DEVELOPMENT OF SOLUTIONS FOR DISPOSAL OF SPENT FUEL AND OTHER RADIOACTIVE WASTE IN ONE OR MORE DEEP BOREHOLES

SUBCONTRACT 2

TASK C004 –OPTIONEERING

February 2025

Final report

Multi-criteria analysis to identify preferred Deep Borehole Disposal concept options in Norway

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EXECUTIVE SUMMARY

In Norway, the KLDRA-Himdalen near-surface disposal facility is used to manage low-level waste (LLW) and short-lived intermediate-level waste (ILW) from the Halden and Kjeller nuclear research reactors, as well as LLW generated by other industries, such as the medical sector. However, the capacity of the facility will not be sufficient to accommodate projected waste volumes arising from the decommissioning of the research reactors, nor is the facility licensed for long-lived ILW, high-level waste (HLW) and/or spent nuclear fuel (SNF).

Norwegian Nuclear Decommissioning (NND) has therefore initiated a process to develop disposal solutions for all classes of radioactive waste. Two concepts have been explored to manage SNF / HLW: a mined deep geological repository (DGR) and disposal in one or more deep boreholes (Deep Borehole Disposal, DBD). The long-term waste management programme for SNF remains at a generic stage and there is not yet a preferred treatment method for the various fuel types in Norway, no siting process has commenced, and no choice between DBD and a mined DGR has yet been made.

The multi-criteria analysis (MCA) reported here aims to identify, describe and evaluate preferred DBD concept options potentially suitable for disposal of all Norwegian SNF or HLW depending on treatment method, and which could be implemented in Norway by around 2050. The study also informs the recommendation of a DBD concept, should DBD be selected as the preferred disposal option.

The study entails a balanced assessment of option safety, environmental impact, socio-economic impact, technical maturity, and cost effectiveness. It consists of the four stages, indicated in Figure ES-1. The present report corresponds to Stage 4, Option Assessment reporting. The shortlist of options resulting from Stages 1 and 2 Option generation and screening is presented in Figure ES-2

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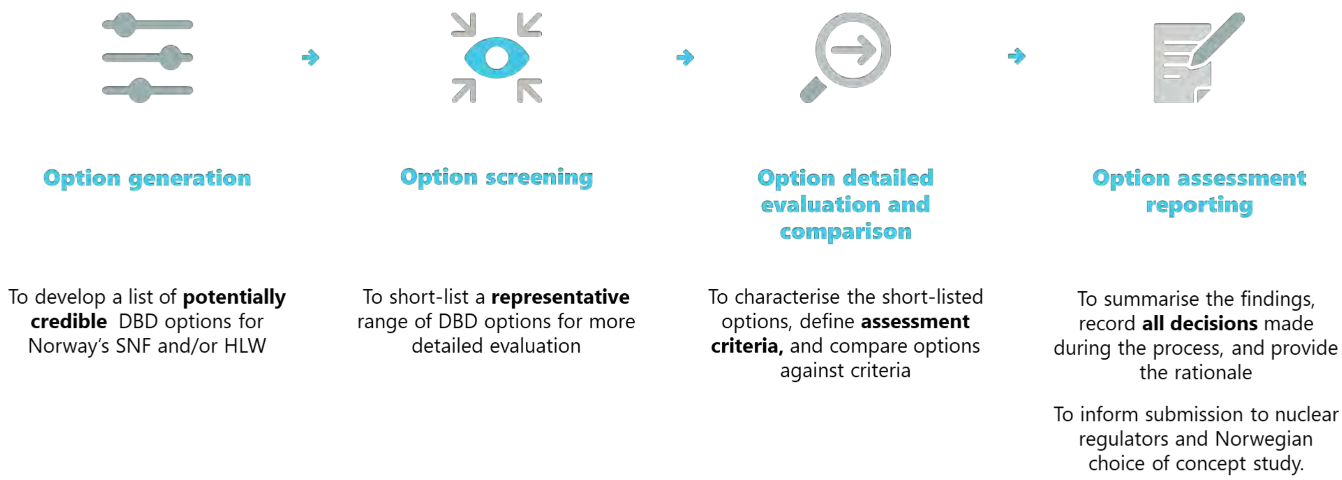
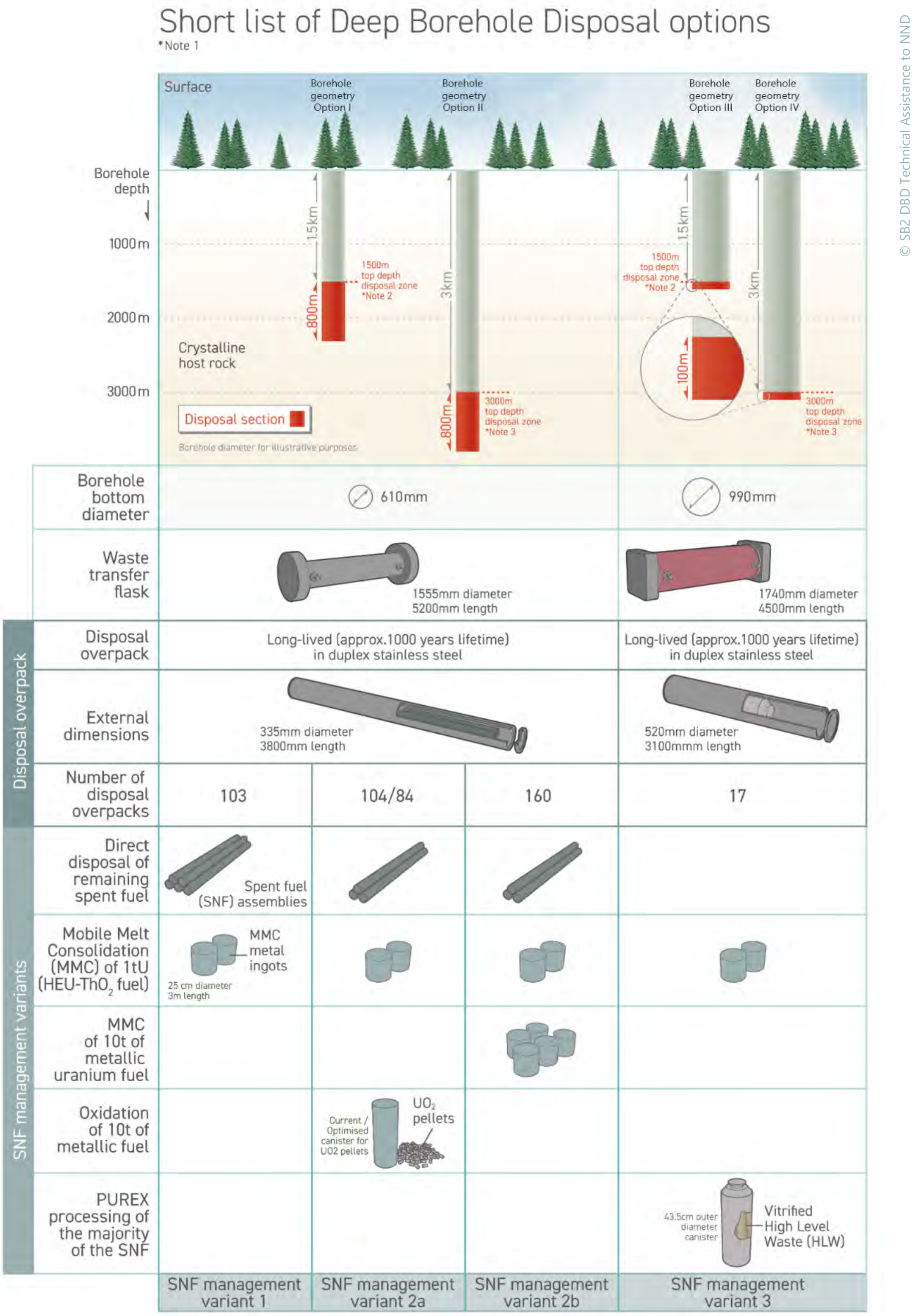
Figure ES- 1: Four-stage multi-criteria optioneering approach



This study considers option lifecycles starting from the termination of storage of HLW/SNF, and encompassing waste encapsulation for disposal, transport to the repository site, and disposal in the borehole, including site identification and characterisation, as well as borehole construction, operation and closure, as presented in Figure ES-3.

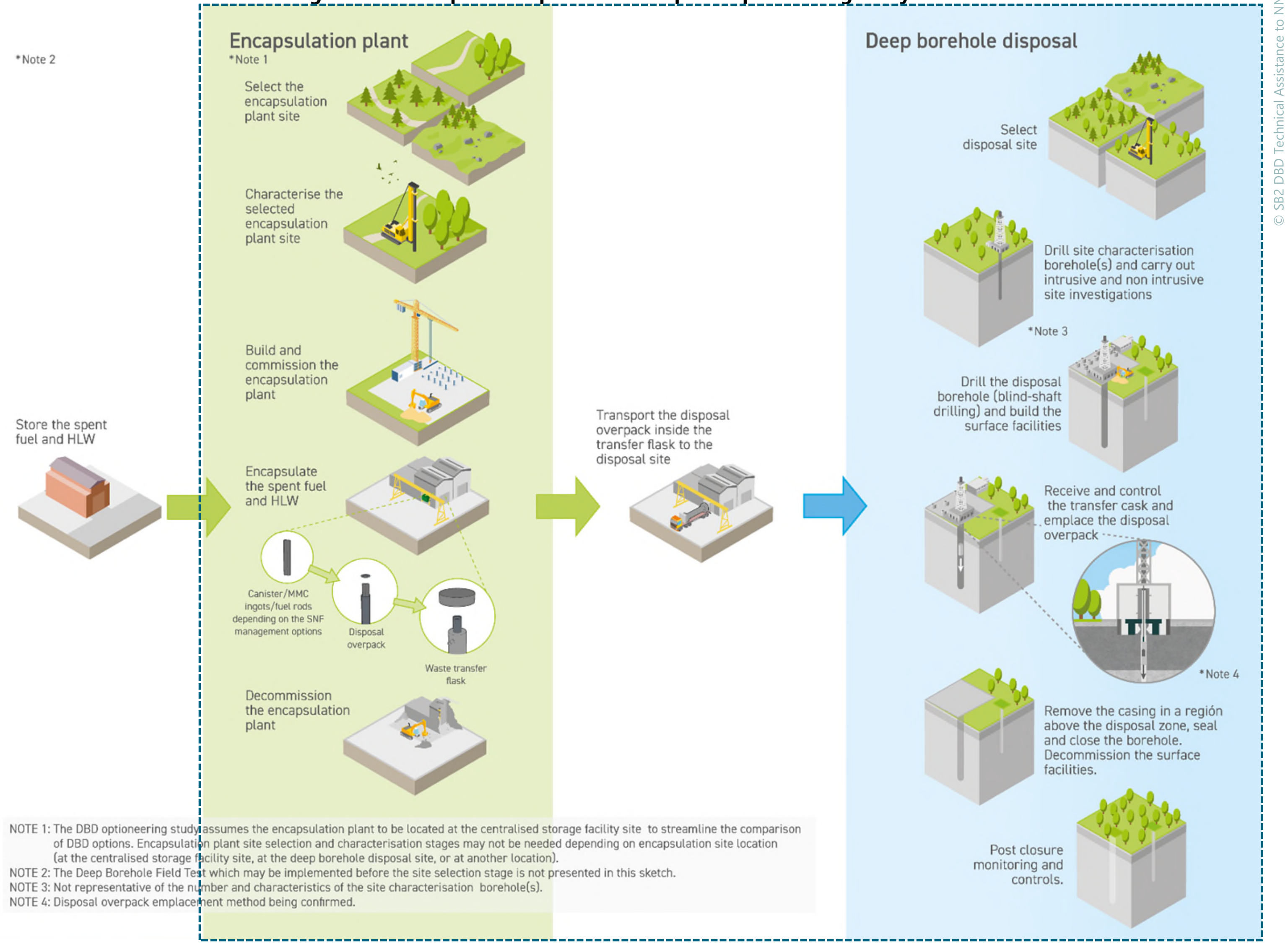
The predisposal conditioning and storage of the SNF, the potential disposal of SNF and/or HLW in mined facilities, and the management and disposal of other waste types are outside the scope of this study.

Figure ES-2: DBD options considered in the further characterisation and option assessment



Note 1: All numerical values are indicative.
Note 2: If suitable host rock conditions are found at a depth of 1000m.
Note 3: If the site characteristics at a depth of 1000m are not suitable for DBD and/or a greater disposal depth is desired to increase stakeholder acceptance.

Figure ES-3: Scope of deep borehole disposal optioneering study



The options have been analysed in detail and information has been collated that allows a comparison of their performance against a suite of criteria and sub-criteria (option safety, environmental impact, socio-economic impact, technical maturity, and cost). On the basis of relative performance, each option has been ranked and then scored against each criterion or sub-criterion. The scores represent an objective assessment of performance that is made quantitative where possible and where relevant data is available, but are otherwise based on expert judgement and reasoned argument.

Subsequently, the scores were analysed by applying weighting to the different criteria. Such weight sets are inherently subjective and based on the value judgements of different stakeholders, but they enable consideration of the robustness of the MCA outcome and its susceptibility to the weight on particular criteria. A number of different weight sets have been considered, as well as consideration of the impact of extreme weighting on certain criteria. For example, the MCA outcome using a baseline weight set (that aligns with the baseline of the Amentum and GeorReN studies) is shown in ES-4.

The main value of the MCA lies in its ability to highlight the various pros and cons of each option, providing insight into why certain options may be preferred over others. Ultimately, which options are deemed preferable will depend on the relative importance assigned to different aspects. That relative importance is influenced by individual preferences and is subjective. The MCA offers a valuable tool for clarifying how these preferences shape the selection of a DBD option.

The shallow DBD options perform better than the deeper options in several key areas:

- Conventional safety for workers and the public as they require fewer working days and truckloads for spoil removal.
- Technological maturity.
- Environmental impact as material and energy demands and carbon footprint are lower.
- Cost.

The deeper options score better in the following areas:

- Post-closure safety as they offer greater isolation and result in longer radionuclide travel times to the biosphere.
- Flexibility as they provide a larger disposal volume, although waste retrievability may be more complex in deeper boreholes.
- Ease of finding a suitable site as suitable site characteristics are more likely to be found at greater depths.

It is essential to note that shallow options would only be implemented at a site that meets the required characteristics for borehole disposal.

