse and sophisticated array of subsurface characterization technologies developed by the oil and gas industry (and international research organizations) for well bores can be brought to bear for site evaluation for horizontal borehole repositories. These include methods to characterize fracture networks, regional stress fields, collect fluid samples and cores, and assess local and formation scale rock mechanical and hydrologic properties, among others. In sedimentary basins, high resolution 3-D seismic volumes provide a wealth of data that can be integrated on a much more detailed scale. This is especially true of porosity and permeability mapping, fracture mapping, geo-pressure detection and quantifying the overall coherency of events. The validity of computational data is tested with information provided by well logs, down hole measurements of all kinds and core data. In short, these tools provide superior quality information to inform and assess the potential of a site and host rock formations for application of Deep Isolation's solution.
- **Emplacement and retrieval:** Daily operations in the oil and gas industry involve the emplacement and retrieval of equipment in the subsurface. Most of these operations are for routine services to the well bore and there are well developed latching mechanisms and fail safes. In addition, the retrieval and removal of objects stuck in well bores is also highly developed. Many elements of these commonly used emplacement and retrieval technologies have essentially 'off the shelf' applicability to emplacement of waste disposal canisters.

Exhibit A4: Multiple engineered barriers

Although the characteristics of the geosphere and great depth of the repositories are central to the long-term one-million-year safety case, there are many elements of the solution that contribute to the nearer term safety case. These engineered barriers perform important safety functions in the emplacement and pre-closure phase of the repository and provide additional long-term protection after the repository is sealed.

Key elements of the Engineered Barrier System (EBS) include:

- **Corrosion-resistant canisters:** Disposal canisters are designed to fit individual geologic environments and provide containment and protection during emplacement and to isolate waste forms from the geosphere for millennia. The disposal canisters themselves will not provide adequate shielding for above-surface radiation protection so a transfer cask is expected to be used to move the loaded disposal canister to the rig for emplacement. Once underground, the geologic environment will provide the

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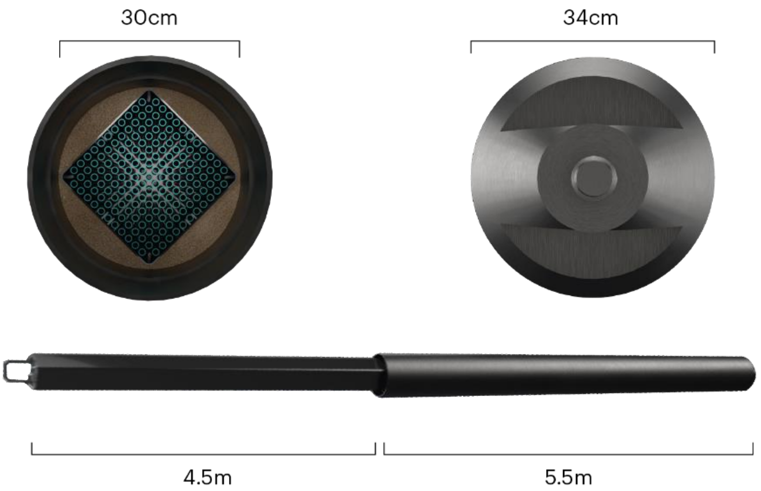
[11] https://www.eia.gov/

[12] DI internal report, Schlumberger

shielding to protect the surface.



A standard Deep Isolation waste canister[13]

Our initial canister design is sized to hold complete spent PWR (Pressurized Water Reactor) nuclear fuel assemblies, but can be used for other forms of compact high-level radioactive waste. Additional specialized canisters can be developed as required to provide for smaller or larger waste forms. The oil and gas drilling industry handles drill pipes that are up to 29 m long, so disposal canister lengths should be less than that for handling purposes.

Nickel-chromium-molybdenum alloys (Alloy 22 - UNS N0622, and Alloy 625 - UNS N06625) are expected to be very stable in the saline, reducing conditions expected at depth[14].

