Deep Isolation for TRIGA II in Slovenia

Preliminary feasibility study on disposal of TRIGA II research reactor spent fuel using a Deep Isolation repository

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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 Slovenia's TRIGA II research reactor fuel using Deep Isolation's innovative borehole solution.

Initial conclusions from this preliminary assessment are:

1. The TRIGA II spent fuel is suitable for deep borehole disposal (DBD).
2. All of the spent fuel could be disposed of within a DBD 'micro-repository' consisting of a single borehole at a site with a surface footprint of 900 m^2.
3. If relevant planning and licensing activities are commenced well in advance with sufficient contingencies for regulator and stakeholder engagement, this repository could be constructed, operated and closed within 12 months of the TRIGA II reactor's planned closure in 2043 – avoiding the need for planned expenditure on temporary storage for this waste of €25 million.
4. Although the costs and geologically-driven design requirements of the repository will vary by location, <u>all areas of Slovenia</u> are potentially suitable for deep borehole disposal of nuclear waste:
    - Any Slovenian community wishing to host a DBD repository would be likely, subject to detailed site investigations and site characterization, to offer host rocks that are capable of delivering the necessary isolation and stability
    - This includes communities in the vicinity of both the TRIGA II research reactor and the Krško nuclear power plant.
5. The cost for delivering such a stand-alone micro-repository would be (across the four relevant scenarios we have studied) between €11.6 – 26.3 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 €37.1 million – although these estimates are considerably more uncertain.
6. Of this total cost range of €48.7 – 63.4 million[1], we recommend that the highest value should be used as the conservative basis for estimating and accounting for the disposal liability to be managed by Josef Stefan Institute (JSI).
7. The optimum approach, however, would involve not such a stand-alone micro-repository but instead co-disposal: with the TRIGA II waste disposed of in a larger DBD repository also disposing spent fuel from the Krško nuclear power plant.
8. The overall cost-effectiveness of Slovenia's waste disposal programme would be significantly increased by approaching TRIGA II spent fuel as an initial 'pathfinder' project – with 100% of the investment required to dispose of it in a borehole in 2043 representing an invaluable contribution to research, demonstration and site characterization for a broader national repository (irrespective of whether the Slovenian government eventually determines this should be a mined facility or a DBD repository).

The report sets out recommendations on next steps, including: refinement of these preliminary cost estimates; development of an integrated roadmap and business case for disposing all Slovenia's spent fuel in an integrated DBD repository, supported by a Generic Safety Case calculating environmental impacts over a 1 million-year plus timeframe; and collaboration by ARAO with international efforts on DBD research and demonstration.

[1] This cost range is a preliminary, high level estimate. Our recommendations for developing and validating more detailed cost estimates within Slovenia's local supply chain are set out in Section 8.

1. Introduction

1.1 About this paper

This report has been commissioned from Deep Isolation EMEA Limited for Slovenia's Agencija za adioaktivne odpadke (ARAO). The purpose of this report is to provide an initial assessment of Deep Isolation's deep borehole solution for disposal of Slovenia's TRIGA II research reactor fuel.

1.2 Context

Deep borehole disposal (DBD) is a method for geological isolation of radioactive materials. It can offer particular benefits for some waste types and can be used either independently or as an adjunct to a mined geological disposal facility (GDF).

Deep Isolation has developed a DBD solution that combines established directional drilling techniques with patented new technologies and processes, in ways that address key challenges for geological disposal around costs and community consent, while at the same time opening up a greater range of potential geological settings in which disposal can safely be undertaken with a 1 million year plus safety case. This new solution is currently being examined by a number of other countries in Europe and globally.

ERDO, the European Repository Development Organization of which Slovenia is a founding member, commissioned Deep Isolation earlier in 2021 to undertake a review of the applicability of this solution to the national inventories of its members. That project is now live[2]. It will include a high-level feasibility assessment and cost estimate for disposing ERDO inventories, including the Slovenian and Croatian radioactive materials currently stored at the Krško NPP. However, Slovenia's TRIGA II research reactor spent fuel is not included in the scope of the ERDO project.

Against that background, ARAO has initiated a separate study to assess the feasibility of using DBD disposal for this one waste group.

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. These repositories are constructed 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 [1-6]
- Over 40 patented inventions granted and in development
- Extensive supply-chain partnerships with leading companies from the global drilling and radioactive waste management sectors.

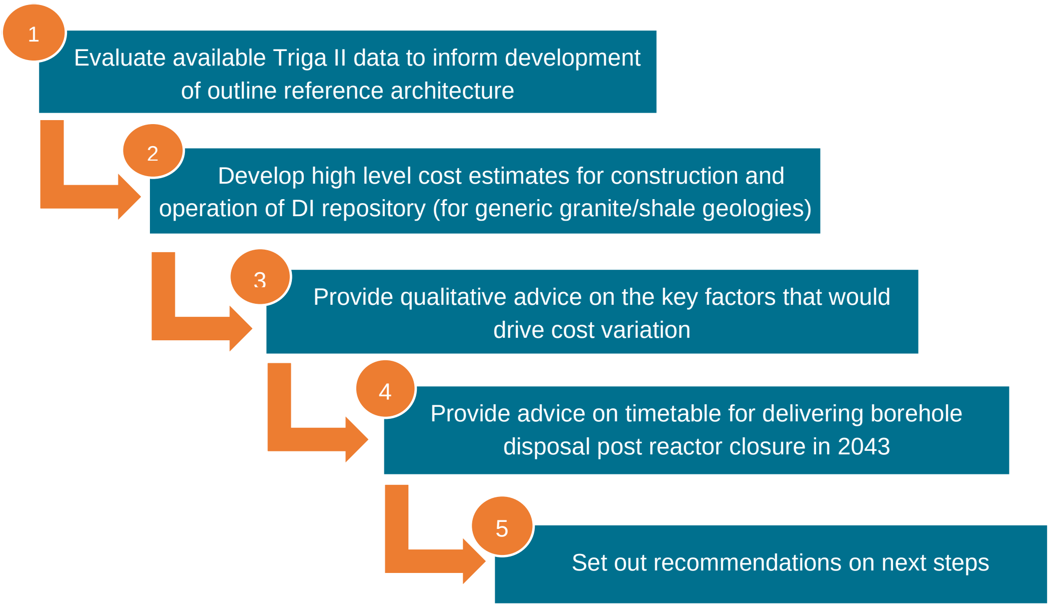
As part of our commitment to bring this innovative solution to markets around the world, in 2020 we established a European business, Deep Isolation EMEA Limited – which has led our work with ARAO for this review.

[2] The preliminary assessment prepared for ERDO by Deep Isolation has been published here

1.4 Purpose and objectives of this study

The purpose of this study is to carry out an assessment of the suitability and costs of disposing Slovenia's TRIGA II research reactor fuel using Deep Isolation's innovative borehole solution.

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



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 the available data on the TRIGA II spent fuel elements and fuel followers for disposal using Deep Isolation's solution.
- Section 4 presents the set of generic **Geological requirements** within which suitable host rocks could be located for a DI repository, and then provides a commentary on the extent to which such characteristics are likely to be present within Slovenian geology.
- Section 5 presents our proposed **Outline reference architecture** for the DI repository for ARAO capable of disposing of all the Triga II spent fuel, based on three separate options.
- Section 6 then presents our **High-level cost estimates** for implementation of the outline reference architecture for each of these three options and discusses the key considerations that would drive any variations on these estimates.
- Section 7 sets out our **Preliminary conclusions**
- Finally, Section 8 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 ARAO.

This main report is supported by two annexes:

- Annex A provides further **technical detail** on Deep Isolation's solution.
- Annex B presents our recommended **Geological Site Screening Criteria**
- Annex C contains the report's **bibliography** and a list of **abbreviations**.

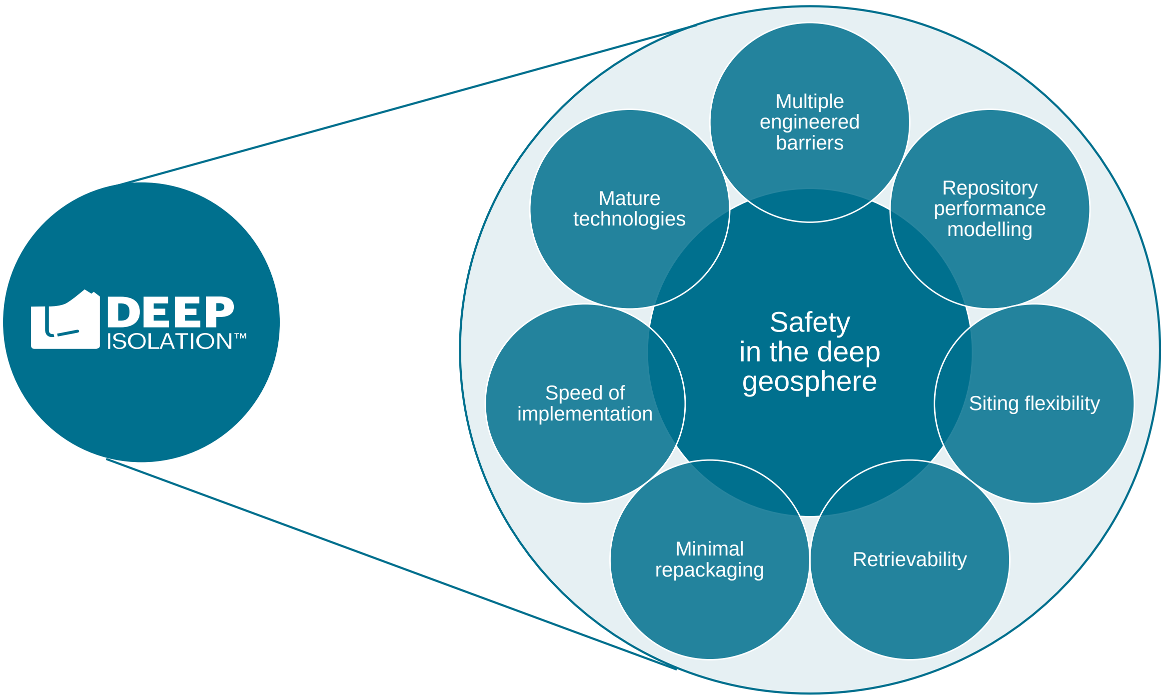
2. Deep Isolation's technical solution

Deep Isolation's solution places corrosion-resistant canisters containing radioactive waste and spent fuel in deep boreholes 1-5 kilometres underground. This 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 1, 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 1: Key features of Deep Isolation's solution