Next, the different spent fuel treatment options can be compared based on their implications for borehole disposal of the resulting SNF and/or HLW. In this case, a clearer and less ambiguous picture emerges than with the comparison between shallower and deeper options. The DBD options for PUREX reprocessed HLW perform better in several key areas:

- Conventional and radiological safety to workers as they involve a smaller variety of waste types to be encapsulated and require fewer overpacks.
- Maturity of the encapsulation process as the greater variety of waste forms in the other options necessitates the use of various types of internal baskets to adequately fill the space around the waste within the overpacks. This is believed to outweigh the slightly more demanding requirements on the welding process for the wider overpacks for PUREX reprocessed HLW.

- Flexibility as the wider boreholes in these options provide a larger disposal volume, although waste retrievability may be more complex in wider boreholes.
- Cost because fewer overpacks are needed.

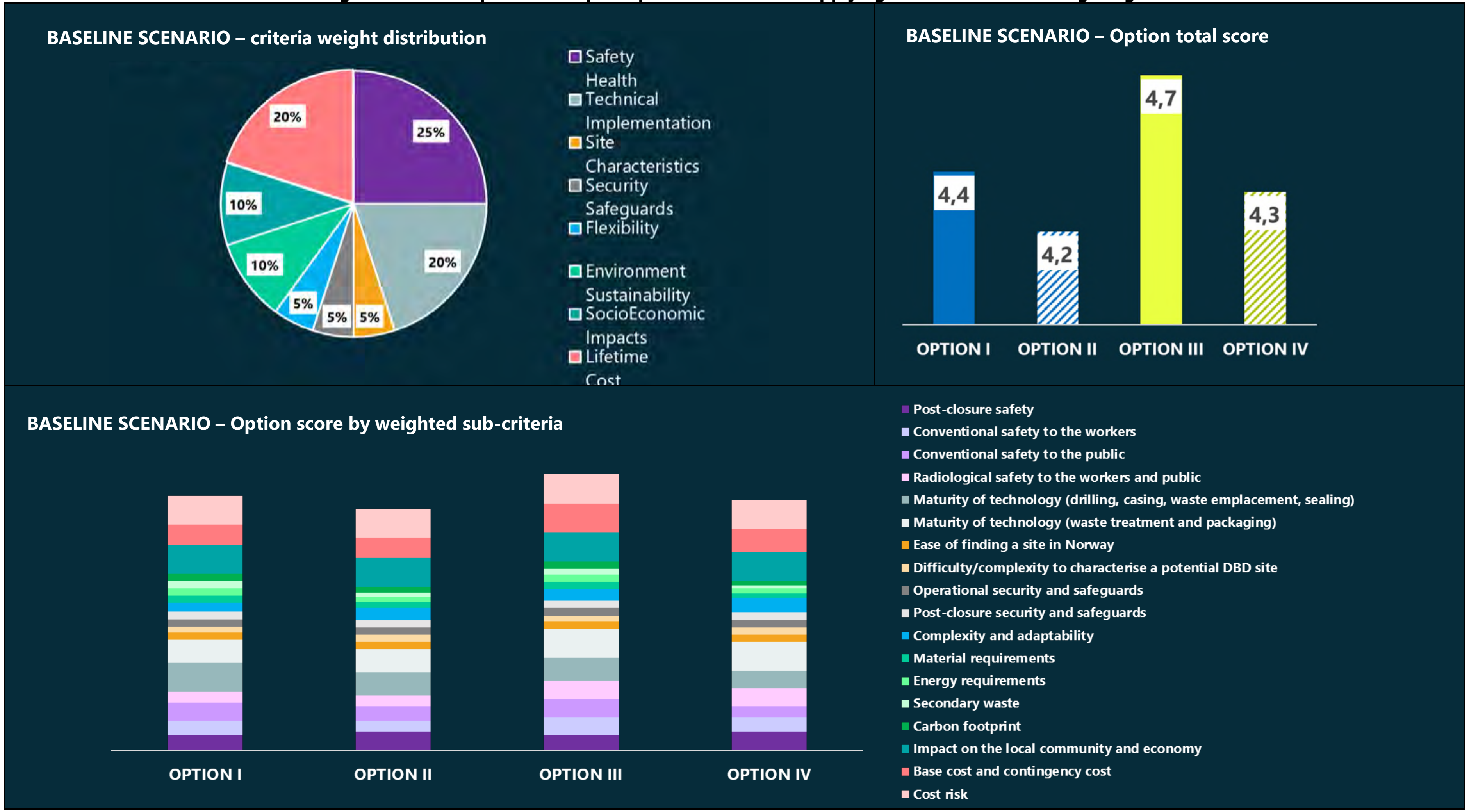
However, the DBD options for PUREX reprocessed HLW require wider overpacks and wider boreholes, leading to lower scores in the following areas:

- Technological maturity of the drilling technology.
- Environmental impact as material demands, secondary waste generated and carbon footprint.

Based on this analysis, and solely from the viewpoint of borehole disposal of the waste, PUREX reprocessing of spent fuel emerges as the preferred option. However, selecting a spent fuel treatment strategy encompasses a wide range of factors beyond disposal considerations. Nevertheless, the optioneering approach has shown that none of the DBD options constrains the optioneering of the spent fuel treatment strategy.

A potential DBD programme from now through to borehole closure (termed a "roadmap") has been summarised in another task under the framework contract. The conclusion of this report highlights activities that could be launched by NND in the short to medium term to build confidence in the DBD concept and the capability to achieve it whilst addressing planning and safety requirements.

Figure ES- 4: Comparison of option performance when applying baseline scenario weighting



CONTENTS

APPENDIXES

Appendix 1	Programme risk and opportunity register supporting the MCA outcomes summarised in Section IX and the consideration of next steps in Section X.
Appendix 2	Minutes of Option Assessment Panel (OAP) Session 1 supporting the MCA outcomes summarised in Section IX.
Appendix 3	Minutes of Option Assessment Panel (OAP) Session 2 supporting the MCA outcomes summarised in Section IX.

ABBREVIATIONS

ACE	Assumption, Constraint, Exclusion
ALARP	As Low As Reasonably Practicable
ANDRA	French National Radioactive Waste Management Agency
BWR	Boiling Water Reactor
CFD	Computational Fluid Dynamics
CONOPS	Concept of Operations
CRP	Coordinated Research Programme
DBD	Deep Borehole Disposal
DBFT	Deep Borehole Field Test
DHC	Drillhole Canister
DPS	Downward Placement System
DRZ	Disposal Rock Zone
DSA	Norwegian Radiation and Nuclear Safety Authority
DWOP	Drilling Well on Paper’
DZ	Disposal Zone
EDZ	Excavation Disturbed Zone
EIA	Environmental Impact Assessment
ERDO	European Repository Development Organisation
ESG	Environment and Social Governance
FA	Fuel Assembly
FEA	Finite Element Analysis
GDF / DGR	Geological Disposal facility / Deep Geological Repository
GHG	Green House Gas
GTK	Geological Survey of Finland
HBWR	Halden Boiling Water Reactor
HEU	Highly Enriched Uranium
HLW	High-Level Waste
IAEA	International Atomic Energy Agency
ICE	Internal Combustion Engine
ID	Inner Diameter
IFE	Institute for Energy Technology
ILW	Intermediate-Level Waste
JEEP	Joint Establishment Experimental Pile
LILW	Low-level and short-lived Intermediate-Level Waste
LL-ILW	Long-Lived Intermediate-Level Waste

LLW	Low-Level Waste
MCA	Multi-Criteria Analysis
MMC	Mobile Melt Consolidation
MOX	Mixed Oxide
N0RA	Norwegian zero effect Reactor Assembly
NAMRC	Nuclear Advanced Manufacturing Research Centre
NIMBY	Not In My Backyard
NND	Norwegian Nuclear Decommissioning
OAP	Option Assessment Panel
OD	Outer Diameter
PDF	Probability Distribution Function
PSA	Probabilistic Sensitivity Analysis
PWR	Pressurised Water Reactor
R&D	Research & Development
RCC	Rank Correlation Coefficients
RD&D	Research, Development & Demonstration
SAPIERR	Support Action: Pilot Initiative on European Regional Repository
SB2	Subcontract 2: DBD Technical Assistance to NND
SNF	Spent Nuclear Fuel
SNFA	Spent Nuclear Fuel Assemblies
SNL	Sandia Nuclear Laboratories
SSM	Sealing and Support Matrix
STP	Standard Temperature and Pressure
TA	Technical Assistance
TD	Total Depth
TDS	Total Dissolved Solids
TRL	Technology Readiness Level
WBS	Work Breakdown Structure

GLOSSARY

Selection of terms from the SB2 Glossary [1], SB2 Glossary includes a comparison with NND Glossary [2] (additional terms and where definitions have been amended and why):

Borehole	Any cylindrical ground excavation made by a drilling device for purposes such as site investigation, testing, monitoring, resource exploitation, or disposal.
Borehole Disposal	A disposal concept that entails the emplacement of waste in a borehole directly from the land surface.
Canister	Spent nuclear fuel or high-level waste is put in canisters, which are the primary container.
Closure	Administrative and technical actions directed at a disposal facility at the end of its operating lifetime.
Co-location	Co-location is: • Separate disposal modules at the same location with common infrastructure. • Separate disposal facilities for different types of waste at the same location.
CRP	Coordinated Research Programme
Deep Borehole Disposal	The concept of disposing of waste at a depth of one or more kilometers in boreholes with waste emplaced directly from the land surface.
Engineered barrier system	The combination of the engineered components of a disposal facility, including the waste packages / disposal containers, any buffer, backfills and seals, collectively designed to isolate radioactive waste in, and to prevent or to inhibit migration of radionuclides from, a disposal facility.
Geological / natural barrier	In the context of geological disposal this comprises the host rock in which a disposal facility is constructed, and the surrounding rocks.
Geological disposal facility / Deep Geological Repository	A facility for radioactive waste disposal located underground (usually several hundred metres or more below the surface) in a stable geological formation to provide long-term isolation of radionuclides from the biosphere. Includes both mined disposal and deep borehole disposal.
Groundwater	All water which is below the surface of the earth in the saturated zone and in direct contact with the ground or subsoil.
High level waste (HLW)	The radioactive liquid containing most of the fission products and actinides present in spent fuel — which forms the residue from the first solvent extraction cycle in reprocessing — and some of the associated waste streams; HLW also comprises the same material following solidification, usually by vitrification.
Host rock	The rock in which a disposal facility is located.
Intermediate level waste (ILW)	Radioactive waste that, because of its content, in particular its content of long lived radionuclides, requires a greater degree of containment and isolation than that provided by near surface disposal.
Inventory for disposal	The total amount of radioactive material, radioactive sources or radioactive waste within a certain specified area or intended to be managed in a certain specified way (or a breakdown of the characteristics of the material or waste within that total amount, for example the total activity of each radionuclide present).
Low level waste (LLW)	Radioactive waste that is above clearance levels, but with limited amounts of long lived radionuclides.
Mined Repository	Used in this study in place of Geological Disposal Facility / Deep Geological Repository as DBD is also a Geological Disposal Facility.

	A disposal facility / repository where waste is disposed of in openings that are excavated at depth, and the disposal area is accessed via a shaft or an inclined tunnel.
Multi-barrier system	Two or more natural or engineered barriers used to isolate radioactive waste in, and to prevent or to inhibit migration of radionuclides from, a disposal facility.
Multi-criteria analysis (MCA)	MCA is a systematic method for making complex decisions by using criteria, objectives, and other tools to rank and compare options.
Optioneering	A structured evaluation of options in support of decision-making. Such an evaluation may take the form of an option study that collates information on the options and the different attributes that will influence the decision to be made and may also consider how the decision is influenced by different value judgements.
Overpack	A secondary or additional outer container for one or more waste packages, used for their handling, transport, storage or disposal.
Retrievability	Retrievability is a special case of reversibility, being the ability to reverse the action of waste emplacement in a repository; retrieval is the action of removal of the waste or waste packages. Retrievability implies making provisions in order to allow retrieval should it be required.
Reversibility	Reversibility is the ability to reverse one or a series of steps in repository development (including predisposal waste management) at any stage of the programme.
Safety Case	A collection of arguments and evidence in support of the safety of a facility or activity. This will normally include the findings of a safety assessment and a statement of confidence in these findings. For a GDF, there will be a number of safety cases required covering nuclear safety, environmental safety, and transport. A safety case may also relate to a given stage of development (e.g. site investigations, commissioning, operations, closure, post-closure, etc.). The safety case should acknowledge the existence of any unresolved issues and should provide guidance for work to resolve these issues in future development stages.
Saline and salinity	Saline groundwater contains significant amounts of dissolved salts and is not potable. Definitions of the distinction between freshwater, brackish water and saline water vary, but saline water normally has a total concentration of dissolved solids (TDS) >10 g/l. Salinity is the measure of the amount of dissolved solids in water, usually expressed in grams or milligrams per litre.
Screening	In multi-criteria analysis (MCA), screening is a way to filter options before more detailed analysis or to compare options that are difficult to quantify.
Spent Nuclear Fuel (SNF)	Nuclear fuel removed from a reactor following irradiation that is no longer usable in its present form because of depletion of fissile material, poison build-up or radiation damage.
Waste container	The vessel into which the waste form is placed for handling, transport, storage and/or eventual disposal; also the outer barrier protecting the waste from external intrusions. The waste container is a component of the waste package. For example, molten high level waste glass would be poured into a specially designed container (canister), where it would cool and solidify.
Waste form	Waste in its physical and chemical form after treatment and/or conditioning (resulting in a solid) prior to packaging.
Waste package	The product of conditioning that includes the waste form and any container(s) and internal barriers (e.g. absorbing materials and liner), as prepared in accordance with requirements for handling, transport, storage and/or disposal.

ASSUMPTIONS, CONSTRAINTS, EXCLUSIONS (ACE)

The optioneering stage when the ACE was raised or modified is captured in the first column of this table.