- **Durable vitrified and ceramic waste forms:** Many common forms of HLW are themselves very substantial engineered barriers that contribute to long term post closure safety. Vitrified HLW may retain the bulk of its radionuclide inventory for many tens of thousands of years to hundreds of thousands of years post closure [15]-[16]. Ceramic fuel forms such as UO_2 fuel pellets are similarly stable in reducing environments and may retain the bulk of their radioactive inventory for similar time frames. The best estimate for the fractional dissolution rate for UO_2 spent fuel in reducing conditions is on the order of 10^{-6} / year to 10^{-7}/ year [17]. This corresponds to ~50% dissolution and consonant release of ~50% radionuclides to the geosphere between 690,000 years and 6,900,000 years. A conservative fractional dissolution rate of 10^{-5} / year, corresponding to 50% release of radionuclides in 69,000 years, is used in our safety calculations.
- **Casings, backfills and seals**: Casing made of low alloy carbon steel (9Cr-L80, P 110) or other appropriate alloys provide a reliable and smooth conduit for canister placement and retrieval. In appropriate reducing environments casings are expected to retain their functionality for many decades to support emplacement and pre-closure retrieval.

  For permanent closure, the disposal section is plugged, the casing is removed from the vertical access hole, and the borehole is then sealed using methods in alignment with those being developed and tested by the international community. The current reference design assumes that the casing in the disposal zone will remain in place, forming an additional component of the engineered barrier system. Potential sealing materials include - where technically appropriate - bentonite clays, cements, asphaltic compounds, and various crushed rock forms used in combination. The backfilled and sealed portion of the borehole may be over a kilometre in length and provides a robust barrier to radionuclide transport.
- **Repository geometry:** There are a number of passive design features of the Deep Isolation repository

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[13] Upper left shows the cross section when holding a spent nuclear fuel assembly. Upper right shows the end cap. Bottom shows the assembly being placed in the canister

[14] Our current canister corrosion analyses have focussed not on crystalline basement but on a 'generic' shale geochemical environment, where we are considering a number of alloys. For example, our initial corrosion analysis for Alloy 625 suggests a lifespan of >40,000 years under conditions of passive corrosion (Payer, J.; Finsterle, S.; Apps, J.; Muller, R.A. Corrosion performance of engineered barrier system in deep horizontal drillholes. Energies 2019, 12, 1491). A more recent study on Alloy 22 predicts a >500,000-year time frame for the passive corrosion of a 1cm wall thickness canister at 1 km depth in a nominal shale environment (Macdonald, Digby. "The general Corrosion of Alloy 22", Deep Isolation internal report, 2020).

that perform engineered barrier functions and provide enhanced safety. These include:

  - An offset of the vertical access hole from the horizontal repository which similarly decouples simple hydrologic gradients from driving radionuclide migration upward through the vertical access hole and associated Excavation Disturbed Zone (EDZ).

Exhibit A5: Repository performance modelling

- Deep Isolation uses numerical modelling to improve system understanding, to identify key factors affecting repository performance, and to calculate safety-relevant performance metrics.
- For the assessment of the long-term safety of a deep horizontal borehole repository, Deep Isolation simulates coupled thermal-hydrological processes as well as radionuclide transport in an integrated model that includes the source term, engineered barrier components, near field, geosphere, and biosphere. Chemical and mechanical aspects are represented by effective parameters. The model is used to evaluate the long-term safety for a wide range of conditions and alternative system evolutions, using deterministic simulations, sensitivity analyses, and a sampling-based uncertainty propagation analysis.
- Our modelling results for a generic deep horizontal borehole repository demonstrate that the combined effect of the features described in Exhibits 2.1 – 2.3 above (deep geologic barrier, mature technologies for horizontal repository development, and the EBS features of our solution) deliver a high level of safety and provide confidence in the robustness of the repository solution.

Exhibit A6: Minimal repackaging

- In many cases, the spent nuclear fuel assemblies that hold the waste can be placed directly in disposal canisters without modification; so too can the internal fuel rods within the assemblies if these have already been removed for storage purposes. The standard dimensions of the fuel assemblies used across the nuclear industry (up to around 30 centimetres in diameter and up to 5 metres long), are extremely well matched to borehole sizes.

