# Boreholes as a permanent solution for national inventories of radioactive waste

ERDO | Association for Multinational Radioactive Waste Solutions


## Abstract

This report considers whether borehole disposal might be suitable for inventories of radioactive waste from Austria, Croatia, Denmark, The Netherlands, Norway, and Slovenia. A concept is described briefly, with references to more comprehensive technical descriptions. The same is done for site-evaluation factors, regulatory framework, and cost estimates. Emphasis is placed on disposal of high-level radioactive waste in deep boreholes. Deep borehole disposal is feasible with existing technology and may be a suitable and cost-competitive alternative for the most radioactive waste types that Croatia, Denmark, The Netherlands, Norway, and Slovenia need to handle. If these countries were to construct a shared deep-borehole repository, costs could decrease by approximately one third compared to separate national repositories of the same design. The natural next step in the development of deep borehole disposal is a full-scale demonstration of site characterisation, drilling, waste emplacement and borehole sealing, combined with development of a comprehensive safety case.

In addition to deep borehole disposal (depths of 1000 to 3500 meters), a concept for shallower disposal of 200-liter drums containing low- and intermediate-level waste is briefly described. In most countries, such wastes are present in quantities that are too large for borehole disposal to be efficient, but it may be a potential solution for very small volumes of long-lived low- and intermediate-level waste, such as in Austria.



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# Abbreviations

| | |
|---|---|
| CRZ | Containment-providing rock zone |
| CSD-v | Colis Standard Déchet-vitrified |
| CSD-c | Colis Standard Déchet-compacted |
| DBD | Deep Borehole Disposal |
| DSRS | Disused Sealed Radioactive Sources |
| HLW | High-level waste |
| ILW | Intermediate-level waste |
| LILW | Low- and intermediate-level waste |
| LILW-LL | Long-lived LILW |
| LILW-SL | Short-lived LILW |
| LLW | Low-level waste |
| NES | Nuclear Engineering Seibersdorf GmbH |
| NND | Norwegian Nuclear Decommissioning |
| NPP | Nuclear Power Plant |
| SNF | Spent nuclear fuel |
| SSG | Specific Safety Guidelines |

# 1. Introduction and background

This report considers borehole disposal of radioactive waste. The term high-level waste (HLW) is used for spent nuclear fuel (SNF) which has been designated as waste and vitrified waste from reprocessing [1]. A concept for disposal of low- and intermediate level waste (LILW) is also briefly described, although such wastes often arise in large enough quantities to make alternative and equally safe disposal options more economical. Such alternatives include landfills or near-surface silos, vaults, or caverns with engineered barriers [2].

The potential benefits of borehole disposal can best be assessed by comparing borehole disposal as an alternative to mined repositories, which are the only generally accepted and available disposal options for ILW and HLW. The aim of this report is to assess whether borehole disposal might constitute a viable alternative to mined repositories. Any type of repository must abide by the same general safety criteria. Therefore, the goal is not to decide whether a borehole disposal might be saf*er* than mined repositories, but to considering whether the same level of safety could be obtained. If so, then costs, implementation time and other attributes might make borehole disposal an attractive alternative or supplement to mined repositories [3].

This report concludes a project that has been carried out by the ERDO Association and funded by Norwegian Nuclear Decommissioning (NND). Additional participants have been:

- ARAO – Agency for Radwaste Management, Slovenia
- Fund for Financing the Decommissioning of the Krško NPP, Croatia
- COVRA, The Netherlands
- Danish Decommissioning, Denmark
- Nuclear Engineering Seibersdorf GmbH (NES), Austria

The project strategy has been a simple and low-threshold form of international collaboration: Simultaneously with the project, NND has commissioned several studies of how to dispose of Norwegian radioactive waste. The project has to a large extent consisted of extrapolating the results of these studies to the waste inventories of the other countries. As an addition to this, NND commissioned Deep Isolation to prepare a case study on the feasibility and economics of deep borehole disposal of the waste from the respective countries in a shared multinational DBD-facility [4]. This report is purposely kept short and concise. Abundant supporting information is available in the references.

Various concepts for borehole disposal have been considered internationally since the 1950s. The concepts have included both injection of liquid radioactive waste into boreholes and the emplacement of canisters containing solid waste [5]. USA and Russia carried out liquid injection of radioactive waste during the 1960s and -70s. Because liquid injection relies solely on the geosphere for containment and isolation, it is questionable whether liquid injection complies with the current international principle of defence in depth by multiple safety functions [5, 6]. Current projects on DBD, including this report, focus on the disposal of canisters containing solid waste, not injection of liquid waste.

The use of drilling technology for disposal of capsules containing high-level waste has been discussed since at least as early as 1976 [7]. This was around the same time as work on the now more advanced concepts for disposal in mined caverns began [8]. In 1979, O'Brien et al. evaluated DBD of nuclear waste. Their study was a contribution to a generic environment impact assessment by the U.S Department of Energy [9]. Almost half a century later, much of their report remains relevant and useful, including the second paragraph of the abstract:

> ““How deep is deep enough?” depends upon the geologic characteristics of the site, especially hydrologic conditions, rock strength, and rock-waste interactions. Thus comparatively shallow depths may suffice in domal salt because of its relatively low permeability, whereas in other areas, required depths would be greater an might exceed depths that could be mined or drilled in the foreseeable future”.

O’Brien et al. [9] assessed many of the same parameters as subsequent reports about borehole disposal have considered. This includes the capability of available drilling technology, relevant host rock properties, and the temporal temperature effect of the radiogenic heat from the waste. They deemed it possible to drill a 9 km deep borehole with a diameter of 0.31 m in crystalline rock where no gas pressure exists.

Swedish Nuclear Fuel and Waste Management Company (SKB) published a feasibility study about deep borehole disposal in 1989 [10]. They considered three different concepts:

- Option A: Disposal of waste in 0.8 m diameter borehole from 2 to 4 km depth
- Option B: 0.375 m diameter from 2 to 5.5 km depth
- Option C: 0.375 m diameter from 2 to 4 km

Option A was considered the most attractive from an engineering and economic perspective. The proposed diameter and depth of option A was considered feasible with the shaft drilling technology available at the time. Major innovation was considered required for the casing, which would need to be made of nonreactive material and which would have to be emplaced without being cemented in place. In 1992, SKB’s Project on Alternative Systems Study (PASS) concluded that within the Swedish context (waste inventory and geological setting), KBS-3 and similar concepts for mined repositories scored better on technological readiness, long-term performance, and costs [11].