ACE 1 *(Option generation stage)*	**Potential inventory of SNF and/or HLW.** The optioneering only concerns DBD of Norwegian legacy SNF and/or HLW. The disposal of Norway's ILW or LLW by DBD is excluded, as is any potential waste associated with future new build activities or SNF or HLW derived from nuclear programmes in other countries.
ACE 2 *(Option generation stage)*	**Host rock properties.** Host rock properties are assumed to be consistent with the geoscientific target properties specified by Hagros et al [24]. Only crystalline rock is considered in this study.
ACE 3 *(Option generation stage, modified in option characterisation stage)*	**Regulatory and stakeholder expectations.** There is currently no requirement regarding waste retrievability in Norway. However, to err on the side of caution, the DBD optioneering considers the potential need for and implications of waste retrievability under the flexibility criterion. A disposal option can only be successfully implemented if it has the support of stakeholders, including local communities. Stakeholders may have preferences for or against some disposal options and may have specific requirements (e.g., waste retrievability, minimum depth for waste emplacement). The Sensitivity analysis assumes weights sets to respectively reflect potential interests of local communities, waste owners, and regulators to start discussion of the impact of weighting. Such weigh sets may be revisited following further engagement with stakeholders.
ACE 4 *(Option generation stage, modified in option characterisation stage)*	**Potential SNF management variants**. Because the SNF management strategy has yet to be decided, four variants of SNF management are assumed. All four variants include MMC treatment of 1 t of uranium. • SNF management variant 1: Direct disposal of all SNF • SNF management variant 2a: Oxidation of the metallic uranium fuel and direct disposal of the rest of the SNF • SNF management variant 2b: MMC treatment of metallic uranium fuel and direct disposal of the rest of the SNF • SNF management variant 3: PUREX reprocessing of all fuel assemblies resulting in the return of 8 CSD-V containers with vitrified HLW, and direct disposal of remaining un-reprocessed fuel assemblies. Since the specific amount of spent fuel in the tonne of uranium processed at the MMC facility is unclear, it is conservatively assumed that the entire inventory of UO_2 fuel (6.5tU) is treated in each SNF management variant considered.
ACE 5 *(Option generation stage, modified in option characterisation stage)*	**Potential SNF management variants and spent fuel inventory** No data were provided on the number of HLW stainless steel overpacks that would be produced by dry oxidation. Based on the following assumptions, it was estimated that 120 stainless steel canisters would be produced by the oxidation process: • UO_2 produced by dry oxidation: 11.3 t. • UO_2 density: 10.3 t/m^3. • canister thickness: 5 mm. • void volume in the canister after filling: 30%. • canisters dimensions: approximately 1.4 m long and 120 mm in outer diameter. Further optimisation of the returned stainless-steel canisters could enable to reduce the number of disposal overpacks. It is assumed that the returned waste from PUREX reprocessing by Orano in France will consist of 8 CSD-V canisters with vitrified HLW.

	The following fuel inventory assumptions have been made: • 80% of the HBWR 5th charge, HBWR booster and experimental fuel assemblies have been disassembled and the individual rods are in storage. The remaining 20% have been stored as assemblies (no disassembly) and will be disposed of in that condition. • A length of 3.66 m is adopted for the fuel assemblies for Halden HBWR 3rd to 5th charges, booster and experimental fuel. • The uranium mass per rod for the 2nd, 3rd, 4th and 5th HBWR charges has been calculated assuming the uranium content is proportional to the rod volume. A rod diameter of 13.28 mm was used for the 2nd, 3rd and 4th HBWR charges and 12.25 mm for the 5th HBWR charge. • The uranium mass per rod for the HBWR Experimental fuel was calculated based on a total mass of 400 kg and assuming the uranium content is proportional to the rod length.
ACE 6 *(Option generation stage, modified in option characterisation stage)*	**Potential SNF management variants.** It is assumed that MMC ingots are manufactured in containers with an outer diameter of 25 cm and a length of 3 m. NND informed stainless steel represents 86% to 88% of the weight of the MMC ingot. To derive the number of overpacks, it is assumed that 90% of the ingot mass consists of stainless steel and 10% is heavy metals (uranium, plutonium, or thorium).
ACE 7 *(Option generation stage, modified in option characterisation stage)*	**Disposal overpacks design and length of the disposal section.** Several design choices regarding the design and dimensions of the disposal overpacks in which the SNF and/or HLW will be packaged before disposal, the spacing between these disposal overpacks in the borehole, the clearance between the disposal container and the borehole casing have been assumed to characterize the options. The disposal overpacks dimensions have been estimated considering the following assumptions, the data currently available on SNF assemblies, rods combined with known data on MMC and PUREX form, and a review of DBD disposal overpack for SNF or HLW disposal previously designed in the USA, Germany, Australia and Norway. • It is assumed that an overpack only contains SNF from a given group or one type of waste. In case of direct disposal, a given overpack only contains complete fuel assemblies or consolidates fuel rods. • The narrow overpack needs to be long enough to contain the longest fuel assembly. • The narrow overpack needs to have a diameter wide enough to contain the MMC ingot. • The wide overpack needs to be long enough to contain the MMC ingot. • The wide overpack needs to have a diameter wide enough to contain the CSD-V canister. • The wall, lid and bottom of the disposal overpacks are 4 cm thick. • The base is assumed to be welded to the body in the manufacturing plant. • A simple hydraulically actuated system is assumed to latch to the lid. • A margin of 10 mm is added to the diameter of the FAs to account for the use of a basket for proper placement inside the overpack. • A spacing of 1 m has been assumed between the overpacks in the borehole. The required spacing will mainly be determined by the thermal output of the overpacks. • A clearance of about 40 mm has been assumed between the overpack and the borehole casing, and between the inner borehole casing and the borehole wall itself. • The top of the waste stack is assumed to be at an indicative depth of 3000 m for the option considering DBD at greater depths. • Duplex stainless steel is the material selected for the options assessment process owing to its resistance to uniform and localised corrosion. Site-specific data will be needed for a proper evaluation of uniform and localised corrosion rates.

	• It is assumed that the overpack designed at this stage will ensure containment of the waste during the thermal phase. • Electron Beam Welding (EBW) is assumed for all options.
ACE 8 *(Option generation stage)*	**Maturity of the DBD options and future RD&D needs.** The DBD optioneering has taken account an initial review of the technical maturity of the DBD concepts considered. A demonstration of waste emplacement and borehole closure has not yet been carried out. It is assumed the technical maturity for borehole closure is the same for all options with the caveat that no tests have been carried out at a 3 km depth. Further RD&D is needed to increase the Technology Readiness Level and safety demonstration of DBD concept, including demonstration of container lifetime, waste emplacement and borehole closure.
ACE 9 *(Option characterisation stage)*	**Encapsulation plant and optioneering study boundaries.** It is assumed that the encapsulation plant is co-located with the centralised storage facility to streamline comparison of DBD options. Alternative encapsulation plan locations are discussed in Section VII.2.2. This study considered option lifecycles starting from the termination of storage of HLW/SNF, and encompassing waste encapsulation for disposal, transport to the repository site, and disposal in the borehole, including site identification and characterisation, as well as borehole construction, operation and closure. The predisposal conditioning and storage of the SNF, the potential disposal of SNF and/or HLW in mined facilities, and the management and disposal of other waste types are outside the scope of this study.
ACE 10 *(Option characterisation stage)*	**Transport Cask.** The transport casks dimensions have been estimated considering the following assumptions, the overpack dimensions and features, and combining a design from Filbert et al. [1] and Orano TN9/4 for the narrow overpack and Orano TN28 for the wide overpack. • The transport cask has an internal space that is sufficient to contain the overpack that is used in the chosen treatment options • An estimated wall thickness of 600 mm is assumed for the transport cask for shielding purposes. • The transport cask only contains one overpack. • The number of transport casks and transport utilised required is based on the following assumptions: • Each waste transport utilities one transport cask. • A road transport system is used • A transport cask needs to be available for loading at the encapsulation facility. • A transport cask is assumed to be being unloaded at the borehole site. • A third cask needs to be available to allow transport operations to take place simultaneously to encapsulation and emplacement at the borehole. At this stage, factors, such as the distance between the disposal site (assumed to be located in a remote area) and the designated spoil removal location have not been considered in the preliminary operational safety comparison of the options due to lack of site-specific knowledge. It is assumed spoil removal will be taken offsite, via grab lorry.
ACE 11 *(Option characterisation stage)*	**Cost assumptions.** The purpose of the cost estimate is to obtain a preliminary and high-level estimate of the cost of the borehole disposal of Norway's SNF and/or HLW to facilitate order of magnitude comparison between options. The level of available information associated with each option does not allow at this stage for full lifecycle cost analysis and detailed cost estimates to be produced.

[1] Filbert W. (2010). Optimization of the Direct Disposal Concept by Emplacing SF Canister in Boreholes Final Report. Technology GmbH.

	The cost estimates have been done using the following assumptions: • To provide a preliminary estimate of the provisions covering potential future costs from project risks, an indicative set of risks and opportunities has been identified for the DBD options. Based on assumed risk probabilities, impacts and risk appetite, a risk provision in the order of ~€10 to 20M was estimated. • As part of the site characterisation assessment, and for costing purposes, it is assumed that a small investigation borehole, approximately 10 cm in diameter, will be required. It is assumed that the investigation borehole(s) are within a 500 m radius of the disposal borehole site. • It is assumed that there is no differentiation between the costs of surface facilities to support the different options. • It is assumed that there is no differentiation between the construction costs of the encapsulation plant, regardless of the number of overpacks that are required and regardless of any differences in technical difficulty in the encapsulation process • It is assumed that there is no differentiation between the decontamination and dismantling of site and the long-term monitoring costs. • It is assumed that during a day of operations the number of workers on site will be the same for all options. • It is assumed that one disposal overpack (and it corresponding SSM) is emplaced per day. • The following costs are excluded from this preliminary assessment: o Costs associated with stakeholder involvement, including potential benefits to local communities. o Costs associated with regulatory review of the license and planning applications. o Costs for predisposal management, such as spent fuel treatment and interim storage o Generic RD&D costs, such as the demonstration borehole or field test. It is assumed at this stage that generic RD&D costs would be similar across the options. The demonstration borehole or field test may be planned in the Programme initiation stage before the site characteristics of the disposal borehole are known and the spent fuel treatment option is selected
ACE 12 *(Option characterisation stage)*	**DBD Programme timeline.** It is assumed that the required start date of disposal operations is 2050.
ACE 13 *(Option characterisation stage)*	**Centralised storage facility.** It is assumed that all the SNF and/or HLW inventory considered for DBD will be stored centrally within the new storage facility and that the storage facility performance would not impact on the disposability of the SNF and/or HLW inventory, and it was not included in the scope of the options assessment.
ACE 14 *(Option characterisation stage)*	**Safeguards**. The specifics of potential safeguards obligations cannot be defined without a licensed design that has undergone evaluation by the IAEA Department of Safeguards. It is assumed that the differences in safeguard requirements between the options are minimal.
ACE 15 *(Option characterisation stage)*	**Fuel burnup and thermal power.** To derive estimates for burnup and thermal power of the various SNFA categories at the time of disposal, as well as for the vitrified HLW generated through PUREX reprocessing, the following burnup assumptions have been made: • JEEP I: assumed burnup of 10000 MWd/tU. • HBWR 1st charge: burnup of 12 MWd/tU . • JEEP II: assumed burnup of 20000 MWd/tU. • HBWR 2nd to 5th charges: assumed burnup of 50000MWd/tU • HBWR booster assumed burnup of 80000MWd/tU • HBWR experimental assumed burnup of 100000MWd/tU

	• All spent fuel will have undergone 30 years of cooling since discharge from the reactor noting some fuel assemblies will have been cooling for nearly 90 years assuming the start of disposal operations in 2050. • If produced in 2040, the CSD-V canisters will undergo 10 years of decay before potential disposal • 85% of the mass of the MMC ingots is stainless steel and the remaining 15% is heavy metal (Uranium, Plutonium or Thorium) for thermal power computation to maximise the thermal power of the MMC ingots, noting NND informed stainless steel represents 86% to 88% of the weight of the MMC ingot..
ACE 16 *(Option characterisation stage)*	**Temperature conditions.** It is assumed an average surface temperature of 5°C and a geothermal gradient of 15°C per kilometre to estimate the ambient temperatures at depths of 1500 m, 3000 m and 5000 m (respectively 27.5°C, 50°C and 80°C). Detailed thermal modelling assumptions are captured in NOTE 3[3].
ACE 17 *(Option characterisation stage)*	**Disposal borehole drilling, casing, backfilling.** Several design choices regarding the disposal borehole and associated drilling plan have been assumed to characterise the options. • The boreholes will be drilled using a blind shaft drilling approach. • Site conditions are assumed to require an additional intermediate casing to provide temporary support to the upper parts of the borehole until the final casing is installed (Drilling Plan B) for Option IV (the wider and deeper options). Options I, II and III costs are based on the cutting rates and casing for the different sizes and depths of borehole without the intermediate casing. • A carbon steel casing reinforced with stiffener rings made from solid rectangular steel bars is proposed. These reinforcements provide enough strength to resist collapse under 5 MPa of external pressure. • The proposed material for casing is assumed to be corrosion-resistant noting the potential for a free gas phase depends not only on casing corrosion but also on the gas dissolution and dissipation rates. Further design considering the potential for gas to dissolve and dissipate and assessing the risk of a free gas phase will enable to confirm the casing material. • Coil tubing is the assumed waste emplacement method. It is assumed a 3000 m round trip could be made in about 80 minutes, plus additional time for latching and unlatching of the overpack. • Emplacement process with solid shielding is assumed as the baseline in this study. • A cementitious backfill is the proposed design, assuming its composition will enable the cement to cement must arrive in situ and fill the annular space without prematurely setting.
ACE 18 *(Option characterisation stage)*	**Borehole depth.**The assumed minimum depth for DBD in Options I and III is 1500 m, based on the expectation that the required conditions are found at a depth of at least 1000 m, with an additional 500 m added to account for uplift, erosion and provide a safety margin. Options II and IV assume a depth of 3000 m as this stage, to reflect the case where a site at 1000 m does not meet the required characteristics, but offers other advantages, such as proximity to other waste management facilities or community support.
ACE 19 *(Option characterisation stage)*	**Environmental assessment.** The following assumptions were made to enable a comparison of the options against the environmental criteria at this stage: • The carbon footprint is assumed to be the same for each option. • The material requirements of the encapsulation plant, surface facilities and investigation boreholes are either assumed to be comparable or cannot be estimated at this time. • It is assumed that the material requirements for the construction of the encapsulation plant and other surface facilities will be similar for all DBD options. • It is assumed that the borehole site will be located in a remote area.

HOLDS

All HOLDs will be removed in Revision C.

HOLD 1	NND confirmed retaining the Programme Risk and Opportunity Register and the Minutes of the OAP meeting shall be appendixed directly to the Final Report. Other supporting information as appendices in Revision B shall be retained inside a consolidated Complementary Technical Study Note.
HOLD 2	NND confirmed DSA will not review the Optioneering final report. The report may be sent to DSA for information once accepted by NND.
HOLD 3	NND/ IFE confirmed that the origin of ingress of moisture into thre JEEP I SNF SNF fuel storage facility remains uunknown, but is considered most likely to have occurred during irradiation in the reactor.
HOLD 4	NND confirmed retaining the information included in Table 30, listing example activities that could be launched by NND in the short and medium term to address knowledge gaps and to increase confidence in the potential for DBD to provide a safe and viable disposal solution whist providing information to satisfy planning and safety requirements.