Exhibit A7: Retrievability

- Borehole retrieval technology is highly developed and, if desired, waste canisters can be retrieved for several decades in a pre-closure phase.
- As discussed at Exhibit 2.2 above, retrieval of objects from deep boreholes is routine in the drilling industry, including uncooperative retrieval. Placement and retrieval of borehole equipment are highly developed and are commonly performed using wirelines with a tractor, coiled tubing, or drill-pipe methods. Deep Isolation's drilling partners are confident that much of this experience is directly transferable to retrieval of disposal canisters containing nuclear waste. (It is worth noting that although we can manage retrievability, it would be practically impossible for any unauthorised party to do so.)
- Deep Isolation builds on this industry experience and is developing additional retrieval technologies that are tailored to our solution. The ability to retrieve waste from horizontal boreholes has been designed into Deep Isolation's solution from the start, including the overarching patented horizontal borehole solution and our emplacement and retrieval systems.
- Deep Isolation's disposal canister design includes a latching mechanism and release elements specifically incorporated to facilitate retrieval - even if stuck during emplacement.
- We have demonstrated the ease of retrieval of small disposal canisters using standard technologies as an initial proof of principle – as illustrated by the short video at https://www.youtube.com/watch?v=3GZ4TC8ttbE. A full-scale demonstration awaits the development of a regional testing facility or potential host site.

Exhibit A8: Siting flexibility

- In principle, the Deep Isolation primary reference model (using a horizontal disposal section) provides access to an increased number of geologic environments that are appropriate for deep geologic disposal, in settings from depth of 1-3 kilometres. Combined with the option of drilling vertically down into crystalline bedrock at depths of up to 5 kilometres, this makes DBD deployable in a wide variety of locations.

- In addition, Deep Isolation’s solution is modular and relatively lower cost, opening up the potential to dispose of waste either at a single site or at multiple locations.
- This combination of siting flexibility and modular delivery opens up a wide range of opportunities, including – subject to community consent, suitable geology and regulatory approval – enabling disposal at or near many of the sites where nuclear waste is produced and stored. In such scenarios, there is potential to minimise transport, and hence to reduce transport costs and the management of associated risks.

Exhibit A9: Speed of implementation

- The governments that are currently engaged in developing mined geologic disposal facilities measure the timescales for planning and constructing these in decades. Partly this is due to the lengthy timescales needed for public consultation and regulatory scrutiny, which will be broadly similar for both mined and borehole facilities. But even after regulatory approval is given, implementation of a mined facility is a very lengthy process. For example, analysis of plans published by the Canadian, Swedish and US governments shows[15]:
    - An average of 1 year between regulatory approval and start of construction
    - An average construction period of 8.3 years
    - An average emplacement period of 10 years.
- Deep Isolation’s solution, by contrast, can start disposing of waste in 1-2 years following regulatory approval:
    - Assuming the Deep Isolation facility is a disposal only facility without a repackaging facility, the mobilization of the drilling equipment and handling facilities can be accomplished in six months.
    - Each borehole can be drilled in a few weeks[16], allowing disposal operations to begin in less than a year from regulatory approval.
    - Borehole construction can be done outside of emplacement activities so construction should never impede the disposal operations after the first borehole is completed and ready for disposal operations.

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[15] See Deep Isolation: An introduction for policy-makers, May 2020
[16] Detailed timings will vary according to geology and site-specific conditions.

Annex B: Detailed inventory analysis table

ERDO Data[1]					Deep Isolation Assessment				
ERDO Waste group		No of disposal units	Total volume (m^3)	Diameter of packaging (m)	Diameter of Deep Isolation drillhole (m)	Ease of disposal	Readiness for disposal	Overall technical suitability	Recommended disposal model taking packaging efficiencies into account
1	Denmark Residues from PIE	33	1.1	0.22	0.34	2 – standard borehole	3 – disposal ready[2]	Highly suitable	Standard-bore, direct disposal
2	Croatia & Slovenia (Krško NPP) SNF	2282	513.7	0.28	0.34	2 – standard borehole	3 – disposal ready	Highly suitable	Standard-bore, direct disposal
3	Netherlands vitrified waste (from both Sellafield and AREVA La Hague)	478	92.8	0.43	0.47	1 – larger borehole	3 – disposal ready	Technically suitable	Larger-bore, direct disposal
4	Netherlands HEU-SNF	30	20.8	0.846	0.34	2 – standard borehole	2 – re-pack	Technically suitable	Standard-bore, direct disposal
5	Netherlands LEU-SNF	120	83.3	0.846	0.34	2 – standard borehole	2 – re-pack	Technically suitable	Standard-bore, direct disposal
6	Netherlands Compacted hulls & ends	600	116.3	0.43	0.47	1 – larger borehole	3 – disposal ready	Technically suitable	Larger-bore, direct disposal
7	Netherlands Other	200	138.9	0.846	n/a	0 – not feasible	0 – not disposal ready	Not suitable	Not recommended for disposal
8	Norway SF	500	6.2	0.11	0.34	2 – standard borehole	3 – disposal ready[3]	Highly suitable	Standard-bore, direct disposal
TOTAL		**4243**	**973.1**						