Britain’s Nuclear Decommissioning Authority published a report on the status of technology for DBD in 2008 [12]. It contained an illustration of the depths and diameter of boreholes drilled until then (Figure 1), which showed that boreholes with the diameter and depths often considered for DBD had rarely or never been drilled. This illustration has since become influential and frequently referred to in publications and discussions about DBD. However, wider and deeper holes have been constructed with shaft-sinking techniques [9]. Moreover, the lack of precedence for deep and wide boreholes is in part (if not completely) due to a previous lack of demand. Extraction of oil and gas or geothermal heat do not require such deep and wide boreholes.

During the last decade, advances in drilling technology and simultaneous lack of progress for some disposal programs have reinvigorated research into borehole disposal. A variety of concepts have been described, based on different assumptions about waste form, geological conditions, and safety strategy. Such generic concepts have been used to demonstrate the feasibility of DBD. Concepts typically involve boreholes with diameters in the range 0.3 to 0.8 m and depths in the range 2000 to 5000 m. Boreholes with the necessary depth and diameter can be drilled with technology that is currently available [13, 14, 15, 16, 17, 18]. Many publications have estimated the costs of DBD [13, 15, 19, 20, 21]. Several of these have indicated that DBD could compete with mined repositories on costs. Preliminary, generic safety analyses have been carried out for specific concepts. These show that the methods and principles for demonstrating the safety of geological disposal are applicable to DBD and that it is feasible to meet the same overall safety requirements as for mined repositories [22, 23, 24].

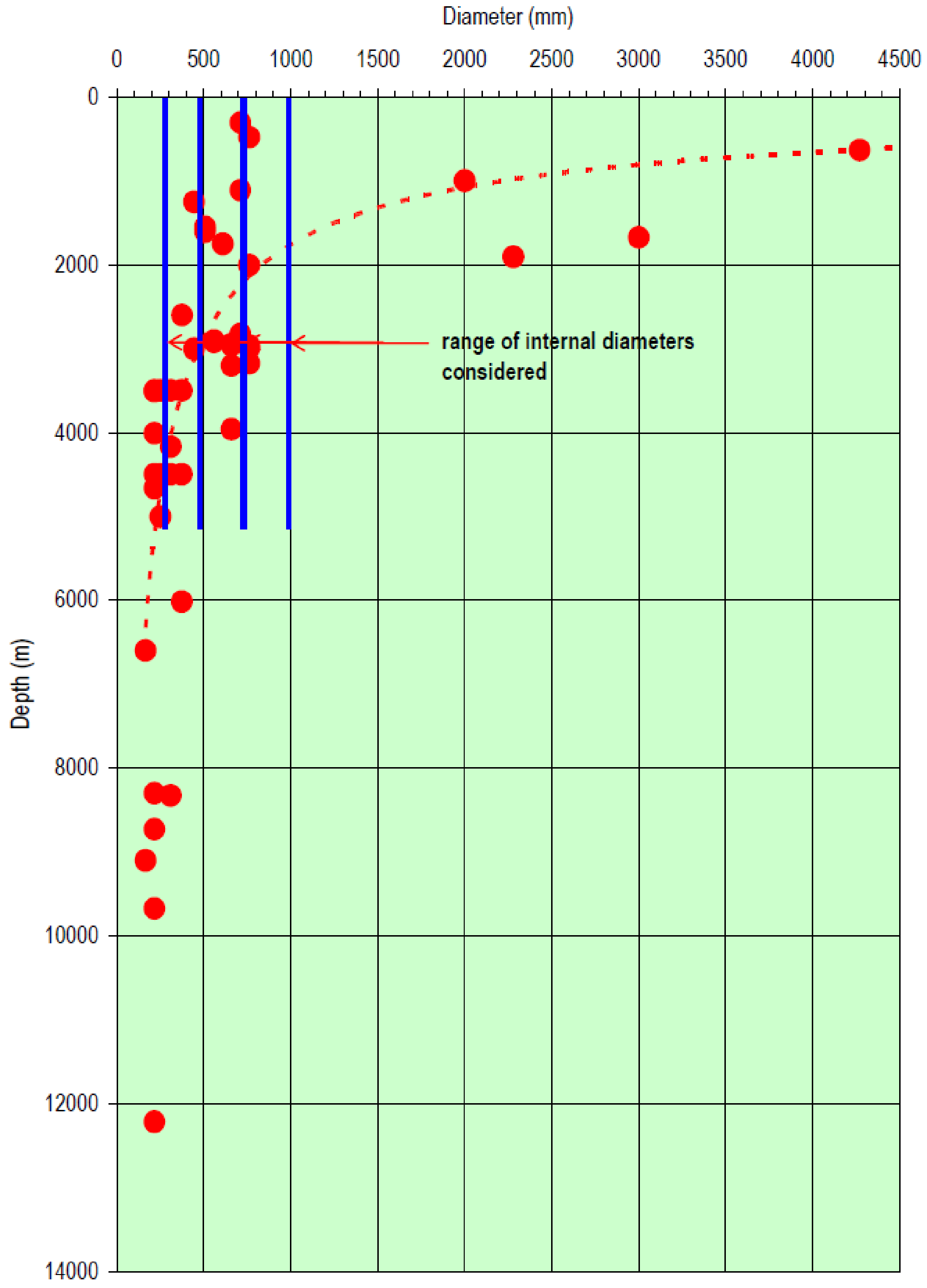


*Figure 1: Depth and diameter of boreholes drilled until 2008 [12].*

Hagros et al. [25] have compiled international agreements and standards (and Norwegian laws and regulations) that are relevant for different disposal concepts, including borehole disposal. Compliance with existing IAEA Safety Standards is feasible, and many of the same requirements apply to mined repositories and borehole repositories. However, it may be worth noting that whereas there are Specific Safety Guidelines (SSG) that are dedicated to deep geological disposal in mined repositories (SSG-14) and disposal of Disused sealed radioactive sources (DSRS) in relatively shallow boreholes (SSG-1), there is no SSG that covers deep borehole disposal.