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I. INTRODUCTION

1. Background to Norway's radioactive waste management

In Norway, KLDRA-Himdalen, the combined disposal and storage facility for low-level waste (LLW) and short-lived intermediate-level waste (ILW), has been operating since 1999. The facility is used to manage waste from the Halden and Kjeller nuclear research reactor facilities and LLW generated by other industries, such as the medical sector in Norway. However, the capacity of the facility will not be sufficient to accommodate projected waste volumes arising from the decommissioning of the research reactors. Further, long-lived ILW, high-level waste (HLW) and/or spent nuclear fuel (SNF) from the decommissioned research reactors will also need to be managed, and the facility is not licensed for such waste types.

Norwegian Nuclear Decommissioning (NND) has therefore initiated a process to develop disposal solutions for all classes of radioactive waste. Two concepts have been explored to manage SNF / HLW: a mined geological disposal facility (DGR) and disposal in one or more deep boreholes (Deep Borehole Disposal, DBD). Initial consideration has been given to concept description, overpack design, spent fuel processing options and co-location issues for both disposal concepts. However, the long-term waste management programme for SNF remains at a generic stage, there is not yet a preferred treatment method for the various fuel types in Norway, no siting process has commenced, and no choice between DBD and a mined DGR option has yet been made.

Because of the relatively low technology readiness level of DBD compared to other disposal concepts, NND has set up a framework contract (Framework Subcontract 2, or SB2) specifically to evaluate and advance DBD concept options for SNF and HLW in Norway, including a multi-criteria analysis (MCA) of DBD concept options. Parallel MCA studies led by other organisations under contract to NND are considering options (including DBD, DGR and nearer-surface disposal) at a high level for all radioactive waste types in Norway, and options for predisposal treatment of the SNF component of the inventory (i.e. for the inventory component considered for DBD, the final waste form for disposal is still unknown).

2. Objective

The objective of the DBD optioneering study reported here was to identify, describe and evaluate preferred options that could result in disposal of all Norwegian SNF or HLW depending on treatment method, and be implemented in Norway by around 2050. The study also informs the recommendation of a DBD concept, should DBD be selected as the disposal option.

The MCA analysis entailed a balanced assessment of option safety, environmental impact, socio-economic impact, technical maturity, and cost effectiveness. The MCA consisted of the following stages:

- **Stage 1**: Identification of an initial list of potentially viable DBD options. This step identifies waste types, processing methods, container types, borehole geometries and depths, locations, and geological environment options suitable for DBD.
- **Stage 2**: Screening of DBD options identified in Stage 1, to provide a representative range (i.e., shortlist) of DBD options for a more detailed evaluation.

- **Stage 3**: Evaluation and comparison of short-listed options:
  - Characterisation of the short-listed options.
  - Identification of technical, safety, environmental, socio-economic, and cost assessment criteria, and development of an evaluation or scoring methodology for each criterion.
  - Detailed evaluation and comparison of short-listed DBD options against the criteria, considering stakeholder views and potential criteria weightings to inform sensitivity analysis and identification of preferred options.
- **Stage 4**: Summary reporting - the present report.

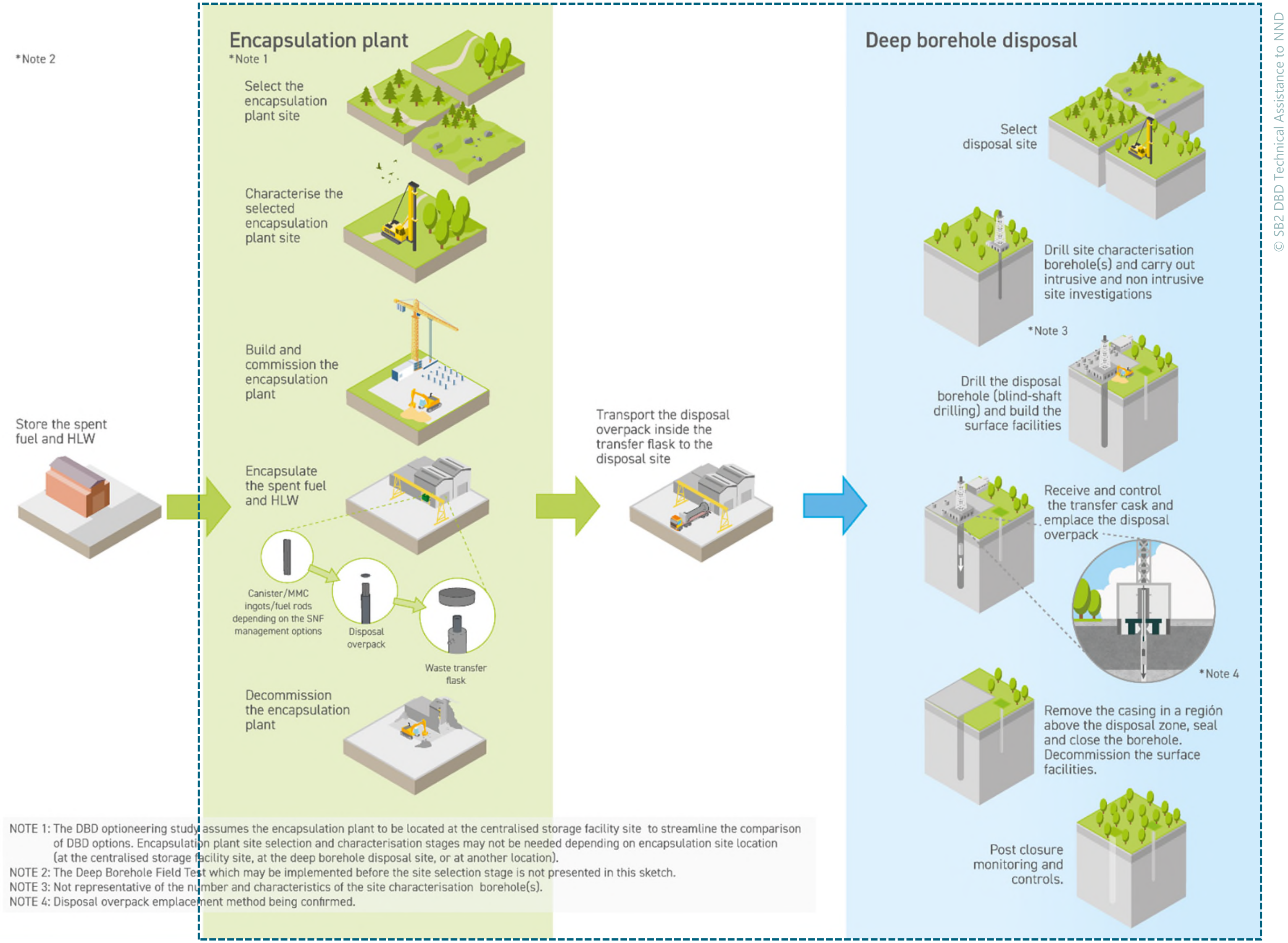
This report aims to provide a comprehensive summary of the outcomes of the DBD MCA study. It describes the project context and specifies the assumptions, constraints and exclusions that apply. It presents the key achievements and lessons learned. This particularly includes the characterisation of a shortlist of DBD options and the ranking of these options. Finally, the report identifies potential next steps and opportunities for further development.

3. Scope

The tasks completed under this optioneering study only concern the DBD of SNF and/or HLW. The disposal of Norway's ILW or LLW by DBD is excluded (ACE 1), as is any potential waste associated with future new build activities in Norway or SNF or HLW derived from nuclear programmes in other countries. However, the potential for the wider borehole options considered here to accept additional waste package types, as a potential future opportunity, is addressed under the Flexibility criterion.

This study considered option lifecycles starting from the termination of storage of HLW/SNF, and encompassing waste encapsulation for disposal, transport to the repository site, and disposal in the borehole, including site identification and characterisation, as well as borehole construction, operation and closure, as presented in Figure 1. The predisposal conditioning and storage of the SNF, the potential disposal of SNF and/or HLW in mined facilities, and the management and disposal of other waste types are outside the scope of this study.

Figure 1: Scope of deep borehole disposal Optioneering study



4. Structure

This report is structured as follows:

- Section II presents the roles and responsibilities of all organisations and actors involved in the management of the Norwegian inventory of radioactive waste. The section also explains how the interfaces with other teams supporting NND optioneering studies on SNF management and disposal are managed.
- Section III describes the current SNF and HLW management situation in Norway and explores the potential implications of a hypothetical scenario where no disposal route is developed.
- Section IV identifies the main constraints relevant to a potential DBD programme in Norway.
- Section V summarises the main findings from previous national and international research on DBD, including an overview of knowledge and technical gaps associated with implementing DBD in Norway.
- Section VI details the assessment methodology used to evaluate and rank potential DBD options in Norway based on their suitability for disposing of Norway's inventory of SNF or HLW.
- Section VII presents the longlist and shortlist of DBD options that were generated during this study.
- Section VIII provides a comprehensive summary of the characterisation of the shortlisted DBD options.
- Section IX presents the outcomes of the MCA ranking the shortlisted DBD options.
- Section X discusses next steps for implementing DBD in Norway.

This report contains three Appendices:

- Appendix 1 contains a programme risk and opportunity register supporting the MCA outcomes summarised in Section IX and the consideration of next steps in Section X.
- Appendices 2 and 3 contain minutes of two Option Assessment Panel (OAP) meetings supporting the MCA outcomes summarised in Section IX.

This report has been prepared as a document that can be read and understood without reference to supporting technical detail. However, detailed notes containing further information on the characterisation and comparison of the DBD options – mainly in support of the assessments presented in Section IX - are available separately [3], and are referred to here as Complementary Note X (where X is the number of the Note).

II. ROLES, RESPONSIBILITIES AND INTERFACES WITH DBD OPTIONEERING STUDY

1. Stakeholder mapping and responsibilities in the optioneering study

Successfully implementing radioactive waste management strategies requires identifying and addressing the requirements, expectations and concerns of stakeholders. Effective communication and involvement with stakeholders are essential for ensuring stakeholder views are understood, building trust, and increasing confidence in chosen disposal options.

Stakeholders with a potential interest in studies on DBD have been identified. This section outlines their roles and responsibilities, and identifies interfaces to ensure that potential requirements, needs and expectations have been accounted for in the optioneering study.
The mapping of stakeholder interfaces with DBD optioneering is discussed in further detail in [4].

Stakeholders have been categorised into primary and secondary stakeholders. Primary stakeholders have a significant interest in the project and may be directly impacted by its outcomes therefore, having a high influence on the programme.

- The primary stakeholders, their mandate and the interface with the DBD optioneering study are given in Table 1.
- Secondary stakeholders, in contrast, have a more indirect interest or influence on the project. These include Non-Governmental Organisations (NGOs), civil society organisations, the Oil & Gas and drilling industries, organisation involved in the European Repository Development Organisation ERDO initiative (ERDO) and other institutions considering or researching DBD.

The optioneering study sensitivity analysis discusses alternative weightings that might be proposed by different stakeholders (section VI.3.4).

Table 1: Stakeholders

Stakeholder	Mandate	Interface(s) with DBD Optioneering Study
NND	The radioactive waste management organisation in Norway, established in 2018, responsible for decommissioning and safe handling, storage, transport and disposal of nuclear waste in Norway. NND requires that the management of SNF and HLW is appropriate, safe, secure, and carried out in accordance with laws, regulations, and good international practice**.**	• NND approves implementation arrangements, steers, supervises and monitors the optioneering study. • NND attends as an Observer at the DBD OAP meetings. • NND approves this DBD optioneering final report.
IAEA (International Atomic Energy Agency)	The IAEA has Specific Safety Requirements and Standards, which must be met. The IAEA launched a Coordinated Research Programme (CRP) on DBD Implementation in 2024. The IAEA may launch a CRP on the safety case and safety assessment approach applicable to DBD.	• NND's IAEA representative is included in the SNF OAP. • Applicable IAEA requirements in relation to DBD site selection and characterisation, design and engineering, post-closure safety and safety assessment, operational safety, monitoring and retrievability, that are relevant to DBD have been reviewed as part of this study (see section IV and [5]). • The outcomes from the optioneering study will feed into NND's inputs to the IAEA CRP on DBD Implementation.
DSA (Norwegian Radiation and Nuclear Safety Authority)	The DSA will give guidance and input on NND's proposals, to ensure compliance with regulatory requirements. The DSA has published a national strategy for radioactive waste management in Norway, for consideration and potential endorsement by the Government [6].	• The DSA acts as the ultimate organisation concerning security issues. • Norwegian regulatory requirements applicable to DBD have been reviewed as part of this study (see section IV and [5]). • The DSA may be sent the DBD optioneering final report for information • This optioneering report will feed into NND's Choice of Disposal Concept Study, which will be reviewed by the DSA.
Waste producers / IFE (Institute for Energy Technology)	IFE owns the operating licenses of the research reactors and provides information on facilities and SNF. IFE ownership and responsibility will be moved to NND in the coming years.	• IFE provides the assumptions for the spent fuel inventory. • IFE representative attends as Observer the OAP. • IFE representative reviews this DBD optioneering final report. • IFE is developing a new storage facility for SNF in Norway.
Contractors responsible for interfacing frameworks	Amentum (formerly Jacobs) and Multiconsult comparing SNF treatment options, defining the HLW and SNF waste form for disposal.	• Interface management is implemented to ensure consistency where needed of optioneering approach, assumptions, assessment criteria, input data, outcomes and

Stakeholder	Mandate	Interface(s) with DBD Optioneering Study
(GeoReN and Amentum and Multiconsult optioneering studies)	GeoReN is developing a comparative evaluation of DBD against a mined repository concept.	terminology, and that any differences are understood. • Mutual attendance of OAPs is implemented. • GeoReN will carry out a peer review of this report once accepted by NND. The DBD Technical Assistance Team will similarly review the GeoReN final report once accepted by NND.
Ministry of Trade, Industry and Fisheries	The Ministry of Trade, Industry and Fisheries is the parent Minister of NND.	• The Ministry of Trade, Industry and Fisheries is the owner of the study, providing funding and assigning tasks to NND.
Ministry of Finance	The Ministry of Finance is responsible for planning and implementing the Norwegian economic policy and for coordinating the work with the Fiscal Budget.	• This report will feed into the Choice of Concept Study.

2. Option Assessment Panel

The optioneering study was led, facilitated and documented by a core team, with the support of a multi-disciplinary OAP representing required subject areas. The OAP, shown in Table 2, consisted of experts working on the Norwegian DBD programme.