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[1] Data taken from the following documents: “Waste families in OPERA,” Netherlands, 2016, “Inventory of SF and HLW for possible Deep Borehole Disposal-Slovenia,” Slovenia, 2020, email from Heidi Sjølin Thomsen entitled “Borehole Solution”, Denmark, 2020 and “Overview minus Greece and Austria” spreadsheet compiled by Håvard Kristiansen, 2021.

[2] Note that further work will be needed following this preliminary assessment to ascertain whether any additional disposition investments are needed ahead of placing the waste forms in disposal canisters. For example, we understand that the Danish waste is poorly characterized, mixed with small amounts of other wastes, and in containers that may contain voids. Overall, our view is that a simple and safe way forward is likely to be direct emplacement in disposal canisters, but further work including canister design, gas generation and heat transfer analysis is needed to verify this.

[3] 10 of the 17 tons are from the JEEP 1 and Halden Boiling Heavy Water Reactor (HBWR) and are metallic uranium contained within aluminium cladding. This fuel is not technically disposal ready until additional repackaging and/or processing occurs. For the purpose of this preliminary estimate, it assumed to have been already converted to oxide form (to improve long term stability) and repackaged into canisters. The necessity of the oxide conversion (as opposed to other alternatives including a simpler repackaging operation) may be reconsidered in future work.

Annex C: Relative benefits of different borehole geometries

Introduction

Our reference model assumes horizontal geometry for the disposal section of boreholes. But there is no single right design for a deep borehole repository. Actual decisions on borehole geometry will be dependent on geological conditions at a specific disposal site and stakeholder priorities across the range of relative benefits that different geometries can offer.

A high-level view of some of the key considerations and relative benefits that need to be addressed as part of the repository development process is summarized in Exhibit B1 on the following page.

This looks at four different types of repository:

- H **Horizontal:** a borehole drilled vertically, before curving gently to create a horizontal disposal section at the desired safe disposal depth (typically 1-3 kilometres). It has an upper vertical section, a tangential section to build angle to the horizontal section.
- V **Vertical:** a borehole drilled vertically downwards into crystalline bed rock. In typical vertical schemes, this might be at depths of 4-5 kilometres. A vertical well is usually accepted to have a less than 5 degree deviation from vertical at Total Depth (TD).
- S **Slanted:** a borehole with an upper vertical section and a lower tangential section to achieve a less than c.50 degree deviation.
- Hy **Hybrid:** a repository combining a mined disposal facility with one or more deep boreholes.

Relative benefits of each repository type are mapped against two dimensions, illustrating the extent to which the benefit is relevant to:

- **Delivery of the repository:** that is the extent to which this geometry choice can help reduce the costs, time and/or complexity of repository construction and operation
- **Performance of the repository:** that is, the extent to which this benefit supports fit with policy and regulatory requirements, stakeholder needs and/or greater ease of demonstrating the safety case.

The scale of the two dimensions reflects the extent to which the geometry offers **some** benefits relative to other options, **significant** benefits or **very significant** benefits. This is deliberately a qualitative and subjective scale, because the relative importance of these benefits will differ between regulatory environments and between different stakeholder and community settings. The model at Exhibit C1 is therefore intended as an initial discovery tool, for collaborative adjustment and calibration according to stakeholder priorities.