3. Inventory analysis

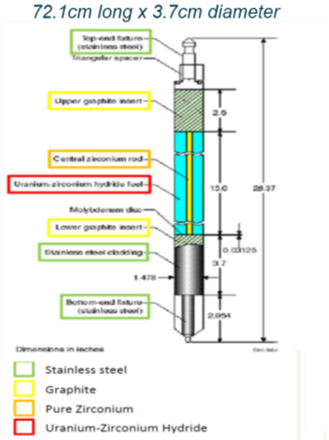
The project has reviewed the available data on the TRIGA II research reactor spent fuel published within the “ARAO Inventory of SF and HLW for possible Deep Borehole Disposal – Slovenia” (dated April 2020). By 2043, the point at which the research reactor will cease operations, there will be a total inventory of 84 TRIGA spent fuel items (both fuel elements and fuel followers) ready for disposal.

Exhibit 2 below provides a summary of the inventory in scope for this review, including quantities, dimensions and uranium content (of new fuel elements).

Exhibit 2: Summary of TRIGA II spent fuel inventory in 2043

80 fuel elements

72.1cm long x 3.7cm diameter



Source: Institute Jozef Stefan website

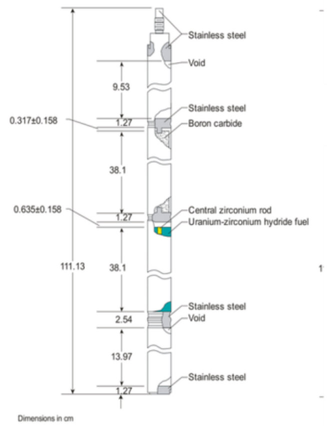
- 71 standard spent fuel elements with 12% uranium content, in cylindrical formation (2 of them are equipped with thermocouples)
- 9 fresh fuel elements

- 3 spent fuel followers for control rods
- 1 fresh fuel follower for control rod

Uranium content	
Total mass of uranium (g)	278.0 g
Mass of ^{235}U (g)	*55.4 g*
U in U-ZrH (wt. %)	11.9%
Enrichment (wt. %)	19.9%
H/Zr atom ratio	1.6

4 fuel followers

111cm long x assuming same 3.7cm diameter



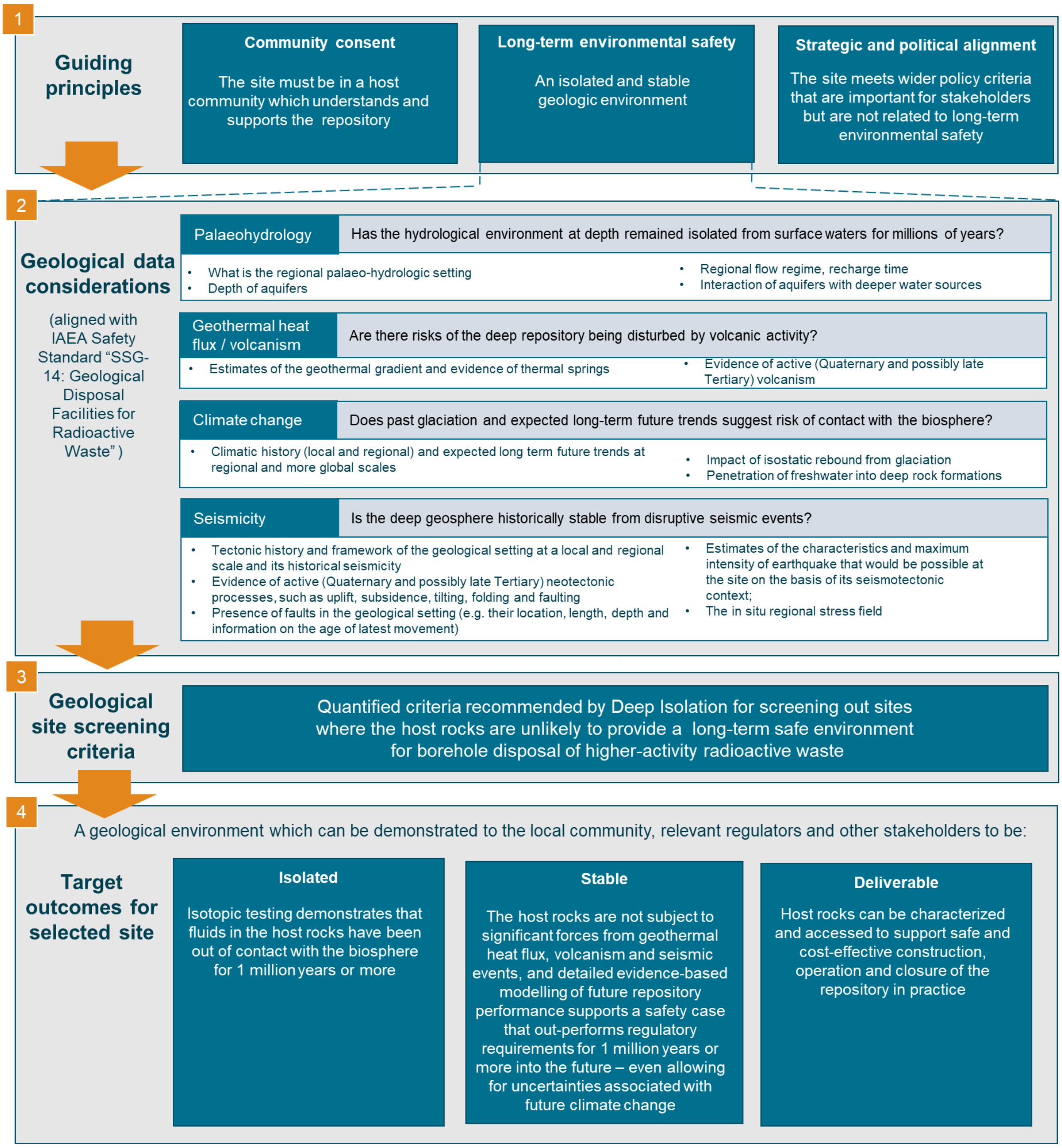
Note that ARAO have not been able to provide us information on the expected radioactivity and heat levels of the spent fuel elements in 2043.

4. Geological requirements

4.1 Overview of geological requirements

Exhibit 3 summarizes the framework that Deep Isolation recommends for selecting a suitable site for a deep borehole repository.

Exhibit 3: Overview of DBD site selection framework



This approach is rooted in three guiding principles: community consent; long-term environmental safety; and strategic and political alignment.

In this limited-scope project, we have been asked to comment only on the second of these: that is, the extent to which Slovenian geology is likely to provide host rocks that perform against requirements for long-term environmental safety of a deep borehole repository. In future, we would recommend also looking at development of additional site screening criteria in relation to:

- **Community consent**: obtaining municipality council approval after successful public debate, in accordance with the Slovenian siting legislative framework.
- **Wider policy criteria:** addressing considerations that are not directly related to long-term environmental safety but are nevertheless important for stakeholders in Slovenia, in the context of Slovenia's overall radioactive waste management strategy.

As illustrated at Exhibit 3 above, our starting point for this geological assessment is IAEA Safety Standard SSG-14: Geological Disposal Facilities for Radioactive Waste [7]. This sets out, in Section 6 and Appendix A, a wide range of datasets that should be considered when assessing the site of a geological disposal facility – which we have summarized in Exhibit 3 under four headings: paleohydrology, geothermal flux / volcanism, climate change and seismicity.

SSG-14 itself does not set quantified parameters on such issues in relation to DBD repositories, and its detailed guidance is more relevant to mined repositories that are typically at shallower depths than a DBD repository. We therefore recommend that in any initial sifting, ARAO should take as its starting point Deep Isolation's preliminary and generic site screening criteria as set out at Annex B. These are informed by: IAEA's Safety Standard SSG-14 [7], our own extensive work in modelling the long-term performance of both vertical and horizontal configurations for deep borehole repositories [1-6], and a review of prior work by organizations including Sandia National Laboratories [8-9] and the US Department of Energy.