# 2. Reference design

## 2.1. Concept for high-level waste

A reference design for DBD has been selected in this project, based on Fischer et al. [14]. Wunderlich et al. [26] provides additional details on the canister design. The reference borehole is 3500 m deep and 0.775 m wide. The reference canister has an outer diameter of 0.6 m, which leaves room for casing within the borehole. However, casing might not be necessary in the lower part of the borehole if a host rock formation with sufficient rock stability and low pore pressure is selected. The canister exterior consists of 80 mm of austenitic or duplex steel, which gives sufficient mechanical strength to withstand the pressures at the bottom of the borehole and enough chemical stability to remain intact for at least 1000 years, which is the potential duration of the heat pulse caused by the decay energy in the waste [9, 27, 28]. Thereby, the canister ensures compliance with requirement 8 in IAEA Specific Safety Requirements No. SSR-5 Disposal of Radioactive Waste, which says that:

> "The engineered barriers, including the waste form and packaging, shall be designed, and the host environment shall be selected, so as to provide containment of the radionuclides associated with the waste. Containment shall be provided until radioactive decay has significantly reduced the hazard posed by the waste. In addition, in the case of heat generating waste, containment shall be provided while the waste is still producing heat energy in amounts that could adversely affect the performance of the disposal system"

For this project, a reference canister design has been selected. The ambition has been that one canister design should be able to accommodate as many of the waste forms from the different countries as possible. Figure 2 shows the canister filled with three different waste forms:

- reprocessing waste (which is part of the Dutch waste inventory)
- a fuel assembly from Krško nuclear power plant (NPP), which Croatia and Slovenia share ownership of
- primary packages in which Danish spent-fuel residues are contained.

For Norwegian HLW, a decision on pre-disposal treatment method has not been made yet. Depending on pre-disposal treatment method, either of the illustrations in Figure 2 may be applicable.

A shared canister design has the advantage that all the waste types can be handled by a single repository design. Also, the same handling equipment and safety assessment assumptions can be used. On the other hand, it may be cost efficient to implement smaller canisters for the smaller waste forms, such as narrower canisters for SNF from Krško NPP and Danish long-lived intermediate-level waste. A narrower canister design could reduce costs of both canisters and boreholes. Material and manufacturing costs for smaller canisters can be expected to be lower than for large canisters. And narrower boreholes cost less than wider ones.

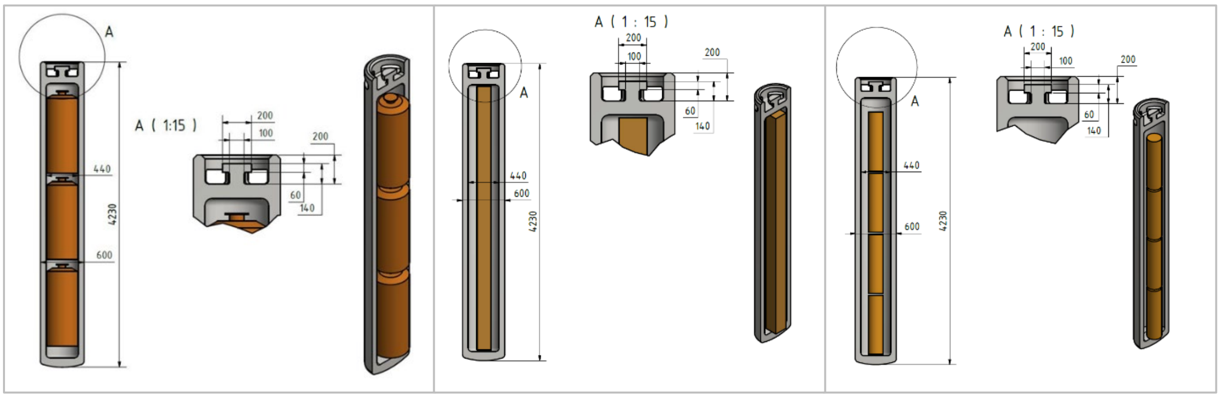


*Figure 2: Canister with reprocessing waste (left), SNF (Krško NPP, middle), and Danish waste (right). Figure made by BGE-TEC.*

Hagros et al. [29] describe safety functions, target properties and site evaluation factors related to the host rock. Bates [21] and Aadnøy & Dusseault [13] similarly describe site evaluation factors as well as methods for site investigation. Information collected through site surveys should be collected in a geological engineering model and used as basis for safety assessments.

Like mined repositories, a borehole repository can be constructed in several types of rock formations. Several publications describe drilling down into a crystalline basement and emplacing the waste there [15, 20, 24, 29]. But the emplacement zone could also be in other rock types such as shale [23] or salt [30]. The reference design is assumed to be located in crystalline rock. However, that does not rule out the possibility that the concept could be adapted to other types of host rock.

Repositories for radioactive waste must be developed on a site, waste, and system-specific basis. Design, licensing, and safety assessment are interconnected parts of the development process, as shown in Figure 3 [31]. This project has not included siting and licensing. It has identified potential design features based on available technology. The references on which the reference design in this report is based, partially overlap with the *Generic Design* and *Conceptual Design for Site Selection* in Figures 3, 4, and 5 [31].

Saanio et al [19] estimated that preliminary site investigations would take 2-4 years and detailed site investigations 3-5 years for a facility that included a landfill for non-radioactive waste and near-surface caverns for low- and intermediate level waste (LILW) as well as a deep borehole repository. Construction, drilling, and waste emplacement is estimated to take approximately one year [19]. Deep Isolation estimates that demonstration, characterisation and licensing of a deep borehole repository would take 2-5 years [32].

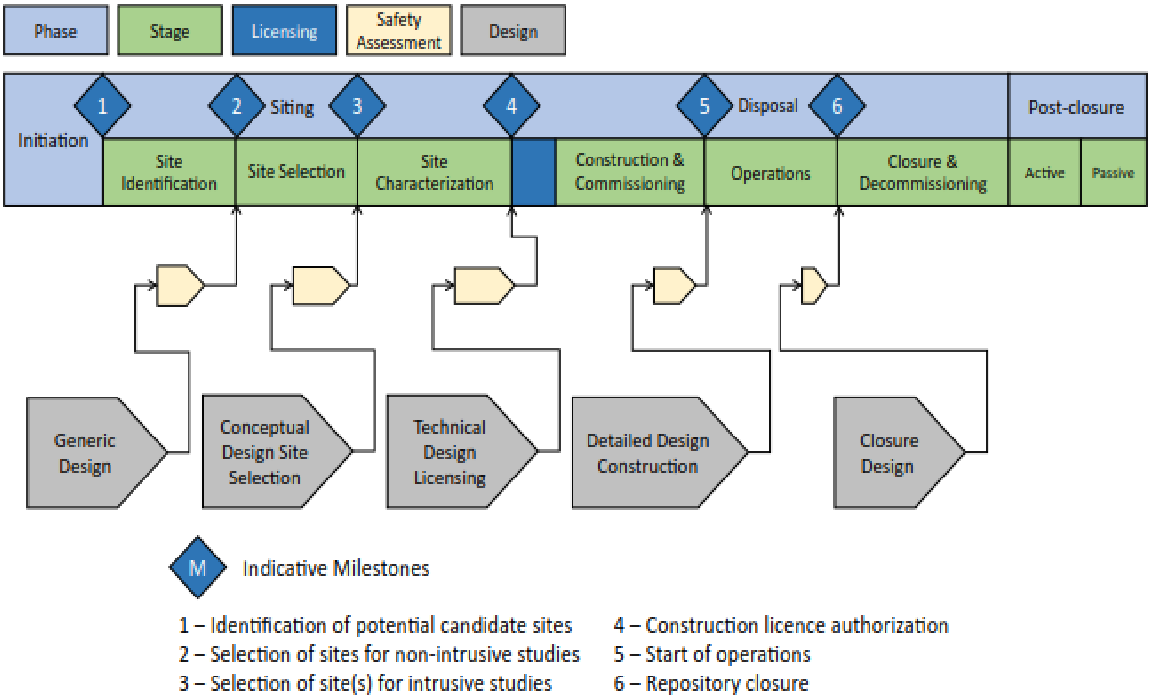


*Figure 3: Design, siting, and licensing of radioactive waste repositories [31].*