Key relative benefits of the four options are summarized in Exhibit C1, and then discussed in more detail in the section that follows.

Exhibit C1: Relative benefits of different repository geometries

Delivery benefits
(Reduces costs, time and/or complexity of repository construction and operation)

Key:
- V Benefit typically associated with **vertical** repositories
- H Benefit typically associated with **horizontal** repositories
- S Benefit typically associated with **slanted** repositories
- Hy Benefit of a **hybrid** repository combining mined GDF and boreholes

	Some performance benefits relative to other options	Significant performance benefits relative to other options	Very significant performance benefits relative to other options
Very significant delivery benefits relative to other options	V **Likely to be lowest cost option for small inventories**, particularly where very short disposal sections avoid the need for great depth V **Basic directional control** means that drilling operations are simpler and more predictable	H **Can reduce costs:** by making it easier to access host rock formations in which long disposal sections can be drilled while crossing fewer geological boundaries, horizontal repositories can often reduce overall drilling and casing costs	H **Increased passive safety:** passive features of a horizontal repository intrinsically deliver safety benefits that are otherwise absent or require additional investment in Engineered Barrier Systems Hy **Size**: Enables large, varied inventories to use mined GDF for bulky ILW, while securing the benefits of boreholes for HLW
Significant delivery benefits relative to other options	V **Lower cost sealing and backfill**, due to simpler geometry and gravity assistance	S Combines the **simplicity of drilling** seen in vertical with the additional **siting flexibility** offered by directional drilling	H **Less complex retrievability:** because canisters rest on the repository floor, without the bridge plugs and support matrices required in other designs
Some delivery benefits relative to other options		V **Small surface and sub-surface footprint:** can simplify management of land rights, and has potential to offer a simpler site characterization process H S **Smaller surface footprint for multiple boreholes** because of ability to drill holes at offset angles	H **Greater siting flexibility:** enables suitable host rocks to be accessed from a wider range of locations, and is not restricted to crystalline basement

(Supports fit with policy & regulatory requirements, and/or greater ease of demonstrating the safety case)
Performance benefits

Relative benefits of horizontal borehole repositories

As illustrated in Exhibit C1, horizontal geometry offers a good mixture of delivery and performance benefits - which is why Deep isolation uses it as our primary reference model. Key relative benefits include:

- **Increased passive safety**

  All borehole designs offer significant levels of increased passive safety when compared to a mined repository, because the extra depth by definition offers additional protections in terms of natural events and climate change effects and safety from human intrusion. Horizontal borehole geometry in particular delivers a set of safety benefits that are otherwise absent or require additional investment in Engineered Barrier Systems in other DBD designs. These intrinsic passive safety benefits include:

  - The disposal section is offset from the vertical access hole, which decouples hydrologic gradients from driving radionuclide migration upward through the vertical hole and associated Excavation Disturbed Zone (EDZ).
  - All waste is stored within a single layer of rock, and thus the chemical conditions experienced across the waste packages are more similar and predictable.
  - All canisters lie horizontally and with zero pressure from other canisters – unlike in vertical schemes, where waste canisters at the bottom of a borehole face significant pressures from the cumulative weight on top of them (which requires investment in bridge plugs, support matrices etc to protect them).
  - In the event of a dropped canister during emplacement, the gently-curved transition from vertical to horizontal (coupled with the fact that the narrow borehole is filled with water or drilling fluids) means that the canister will not fall but drift slowly and safely to a halt prior to entering the horizontal disposal section of the repository.

- **Greater siting flexibility**

  Directional drilling techniques allow horizontal repositories to access suitable rock formations at a greater range of depths and in a greater range of geological locations than is feasible for other forms of geological disposal. Horizontal repositories are suitable for sedimentary and evaporite formations, as well as the hard rocks which are the focus of vertical DBD. The borehole can be steered to avoid hazards or take advantage of geological structures to enhance safety performance of the repository.