Deep Isolation welcomes feedback on these preliminary screening criteria from stakeholders in Slovenia and elsewhere, and will continue to refine and evolve the framework described at Annex B.

It is worth noting that rock formations that comply with these minimum parameters can be accessed from a large proportion of the earth's surface. DBD 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. **Overall, this makes DBD a highly flexible option for use in a community-consent based siting process.**

4.2 The extent to which these geological requirements are present in Slovenia

In this preliminary study, we have not undertaken detailed screening of Slovenian communities against the criteria at Annex B. However, an initial high-level data review suggests that:

- **Palaeohydrology:** Palaeohydrology provides a link between recent and present knowledge of waters of the earth and past hydrological environments in geological time reflecting our understanding of the impacts of both geological and human activity on the hydrological cycle, water balance, sediment yield, river channel morphology, and basin characteristics. Key considerations to address in deep borehole site assessment in Slovenia include:
    - Approximately 8000 years ago In the Central-European region a short climatic change is observed in lake sediments and associated with a cool and rainy phase with extensive woodland becoming more open by the Late Glacial and Early Holocene, and then gradual changes to a Continental then sub-Mediterranean climatic influence. These changes influenced the rate, volume, and distribution of surface water within the catchment areas of present-day Europe and controlled the rate and volume of surface waters penetrating the subsurface as well as erosion and subsequent deposition. Given the diverse geologies of Slovenia these palaeohydrogeological changes have expressed themselves in different ways, especially in vulnerable karst aquifers.

- Aquifers and their properties are well defined in Slovenian scientific literature and managed by the relevant government departments. In specific areas of geological interest there are defined aquifers and perched aquifers exploited in the Ljubljana region, and stacked aquifers exploited in the Krško region. Monitoring boreholes and data acquisition methods can acquire discreet water samples from water-bearing zones to fingerprint the water chemistry and in deeper water bearing strata prove isotopic isolation and act as environmental benchmarks. In well design, specific wellbore elements using the correct materials will ensure zonal isolation across all pertinent aquifers to isolate deeper fluids from shallow fluids.

- **Geothermal heat flux / volcanism:** Slovenia is located in a region with no volcanism and moderately low crustal heat flow. We have seen no evidence that thermal driving forces exist beneath Slovenia that might compromise repository integrity or adversely affect its safety functions.
- **Climate change:** Climate change impacts including the crustal effects of glacial loading and unloading appear to be quite small in Slovenia. The major safety-relevant repository impacts which will need to be addressed during the process of FEP development (Features, Events, and Processes) for the repository are related to:
  - the tectonic effect of the geological compressive zone in the east that will be prevalent for the lifetime of the subsurface repository
  - the tectonic and seismic effects of any Alpine glacial loading (indeterminate weight of any glacial ice) and isostatic rebound (resultant uplift when the ice melts)
  - surface erosion due to migration of ice sheets and / or changes of water courses due to tectonically activated ground surface distortion
  - the potential incursion of fresh water into the deep basement hydrologic system.
- **Seismicity:** all areas of Slovenia are at least potentially suitable on seismicity-related criteria. However, compression regimes in the west could reactivate well mapped thrust-fault systems between the western coast and central Slovenia – a risk should be addressed in detailed site characterization efforts.

In summary, the controlling environmental factors over the lifetime of a DBD repository in Slovenia will be tectonic movement from Adria as it pushes into Europe and potential climate change impacts that might alter the surface and shallow subsurface and hydrology around the repository.

These are factors that will need to be addressed during detailed site characterization work and factored into the design and planning of borehole construction at any selected site. That said, our preliminary conclusion, based on this initial qualitative review, is that **all areas of Slovenia are potentially suitable for deep borehole disposal of nuclear waste.**

In other words, we believe that <u>any</u> Slovenian community wishing to host a DBD repository would be likely, subject to detailed site investigations and site characterization, to offer host rocks that are capable of both:

- Meeting the **site screening criteria** at Annex B; and
- Achieving the **target outcomes** listed at Exhibit 3 above:
  - ✓ ***Isolated*:** isotopic testing demonstrates that fluids in the host rocks have been out of contact with the biosphere for 1 million years or more.
  - ✓ ***Stable*:** the host rocks are not subject to significant forces from geothermal heat flux, volcanism and seismic events, and detailed evidence-based modelling of future repository performance supports a safety case that out-performs regulatory requirements for 1 million years or more into the future – even allowing for uncertainties associated with future climate change.
  - ✓ ***Deliverable*:** host rocks can be characterized and accessed to support safe and cost-effective basis construction, operation and closure of the repository in practice.

This does not mean that all sites in Slovenia are equally attractive. Some areas will require more complex borehole designs and require more time and cost to construct - but all are likely to be achievable. The data acquired as part of detailed Site Characterisation (focused on tectonics / geomechanics, structure, poroperm and geological evolution) will define the geological parameters to be addressed in the engineering design for a specific site.

It is worth commenting in particular on the two communities that are currently hosting nuclear facilities in Slovenia: the Krško nuclear power plant and the Jozef Stefan Institute research reactor. Experience in other countries suggests that such communities – which understand nuclear energy and have benefitted from it economically - can be more willing to host geological disposal facilities. Existing data on these two areas suggest that:

- **Krško: Relevant geology of the Krško region / Sava folds**

  The Krško nuclear facility is situated on a river terrace of the river Sava, approximately 2km south-east of Krško town in the Lower Sava Statistical Region. The facility is sited on Quaternary sediments, with hills of Tertiary rocks and sediments and harder Mesozoic rocks underlying the Quaternary sediments and expressed at surface to the north and south forming boundaries of the Krško basin, part of the larger tectonic Sava folds structure stretching from central Slovenia to north-west Croatia. Research indicates there is relative uplift of the basin (<1mm per year) assumed to be from the compressional regime active from the end of the Neogene to Quaternary causing the folding of the Krško syncline and impacting the entire Sava folds structure [10]. This same compressional regime would be the source of past local seismic events.

  Hydrogeologically the facility sits above three locally typical aquifers. The first two aquifers are relatively shallow and with the shallowest occurring in the Quaternary sediments and being locally moderately to highly productive, periodically low productive aquifers. The second is in the deeper and older Pleistocene and Tertiary sediments under alluvial deposits. Both these aquifers would be isolated behind relatively shallow wellbore casing. The third aquifer or group of Tertiary carbonates would probably require an additional isolating string of casing pending further investigations.

- **JSI: Relevant geology of the Ljubljana area (Josef Stefan Institute)**

  Ljubljana is situated in the subalpine region of central Slovenia, above mostly Holocene and Pleistocene silt, sand and gravel deposits and Upper Palaeozoic calcareous shales. Structurally, Ljubljana is south of the Julian Alps Thrust, and between the major regional faults of Ravne fault and Žužemberk / Želimlje faults that run primarily north-east to south-west, parallel to the compressive force of local tectonics under Southern Alps and Dinarides influence. Recent work by the Slovenian Ministry of the Environment shows the Ljubljana area to be of high risk of peak ground acceleration in response to seismic hazard [11].

  The city of Ljubljana is above the generally unconstrained Ljubljana polje aquifer, one of the biggest and most important aquifers in Slovenia. This aquifer is encountered at relatively shallow depths and will be isolated by placement of wellbore casing to achieve zonal isolation.

5. Outline reference architecture

5.1 Options analysis

All of Slovenia’s TRIGA II waste could be disposed of in a single standard Deep Isolation disposal canister.

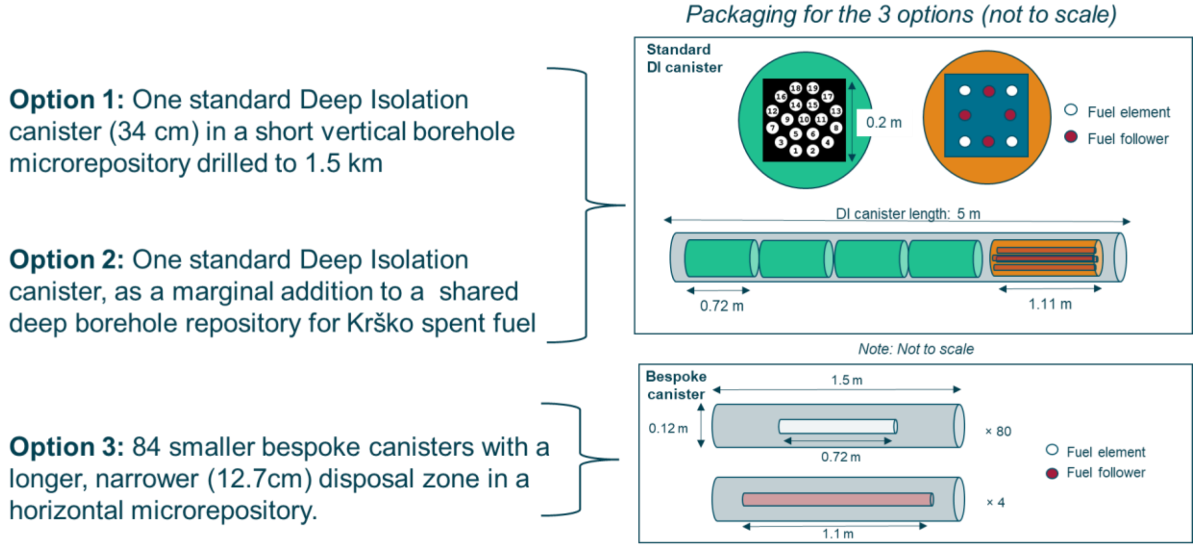
Our baseline disposal architecture (Option 1) is therefore based on a vertical borehole drilled to a safe depth that can deliver 1 million-year plus isolation (for generic costing purposes, we have assumed a depth of 1.5 kilometres), with a very short vertical disposal section.