Table 2: OAP – SB2 members

Name – Entity	Relevant experience	OAP focus	Screening OAP	Assessment OAP	
				#1	#2
Daniel Galson SB2 | Galson Sciences Ltd, part of Egis group	Over 30 years' technical and management experience of safety and risk assessments for geological and near-surface radioactive waste disposal.	SB2 Framework Technical Director	✓	✓	✓
Mark Crawford SB2 | Galson Sciences Ltd, part of Egis group	Over 25 years' technical and management experience of safety and risk assessments for geological and near-surface radioactive and hazardous waste disposal and 35 years' experience in geochemical modelling and software development.	SB2 Environmental safety and geological disposal requirements management specialist	✓	×	✓
José Luis Cormenzana SB2 | Empresarios Agrupados	Over 25 years' experience in the nuclear industry including radioactive waste disposal site selection, repository design, alternative concept review, performance assessment and disposability (waste acceptance criteria) for geological disposal facilities.	SB2 Geological disposal safety and IAEA standards specialist	✓	✓	✓

Name – Entity	Relevant experience	OAP focus	Screening OAP	Assessment OAP	
				#1	#2
Paul Shaughnessy SB2 | Orano	Over 20 years' engineering and management experience specialising in machine design and materials handling, 12 years of which have been in the nuclear industry.	SB2 Mechanical and waste packaging and encapsulation specialist	✓	✓	✓
Karl Patrick Travis SB2 | University of Sheffield	Over 20 years' experience in computational modelling most of which involves research related to nuclear waste disposal. He is an internationally recognised authority on DBD, leading a DBD research group. Ongoing research activities focus on cementitious grouts for DBD applications, rock welding, sealing and support matrices for waste packages, and the safety case for DBD.	SB2 Borehole closure, backfilling and sealing specialist	✓	✓	✓
John Beswick SB2 | Marriott Drilling	Over 45 years' experience in studies of radioactive waste repositories and 35 years' involvement in developing and evaluating the concept of deep borehole disposal. He has led deep drilling operations in over 50 countries, including Scandinavia, with depths up to almost 7000 m.	SB2 Drilling specialist	✓	✓	✓
Philippe Van Marcke SB2 | Galson Sciences Ltd, part of Egis group	Over 15 years' experience in developing and evaluating radioactive waste disposal concepts worldwide. He was also the IAEA Chief Scientific Investigator for the IAEA Research Coordination Project on borehole disposal.	SB2 Deep borehole disposal specialist SB2 OAP facilitator.	✓	✓	✓
Steve Wickham SB2 | Galson Sciences Ltd, part of Egis group	30 years consultancy support to the nuclear industry concerning radioactive waste management and disposal across a wide range of diverse technical fields. He specializes in strategic multicriteria options appraisal and cost-benefit analysis and has supported geological disposal cost assessments in the UK, Belgium and Switzerland over the past 15 years.	SB2 Lifecycle planning, cost and MCA specialist	✓	✓	✓
Phil Richardson SB2 | Galson Sciences Ltd, part of Egis group	Over 30 years' experience in monitoring social and geological aspects of waste management programmes globally. He is an internationally recognised expert in developing stakeholder involvement methodologies and best practice, leading the development of 2022 IAEA Nuclear Energy Series Report on Communication and stakeholder involvement in radioactive waste disposal.	SB2 Community engagement specialist	✓	✓	✓

Name – Entity	Relevant experience	OAP focus	Screening OAP	Assessment OAP	
				#1	#2
Rune Skarstein SB2 | COWI	Over 30 years' experience in Norwegian infrastructure project management, design management, planning, regulatory and authority handling. He has supported NND as a Project Manager for the public plan for decommissioning of the nuclear facilities at Halden and Kjeller.	SB2 Norwegian regulatory and permitting framework specialist	✓	×	×
Elham Farahi SB2 | Orano	Over 15 years' experience in the nuclear industry covering radioactive waste predisposal and disposal and nuclear decommissioning. She specialises in waste encapsulation and immobilisation and disposability assessment.	SB2 Spent fuel management and predisposal specialist	✓	✓	×
Andrew Freer SB2 | Orano	Over 15 years' experience as a radioactive waste transport and nuclear safety specialist. For the UK geological disposal programme, he managed production of the Transport Safety Case and Operational Environmental Safety Assessment as part of the 2016 generic Disposal System Safety Case.	SB2 Operational safety and transport specialist	×	✓	×
Merete Grøtt Grinde SB2 | COWI	Over 5 years' experience supporting a wide array of infrastructure projects across Norway, carrying out and reviewing impact assessments, cost-benefit analyses and socio-economic analysis.	SB2 Socio-economic consultant	×	✓	×
Laure Prévot SB2 | Egis	Over 10 years' experience in coordinating multi-disciplinary consultancy framework contracts and engineering projects across their lifecycle worldwide. She is supporting site evaluation for the UK geological disposal programme, is participating in the IAEA CRP on DBD Implementation, and is leading a Task on DBD within the EURAD-2 European collaborative research project.	SB2 Framework Manager. Ensures compliance with the optioneering scope and task objectives and consistency of delivery.	✓	✓	✓
Shivangi Prasad SB2 | Galson Sciences Ltd, part of Egis group	Over 2 years' experience in consultancy for radioactive waste predisposal and disposal programme, supporting the UK Deep Geological Disposal programme site evaluation, inventory analysis and PREDIS European collaborative research programme to compare and assess value of predisposal technologies.	SB2 Framework Manager Deputy. Minutes the OAP and coordinates the inputs.	✓	✓	✓

Legend: ✓ Attending - × Not present, SB2 experts not attending Screening OAP, or Assessment OAP Session 1 or Session 2 have participated in the preparation of the OAP

The OAP was supplemented with representatives from the parallel option studies, GeoReN and Amentum and Multi-consult TA.

- **Cristiano Padovani** (Amentum): Spent fuel and disposal specialist and Amentum and Multi-consult TA representative for the Screening OAP.
- **Michelle Dickinson** (Amentum): Spent fuel and HLW predisposal and MCA approach specialist, and Amentum and Multi-consult TA representative for the Screening OAP.
- **Bernt Haverkamp** (BGE-Tech): Radioactive waste disposal specialist and GeoReN representative for the Screening OAP.
- **Pirjo Hella** (VTT): Radioactive waste disposal specialist and GeoReN representative for the Assessment OAP sessions 1 and 2.
- **Timmo Seppälä** (Mitta), Radioactive waste disposal and predisposal specialist and GeoReN representative for the Assessment OAP sessions 1 and 2, also attending Amentum and Multi-consult OAP.

NND and IFE representatives attended the OAP as Observers:

- **Marit Stokkeland Asklien**: NND Technical Lead Repository and NND representative (all OAPs).
- **Peter Bennett**: NND and IFE specialist and representative (all OAPs).

Minutes of the Assessment OAP are provided in Appendices 2 and 3 of this report. Minutes of the Screening OAP are provided in Appendix 2 of the Option Short List [7].

3. Interfaces with parallel option studies

The interfaces between the three NND optioneering studies on spent fuel management and disposal concepts are particularly relevant:

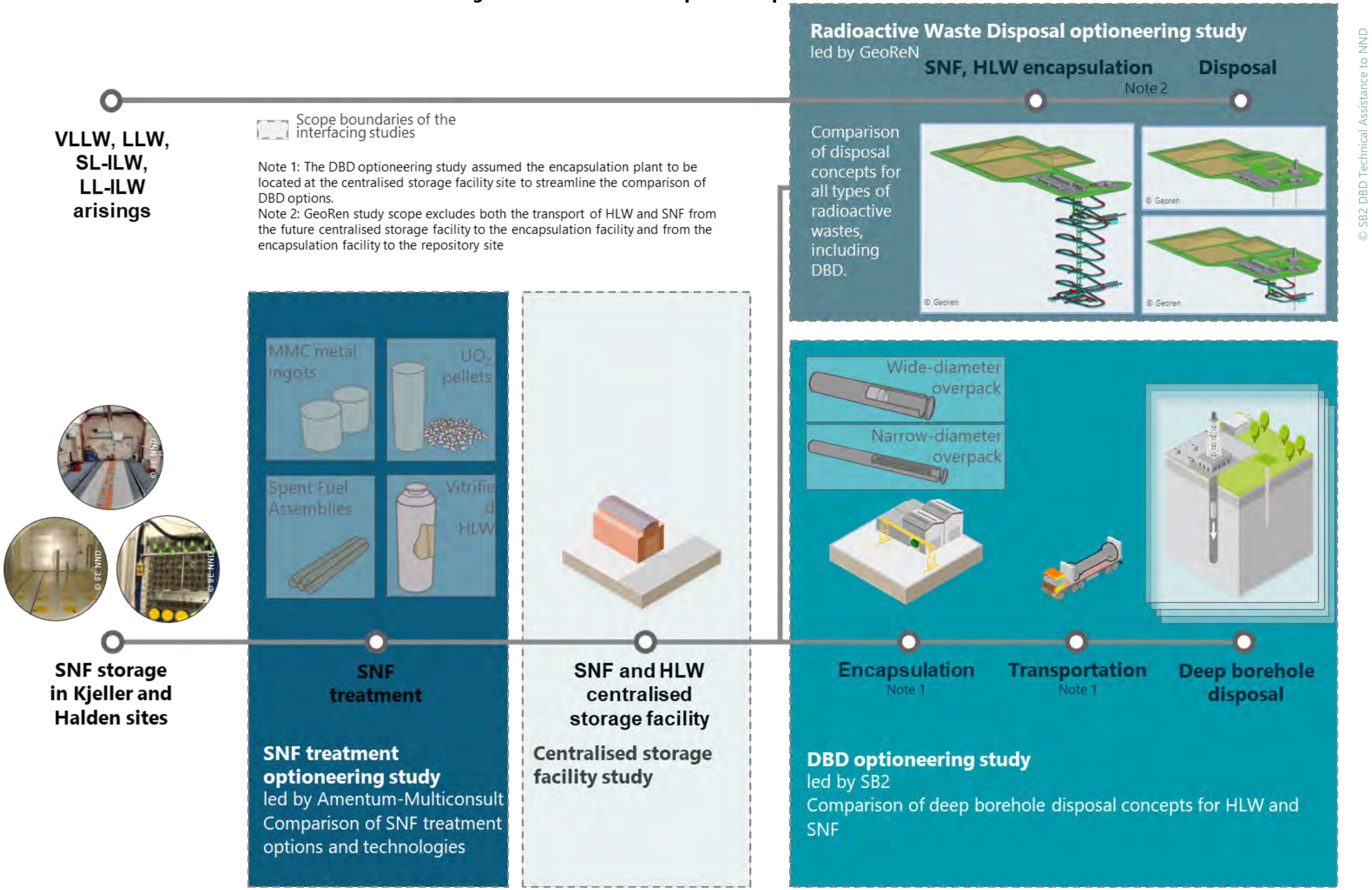
- **Amentum Multiconsult**: Supports the selection of one or more preferred options/strategies that will provide safe management of the entire SNF inventory until it can be disposed of in a repository. In consultation with NND, SB2 and GeoReN (see below) optioneering study assumed four variants of SNF treatment. SNF treatment optioneering will be completed in 2025, and the consistency of its outcomes with SB2 and GeoReN assumptions will be reviewed by NND.
- **GeoReN**: Supports the development of disposal solutions for SNF and other radioactive waste. GeoReN optioneering study included the comparison of DGR with DBD for HLW and SNF, and disposal of LL-ILW into a separate Borehole as a LL-ILW disposal option. The generic DBD concept considered by GeoReN at this optioneering stage was not underpinned by SB2 shorlisted options, consistency will be further reviewed once the SNF treatment optioneering study is completed. GeoReN scope excludes both the transport of HLW and SNF from the future centralised storage facility to the encapsulation facility and from the encapsulation facility to the repository site.
- **Subcontract 2**: Supports the development of disposal solutions for SNF or other HLW in one or more boreholes.

These optioneering studies were running in parallel and were interconnected as highlighted in Figure 2.

Several interface management measures were put in place to ensure consistency between the work conducted within the parallel option studies where feasible considering the studies planning requirements and scope. Measures included: mutual attendance at OAP meetings, periodic interface meetings, review of assumptions, a consistent approach to SNF and HLW inventory review, and mutual review of deliverables. An Assumptions, Constraints, and Exclusions (ACE) log was developed to keep track of all ACEs among all SB2 Tasks and where necessary, escalate ACE's to GeoReN, Amentum Multiconsult and NND. SB2 ACEs are listed at the beginning of the report.

In addition, in 2022 IFE started a procurement process to develop a new storage facility for SNF in Norway. The DBD optioneering study considers that all SNF and/or HLW inventory considered for DBD will be stored centrally within the new storage facility and that the storage facility performance would not impact on the disposability of the SNF and/or HLW inventory, and it was not included in the scope of the options assessment. (ACE 13). As mentioned previously, the DBD option lifecycle begins with waste being encapsulated for disposal (assumed to be at the same location as the new store).

Figure 2: Interfaces with parallel option studies



III. CURRENT SITUATION

1. SNF inventory

1.1. Overview of SNF inventory

Norway has no nuclear power programme, but has had four heavy water research reactors operated by IFE at Kjeller and Halden, all of which are now permanently shut down [8]:

- The first research reactor at Kjeller, **JEEP I** (Joint Establishment Experimental Pile), reached criticality in June 1951. It was permanently shut down in 1967 and partially decommissioned.
- The Halden boiling water reactor (**HBWR**), a 25 MW reactor, started operation in 1959. It was permanently shut down in 2018.
- The **N0RA** (Norwegian zero effect Reactor Assembly) reactor at Kjeller was started in 1961 and was permanently shut down in 1968 and partially decommissioned.
- **JEEP II**, a 2 MW heavy water pool reactor, reached criticality in December 1966 and was permanently shut down in 2019.

The JEEP I and JEEP II reactors used metallic natural uranium fuel and 3.5% enriched uranium dioxide, respectively. The fuel used in the HBWR after the first charge was typically low enriched UO_2. The enrichment was mostly in the range from 1.5 to 6 %, although metallic natural uranium fuel was used in the first charge. For experimental purposes, uranium fuel enriched to up to 20% was sometimes used, including a small amount that was enriched to 93%. Mixed oxide (MOX) fuel with enrichment up to 10% fissile plutonium has also been used to a limited extent as part of the experimental programme.

The SNF consists of fuel assemblies and individual fuel rods. Some fuel rods are whole, others have been sectioned and some fuel rods are damaged or the cladding has failed. The inventory is characterised by a large variation in fuel and cladding materials, dimensions, enrichment and burn-up [9]. The SNF inventory from these reactors amounts to approximately 16.5 t, of which roughly six tonnes are stored at Kjeller and 10.5 tonnes in Halden, including the fuel currently in the HBWR core.

Due to its use as a fuel testing reactor, the spent fuel from the HBWR comprises a wide range of types, unlike the spent fuel from the JEEP I and JEEP II reactors, with similar inventories. The HBWR fuel can be divided into three types:

- **Driver fuel**, which is the fuel used to operate the reactor and is split into 1st to 5th charges, depending on the fuel material, cladding material and enrichment.
- **Experimental fuel**, which is the fuel that was the subject of the experiments in the HBWR.
- **Booster fuel**, which is the fuel that was used to supply high fluxes of fast neutrons to experimental fuel and material assemblies.