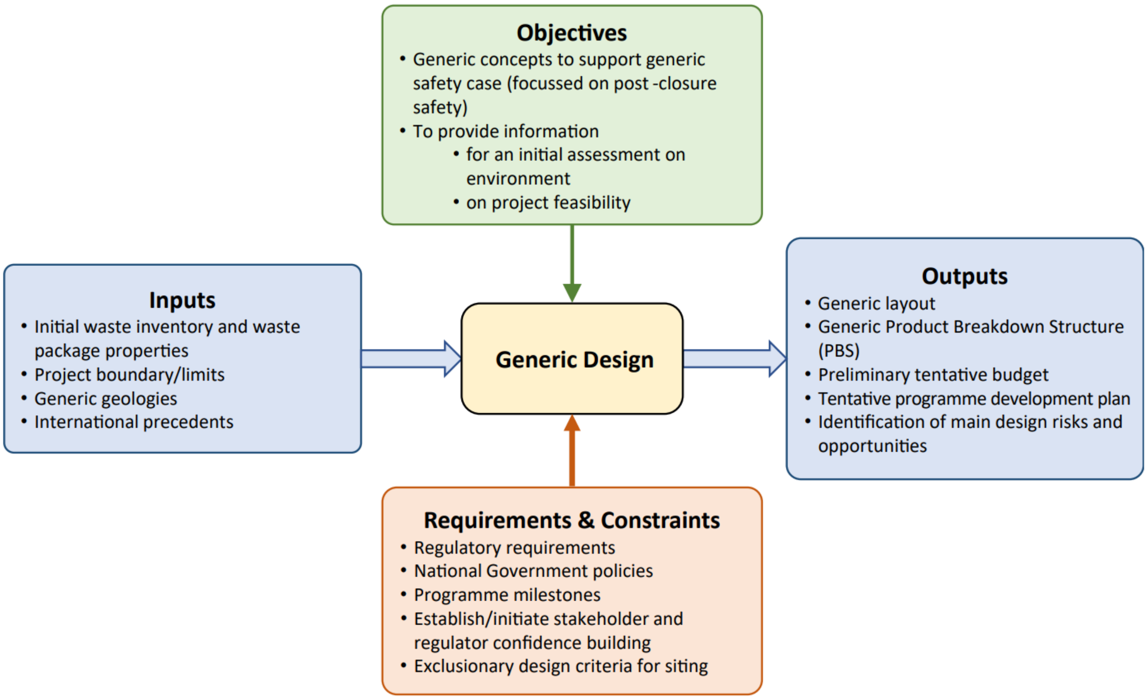


*Figure 4: Generic design: objectives, inputs, constraints, requirements, and outputs [31].*

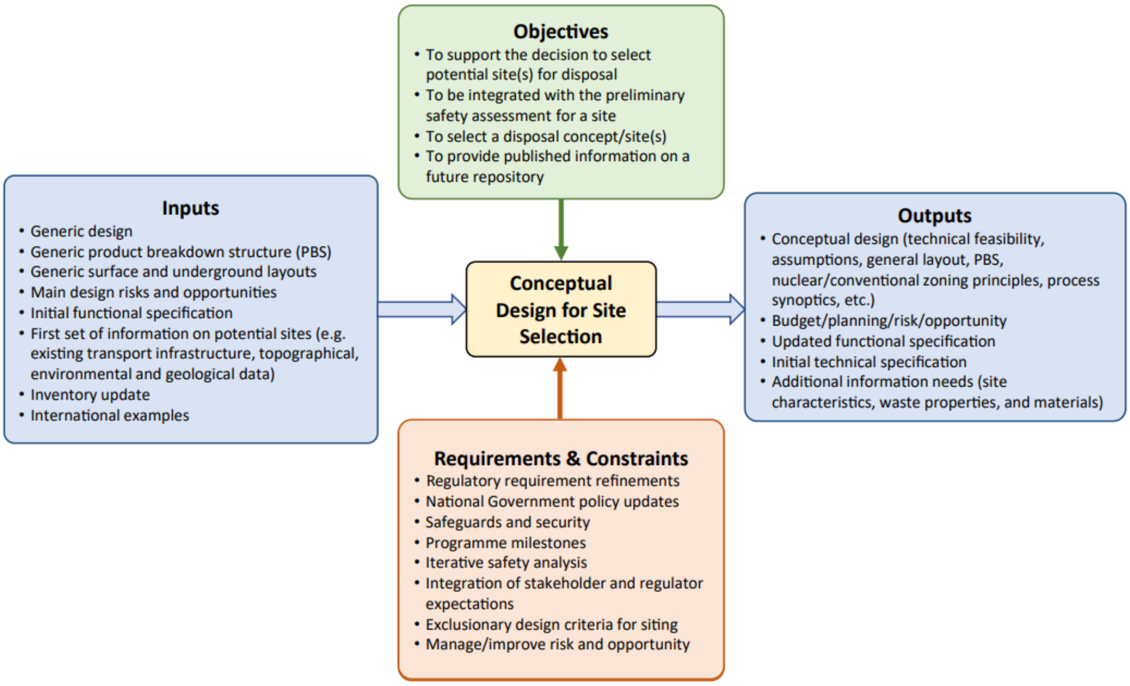


*Figure 5: Conceptual design for site selection: objectives, inputs, constraints, requirements, and outputs [31].*

## 2.2. Concept for low- and intermediate level waste

The reference concept for LILW involves putting 200-liter drums in an overpack and emplacing these in the lower 400 meters of a 500 m deep and 0.7 m wide borehole [33]. The upper 100 m are used for sealing and backfilling, based on the assumption that the water table will not migrate deeper than this. The total depth and the distance allocated to waste emplacement would have be determined on a site-specific basis. Each overpack can hold four drums axially (Figure 6). The overpack is 3.7 m long, has an outer diameter of 0.645 m and 5 mm thick walls of carbon steel [34]. A prototype of the overpack has been estimated to cost NOK 137 000, equal to around EUR 14 000. Accounting for delivery costs etc, we assume a cost of EUR 15 000 per overpack in this report.