In addition, we have explored two other potential scenarios:

- Option 2: disposing the same standard single canister, not within a borehole repository dedicated only to TRIGA II waste but as a marginal addition to a larger borehole repository that is also disposing the spent fuel from the Krško nuclear power plant.
- Option 3: developing a bespoke canister specially for the TRIGA II fuel elements, enabling use of a significantly lower diameter (and hence lower cost) borehole.

These options are illustrated in Exhibit 5 below. For each option, Section 5.2 documents our key assumptions that will impact on the repository design and associated costs.

Exhibit 5: Summary of the options analysed during this study



It is worth noting that in Option 3 we have selected the ‘extreme’ version of a multiple-canister scenario: that is, a single very small disposal canister for each individual fuel element – so 84 canisters in total. This scenario results in the smallest unit cost per canister and the smallest average cost-per-metre in borehole drilling – but with additional costs from the longer disposal section.

In practice, of course, a range of intermediate options are also available, and it is possible that the optimum balance might be somewhere in between options 1 and 3: for example, several TRIGA II elements clustered within a canister that is still significantly smaller in diameter than our standard canister but not as narrow as illustrated above for Option 3. Further analysis will be needed on this during the design phase; for the purposes of this preliminary overview, however, we believe that Options 1 and 3 are useful in illustrating some of the key factors.

5.2 Design assumptions

A Deep Isolation repository follows the seven design principles recommended by IAEA in its guidance [12] 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 ARAO needed to develop and document a full set of stakeholder requirements and a Conceptual Design for this repository. However, we have discussed with ARAO during the project a set of high-level design assumptions for this repository, as shown at Exhibit 6.

Exhibit 6: Design assumptions underpinning our three preliminary architecture options

Design parameter	Design assumptions: 1) Single canister in micro-repository	2) Single canister in Krško repository	3) 84 canisters in micro-repository
Fuel type	TRIGA fuel elements and followers		
Waste encapsulation and transport	Waste 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.		
Host rock	Crystalline rock or shale		
Borehole diameter	0.46 m	0.46 m	0.127 m
Canister configuration	0.34 m diameter DI canister	0.34 m diameter DI canister	0.12 m diameter 'bespoke' DI canister
Number of boreholes configuration	Single vertical borehole	Krško fuel repository with horizontal boreholes spaced 30-100 m apart[3]	Single horizontal borehole
#/spacing of canisters	1, no spacing required	1, no spacing required	84, spaced 1 m apart
Borehole disposal depth	1.5 km	1.5 km, with 1.5 km disposal zone	1.5 km, with 300 m disposal zone
Fuel characteristics and heat load	<5 W/fuel element (Based on current repository modelling assumptions of 50 MW-d/kg burnup pressurized water reactor fuel with 30 years of cooling. Increases in heat load are possible based on current margins to limits but would need to be assessed in a level of detail that is outside the scope of this study.)		
Canister emplacement period	1 day	1 day	≈ 18 weeks (assuming 5 canisters/week)
Canister retrieval	Retrieval prior to closure is considered as an off-normal requirement. After repository closure, not within the design basis.		

[3] A repository for Krško spent fuel is expected to contain 11 boreholes, with 2,283 canisters of waste, and with boreholes drilled in parallel and bending to be horizontal or sub-horizontal. These generic assumptions may change depending on the geology of a specific selected site.

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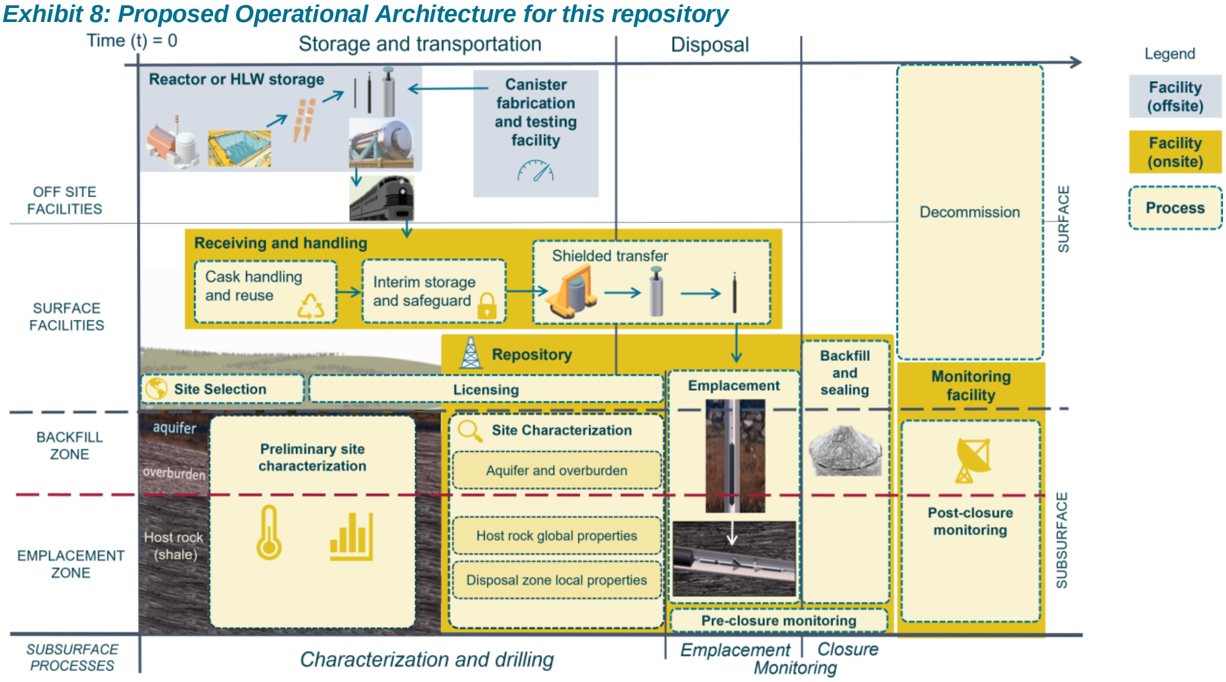
5.3 Concept of Operations for a Repository

Exhibit 7 defines the key ***functions*** of a deep borehole repository, 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 design assumptions set out at Section 5.2 above.

Exhibit 7: Key functions within the Concept of Operations for this 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: Proposed Operational Architecture for this repository



6. 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 5, for each of the three options we have considered. At this stage, the purpose of these estimates is to support a possible decision to further explore the deep borehole disposal option for TRIGA II fuel. Further work would be required to refine these cost estimates as part of a full options appraisal.

6.1 Methodology and assumptions

We have estimated costs for a Deep Isolation repository in line with the design assumptions at Exhibit 6 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 20-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 e.g. 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	• Site screening • Community engagement • Third party technical review • Site characterisation, including two characterisation holes • Licensing costs
Construction	• Drilling costs, including borehole casing • Transfer casks and equipment • Other on-site capex (well-head shielding etc)
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, including the placement of seals and backfills • Establishing post-closure monitoring processes • 20 years of post-closure monitoring

We used the inventory data summarised at Exhibit 2 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 Slovenia and have not undertaken bottom-up costing for such implementation. Rather, we have:

1. 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. This assumes:
    - Disposal is at a nuclear power plant with existing infrastructure

[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 = €0.841195. This represents the average exchange rate in the 12 months to 25 November 2021. (source: www.ofx.com)

- Standard-sized canister and shale geology as our baseline cost.

2. Then scaled these estimates for the Slovenian context by:

   - Calibrating our US cost estimates on regulatory compliance through comparison with detailed costings undertaken by ARAO in relation to the costs of characterizing, licensing and monitoring a mined repository in Slovenia[5]
   - Assuming that canister costs vary by size of canister and drilling costs by rock type and size, but all other delivery costs are held constant per unit of costing:
     – We used a standard-sized canister and shale geology as our baseline cost, with granitic geology assumed as 70% higher for drilling and well closure costs.
     – We then assumed the narrower canister and narrower borehole needed for Option 3 would cost 50% less.

These assumptions 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.