- **Potential for cost reduction**

  Broadly speaking, Deep Isolation expects costs to increase at a faster rate as the borehole goes vertically deeper, but that the costs of extending horizontally increase on a more linear basis. This is driven by the way that very deep vertical holes tend to penetrate multiple formations and cross multiple geological barriers. This increases the cost and complexity of drilling and also requires additional investment in casing – resulting in a significantly increased borehole diameter at the surface. Depending on waste form, the drilling and borehole casing technologies required for both the vertical and horizontal sections of a horizontal repository are ones that are used on a daily basis in the oil and gas sector. For vertical repositories, however, the significantly larger starting diameter is likely to add cost and operational complexity.

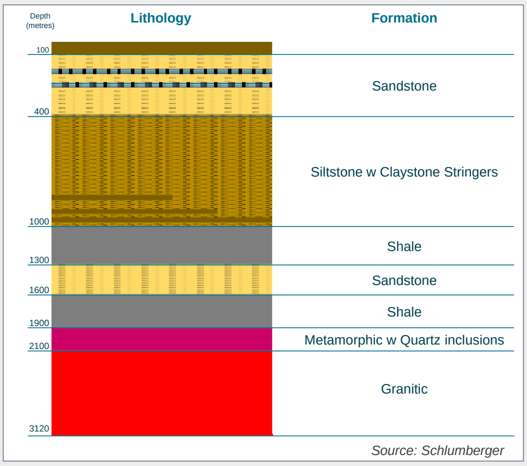
  An illustrative comparison – using a mixed geology representative of many European locations - is shown at Exhibit C2. This has been developed collaboratively between Deep Isolation and our principal drilling advisor Schlumberger, using wellbore planning tools that are used on a daily basis across the oil and gas sector and informed by extensive Schlumberger data on the time and cost of drilling in different lithologies and depths.

Exhibit C2: Illustrative comparison between vertical and horizontal borehole costs

Step 1: Model a geological environment for borehole disposal

We documented a geology capable of supporting both vertical and horizontal borehole repositories. As illustrated to the right:

- This contains a lithology typical of many European countries.
- Provides a disposal zone in the range of 1.0 – 1.6 km sealed within a layer of shale that provides ideal conditions to construct a deeply isolated horizontal repository
- Contains deeper layers of granite, of the sort targeted in deep vertical borehole repositories.



Source: Schlumberger

Step 2: Specify two comparable borehole scenarios for this location

	Vertical	Horizontal
Length of disposal section	1.5 km	1.5 km
Measured depth (total length of borehole)	3 km	3.5 km
Total vertical depth	3 km	1.5 km
Borehole outside diameter in disposal section	~ 46 cm	~ 46 cm
Borehole outside diameter at surface	~ 122 cm	~ 91 cm
Number of casing sections	3	2

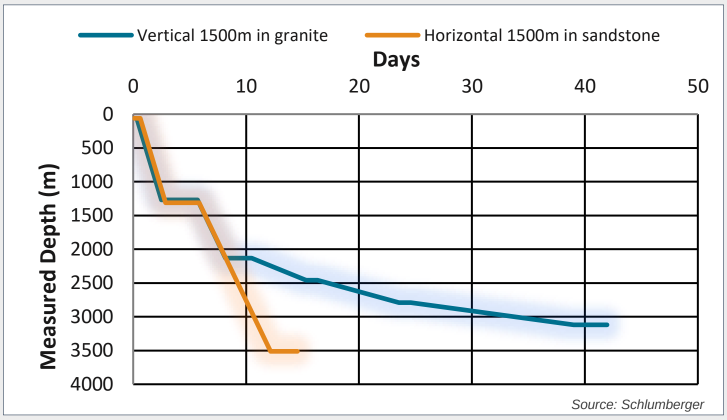
Step 3: Use industry benchmarks on Rate of Penetration (RoP) by lithology and depth to calculate time and cost in each scenario

Time:

- Vertical = **42.0** days
- Horizontal = **14.6** days

Cost:

- For every **€1** spent to construct the horizontal repository, we would need to spend **€1.80** to construct the vertical repository.



Source: Schlumberger

Key drivers of cost difference:

- Slower ROP in the granite (1-3 metres per hour, compared with 6-30 metres per hour in the horizontal sandstone section)
- The vertical well crosses more geological boundaries, so requires more investment in casing sections, which in turn requires larger diameter borehole at surface, more mud volumes and larger surface hole equipment.