Operational costs for the concept have not been estimated during this project but could be significant in comparison to investment costs. Operational cost should therefore be estimated as part of any future work on the concept.

As shown in chapter 3, the utility of this borehole concept for LILW is limited to small inventories of waste. If the concept was modified to include a wider shaft, it could become relevant for larger inventories [33].

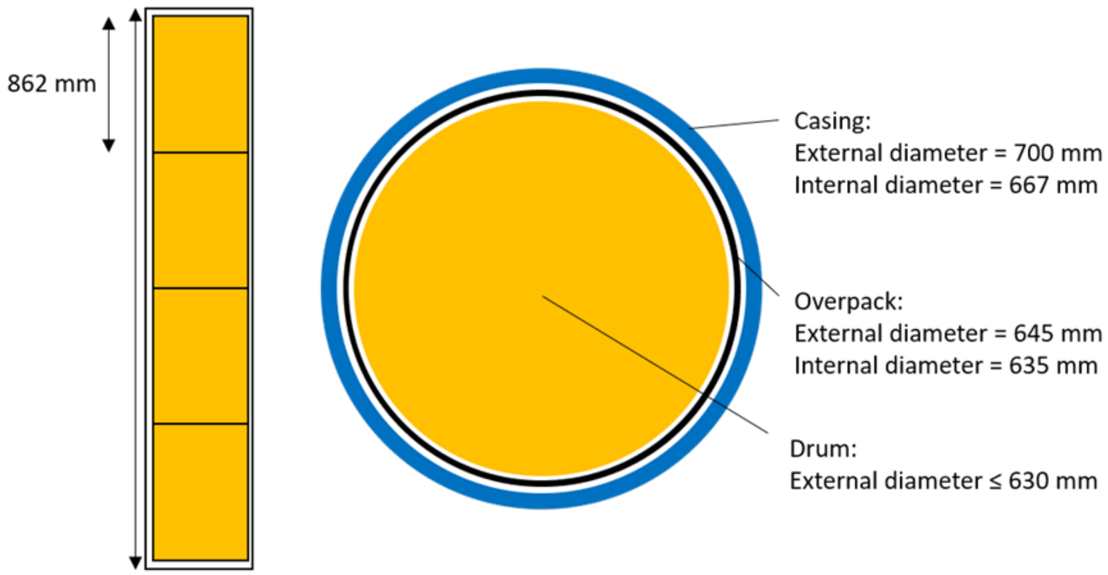


*Figure 6: Sketched overpack for 200-liter drums, shown from the side (left) and axially (right).*

# 3. Waste inventory and strategic potential of borehole disposal

All the nations represented in the project need to manage LILW. Croatia, Slovenia, The Netherlands, and Norway also have HLW (including spent fuel designated as waste). Austria and Denmark have only LILW. In this chapter, the inventory of each nation is described, and the compatibility with the borehole concepts assessed.

## 3.1. Austria

Austria has no nuclear power plants or any other fuel cycle facilities in operation, except for a small TRIGA research reactor in Vienna. SNF from the reactor is stored on site. SNF will be repatriated to the USA. Therefore, there will be no disposal of HLW/SNF in Austria.

NES is the central facility for management and storage of radioactive waste in Austria. NES treat and store all Austrian LILW. The sources of LILW are:

- The use of radioactivity in medical applications, research, and industry (approximately 15 tons per year)
- Decommissioning of nuclear research facilities (30-110 tons per year). The facilities being decommissioned include a hot-cell laboratory.

The Austrian classification of radioactive waste separates LILW into two subclasses: short-lived (LILW-SL) and long-lived (LILW-LL). The concentration of long-lived alpha-emitting radionuclides determines whether waste is long-lived or short-lived (Radionuclides with half-life longer than 30 years are termed long-lived). The threshold between short-lived and long-lived waste is formally set at 4000 Bq/g in a single waste package and 400 Bg/g on average for the total waste volume. For classification purposes for NES internal waste-acceptance criteria for interim storage the limit of 400 Bq/g of long-lived alpha emitting radionuclides per waste package is being used [35].

There is no disposal facility in operation in Austria. All radioactive waste is being treated and conditioned and then stored at the interim storage site at NES. As per the end of 2016, 2240 of the 2300 $m^3$ of the waste in temporary storage was short lived (LILW-SL). It is currently foreseen that Austria will need to dispose of 60 $m^3$ LILW-LL. The Austrian inventory of radioactive waste is summarized in Table 1

The LILW-SL consists of 10922 packages of 200-liter drums, 5 MOSAIK®-type casks (Figure 6), and 5 Konrad Type II steel boxes. MOSAIK® casks (l=1.5 ø=1.06 m) and Konrad boxes (0.846m x 0.846 m x 1.7 m) are too large for borehole disposal but it may be feasible to transfer the waste currently in these containers to 200-litre drums. If so, then the entire Austrian inventory could be in 200-litre drums.

*Figure 7: Mosaik® cask. Height: 1.5 m. Diameter: 1.06 m. Illustration: GNS (https://www.gns.de/language=en/24296/mosaik).*

The more than 2000 $m^3$ of LILW-SL is too voluminous for borehole disposal to be an efficient solution. The 60 $m^3$ of LILW-LL on the other hand, could fit in approximately 300 drums, which would require 75 overpacks. The combined length of these would be 263 m. For Austria, therefore, one option is to build a near-surface disposal facility for short-lived LILW and one to three boreholes for long-lived LILW. The boreholes would cost approximately 2 to 6 MEUR (2 MEUR per borehole). 75 overpacks would cost around 75 x EUR 15 000 = 1 125 000 EUR.

*Table 1: Waste from Austria considered in this project.*

| **Waste type** | **Container type** | **Suitability for borehole disposal** | **$m^3$** |
|---|---|---|---|
| Institutional waste (LILW-SL) | Drum (200 l) | Not suitable (too large total volume) | 2215 |
| Decommissioning waste (LILW-SL) | Mosaik® | Not suitable (too large container) | 7 |
| Decommissioning waste (LILW-SL) | Konrad type II | Not suitable (too large container) | 23 |
| Long-lived LILW | Drum (200 l) | Suitable for drum concept | 60 |

## 3.2. Croatia and Slovenia

Croatia and Slovenia share ownership and responsibility for the nuclear powerplant in Krško, Slovenia. It has been in operation since 1983 and is expected to remain in operation until 2043, by which time 2282 assemblies of spent fuel will have been generated [36].