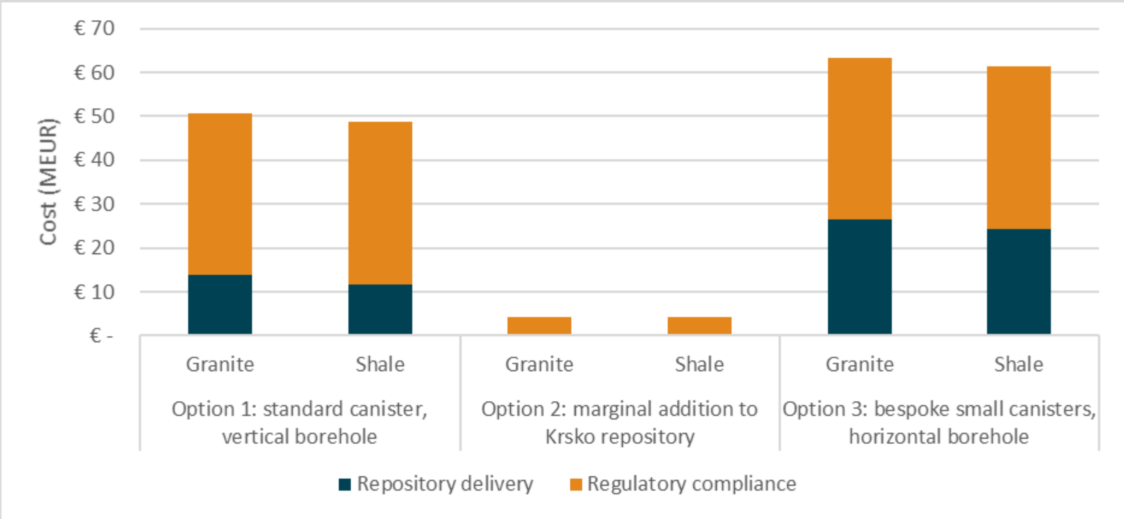
6.2 Cost results

The chart on the next page shows total costs, in both a generic shale geology and a generic granite geology, for each option:

1. One standard Deep Isolation canister (34 cm) with a short vertical borehole
2. One standard Deep Isolation canister, but as a marginal addition to the deep borehole repository for Krško spent fuel
3. 84 smaller bespoke canisters with a longer, narrower (12.7 cm) borehole and horizontal disposal section.

[5] Cost estimates for a Slovenian mined repository are taken from *"Reference scenario for geological disposal facility in hard rock with cost estimation for its implementation",* ARAO 2019. This includes 29 budgeted activities in relation to siting and licensing of the mined disposal facility, representing a total budget of over €102 million. Of these 29 activities, we estimated that: 13 represent fixed costs which would be incurred for any type of geological disposal facility; 10 represent costs that are driven by the complexity of the design being licensed; and 6 represent costs where the driving factor is the geographical extent of the site under consideration. We have then weighted relevant costs by 100%, 50% and 15% respectively when estimating the cost of siting and licensing a deep borehole repository in Slovenia. These weightings are highly conservative given that a single borehole repository is very significantly less complex than the reference design for a Slovenian mined disposal facility, and that the surface footprint of the former will be only 900m^2 compared with the 150,000 m^2 required for the latter.

Exhibit 10: Overview of costed scenarios for deep borehole disposal of TRIGA II spent fuel



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 <u>repository delivery</u>** (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 construction costs for a borehole repository are based on off-the-shelf technologies that are used on a daily basis in the oil and gas sector, reducing the risk of cost and delivery overruns when compared with the major civil engineering challenge that is represented by a mined repository.
- **Our estimates for <u>regulatory compliance</u> (which includes work on site characterization, licensing, and post-closure monitoring)** are much more uncertain, because no deep borehole repository has yet been taken through a full regulatory approvals process.

As illustrated above, for option 1 around three-quarters of our estimated costs are in the latter category. Further work to map out regulatory requirements and pathways in Slovenia is needed to develop and refine these initial estimates.

The sections below break down these high-level cost estimates by life-cycle stage for each option.

6.2.1 One standard canister in a micro-repository

A summary of our high-level cost estimate for option 1 is shown at Exhibit 11.

Exhibit 11: Estimated lifecycle costs of a single canister within a vertical micro-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	€23.1	€23.1
Construction	Repository delivery	€11.2	€9.9
Operations	Repository delivery	€0.5	€0.5
Repository closure	Repository delivery	€2.0	€1.2
Post-closure monitoring	Regulatory compliance	€14.0	€14.0
Total		**€50.8**	**€48.7**

6.2.2 One standard canister in a Krško repository

During our project with ERDO, we developed cost estimates for disposal of the Krško spent fuel, both within a centralized ERDO repository and on a decentralized basis (that is, with the Slovenian and Croatian inventories from Krško being disposed of at a single site within one of those two countries). We have used the findings from that project to develop the high-level cost estimate for option 2 that is shown at Exhibit 12.

Exhibit 12: Estimated lifecycle costs of a single canister within a Krško repository

Life-cycle stage	Cost category	Cost in MEUR
Siting and licensing	Regulatory compliance	€4.2
Construction	Repository delivery	€0
Operations	Repository delivery	€0.04
Repository closure	Repository delivery	€0
Post-closure monitoring	Regulatory compliance	€0
Total		**€4.24**

Note that this captures only the marginal technical cost of deploying one additional canister within the repository. This does not reflect the full economic cost of disposing the TRIGA II fuel. If ARAO decides to pursue a combined DBD repository for Krško and TRIGA II spent fuel, further analysis will be needed to determine the value of the fixed costs of siting, licensing and capex for the repository as a whole that should properly be accounted for by the TRIGA II element.

6.2.3 84 individual canisters in a horizontal micro-repository

A summary of our high-level cost estimate for option 3 is shown at Exhibit 13.

Exhibit 13: Estimated lifecycle costs of 84 canisters within a horizontal micro-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	€23.1	€23.1
Construction	Repository delivery	€13.5	€11.3
Operations	Repository delivery	€11.8	€11.8
Repository closure	Repository delivery	€1.0	€0.6
Post-closure monitoring	Regulatory compliance	€14.0	€14.0
Total		**€63.4**	**€60.8**

6.3 Options analysis

It is clear that option 2 (adding the TRIGA fuel to an existing repository for Krško spent fuel) is by far the most cost-effective option – and will remain so even when further work is undertaken to account for the wider fixed costs of that repository that should properly be accounted for by the TRIGA fuel.

However, this is not an option that the waste owners (the Jozef Stalin Institute) can rely on, because it is dependent on decisions taken by other organizations. Looking at the two stand-alone options for

TRIGA II disposal, then option 3 is around a quarter more expensive than option 1. That said, there are also potential delivery benefits to weigh against each other, as summarized in the table below.

Exhibit 14: Comparison of relative benefits between Option 1 and Option 3

Delivery benefit	Option 1 – one standard canister	Option 3 – 84 smaller canister
Cost	10% lower	
Operational safety and retrieval	Far fewer canisters to emplace or potentially retrieve	
Thermal limits/ storage time		Higher heat load decreases required cooling period prior to disposal.
Long term safety		Potential safety benefits associated with more dispersed fuel
Criticality		Improved margin for criticality safety (if additional analysis shows this is an important)
Proliferation	Consolidating fuel will improve self-protection	

Further work will be needed during the design process to evaluate these relative benefits. For the time being – and in particular because of the need to undertake criticality analysis to confirm safety considerations in relation to Option 1 – **we recommend using the costs of Option 3 as the baseline assessment for future liability in relation to TRIGA II spent fuel disposal.**

It is also worth highlighting that Options 1 and 3 both offer the advantage that they would enable the disposal of TRIGA II spent fuel **within just one year** of the research reactor's planned closure in 2043. Further work is needed to develop a detailed implementation plan aligned to Slovenia's regulatory processes, but Exhibit 15 below gives some preliminary high-level estimates of time scales required for different phases of implementation.

Exhibit 15: implementation times

Can be undertaken in advance of reactor closure to enable disposal to start in 2043

	Micro-repository (Options 1&3)	Shared repository (Options 2)
1. Siting and site characterization	2 years	Depends on scale and requirements of a larger borehole repository capable of disposing Slovenian SNF (or Slovenian/Croatian SNF) – out of scope for this project.
2. Licensing	3 years	
3. Construction	<1 year	
4. Emplacement	<5 months	
5. Closure	<5 months (estimated)	
6. Post closure monitoring	20 years	

This offers benefits that are potentially significant in terms of Slovenia's overall waste management programme. In particular:

- It opens up the opportunity of putting the TRIGA II fuel permanently beyond reach as rapidly as possible, with significant nuclear security benefits.
- It would avoid the need for costly investment in temporary storage for the TRIGA II fuel pending final disposal in a national repository. Exhibit 16 on the next page sets out ARAO's current cost estimates for such storage, which total €25 million ahead of eventual disposal.

Exhibit 16: current ARAO budget estimates for storage and disposal of TRIGA II fuel

Current budget assumptions for TRIGA II fuel (Source: Strokovne podlage za Nacionalni program ravnanja z radioaktivnimi odpadki in izrabljenim gorivom za obdobje 2023–2032 (ReNPRRO23-32), ARAO, Revizija 0, september 2021)	**Million Euros**
Cost of three CASTOR storage canisters and transportation to local storage	€1.5 million
Storage opex costs at c €0.5 million annually from 2043 to 2093	€23.5 million
Disposal costs calculated as 0.34% of the c €1.4 billion cost of the mined repository (assumes 2 x LO1-2 disposal canisters and 2 additional disposal boreholes, and no additional costs for eg research, licensing, analysis)	€4.8 million
Total	**€29.8 million**

As discussed in Section 6.2, the costs of constructing and operating a single borehole to dispose of this waste in full during 2043 (€11.6 – 26.3 million Euros across the four relevant scenarios studied in this report) would represent between 39% - 98% of the current storage budget.