The inventory contains different SNF types with varying properties, including chemical composition, cladding material, maximum enrichment and burn-up (Table 3). More details about the spent fuel inventory can be found in Complementary Note 1 [3].

Several assumptions were made when determining parameters to describe the characteristics of the fuel, based on the input information available, which increases the level of uncertainty in the inventory data presented (ACE 4, ACE 5). The information about the SNF produced in IFE reactors was compiled and additional data generated based on NND feedback and by making the following assumptions:

- 80% of the HBWR 5th charge, HBWR booster and experimental fuel assemblies have been disassembled and individual rods are in storage. 20% of the HBWR 5th charge, HBWR booster and experimental fuel assemblies are stored and will be disposed of intact (without disassembling).
- The total volume of UO_2 produced in the uranium oxidation process, and the number of stainless-steel canisters containing vitrified HLW from reprocessing has been estimated. The oxidation of 10 tU would produce 11.34 t of UO_2, with the following assumed characteristics (ACE 5):
  - UO_2 density: 10.3 t/m^3.
  - canister thickness: 5 mm.
  - void volume in the canister after filling: 30%.
- According to the Generic Safety Assessment for the Norwegian National Facility [10] the burnup of the spent fuel is not known with accuracy, and the following assumptions on burnup was made (ACE 15):
  - **JEEP I**: typical burnup of 200-400 MWd/tU according to [11], and a value of 300 MWd/tU was selected.
  - **HBWR 1st charge**: burnup of only 12 MWd/tU [11].
  - **JEEP II**: burnup of 15000 MWd/tU.
  - **HBWR 2nd to 5th charges**: burnup of 40000 MWd/tU.
  - **HBWR booster/experimental**: burnup of 80000 MWd/tU.

Table 3: Fuel types and characteristics (Complementary Note 1 [3] – Table A1-1)

	JEEP I in Kjeller	HBWR in Halden 1st charge	JEEP II in Kjeller	HBWR driver 2nd charge	HBWR driver 3rd charge	HBWR driver 4th charge	HBWR driver 5th charge	HBWR booster	HBWR Experimental 1 (early)	HBWR Experimental 2 (late)
Fuel	U metal	U metal	UO_2	UO_2	UO_2	UO_2	UO_2	UO_2	UO_2, MOX, ThO_2	UO_2, MOX, ThO_2
U235 enrichment (%)	0.72	0.72	3.5	≤10	≤10	≤10	≤10 (mostly 6%)	≤20	≤20 or higher	≤20 or higher
Cladding material	Al	Al	Al	Zircaloy	Zircaloy	Zircaloy	Zircaloy	Zircaloy	Various	Various
Uranium mass per rod (kg) – From tables	19	22	1	0.6-0.9	0.6-0.9	0.6-0.9	0.4-0.9	0.2-0.9	0.1-0.9	0.1-0.9
Uranium mass per rod (kg) – Calculated	17.6	23.3	1.0	1.25	1.25	1.25	0.65	0.67	0.26	0.092
Burn up (MWd/kg HM)	≤1	≤0.021	≤15	≤ 79.4	≤ 79.4	≤ 79.4	≤ 79.4	≤79.4	≤102.1	≤102.1
Number of fuel rods	170	300	1500	49	413	84	4500: 900 in FAs[1] and 3600 consolidated	1500: 300 in FAs[1] and 1200 consolidated	900: 180 in FAs[1] and 720 consolidated	1800: 360 in FAs[1] and 1440 consolidated
Fuel rod diameter (mm)	25	40	15	12.25-14.3	12.25-14.3	12.25-14.3	12.25	6.25-9.5	6.25-14.3	6.25-14.3
Fuel rod length (m)	2.4	2.8	1.5	1.8	1.8	1.8	1.1	1.1	1.7	0.6
Number of rods per FA	2	1	11	7	7	7	8, 9 or 13 (10 is adopted)	Variable (assumed to be 10)		
FA diameter (mm)	70	40	90	≤ 70	≤ 70	≤ 70	≤ 70	≤ 70	≤ 70	≤ 70
Number of FAs	85	300	136	7	59	12	90[1] (900 rods)	30[1] (300 rods)	18[1] (180 rods)	36[1] (360 rods)
FA length (m)	2.8	2.8	1.5	2.83	3.66	3.66	3.66[2]	3.66	3.66	3.66
Mass of HM (kg)	3000	7000	1500	3600	3600	3600	3600	1000	400	400

1 Assuming that 80% of the fuel assemblies have been consolidated

2 Based on information transmitted by NND [12]: HBWR 5th charge rods are 1.1 m long and the fuel assemblies are 3.7m long. It is assumed that 3.7m is the same value than for the 2nd to 4th charges and for that reason a length of 3.66 m is used for the 5th charge (ACE 5)

1.2. Spent fuel inventory data gap and uncertainties

There are still several uncertainties and gaps in the available spent fuel inventory data, including fuel condition, nuclide concentrations, activity levels, cladding mass, neutron and gamma dose rates, thermal properties (thermal conductivity), diverse physical and chemical properties and power history for a limited number of fuel rods.

Aside from fuel condition, the lack of information should not have an impact on the optioneering study, because it does not constrain the choice of which treatment methods, if any, to employ. Conversely, the fuel condition (i.e. its level of degradation) could influence the need for treatment and choice of treatment method as well as the feasibility of transportation in an unconditioned state.

2. SNF storage

2.1. Overview of current facilities

The SNF inventory is currently stored on-site at the Kjeller and Halden sites [11]. At the Kjeller site, in addition to short-term storage in the JEEP II reactor, there are two separate storage facilities for spent fuel. Halden has three facilities, two of which are in a separate structure called the Fuel Bunker Building and one that is inside the reactor hall.

Jeep I fuel

After discharge, JEEP I fuel was initially stored in aluminium baskets in a wet storage facility for up to 10 years. Following this period, the fuel was repacked into stainless steel baskets and transferred to the JEEP I dry storage facility. This facility consists of top and bottom concrete slabs, with vertical holes in between. Within these holes, stainless steel pipes are installed to hold the stainless steel baskets with the spent fuel assemblies.

Figure 3: JEEP I stavbrønn storage facility on the Kjeller site
(Source: Peter Bennett, 2024 [99], Figures 4 and 5)

Jeep II fuel

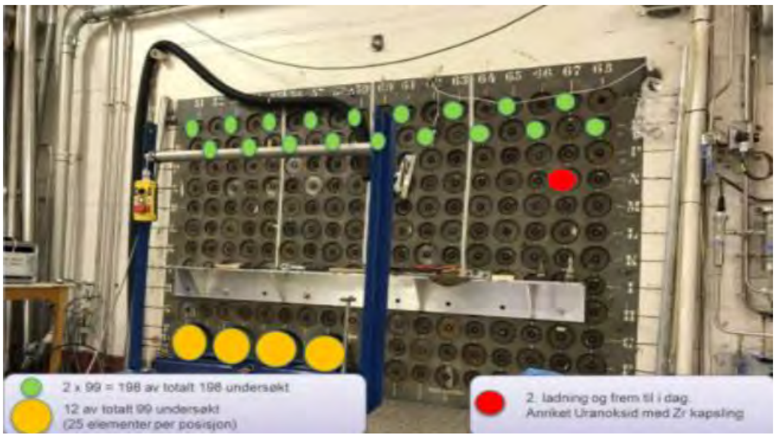
Spent fuel from JEEP II is stored in water-filled wells for 6 to 12 months. After this period, the fuel is packed into stainless steel cans and transferred to Brønnhuset dry storage facility. The JEEP II dry storage facility consists of a concrete block, which is clad externally with aluminum sheets, with vertical steel tubes used to house the stainless-steel cans. These tubes are sealed with lead plugs.

Figure 4: JEEP II Brønnhuset storage facility on the Kjeller site
(Source: Peter Bennett, 2024 [99], Figure 7)

1st charge HBWR

The 1st charge HBWR fuel was placed in wet storage, for about three years, in the Fuel Bunker Building at Halden. In 1962, the rods were dried and transferred into aluminium storage capsules. These capsules were then inserted into steel tubes, which were subsequently loaded into a dry storage facility. This facility comprises a concrete shell with horizontal holes, into which the steel tubes containing the fuel are placed. The dry storage facility also holds some Zircaloy-clad, UO_2 driver fuel from the HBWR.

Figure 5: Front elevation of dry storage facility in the Fuel Bunker Building
(Source: Peter Bennett, 2024 [99], Figure 9)



Other HBWR fuel

There are wet storage pits in the HBWR reactor hall, built with the purpose of short-term storage of discharged fuel from the reactor before transfer to the external Fuel Bunker Building at the Halden. The 2nd – 5th charges HBWR fuel, along with the HBWR Experimental fuel, are all stored in Fuel Storage Pond wet storage facility, within the Fuel Bunker Building. These facilities consist of pits lined with steel.

Figure 6: Fuel Storage Pond in Fuel Bunker Building
(Source: Peter Bennett, 2024 [99], Figure 10)

2.2. SNF storage conditions data gaps and uncertainties

There are some data gaps and uncertainties in the state of the SNF storage facilities and SNF conditions [99].

The safety assessments and safety reports for all the SNF storage facilities are currently being updated by IFE, to include recommendations to improve storage conditions. Currently, lifetime assessments are based on a combination of the limited information available, inspections and known degradation mechanisms. Updates made should not have an impact on the conclusions of the optioneering studies because they will not impact decisions on appropriate treatment options. The updates will however have an impact on the practicalities of exporting and transporting the fuel from the current facilities.

Storage of the spent fuel in the current facilities, with modifications made from the updates, must be accepted until the fuel can be moved to an international processing facility or to a new national facility, which will most likely be a centralised storage facility.

Corrosion was noted on many of the earliest JEEP I fuel rods upon inspection in 1982. HBWR first charge fuel was inspected in 2018, and while some imperfections were observed, the rods were seen to be intact. Two JEEP II assemblies are suspected of having at least one leaking rod, otherwise there are no indications of damage or failures, but these assemblies have not been inspected. The cladding and rig structures of some of the oldest fuel rods with Zircaloy cladding from the HBWR in dry storage in the Fuel Bunker Building, have undergone significant embrittlement. Oxidation of Zircaloy cladding is not considered to be an issue, due to the long cooling time, resulting in low temperatures.

The physical condition of most of the fuel rods is unknown and although there are known failures and damaged rods, further degradation in storage cannot be ruled out. Most of the rods with known failures, due to fretting corrosion, cladding corrosion or pellet-cladding mechanical interaction, are in wet storage in the fuel storage pond in Halden. Spent fuel in dry storage at IFE is stored in air, not in an inert environment. However, degradation of these fuels due to reaction with air is not thought to be significant.

Except for the final JEEP II core loading, which will be transferred to dry storage in Brønnhuset as soon as possible, no fuel with aluminum cladding is currently in wet storage. Issues related to wet storage of Al-clad fuels are therefore not further considered. Most of the Zircaloy-clad fuel is in wet storage.

The optioneering study should not be impacted by the absence of the aforementioned information, except for the fuel condition, as the information is not essential to deciding which Deep Borehole Disposal option should be employed. The choice of SNF management method may be influenced by the fuel condition. There may be restrictions on what is considered viable for direct disposal due to fuel condition. This may affect SNF management choices, as well as the practicalities of transportation, as dealing with old and partly degraded fuel could be difficult, regardless of option for treatment and disposal.

3. Risks and hazards related to the current situation

The current storage of the SNF poses some risks or hazards and a comprehensive SNF management strategy is necessary because [13]:

- Inspections in the 1980s revealed corrosion of some JEEP I SNF fuel assemblies. Later inspections also showed the ingress of moisture into the storage facility, although no further corrosion of fuel assemblies was documented. It is required to transfer the SNF to a facility that can manage challenging chemical and radiological conditions such as caused by SNF degradation. The origin of the moisture ingress is to be confirmed by IFE or NND if known (HOLD 3). While other storage facilities are also past their intended lifetime, the buildings themselves currently show no signs of degradation. Urgent retrieval of the SNF from these other facilities is therefore not required.

Figure 7: Corroded storage container and storage tube in JEEP I stavbrønn

(Source: Peter Bennett, 2024 [99], Figure 6)

- Inspections in Halden revealed that the facilities are in sufficiently good condition to be used for at least a further decade.
- A full lifecycle management strategy of the SNF is needed to address issues related to ageing storage facilities and to enable removal of all SNF from the Kjeller and Halden sites so that decommissioning may proceed.
- The storage of SNF is not a safe, secure or effective long-term solution because it requires active management, such as security, maintenance and periodic upgrades. Such active management cannot be guaranteed over the span of hundreds to thousands of years. Therefore, storage serves only as an interim measure until the SNF can be permanently disposed of in a geological disposal facility.
- A strategy must be established to develop the necessary infrastructure, capacity, competency and, if necessary, inter-governmental agreements. Currently, Norway lacks the appropriate facilities and technical capability to process SNF or to manage it in secure dedicated storage facilities going forward. Developing such infrastructure within the country would require a long lead time and will result in large costs.

Long-term storage of radioactive waste places unacceptable burdens on future generations, therefore it is necessary to develop a final disposal solution for the Norwegian spent fuel.

4. Predisposal management options for SNF

SNF predisposal management options are currently being studied by Amentum-Multiconsult as part of NND optioneering studies. The predisposal SNF management strategy and the schedule for its implementation will also affect the characteristics of the inventory of SNF and/or HLW, including the radionuclide content, chemical composition, thermal output, total waste volume, dimensions, weight and shape of the waste form for disposal.

DSA instructed IFE to start a procurement process to develop a new storage facility for SNF in Norway in 2022 [9]. NND is managing the site selection process for the new SNF storage facility. Co-location of the storage facilities for radioactive wastes and for SNF is an option being considered. The local governments in Halden and Aremark have agreed to investigate the possibility of being the host for new radioactive waste management facilities.

IFE has proposed measures to improve the storage situation in JEEP I Stavbrønn by implementation of the Studsvik project, in which the JEEP I fuel will be transported to Studsvik in Sweden for inspection and possible removal of graphite sections. The project has been designed to consider all practicable options for further treatment of the SNF. Fuel can be returned to Norway, transported to La Hague for reprocessing, or be treated at Studsvik with the small-scale oxidation process.