It has been estimated that decommissioning of Krško NPP and operation of an encapsulation facility for spent fuel will generate 82 tons (237 $m^3$) of waste that is classified as HLW according to the Croatian and Slovenian classification system and 650 $m^3$ of LILW. The HLW waste will be packed in HI-SAFE containers that have a diameter of 2.5 m (Figure 8).


*Figure 8: HI-SAFE containers. Photo: Holtec International (https://holtecinternational.com/products-and-services/nuclear-fuel-and-waste-management/dry-cask-and-storage-transport/hi-safe/).*

Slovenia has a TRIGA Mark II research reactor, located at the IJS Reactor Infrastructure Centre, about 12 km northeast of Ljubljana. The TRIGA fuel consists of fuel elements with 0.038 m diameter and 0.721 m length. The estimated number of used fuel elements when TRIGA operations end in 2043 is 84. In 2021, ARAO commissioned a feasibility study on disposal of TRIGA II research reactor spent fuel using a Deep Isolation repository [37]. Based on disposal requirements, suitable geological formations were analysed and for which three disposal options were further developed:

- Option 1: a vertical borehole drilled to a safe depth that can deliver 1 million-year plus isolation with a depth of 1.5 kilometres and with a very short vertical disposal section.
- 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 Krško NPP.
- 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.

It was concluded that TRIGA II spent fuel is potentially suitable for DBD disposal, but further consideration and effort should be given to development of the generic safety case including research of geological formations, development of an overarching strategy and roadmap and international collaboration in exploring, demonstrating and cost sharing for DBD disposal.

The optimum borehole-based 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. This conclusion also supports well the finding of the current report on DBD from ERDO Association countries.

Slovenia is in the process of implementing a near-surface repository for LILW at Vrbina, in the Municipality of Krško. This is intended to receive all radioactive waste other than spent fuel and other HLW, including half of the LILW from operation and decommissioning of Krško NPP. Slovenian LILW is therefore not discussed further in this report.

Croatia has not yet decided on how to dispose of LILW. Borehole disposal may therefore be among the range of possibilities. The inventory consists of:

- DSRS
- Radium sources
- Dismantled smoke detectors
- Legacy waste containing thorium and uranium compounds

The waste is contained in various packages. The largest packages are 200-litre drums. The other packages could all fit inside 200-litre drums. Repackaging or placement of the current packages inside 200-litre drums could therefore be done. The combined volume of the waste is no more than 5 m$^3$. In addition to this, Croatia is responsible for finding a solution for half of the LILW from operation and decommissioning of the Krško NPP. A decision on LILW disposal facility has not been made yet, but a plan has been developed for a near-surface vault type repository, after 40-year storage. Multipurpose cubic reinforced concrete containers (approximately 1.75x1.75x1.75 m) are projected for storage and disposal of the Croatian half of LILW from Krško NPP. Slovenia has invited Croatia to join the project to establish a repository for LILW in Vrbina. Intergovernmental Commission for monitoring the implementation of the Bilateral Agreement on the Krško NPP has decided that joint disposal of LILW from the Krško NPP is not possible (September 2019) and both sides will take care of half of the Krško NPP waste in their countries.

Borehole disposal is considered as an option for DSRS (shallow/intermediate depth borehole for circa 2-3 m$^3$) and for SNF/HLW from Krško NPP (DBD for 2282 SNF-assemblies and HLW form decommissioning, if HLW can be processed into sufficiently small packages). LILW from Krško NPP is not considered suitable for DBD.

Table 2 and Table 3 summarise the waste from Croatia and Slovenia, respectively, considered in this project. Additional waste could arise through operation of future waste handling facilities, but this has been considered outside the scope.

*Table 2: Waste from Croatia considered in this project.*

| **Waste type** | **Container** | **Suitability for borehole disposal** | **m$^3$** |
|---|---|---|---|
| DSRS (LILW) | SS cylinders | Suitable | 0,3 |
| DSRS (LILW) | Drum (200 l) | Suitable | 0,4 |
| DSRS (LILW) | SS cylinders | Suitable | 0,1 |
| DSRS (LILW) | SS cylinders | Suitable | 0,1 |
| DSRS (ILW) | SS cylinders | Suitable | 0,0 |
| Ra-sources (ILW) | Drum (200 l) | Suitable | 0,2 |
| Smoke detectors (ILW) | Drum (200 l) | Suitable | 1,4 |
| DSRS (ILW) | Drum (200 l) | Suitable | 0,4 |
| Operational waste from Krško NPP (LILW) | Cubic reinforced concrete containers | Not suitable (too large containers and too large total volume) | 1503 |
| Decommissioning waste from Krško NPP | Cubic reinforced concrete containers | Not suitable (too large containers and too large total volume) | 1421 |
| SNF (HLW) | DBD-canister | Suitable | 162.5 |
| Decommissioning waste (HLW) | HI-SAFE | Suitable only if processed into small enough pieces | 118.5 |

*Table 3: Waste from Slovenia considered in this project.*

| Waste type | Container | Suitability for borehole disposal | $m^3$ |
|---|---|---|---|
| Spent fuel (HLW) | DBD-canister | Suitable | 162,5 |
| Decommissioning waste (HLW) | HI-SAFE | Suitable only if processed into small enough pieces | 118.5 |

## 3.3. Denmark

Three research reactors have been in operation in Denmark. All have now been shut down. The reactors were located at Risø, along with a hot cell facility and a fuel fabrication plant. The site is being decommissioned. Decommissioning of the first two reactors, Danish Reactor (DR) 1 and 2 was completed in 2005 and 2008, respectively [38]. The used solid reactor fuel has been returned to the country of origin, with the exception of 233 kg bits and pieces of experimentally produced and irradiated spent fuel. Table 4 summarises the waste.

The activity of the irradiated fuel is estimated to 574 TBq fission products and 35 TBq actinides [38]. The thermal power has been estimated to 112 W for all the 233 kg [39]. The waste is packed in 33 containers of stainless steel, which are cylindrical and have a diameter of 0.22 m and 0.87 m length.

Both the activity concentration and the thermal power of the Danish waste is well below the ranges indicated by the IAEA for HLW. The waste is therefore classified as ILW, not HLW. On the other hand, the 2018-Edition of IAEA Safety Glossary [40] , defines "spent fuel" as one form of HLW. However, the most important question is not whether the Danish waste is classified as HLW or ILW, but that the safety of a disposal system can be demonstrated on the basis of the underlying properties of the waste. For the purposes of this project, it has been assumed that the irradiated fuel should be deposited in accordance with the HLW-concept. The HLW-concept is therefore used as the concept for the 233 kg spent research fuel in the Danish inventory.