Clearly, when the regulatory compliance costs for the borehole repository are also factored in, the savings from avoided storage costs do not by themselves make a stand-alone business case. But there is a strong potential case for ARAO treating the TRIGA II repository as a pathfinder project for a wider borehole repository. In other words, **development and construction of a single borehole repository for TRIGA II fuel could be managed as part of the site characterization and R&D programme for a Krško DBD repository.**

7. Preliminary conclusions

Based on this preliminary assessment, our initial conclusions are:

1. The TRIGA II spent fuel is suitable for deep borehole disposal (DBD).
2. All of the spent fuel could be disposed of within a DBD ‘micro-repository’ consisting of a single borehole at a site with a surface footprint of less than 1,000 m^2.
3. If relevant planning and licensing activities are commenced well in advance with sufficient contingencies for regulator and stakeholder engagement, this repository could be constructed, operated and closed within 12 months of the TRIGA II reactor’s planned closure in 2043 – avoiding the need for planned expenditure on temporary storage for this waste of €25 million.
4. All areas of Slovenia are potentially suitable for deep borehole disposal of nuclear waste:
    - Any Slovenian community wishing to host a DBD repository would be likely, subject to detailed site investigations and site characterization, to offer host rocks that are capable of delivering the necessary isolation and stability
    - This includes communities in the vicinity of both the TRIGA II research reactor and the Krško nuclear power plant.
5. The cost for delivering such a stand-alone micro-repository would be (across the four relevant scenarios we have studied) between €11.6 – 26.3 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 €37.1 million – although these estimates are considerably more uncertain.
6. Of this total range of €48.7 – 63.4 million, we recommend that the highest value should be used as the conservative basis for estimating and accounting for the disposal liability to be managed by JSI.
7. The optimum approach, however, would involve not such a stand-alone micro-repository but instead disposing of the TRIGA II waste in a larger DBD repository capable also of disposing spent fuel from the Krško nuclear power plant.
8. The overall cost-effectiveness of Slovenia’s waste disposal programme would be significantly increased by approaching TRIGA II spent fuel as an initial ‘pathfinder’ project – with 100% of the investment required to dispose of it in a borehole in 2043 representing an invaluable contribution to research, demonstration and site characterization for a broader national repository (irrespective of whether the Slovenian government eventually determines this should be a mined facility or a DBD repository).

8. Recommendations and next steps

This report has set out initial high-level assumptions and options for the conceptual design of a deep borehole repository for TRIGA II research reactor waste, along with preliminary cost estimates. Further work is needed to refine this preliminary analysis.

In particular, we recommend the following as next steps:

1 **Development of a Generic Safety Case for deep borehole disposal of the TRIGA II spent fuel.** Safety assessment was out of scope for this preliminary study, given that existing DBD safety analyses are already sufficient to make clear in general terms that this option offers Slovenia very levels of safety over a 1 million-year timeframe and more [1-6]. However, as consideration of the option is taken forward beyond this preliminary stage, it will be essential to document a Generic Safety Case tailored specifically to Slovenian geology. Key issues to address include:

- More detailed safety assessment and criticality analysis for the TRIGA II inventory – including optimization of canister size / number
- Quantitative evaluation of the geologic, hydrologic, rock mechanical and geochemical conditions in potential regions of interest for siting the repository in Slovenia, including regional analysis against the Geological Site Selection Criteria recommended at Annex B.
- Use of these geological data to document one or more generic geological environments in which a repository might be sited in Slovenia.
- Quantitative modelling of the long-term environmental performance of a TRIGA II DBD repository in each of these generic geological environments, calculating the 1 million + timescales for peak dose at the surface.

2 **More detailed analysis to refine our preliminary cost estimates of the disposal liability.** In particular, this work should include:

- Analysis of regulatory and licensing requirements and pathways in Slovenia, including direct engagement with regulatory authorities
- Working with stakeholders to clarify retrievability requirements and post-closure monitoring periods
- Assessing source term in the repository[6]
- Working with supply chain partners to refine cost estimates for the Slovenian labour market
- Refining all cost estimates in the light of the above.

3 **A full strategic appraisal of the costs of borehole disposal for Krško spent fuel**. Based on preliminary estimates undertaken by Deep Isolation in a separate project for ERDO, we estimate the marginal cost of adding the TRIGA II spent fuel to a Krško DBD repository as €4.4 million. But that is based on a generic study that has not assessed licensing pathways in Slovenia and has not analysed specific regulatory and technical requirements for Slovenia. So, although our initial work for ERDO suggests that a DBD repository will save several decades and hundreds of millions of Euros when compared with ARAO's baseline plans for a mined repository, there is a need to support this with a more detailed study to develop the roadmap, engineering design, business case and safety case for a Krško repository. In particular, we recommend that ARAO consider commissioning Deep Isolation, in collaboration with local experts, to undertake a full Foundation Study in relation to the Krško waste.

4 **Development of an overarching strategy and roadmap for combined DBD disposal of both the Krško and TRIGA II spent fuel.** Ring-fenced funding arrangements linked to the polluter-

[6] Current estimates suggest it is >10x lower than equivalent volume of light water reactor fuel and thus >100 x lower than DI's reference design. We therefore see a possibility to reduce drilling costs and implement a shallower (e.g., 500-1000 m) depth for Options 1&3, which would further reduce costs and increase siting options. However, this needs careful consideration to ensure the safety case is not compromised, given the shallower the repository, the more likely it is hydrologically connected to the biosphere and have potential pathways for radionuclide migration.

pays principle means that planning for disposal of these two waste streams is managed separately in Slovenia. However, there would be significant strategic benefits across Slovenia's waste management programme as a whole if ARAO were to develop an integrated disposal roadmap:

- ***Costs savings for TRIGA II SF disposal*** – because *Option 2: Co-disposal* is by far the most cost-effective solution for the TRIGA II waste.
- ***Cost savings for Krško SF disposal*** **-** by using TRIGA II as a 'pathfinder' for a larger national DBD repository, Slovenia could in effect leverage 100% of the costs of TRIGA II disposal as part of the site characterization and R&D programme for the national solution
- ***Early progress coupled with strategic flexibility***– such an integrated roadmap would allow Slovenia to make rapid progress, including early disposal of the TRIGA II fuel without the need to spend costly interim storage, with investments that would deliver detailed empirical knowledge about Slovenia's deep sub-surface that will be valuable in any future scenario for Krško SF disposal (whether in a mined of DBD repository).

5 **International collaboration in relation to DBD demonstration and cost sharing.** In parallel with the above activities, we recommend that ARAO consider investing alongside other national waste management organizations (in ERDO and elsewhere) to support demonstration of the technology and strengthen the empirical evidence that underpins the safety case. ARAO should also explore the potential for sharing fixed costs with other EU countries where research reactor spent fuel disposal is required.

Recent research by Deep Isolation across waste management organizations, national policymakers and regulator found that 4 out of 5 of these stakeholders are keen to see increased international collaboration on DBD, with priorities including in particular an end-to-end demonstration of an operational DBD repository. Deep Isolation is committed to working with ARAO and international stakeholders to support and co-invest in such collaboration.

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

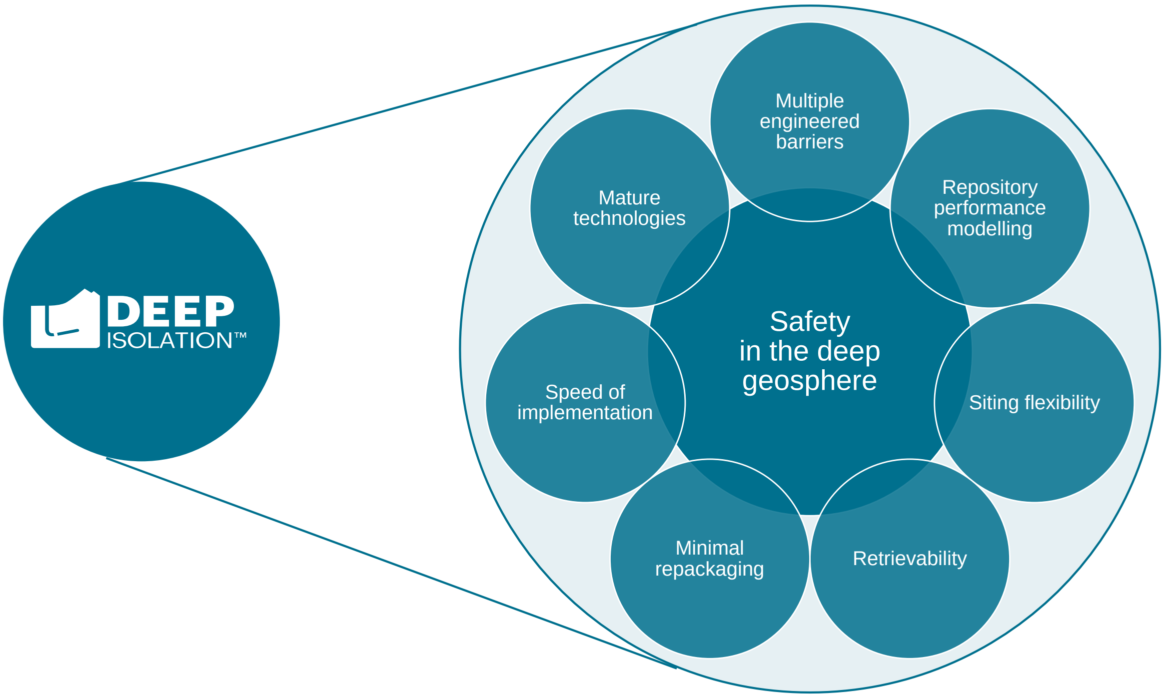


Exhibit A2: Safety in the deep geosphere

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

- **Safety in depth:** The 1-5 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 [13]-[16].