5. Disposal options for SNF

NND was commissioned in 2020 to produce a "choice of concept" study (KVU) on disposal solutions for Norwegian radioactive waste, including SNF/HLW. The current optioneering studies provide supporting information which will be used in the KVU. Two concepts for SNF/HLW are being explored: a mined geological disposal facility (GDF) and disposal in one or more deep boreholes (DBD). Initial consideration has been given to the disposal canister design, spent fuel management variants and issues relating to co-location with other waste disposal facilities for both disposal concepts. A broad options assessment to cover all waste types is being carried out by GeoReN, in parallel with the assessment of options for DBD by SB2.

IV. CONSTRAINTS

The legal and regulatory framework within which the disposal programme operates will provide guidance on what is required of a disposal solution and may even exclude some disposal options. The legal and regulatory requirements that apply to waste disposal in Norway are discussed in [14]. This included the compilation of a table with relevant safety and technical requirements. This table is based on the following sources:

- Norwegian regulations.
- IAEA Safety Standards and IAEA guidance.
- Standards from ICRP and OECD-NEA.

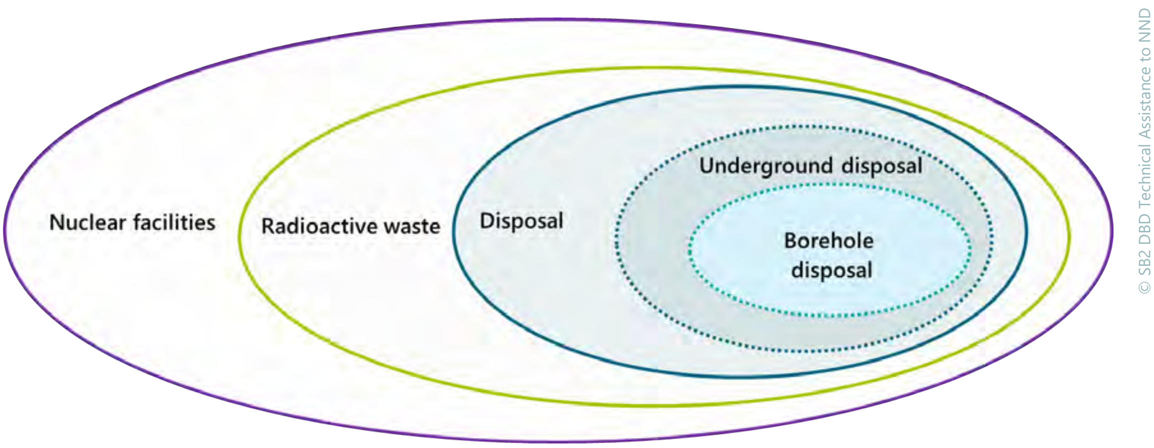
This guidance results in an extensive list of some 627 requirements that provide a good basis for the development of disposal solutions for Norwegian radioactive waste. However, not all requirements are equally relevant to the current stage of the programme, which explores the preferred disposal solutions for the different classes of radioactive waste. Some very general requirements, such as the requirement that a nuclear facility can only be built or operated after obtaining a license, have no influence on the choice of disposal solution. Other requirements, such as the need to maintain signs, fences and guards at sites during an active institutional control phase, are only relevant when implementing the disposal solution.

Therefore, the requirements have been categorised into requirements that apply to:

- Nuclear facilities.
- Radioactive waste management.
- Disposal of radioactive waste.
- Underground disposal of radioactive waste.
- Borehole disposal of radioactive waste.

The categories contain an increasingly specific list of requirements that apply to a more specific type of facility or activity. They each form a subcategory of the previous category, as illustrated in Figure 8. The requirements of these categories are grouped in different tables in the Report appendices [5]. For this study, the most relevant requirements are in the categories "underground disposal" and "borehole disposal". The requirements that are only applicable to near surface or landfill disposal have not been grouped into separate sheets because these are not relevant for this task.

Figure 8: Categorisation of requirements for increasingly specific types of facilities or activities



The compilation in [5] concluded that because disposal in a deep borehole is a form of geological disposal, principles and requirements that apply to geological disposal also apply to DBD. This means that the DBD safety concept is based on containing and isolating the waste and on principles such as passive safety, defence in depth and a graded approach to safety. In addition, there is a need to use proven and tried materials and technologies.

Uncertainties in regulatory framework and non-regulatory requirements.

Several uncertainties are associated with the regulatory process. The Norwegian legal and regulatory framework for nuclear materials is less comprehensive and mature than in other countries, particularly those with nuclear power programmes. This can result in a lack of clarity in the regulations, leaving them open to different interpretations.

There is currently no requirement regarding waste retrievability in Norway (ACE 3). However, owing to the difficulty and cost associated with introducing retrievability in a later design stage, it is advisable to consider retrievability and its possible impact on design in the optioneering work done now on deep borehole disposal.

The most recent facility for radioactive waste in Norway is the combined storage and disposal facility for LILW, KLDRA, which was commissioned in 1998. The regulatory framework has developed since then, and there are uncertainties in the level of effort (and thus resources) necessary from both the licensee and the regulator to obtain approval for new facilities. These uncertainties can at worst result in applications being refused, but even in the case of successful applications, they may significantly delay project timelines.

IAEA Waste Safety Section has reviewed in 2024 the applicability of existing IAEA safety standards to DBD. A preliminary review outcome is to recommend the issue of a specific document on DBD for HLW and LL-ILW [15]. The impact of potential future evolution of the IAEA safety standards applicable to DBD will be assessed in subsequent development stages of the DBD programme.

In addition to the legal and regulatory framework, the DBD option may be bound by requirements or preferences from stakeholders. Such preferences may concern local environmental impacts or the possibility of retrieving the waste for a certain period before closure of the DBD facility. Therefore, it is important to develop a stakeholder engagement plan to identify stakeholders concerns and expectations.

V. BACKGROUND AND STATUS OF KNOWLEDGE

The work on DBD carried out under Subcontract 2 builds on the previous research conducted both nationally and internationally. At the outset of this project, two reports were produced, summarising the findings from reviews of borehole disposal studies within Norway [16] and abroad [17]. A third report reviewing the long-term safety assessment, the definition of required host rock properties and the assessment of the Technology Readiness Level (TRL) of the processes to be conducted as part of DBD in Norway was carried out a little later [18]. These findings will inform the work conducted under Subcontract 2 to develop a roadmap for potential future work on DBD implementation in Norway. They have also supported the work in this assessment to select one or more preferred DBD options for Norway, and will underpin a future TRL assessment of the preferred DBD options.

Disposal in deep boreholes was considered internationally over 50 years ago (NAS, 1957) but was rejected in favour of mined and engineered repositories at depths of only a few hundred metres largely because, at the time, the technology for drilling large enough diameter holes to depths of a few kilometres did not exist. Advances in deep drilling technology over the past 20–30 years have led to the reconsideration of DBD. Australia, Germany, Sweden and, particularly, the United States (US) have developed DBD concepts. These have focused on SNF and/ or vitrified high-level waste, with the notable exception of Australia, where DBD concepts for long-lived intermediate-level waste (LL-ILW) have been considered. Work has focused on development of DBD concepts, safety analysis and cost estimation, with little experimental or field-based work. Other countries have undertaken periodic reviews of international developments related to DBD. The IAEA has launched in 2024 a four-year Coordinated Research Programme (CRP) to increase international knowledge and drive progress towards testing DBD for ILW and HLW [19]

A considerable amount of R&D on DBD in Norway has been undertaken recently by AINS on behalf of NND in consideration of management of radioactive waste. This work has informed the contribution of NND to the European Repository Development Organisation (ERDO) Association. This association was established in 2021 by Dekom (Denmark), NND (Norway) and COVRA (Netherlands) to allow national organisations to work more closely together on the common challenges in managing radioactive waste safely by sharing knowledge, implementing joint projects and promoting multinational waste management solutions. ERDO follows from the European Commission SAPIERR (Support Action: Pilot Initiative on European Regional Repository) projects started in 2002 and an ERDO Working Group started in 2009.

Several programmes / organisations have done planning for taking DBD forward by considering knowledge and technical gaps. The work undertaken by NND to-date on DBD was reviewed for the same purpose at the start of SB2 [1616].

There is an international consensus that DBD needs a proof-of-concept covering borehole drilling and casing, disposal canister emplacement and recovery and borehole sealing and closure. In the 2010s, Sandia National Laboratories (SNL) developed a proposal for a Deep Borehole Field Test (DBFT) involving the drilling of two 5000-m deep boreholes: first a characterisation borehole and later a full-sized borehole for testing different aspects of DBD. The DBFT was cancelled by the US Department of Energy in 2017 due to "changes in budget priorities". In the early 2020s, Australia developed plans for a 2000 m deep demonstration borehole for disposal of LL-ILW, but the current status of this project is uncertain.

Cost estimates for DBD are highly uncertain due to significant differences between DBD boreholes and practical drilling in the hydrocarbon, geothermal and mining industries, and due to the lack of any experience of actual implementation of DBD of radioactive wastes to date. Therefore, significant cost contingencies must be included in cost estimates to allow for events with a reasonable probability of occurrence that may have a cost or schedule impact. However, even taking these contingencies into account, it is noted that cost estimates in several countries have found that DBD has the potential to be cheaper for HLW/SNF compared to disposal in a mined GDF.

Other issues or knowledge gaps that have formed the backdrop to this assessment include:

- Is the waste concerned of a type and volume to be managed effectively using DBD?
- Can one or more DBD concepts be defined?
- Given the concept options and safety principles, what requirements should be placed on the overpack?
- Can an overpack that meets the design requirements and associated knowledge of a site be manufactured?
- Can a methodology for site identification be developed?
- Can a process be developed for demonstrating that groundwater at the depth of the disposal horizon is stagnant and does not communicate with flowing groundwater, even after being penetrated by characterisation and disposal boreholes?
- How can the selected site for DBD be characterised?
- Can a borehole of the appropriate depth and diameter be drilled?
- Over what operating duration can borehole stability be guaranteed?
- Can the overpacks be safely emplaced at the required depth? Can a scenario whereby a container gets stuck be dealt with, irrespective of likelihood?
- Can the boreholes be sealed to provide sufficient assurance to relax oversight of the disposals?

VI. OPTION ASSESSMENT METHODOLOGY

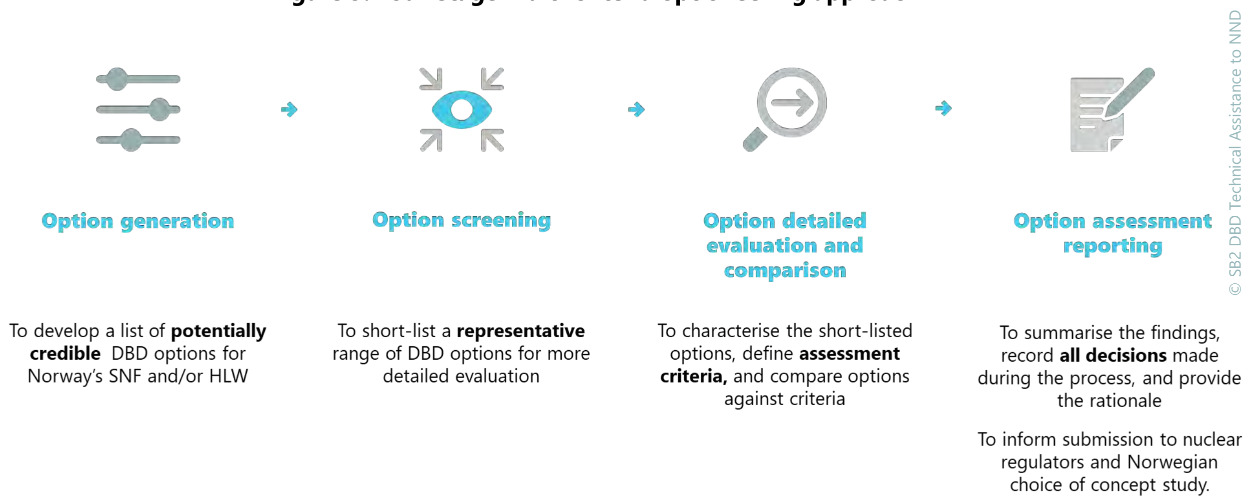
An option assessment methodology was defined to evaluate and rank potential DBD options in Norway based on their suitability for disposing of Norway's inventory of SNF or HLW [20], and further refined following the Option screening stage [21]. The methodology took account of the assessment methodologies used or proposed by Amentum-Multiconsult and GeoReN for ranking SNF pre-disposal management options and disposal options, respectively. This ensured consistency across the various assessment methodologies.

The proposed methodology for assessing DBD options consisted of the following four stages (Figure 9):

- Stage 1: Generate a longlist of options.
- Stage 2: Screen the options on the longlist.
- Stage 3: Characterise and compare the shortlisted options against defined assessment criteria.
- Stage 4: Report on the assessment outcomes.

These stages are further specified in the following sections.

Figure 9: Four-stage multi-criteria optioneering approach



The approach was implemented by an OAP. This panel consisted of experts working on task T004, supplemented with representatives from NND and IFE, Amentum-Multiconsult and GeoReN. (See Section II.2 for OAP composition).

Special attention was paid to managing several uncertainties regarding radioactive waste management in Norway that will impact the option assessment. These uncertainties related to a range of topics, from the types of waste and their waste form to regulatory requirements or stakeholder expectations. Uncertainties or gaps in the data were identified and documented in the ACE register, summarised at the beginning of this report.

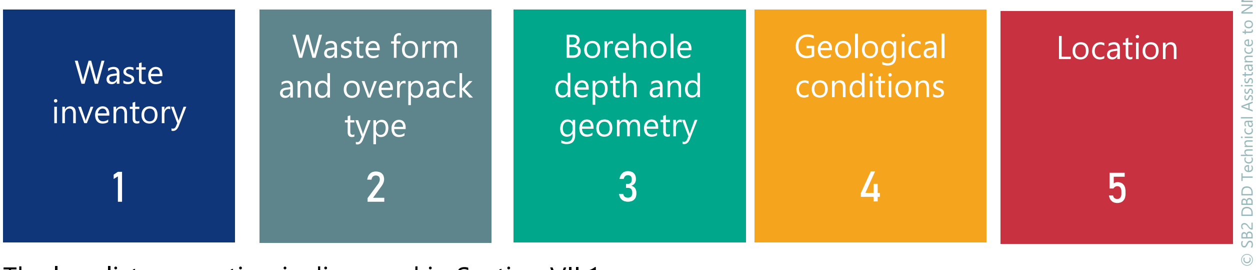
1. Generate a longlist of DBD options

A longlist of DBD options was generated and consolidated, encompassing all plausible scenarios for DBD. This included those options that, based on global practices and stakeholder input, are considered available, reliable and reasonably robust within the timeframe required for achieving a solution (ACE 19). Options that do not meet those criteria were excluded at this stage.