In addition to the residues of spent fuel, decommissioning of the nuclear facilities at Risø will generate LILW. Denmark also manages institutional radioactive waste, such as medical waste and DSRS. Lacking a disposal facility, Denmark is developing a storage facility, with a planned capacity of 17 500 $m^3$ waste containers including 25% buffer capacity. Borehole disposal is an unlikely solution for an inventory of that size.

*Table 4: Waste from Denmark considered in this project.*

| Waste type | Container | Suitability for borehole disposal | $m^3$ |
|---|---|---|---|
| SNF-residues (LL-ILW) | Stainless-steel cylinders | Suitable | 1 |
| Other LILW | Various | Not suitable (too large total volume) | Amounts not compiled yet |

## 3.4. The Netherlands

The Netherlands has one NPP in operation, in Borssele (485 $MW_e$). Another NPP in Dodewaard (60 $MW_e$) was in operation from 1969 to 1997 and is now in a state of safe enclosure. Two research reactors are in operation, and one is being decommissioned. Dutch Government practice in principle leaves the choice of whether or not to reprocess SNF to the operator of a nuclear facility. In practice, this has meant that SNF from NPPs has been reprocessed, while research-reactor fuel has not [41]. The fuel has been reprocessed at Sellafield (UK) or La Hague (France). Residues from reprocessing are returned to The Netherlands, where they are stored at the facilities of COVRA. Two types of residues are returned:

- CSD-v (Colis Standard Déchet-vitrified): Fission products and actinides contained in a glass matrix.

- CSD-c (Colis Standard Déchet-compacted): Compacted hulls and end-pieces from SNF.

COVRA classifies CSD-v as heat-generating HLW and CSD-c as non-heat-generating HLW. Both waste forms are contained in the same type of primary container: stainless-steel cylinders with 0.43 m diameter and 1.335 m height. SNF and other HLW from the Dutch research reactors are stored in ECN containers, which are cylindrical, with a diameter of 0.846 m and are 1.236 m long. The Dutch waste management strategy involves storing waste at COVRA until 2130, by when a disposal route should become operational. The estimated quantity of waste packages in 2130 is 478 CSD-v, 600 CSD-c, and 350 ECN [42].

The anticipated Dutch waste inventory also includes more than 40 000 $m^3$ LILW. This is considered unsuitable for borehole disposal, because the combined volume is too large and because the waste is contained within containers that are too large. These are 1000-liter concrete boxes and Konrad type II boxes. The Dutch inventory is summarised in Table 5.

*Table 5: Dutch waste inventory [43].*

| **Waste type** | **Container** | **Suitability for borehole disposal** | **$m^3$** |
|---|---|---|---|
| Vitrified reprocessing waste (from Sellafield and La Hague) | CSD-v | Suitable | 93 |
| Hulls & ends from reprocessing (Non-heat generating HLW) | CSD-c | Suitable | 116 |
| HEU-SNF in ECN container (HLW) | ECN | Needs re-packaging | 21 |
| LEU-SNF in ECN container (HLW) | ECN | Needs re-packaging | 83 |
| Other HLW | ECN | Needs re-packaging | 116 |
| Compacted waste (LILW) | Drum (200 l) | Not suitable (too large total volume) | 28 000 |
| Resins/immobilised liquid (LILW) | Concrete box (1000 l) | Not suitable (too large total volume) | 800 |
| Immobilized liquid I (LILW) | Concrete box (1000 l) | Not suitable (too large total volume) | 1200 |
| Immobilized liquid II (LILW) | Concrete box (1000 l) | Not suitable (too large total volume) | 400 |
| Depleted Uranium (LILW) | Konrad type II | Not suitable (too large total volume) | 11 024 |

## 3.5. Norway

Norway had a total of four research reactors in operation from 1951 to 2019. All have now been taken out of operation. To enable decommissioning, a new infrastructure for management of radioactive waste must be developed. That infrastructure must comprise all classes of radioactive waste, including 17 tons of spent research reactor fuel. Preliminary estimates of waste inventories are summarised in Table 6, based on reference [44].

*Table 6: Norwegian waste inventory.*

| **Waste type** | **Container** | **Suitability for borehole disposal** | **$m^3$** |
|---|---|---|---|
| Spent fuel (HLW) | DBD-canister | Suitable | 6 |
| Decommissioning, institutional (VLLW) | Drum (200 l) | Not suitable (too large total volume) | 6500 |
| Decommissioning, institutional, and legacy (LLW) | Drum (200 l) | Not suitable (too large total volume) | 2000 |
| Decommissioning, institutional, and legacy (ILW) | Drum (200 l) | Not suitable (too large total volume) | 1600 |

All of the Norwegian spent fuel could fit in one deep borehole. Deep borehole disposal is therefore a plausible alternative for this waste class.

The Norwegian inventory of LILW is too large to make borehole disposal cost efficient. Assuming that around 100 $m^3$ of waste could fit in each borehole, approximately 100 boreholes would be required for the entire inventory of LILW (, at an investment cost on the order of 200 MEUR. Near-surface caverns, a shaft or some other large-volume excavated repository is more cost efficient [45]. Using borehole disposal for ILW could be one option, but a cavern- or shaft-type repository is probably more cost-efficient, especially if a combined facility for LLW and ILW is built [33, 45].

# 4. Cost estimate for deep borehole disposal

AINS, BGE-TEC, and VTT have prepared a report where the cost of deep borehole disposal of Norway's spent fuel is estimated to between 151 and 169 MEUR, see table Table 7. A concept description was also developed for a mined repository for the same amount of waste. This was based on the KBS-3-concept that has been developed in Finland and Sweden. The mined repository was estimated to cost 351 MEUR, i.e. more than twice as much as the borehole repository. This shows that for a stand-alone repository for HLW, borehole disposal is the more cost-effective solution. However, AINS, BGE-TEC, and VTT also developed a concept that included caverns for Norway's LILW as well as either a KBS-3-repository or a deep borehole for HLW. In this case, the relative cost difference between deep borehole and KBS-3 is smaller, because of synergies between the LILW- and KBS-3-repostories, such as access via the same tunnel [45].