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.[7] 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[8]. 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

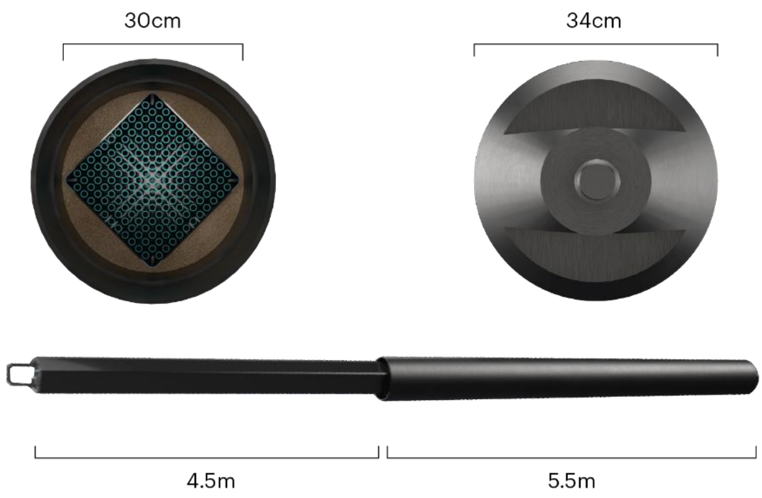
Although the characteristics of the geosphere and great depth of the repositories are central to the long-term one-million-year safety case, there are many elements of the solution that contribute to the nearer term safety case. These engineered barriers perform important safety functions in the emplacement 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 shielding to protect the surface.

[7] https://www.eia.gov/
[8] DI internal report, Schlumberger

A standard Deep Isolation waste canister[9]



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[10].

- **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 [17]-[18]. 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 [19]. 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 that perform engineered barrier functions and provide enhanced safety. These include:

[9] 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

[10] 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).

– 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[11]:
  - 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[12], 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.

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

Annex B: Geological site screening criteria

The site screening process

Site screening is the first step in selecting a site and primarily uses existing datasets with sub-regional and basin-scale geologic characteristics. To manage costs during this stage, DI intends to use readily accessible data from reliable sources, including state/regional geological surveys, groundwater management districts, oil and gas commissions, and departments of natural resources. Potential host country governments could also aid in the compilation of existing data needed to inform the screening process.

After sites are screened according to the criteria presented here, a smaller subset of candidate sites would be compared and selected for preliminary investigations (e.g., potentially using boreholes and some intrusive tests) and thus additional and more detailed data will become available to determine the optimum site for final selection.

Generally, candidate formations should have geologic characteristics—including permeability, thickness, lateral extent, salinity, and pore fluid properties—that can be assessed to identify suitable or unsuitable environments for geologic disposal. Specific criteria on these characteristics are given in the following section. In some cases, explicit criteria are not given and rather recommendations to review data are given (for reasons explained in greater detail in the following subsections).

Connection between site screening and repository design

Site characteristics are inherent drivers of the long-term performance of any repository which can also be strongly modified through changes in engineered features such as depth, configuration, and barriers. Deep borehole repositories emphasize geological barriers by leveraging host rock formations that can be robustly shown to have been isolated from surface processes for hundreds of thousands of years or more. Limiting consideration to sites and disposal depths with favourable hydrogeological histories and properties could simplify site characterization efforts [6] by reducing the importance of near surface and local phenomena (e.g., near field borehole effects) that can be time consuming to characterize. Varying the reference design is also conceivable depending on the specific site (e.g., shallower disposal depths at sites that have the most favourable characteristics, or deeper disposal at sites that have less favourable characteristics). The U.S. Department of Energy (DOE) organized site screening criteria into 4 logically distinct groups: disqualifying conditions, potentially adverse conditions, qualifying conditions, and favourable conditions for site selection [21]. These can also be used to organize the interplay between site characteristics and the repository design. The general relationship between cost, design choices, and site availability is illustrated in Figure 1.

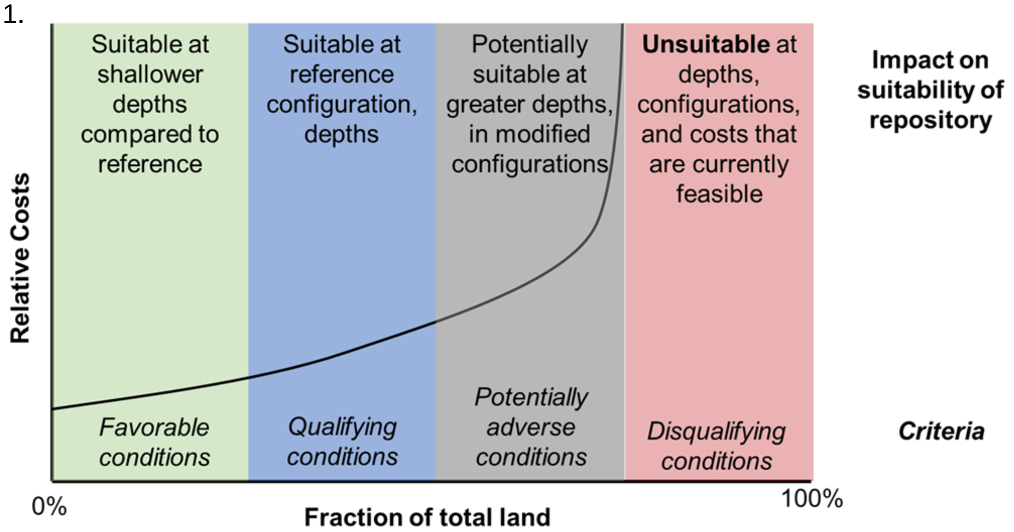


Figure 1. *Relative cost vs. area of land suitable for geologic disposal*

The purpose of site screening criteria (used here synonymously with "disqualifying conditions") at the earliest stages is to rule out sites that would be unsuitable at borehole depths, configurations, or would have currently unfeasible costs (shown in the red box). There also exists a "grey" area where design modifications (and added cost and time) could overcome potentially adverse conditions and yield additional site possibilities. Deep Isolation (DI) continues to explore the vast engineered design space (e.g., depth, disposal zone length and orientation, borehole spacing) and geological design space (host rock properties, geological boundary conditions) to further elucidate key design considerations and trade-offs; however, a clearer picture will only be available during the site screening stage when more detailed data is obtained from candidate sites, based on which DI can advance its repository design. Site criteria based on current performance models (that show significant margin to limits) are explicitly noted here and should be expected to change with future refinements and expansions of modelling efforts.

The US Department of Energy [21] also categorized site screening criteria into pre-closure (i.e., relevant to the construction and operation of the repository) and post-closure (i.e., relevant long term performance). This work focuses on the latter but wherever pre-closure criteria clearly exist they have been explicitly noted.

Cumulative Effects of Various Site Characteristics

A challenging aspect of site screening criteria is that performance is a highly coupled outcome; thus, some site characteristics cannot be considered on their own. For example, there can be cumulative effects from groups of characteristics exceeding certain values that cannot be simply captured by placing restrictions on individual parameters alone. In these cases, recommendations to "review potential impacts" of the characteristics in a holistic manner are given.

Deep Isolation's Geologic Site Screening Criteria

Tables 1-4 below summarize Deep Isolation's preliminary and generic site screening criteria in four areas: palaeohydrology, geothermal, climate change and seismicity.

***Table 1.** Palaeohydrology based site screening criteria*

PALAEOHYDROLOGY: Has the hydrological environment at depth remained isolated from surface waters for millions of years? Can we access suitable rock formations which are isolated from aquifers?		
Site characteristic	**Screening criteria**	**Basis**
Regional palaeo-hydrologic setting and aquifer interactions	• *Favourable condition:* The hydrological environment at the planned disposal depth has remained isolated from the surface for >1 million years. • *Screening criteria:* The hydrological environment at planned disposal depth does not show interactions with surface aquifers within the last >100,000 years.	• Examples of isotopically dated and isolated pore fluid systems with isolation times of >1mY: basement rock [26], sandstone [27], and shale [28].
Confining zone properties	• **Disposal zone:** Existence of a robust disposal zone and/or overlying confining zone that limits fluid migration to the surface environment over repository relevant time scales. • **Rock type**: Suitable sedimentary rock formations might include shales, clays, or salt layers or interbedded strata of the like within other rock types. For crystalline basement rocks, formations with low enough fracture-network and	• In the reference horizontal concept, the waste is emplaced within a confining zone. In a vertical concept, an overlying confining zone is not necessarily required but would serve as an additional barrier. • Rock types from [24]. More specific recommendations on clay properties are available in [29] and may be expanded on in future revisions of this document (e.g., sorption capacity, self-healing properties).

	permeability sufficient to inhibit migration of fluids to the surface. • **Thickness:** Disposal zone layer thickness > 150 m. – *Qualifying condition:* If diffusion dominated transport can be shown to prevail at the repository site, the lateral extent of confining layers or disposal zones should be >10 km beyond planned repository outline.	• For an argillaceous disposal zone, Hendry et. al suggests that 100 m is required [30] to provide a barrier to diffusion. The DOE proposes a minimum thickness of >150 m [29]. 150 m of thickness also gives margin for directional drilling accuracy, which makes this a pre-closure screening criteria. In current DI performance assessments [2] which show significant margins, we have assumed a thickness of 500 m. – Characteristic distance of diffusion transport is much less than 1km in 1 mY [23]. As an example, sedimentary basins in the continental USA usually exhibit thick sedimentary sequences laterally extending hundreds of kilometres [24].
Regional flow regime and recharge time	• Repository is located in a recharge zone or in a discharge zone with low topography-induced vertical head gradients.	• Depth penetration of regional groundwater flow patterns [2], [17].