- **Less complex retrievability**

  Because canisters rest on the repository floor, without the need for bridge plugs and support matrices required in other borehole repository designs, retrieval of canisters can be a less complex process.

- **Smaller surface footprint for multiple boreholes**

  For sites requiring multiple boreholes, the use of horizontal (or slanted) wellbore profiles may – because of the ability to drill at offset angles - allow a greater number of boreholes over a smaller area at the surface compared to vertical boreholes. Established anti-collision planning procedures ensure no wellbores intersect or overlap.

Relative benefits of vertical borehole repositories

As illustrated in Exhibit C1, vertical geometry offers a simplicity and predictability which, particularly for small inventories, may well outweigh the benefits discussed above of horizontal boreholes. Key relative benefits of vertical over other geometries include:

- **Likely to be the lowest cost option for small inventories**

  Provided the inventory can be accommodated in suitable geology within a vertical wellbore profile and without requiring very great depth, the relatively low construction complexity of the vertical borehole will reduce the amount of time required for construction and the overall cost and risk of construction.

- **Basic directional control**

  Vertical wells can be kept vertical using the correct Bottom Hole Assembly (BHA) design and utilising best drilling practice. Monitoring deviation does not require complex and expensive additional service such as Measurement While Drilling (MWD).

- **Lower cost sealing and backfill**

  The vertical wellbore configuration takes advantage of proven drilling industry techniques to place the right cement type, at the right depth to achieve the desired result for zonal isolation and well integrity. Being vertical, canister sealing and backfill can be achieved by either by tubing and pumping or possibly by gravity emplacement e.g., bentonite.

  Sealing in horizontal and highly deviated boreholes is more complex but achievable with good drilling practise, correct packers and wellbore elements and the use of multi-stage cement programmes.

- **Smaller surface and subsurface footprint for single boreholes**

  For small inventories requiring a single borehole, a vertical configuration can simplify land management and sub-surface boundary conflicts, and can support a simpler site characterization and wellbore planning exercise. Characterization requirements might be met in large part by the borehole itself; certainly, there is less need to characterize geological structures in the broader area than is the case for horizontal boreholes that may extend some kilometres.

Relative benefits of various slanted borehole repositories

A slanted borehole combines a) the simplicity of vertical drilling with an option to return to vertical (‘drop’) for Total Depth with b) the potential advantage that directional drilling opens up for displacement from a surface location to avoid surface obstacles or take advantage of geological structures or avoid known subsurface hazards.

Relative benefits of hybrid borehole repositories

A hybrid design – in which a mined disposal facility is combined with one or more deep boreholes – is likely to be the optimal solution for large, varied inventories. It allows a mined facility to deal with bulky intermediate level waste that is not of suitable dimensions for borehole disposal, while using boreholes to secure the benefits of deeper isolation and greater passive safety for high-level waste. Co-locating such facilities can offer economies of scale in site preparation, handling facilities and accession of waste to the site.

Annex D: Bibliography and list of abbreviations

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Abbreviations used in this document

ARAO	Agencija za radioaktivne odpadke (Slovenia)
BHA	Bottom hole assembly
COOP	Concept of operations
COVRA	Centrale Organisatie Voor Radioactieve Afval (Netherlands)
DBD	Deep borehole disposal
DI	Deep Isolation
DSRS	Disused sealed radioactive sources
EBS	Engineered barrier system
ECN	Energy Research Centre of the Netherlands
EDZ	Excavation disturbed zone
ERDO	European Repository Development Organisation
HEU-SNF	Highly-enriched uranium – spent nuclear fuel
HLW	High-level waste
IAEA	International Atomic Energy Agency
ILW	Intermediate level waste
LEU-SNF	Low enriched uranium – spent nuclear fuel
LILW	Low and intermediate level waste
MEUR	€ millions (euros)
MIT	Massachusetts Institute of Technology
MWD	Measurement while drilling
NND	Norwegian Nuclear Decommissioning
PBS	Product breakdown structure
PWR	Pressurized water reactor
R&D	Research and development
RoP	Rate of penetration
SNF	Spent nuclear fuel
TD	Total depth
tHM	Tonnes of heavy metal
VLLW	Very low-level waste