*Table 7: Cost estimate for deep borehole disposal of Norwegian spent fuel. Table 3-18 in reference [19].*

| Summary of cost (including contingencies) | EUR | In case surface facilities are temporary structures due to short operation time |
|---|---|---|
| Site selection and licensing | 33 800 000 | 33 800 000 |
| Site investigation and planning | 2 300 000 | - |
| Construction / borehole drilling | 108 909 500 | 94 535 525 |
| Operations, disposal | 8 556 750 | - |
| Closure | 15 831 150 | -12 492 633 |
| **TOTAL** | **169 397 400** | **151 248 383** |

The costs of a DBD-facility depend on the design, which in turn depends on the waste form, the size of the waste inventory, the geological conditions, and the safety requirements. All these factors could vary from country to country. At a site where a containment-providing rock zone (CRZ) is relatively close to the surface, a small waste inventory could be disposed of in a single, relatively shallow borehole. If a deeper borehole is required, either because the CRZ is deeper down or because a larger inventory is to be disposed of, then a deeper borehole is needed. The radiotoxicity and physicochemical properties of the waste could also affect the required depth. Furthermore, it could be necessary to leave some space between the canisters, to enable heat dissipation and to support each canister with a buffer material. The greater the spacing, the lower waste capacity per unit borehole length. The cost of a borehole increases semi-exponentially with depth [21]. Therefore, there could be large variations in the costs of DBD for different sites, designs, and inventories.

These variations are illustrated by three generic designs with different depths and different emplacement zones, as shown in Table 8. In addition to the described conceptual costs, construction costs per borehole and operational costs per canister are uncertain. In the cost model, ranges for these costs have been used. A flat probability distribution has been used for the ranges. The ranges are based on a literature review [13, 19, 20, 21, 46, 47] and dialogue with the industry.

*Table 8: Cost model for three deep borehole concepts A, B, and C.*

| | | A | B | C |
|---|---|---|---|---|
| Fixed parameters | Total borehole length (m) | 3500 | 2000 | 1000 |
| | Length of emplacement zone (m) | 2000 | 800 | 100 |
| | Length of seals and backfill (m) | 1500 | 1200 | 900 |
| Variables | Cost of site investigation + construction + sealing (MEUR) | 60-120 | 40-80 | 12-30 |
| | Buffer distance between canisters in the disposal zone (m) | 0.4-4 | | |
| | Operational costs per canister (MEUR) | 0.03-0.3 | | |

Estimated costs of using each reference concept (Table 8) for each national inventory are shown in Figure 9. Concept A is the most cost efficient for Dutch reprocessing waste and SNF from Krško NPP. This is due to economies of scale, whereby the larger repository is more cost efficient. The median number of type A boreholes required for the Netherlands and NNP Krško are 2 and 10, respectively. For Norway, Concept B is the most cost-efficient. One such borehole could take the entire Norwegian inventory, whereas around 6 boreholes of type C would be required. The entire Danish inventory could fit in a single borehole of type C, making that the most cost efficient for the Danish ILW.

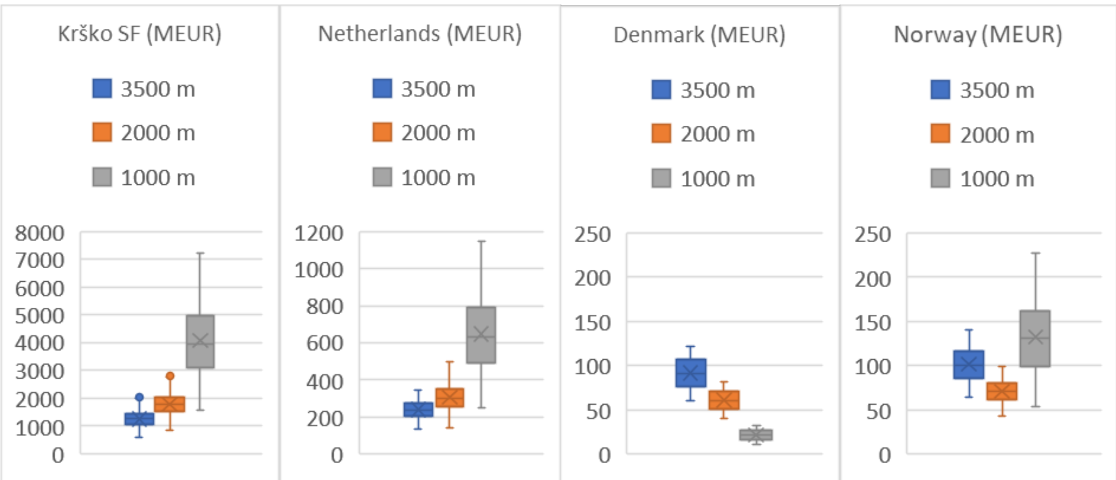


*Figure 9: Cost estimates for disposing of the respective national inventories in boreholes of different depth.*

Deep Isolation Inc. has estimated the cost of a single multinational DBD-repository for the combined inventory from Croatia, Slovenia, Denmark, The Netherlands, Norway. Their design differs slightly from the reference design presented previously in this report and includes a narrow canister for spent fuel and a wider canister designed for residues from reprocessing. Their results are therefore not directly comparable to the costs for there reference design (Figure 9). Deep Isolation's results are shown in Table 9.

Deep Isolation found that their concept would cost between 56 and 65 % less than a mined repository for the suitable waste inventory. They also found that a multinational DBD repository would cost about two thirds of separate DBD repositories in the respective countries [4].

*Table 9: Costs for a shared repository, estimated by Deep Isolation Inc [4].*

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

# 5. Conclusions and future work

The following conclusions can be drawn from the project:

1. DBD is a technologically feasible and potentially cost-efficient solution for high-level or long-lived intermediate level waste from Croatia, Slovenia, Denmark, The Netherlands, and Norway.
2. A multinational DBD-repository is likely to be more cost-effective than separate national repositories.
3. Borehole disposal of LILW could be of interest for very small inventories of LILW, or specific sub-categories of LILW. Specifically, it could be of interest for the Austrian inventory of long-lived LILW.

A lot of work has been done on DBD at the conceptual and generic level. This project recommends that future work continues along the following paths:

- Full-scale demonstration of site characterisation, drilling, waste emplacement, and borehole sealing that is properly supported by the safety case developed in line with best international guidelines and practice. This will enhance confidence in DBD and identify priorities for further development and demonstration work.
- Increased adaption of DBD to site- and waste-specific characteristics. DBD is a less mature concept than mined repositories. This difference can only be made up if DBD becomes part of a national or multinational disposal program in the same way as mined repositories have been developed in several countries over several decades (such as in Finland, Sweden, Canada, France and others).
- Any future investigation of borehole disposal of 200-liter drums containing LILW should assess operational costs, because these have not been estimated in this project and could be a significant portion of total costs.

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