Table 2. *Geothermal heat flow site screening criteria*

GEOTHERMAL HEAT FLUX / VOLCANISM: Are there risks of the deep repository being disturbed by geothermally induced convection and activity?		
Site characteristic	**Screening criteria**	**Basis**
Geothermal gradient and presence of natural convection	• Low crustal heat flow, with geothermal heat flux less than 75 mW/m^2 • *Qualifying condition*: A brine concentration of >10 g/l (corresponding to a density difference of 72 kg/m^3) would promote density stratification [23]. • The average permeability of the host rock should be less than 10^{-17} m^2 (10 microDarcy)	• Proposed by Sandia National Laboratories (SNL) [8]. Limiting the geothermal gradient will also increase margin to boiling, which helps with high heat load waste forms. • Deep saline formations suitable for geologic disposal are defined as those with greater than 10 g/L total dissolved solids (TDS) [24]. • 10^{-17} m is deemed necessary from a performance assessment perspective to limit fluid flow and advective radionuclide transport within the host rock of the repository.
Evidence of thermal springs	• No evidence of high crustal heat flows in the form of thermal springs at the surface. Thermal springs also indicate regions of hydrologic upwelling and discharge which might disqualify sites based solely upon the hydrologic conditions. • Review potential impact of naturally occurring thermal springs within 20 km of the repository.	• Geothermal systems are associated with areas of anomalously high crustal heat flow that may be related to the presence of relatively recent igneous bodies or occur where hot basement rocks are located at relatively shallow depths in regions of crustal extension [25].
Evidence of active volcanism	• Review potential impacts of quaternary volcanism within 30 km of the repository	Modified from SNL's criteria [8].

Table 3. Climate change site screening criteria

CLIMATE CHANGE: Does past glaciation and expected long-term future trends suggest risk of contact with the biosphere?		
Site Characteristic	**Screening criteria**	**Basis**
Evidence of climate related effects on the local and regional deep hydrologic system	• Although borehole disposal concepts are generally thought to provide isolation from surface processes associated with climate change [19], potential effects on the local and regional deep hydrologic system should be evaluated. A complex set of interconnected processes present themselves including: – *Glaciation and isostatic rebound* – *Variations in lithostatic-hydrostatic pressures at depth due to ice loading/ unloading* – *Potential for fault reactivation* – *Sea level changes in coastal regions* – *Erosional processes* • Screening criteria based upon isotopic evidence from deep porewaters provides information on the isolation of the deep geosphere generally, and can also address the overall impact of climate cycles and related processes on the deep hydrologic regime. • A number of major glaciation events with roughly 100,000 year cyclicity have occurred in the quaternary (as recently as 15kyr) and provide a basis to evaluate the relative isolation of the local deep geosphere over repository relevant time frames. Evidence for the effects of these past climatic events is recorded in the isotopic composition of pore waters and minerals at depth (e.g. 18O, 13C, 81Kr,36Cl, noble gases, among others). Evaluation of this isotopic evidence can identify potentially disqualifying climate related effects, such as changes in the redox state at depth and or the penetration of glacial waters into basement formations. • It is unlikely that these data will be available on a local level during initial site screening phases, but some regional data may exist. More detailed site-specific data can be developed from core and well data as site selection is narrowed.	[13], [14], [16], [19], [21], [31], [33], [34], [35]

Table 4. Seismicity site screening criteria

SEISMICITY: Is the deep geosphere historically stable from disruptive seismic events?		
Site characteristic	**Screening criteria**	**Basis**
Distance from active shear zones and tectonic features	• No detrimental observed major basement rock shear zones or tectonic features which might disrupt the repository • Distance to problematic Quaternary faulting is >10 km.	Modified from Sandia National Laboratories (SNL) deep borehole siting criteria [8].
Low probability of disruptive seismic events	• A site shall be screened out if, based on the geologic record during the Quaternary Period, the nature and rates of fault movement or other ground motion are expected to be such that a loss of waste isolation is likely to occur.	Ref. [21]. More specific criteria will depend on available data and design. Existing performance assessments suggest that seismic activation of faults is not a significant long-term transport mechanism [5]. Pre-closure site criteria based on seismicity may also be developed in future work.
In-situ regional stress field	• Excessively large differential in horizontal stress at depth can cause difficulties in drilling and borehole instability or create an enhanced disturbed rock zone around the borehole.	*Pre-closure site criteria:* Borehole breakout tendency increases both with increases with depth and large differential horizontal stresses [22] and impact well bore construction feasibility. Current assessments [5] suggest that the access hole and surrounding disturbed rock zone are not significant transport pathways for long term performance.

In addition to the above geological screening criteria, a site screening process will also need to develop screening criteria in relation to:

- **Community consent:** for example, defining a percentage of citizens in a potential host community that should be required to indicate positive consent to the repository
- **Wider policy criteria:** such criteria would address considerations that are not directly related to long-term environmental safety but are nevertheless important for stakeholders. These might cover:
  - **Legal and regulatory criteria** on issues such as ownership, land rights (surface, and subsurface) and usage
  - **Infrastructure criteria** in relation to existing site facilities, transportation and access to support development of a repository.
  - **Regional proximity criteria:** a set of siting criteria that derive from geographic considerations related to operational efficiencies, operational safety or other conditions identified by stakeholders and regulators that make certain sites more or less desirable (e.g. proximity to population centres, agriculture, tourism.)

Such criteria need to be developed separately for each country considering borehole disposal, and may differ significantly between countries depending on stakeholder attitudes and priorities. Table 5 on the following page gives some illustrations of regional proximity criteria that Deep Isolation believes are sensible to consider in all cases.

Table 5. Regional proximity site screening criteria

REGIONAL PROXIMITY: Can the repository be sited sufficiently far from activities that impact construction, operations, and long-term performance?		
Site characteristic	**Screening criteria**	**Basis**
Distance from anthropogenic effects	• Lack of known existing surface or subsurface radioactive contamination that combined with the waste inventory could exceed regulatory limits.	• Based on SNL [8]
Natural resources	• Identify existing resource development and review potential impact on repository development and performance. Consider existing or prospective mineral leases, as well as the availability of complementary or competing infrastructure. • Exclude areas within 3 km of deep mines and quarries (100 m or more in depth) • Review potential impacts of known hydrocarbon wells within 20 km of the repository	• Site selection guidance used for CCS [24]. • [31] • Deep geologic repositories (e.g., WIPP) have been sited within <20 km (12 mi) of oil injection wells [32].

Conclusions and future work

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. Drilling deeper into the continental crust expands access to stable zones that have demonstrated isolation from flowing groundwater and surface processes for millions of years [18] and drilling deep and horizontally enables disposal in layers of sedimentary rock with similar isolation [24], [28]. This document presents a preliminary set of screening criteria to narrow down potential repository sites as the first step in the site selection process for a repository. It is expected that rock formations complying with these criteria can be accessed from a large proportion of the earth's surface [18] relative to mined repositories, but future work and screening exercises are needed to confirm this and demonstrate precisely what fraction of land would remain after these criteria are applied. Overall, DBD has the potential to be a highly flexible option for use in a community-consent based siting process.

In future, we recommend expanding the pre-closure site criteria needed to support construction and operations, which will show a greater dependency on the borehole configuration (i.e., horizontal vs. vertical) than presently included. Future performance sensitivity analysis and features, events, and processes (FEPs) will also yield additional FEP exclusion criteria which can be translated into site screening criteria. Finally, site selection criteria related to community consent and non-safety related policy important to local stakeholders should be developed. Such criteria might include concerns such as legal rights of landowners and geographic proximity to population centres or agriculture.

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Abbreviations used in this document

ARAO	Agencija za radioaktivne odpadke (Slovenia)
COOP	Concept of operations
DBD	Deep borehole disposal
DI	Deep Isolation
EBS	Engineered barrier system
ERDO	European Repository Development Organisation
HLW	High-level waste
IAEA	International Atomic Energy Agency
MEUR	€ millions (euros)
NND	Norwegian Nuclear Decommissioning
PWR	Pressurized water reactor
R&D	Research and development
SNF	Spent nuclear fuel
tHM	Tonnes of heavy metal