The longlist of DBD options was then specified based on an assessment of the following design parameters (Figure 10):

- Waste inventory and waste form.
- Overpack type.
- Borehole depth and geometry.
- Geological conditions.
- Location.

Figure 10: Factors to be combined to define a DBD option



The longlist generation is discussed in Section VII.1.

2. Screen the options on the longlist

Long-listed options were then assessed to select a short list of options that will be characterised and evaluated in greater detail. The OAP assessed the following design parameters:

- Borehole inclination.
- Borehole depth and diameter.
- Overpack lifetime.

These parameters were screened based on the following criteria:

- **Further evaluation of the technical feasibility of the DBD option**. There are currently no real-life examples of the disposal of radioactive waste in deep boreholes. The feasibility of the concept must therefore be inferred from the use of the proposed materials and technologies in other industries or from expert judgement. Therefore, an assessment was made as to whether the DBD option is likely to be feasible with current technology based on expert judgement and the use of this technology in other industries.
- **Screen out sub-optimal DBD options**. Consideration was given to whether options could have readily identifiable advantages or could help to avoid specific disadvantages. This assessment was used to screen out clearly sub-optimal options from further consideration.

The longlist screening is discussed in Section VII.2.

3. Characterise and compare the shortlisted options against defined assessment criteria

A detailed characterisation of the shortlisted options was prepared to enable a thorough appraisal and comparison, as presented in Section VIII. Following this, an MCA was conducted to rank the shortlisted options. It takes account of the methodologies used by Amentum-Multiconsult and GeoReN for ranking SNF pre-disposal management and disposal options, respectively. Any differences with the other two MCA approaches are identified in [2121] and the rationale for differing from these approaches is given.

The MCA process consisted of the following steps:

- Define the assessment criteria.
- Assign weight factors to the criteria.
- Score the options.
- Perform a sensitivity analysis to test the robustness of the MCA outcomes.

It is important to note that no disposal site has been selected at this stage. The location and characteristics of the site can influence the assessments conducted in the MCA. Any assumptions or uncertainties about the location and characteristics of the site that could affect the scores were identified.

3.1. Assessment criteria

The following assessment criteria used by GeoReN were also used for this MCA:

- Safety/Health.
- Socio-Economic Impacts.
- Site Characteristics.
- Technical Implementation.
- Flexibility.
- Security and safeguards.
- Environment/Sustainability.
- Lifetime Cost.

The 'Licensing' criterion used by GeoReN was not retained. This criterion reflects the effort required to obtain regulatory approval for the disposal concept. Evaluation of such a criterion depends on the presence of similar, real-life disposal projects, the maturity of the disposal concept and any differences in licensing requirements. There are no existing examples of licensed DBD projects to compare against and the maturity of the DBD concept is assessed under the 'Technical Implementation' criterion. Moreover, at the present time, the licensing requirements for all DBD options are the same. It was therefore concluded that the 'Licensing' criterion does not differentiate between the options.

Compared with the MCA approach proposed by Amentum-Multiconsult, the following criteria were added:

- Site characteristics.
- Technical implementation.
- Flexibility.

Proposed Tier 2 criteria are further defined in the paragraph below and summarised in Table 4.

Table 4: Proposed sub-criteria for the MCA on DBD options

Main criteria	Sub-criteria
Safety / Health	• Post-closure safety • Conventional safety of workers • Conventional safety of the public • Radiological safety of workers and of the public
Socio-Economic Impacts	• Impact on the local community and economy
Site Characteristics	• Feasibility of finding an appropriate site • Complexity of the subsequent site characterisation work
Technical Implementation	• Maturity of borehole technology (borehole drilling, casing, waste emplacement, sealing) • Maturity of waste encapsulation technology
Flexibility	• Adaptability to respond to changes in programme or regulatory changes
Security and safeguards	• Operational security and safeguards • Post-closure security and safeguards
Environment/Sustainability	• Material requirements • Energy requirements • Secondary waste • Carbon footprint
Lifetime Cost	• Base cost and contingency cost • Cost risk

Compared with the MCA approach proposed by GeoReN and Amentum-Multiconsult, the following criteria were not retained:

- Risk and hazard reduction.
- Enabling the mission.
- Other: ease of implementation & collaborations.

It is believed that some of these criteria are covered by other assessment criteria. For example, 'Risk and hazard reduction' is addressed under 'Safety/Health' and 'Security,' while aspects of 'Enabling the mission' and 'Other: Ease of Implementation & Collaborations' are reflected in 'Technical Implementation' and 'Flexibility.' Although 'Collaborations' is not explicitly considered, it is thought that there is no significant difference among the DBD options regarding this criterion.

Safety/Health

Safety refers to the protection of people against risks caused by the DBD facility. It encompasses both radiological and conventional risks during the operational phase, as well as long-term radiological risks after closure of the borehole. These latter risks persist as long as the radioactive waste remains hazardous, i.e., hundreds of thousands of years. The DBD options were evaluated against this criterion by considering the protection of people under both expected evolution and alternative scenarios, including fault conditions and accident scenarios.

This criterion can be further detailed into the following sub-criteria:

- Post-closure safety.
- Conventional safety of workers.
- Conventional safety of the public.
- Radiological safety of workers and the public

Socio-Economic Impacts

The socio-economic impact of the DBD options encompasses the impact on the local community and economy. This includes aspects such as job creation, economic development, local infrastructure and services, local benefits payments and potential changes in property values.

Site Characteristics

The 'Site Characteristics' criterion addresses two sub-criteria:

- The challenge of finding a site that has the required hydrogeological properties at the disposal depth.
- The difficulty/complexity to characterise a potential DBD site at the required depth interval.

This criterion thus evaluates both the feasibility of finding an appropriate site and the complexity of the subsequent site characterisation work.

Technical Implementation

The 'Technical Implementation' criterion refers to the difficulty associated with implementing the DBD option. This includes the following sub-criteria:

- Maturity of borehole technology (borehole drilling, casing, waste emplacement, sealing).
- Maturity of waste encapsulation technology.

Flexibility

The 'Flexibility' criterion addresses how well the DBD option can handle changes, for example in the predisposal management or the inventory of the radioactive waste. Flexibility can be considered via:

- Complexity: the sequence of process steps needed to implement each option and vulnerability to faults/risks.
- Adaptability: the ability of the DBD system to respond to changes in waste volumes or characteristics (e.g., due to changes in treatment), operational or regulatory changes (e.g., reversal of the DBD process) or strategic changes (e.g., possible decisions on co-location).

The aspect of complexity is addressed within the operational safety element (i.e., the number of process steps) and, as such, does not require further consideration under flexibility.

Security and safeguards

Security refers to the prevention, detection and response to theft, sabotage, unauthorised access, illegal transfer or other malicious acts involving the radioactive waste. Safeguards refers to the measures to ensure that the IAEA can supervise or prevent fissile materials in the SNF or HLW being diverted for military purposes. The criteria 'Security' and 'Safeguards' are considered together because both address the protection of radioactive waste from unauthorised access or use.

It is considered at two different stages:

- Operational security and safeguards.
- Post-closure security and safeguards.

Environment/Sustainability

The criterion 'Environment/Sustainability' addresses the potential environmental impact and long-term sustainability of the full life cycle of the DBD option. It considers the following sub-criteria:

- Material requirements: the impact of the materials necessary to implement the DBD option.
- Energy requirements: the amount of energy necessary to implement the DBD option.
- Secondary waste: the amount and type of additional waste generated during the implementation of the DBD option.
- Carbon footprint: the total emissions of greenhouse gases during the implementation of the DBD option.

Lifetime Cost

Lifetime cost evaluates the financial costs associated with a DBD option. This includes the sub-criteria:

- The base cost: estimate of the cost to implement the option, excluding any provisions for contingencies or risk.
- Contingency cost: estimate of the costs due to uncertainties related to the implementation of the option (e.g., uncertainties related to the level of maturity of the project, or the technologies to be used when implementing the option in Norway).
- Because contingency varies in the same way as base cost, the OAP decided to combine the sub-criteria for base cost and contingency cost into a single score based on the total of both cost elements.
- Cost risk and opportunity: the potential for unexpected expenses or budget overruns, resulting from unforeseen events, or cost savings from optimisation of activities.

3.2. Weighting factors

Table 5 presents the baseline weighting factors assigned to the different criteria. The weighting factors used by GeoReN to assess disposal concepts for all radioactive waste were used as the baseline. As explained above, the ‘Licensing’ criterion was not retained. This criterion was assigned a weight of 15% in the GeoReN approach. To maintain a total of 100%, this 15% weighting was redistributed equally among the retained criteria ‘Socio-Economic Impacts’, ‘Environment/Sustainability’ and ‘Cost’. This means that the weight of each of these criteria was increased by 5%.

Table 5: Weight criteria for the MCA on DBD options

Assessment criterion		Baseline weighting factor
	Safety/Health	25%
	Socio-Economic Impacts	10%
	Site Characteristics	5%
	Technical Implementation	20%
	Flexibility	5%
	Security and safeguards	5%
	Environment/Sustainability	10%
	Lifetime Cost	20%

Assigning weights to different criteria is inherently subjective. This subjectivity arises because different stakeholders have different values and priorities. For instance, local communities near the disposal site are likely to prioritise public safety, environmental protection and any local socio-economic impacts. They will naturally assign higher weights to these criteria. On the other hand, stakeholders providing the funding for the disposal project may place a higher weight on the lifetime cost. These differing priorities can result in varying weight allocations, which in turn influence the outcomes of the MCA.

Therefore, a sensitivity analysis has been conducted as part of the MCA. This analysis examines how changes in the assigned weights affect the MCA outcomes and helps to demonstrate the robustness of the MCA results, and their sensitivity to alternative weightings.

One of the final outcomes of the MCA is a spreadsheet that enables NND to adjust the weights and observe the impact on the MCA results. This way, if stakeholders in the future express different priorities, NND can test which DBD option best aligns with these stakeholder preferences.

3.3. Scoring method

The scoring was done by the OAP during a workshop, using briefing material sent out to the participants prior to the workshop.

The OAP used its collective expertise and experience to provide qualitative assessments of the advantages and disadvantages of each option, scoring them against the agreed criteria. For most criteria, the differentiators between options were better recognised at sub-criteria level (for instance long-term safety and operational safety are considered separately within the 'Safety' criterion). Conducting the assessments on a collaborative basis with a suitable range of expertise reduced the risk of bias. Although the OAP evaluation often primarily relied on expert judgment, it was evidence-based as much as possible, also relying on sub-criterion-specific data collated in advance of the workshop.

The relative ranking of options against each sub-criterion was discussed by the OAP, using quantitative data where possible, but also using reasoned argument and expert judgement where no or limited data was available. Based on this discussion, the options were placed in relative order of performance. The outcome sometimes placed one option ahead of the others, or sometimes placed several options as having indistinguishable performance against a particular sub-criterion. When the best and worst performing options were identified, the reasons for the difference in performance against each sub-criterion were identified and discussed. The importance of these differences of performance allowed a scoring scale to be established.

For each sub-criterion, the best performing option was given a score of "+5" and scores were assigned to the other options based on how important these differences were judged to be. A relatively small difference led to a score of "+4" being assigned to other options, whereas more significant differences lead to lower scores.

The scoring approach was similar to the approach proposed by GeoReN. However, the scoring scale ranged from "1" (worst-performing option) to "5" (best-performing option) instead of ranging from "-2" to "+2" in the GeoReN approach[2]. This difference was to avoid any implication that a score of 0 represents a baseline score to which other options are compared. The MCA approach used in the present study does not consider a baseline option, and the best-performing option was, by definition, given a score of "5".

Scores were given for all sub-criteria. The ranking of options against the sub-criteria was compared and combined into an overall ranking at the criteria level. In GeoReN's MCA, the rating for the main criterion was not necessarily the average of the sub-criteria scores.

An experienced facilitator led the workshop, presenting the key qualitative arguments for each criterion across all options. A workshop secretary supported the process by ensuring a comprehensive record of the discussion, which included the scores assigned to each option against each sub-criterion and the rationale behind these scores.

The outcome of the MCA was a ranking of the shortlisted DBD options for Norway. The ranking was backed by expert judgment, considering safety, environmental and socio-economic impacts, as well as the feasibility of each option, including factors like technology readiness.

3.4. Sensitivity analysis

Some discrete illustrative weight sets that might be proposed by different stakeholders were developed:

- Weights reflecting potential priorities of local communities, with a stronger emphasis on safety, socio-economic impacts and environment/sustainability.
- Weights reflecting potential priorities of waste producers, with a stronger emphasis on flexibility and lifetime cost.

[2] The following rating scale was used by GeoReN:

- −2: large disadvantages compared to other options
- −1: disadvantages compared to other options
- 0: neither significant advantages nor disadvantages
- +1: advantages compared to other options
- +2: large advantages compared to other options

However, since August 2024, the scoring scale has been adapted as follows to evaluate combined disposal options. The best performing option is given a score of "+2" and scores are assigned to the other options based on how important these differences are judged to be between "-2" and "+2". There is no requirement to give a "-2" to the worst option.

- Weights reflecting potential priorities of the regulatory authorities and the public at large, with a stronger emphasis on technical implementation (i.e., demonstrating the feasibility of the concept).

These illustrative weight sets assumed in the Sensitivity analysis were used to start discussion of the impact of weighting, they may be revisited following further engagement with stakeholders (ACE 3). Complementary Note 12 [3] provides a MCA spreadsheet in editable format which allows NND to adjust the weights, allowing exploration of multiple and potentially extreme weight sets, and to observe the impact on the overall MCA numerical results. This tool allows NND to evaluate which DBD option(s) best align with potential stakeholder preferences that may emerge, and which options are most robust to alternative stakeholder viewpoints.

Any assumptions, constraints and exclusions identified during the characterisation, assessment or comparison of the options were recorded in an ACE register. This register, summarised at the beginning of the report, together with the MCA spreadsheet included in Complementary Note 12 [3] can serve as input for further sensitivity analyses, allowing exploration of possible variations or alternative scenarios to assess their impact on the MCA outcomes. Note however that such numerical analysis can never replace more qualitative evaluation of option strengths and weaknesses, which should be relatively immune to stakeholder preferences.

4. Report on the assessment outcomes

Finally, the MCA process and the conclusions regarding preferred option(s) were clearly documented and summarised in this report, including the main arguments used to favour one option over another against individual criteria. The report integrates the interim deliverables produced at each stage and records all decisions made during the process and provides the rationale for these decisions.

VII. OPTIONS FOR DEEP BOREHOLE DISPOSAL IN NORWAY

As explained in the previous section VI, a longlist of DBD options was developed including those options that are available, reliable and reasonably robust within the required timeframe. From this longlist, a shortlist of DBD options was then derived for further characterisation. The details of the longlist and the shortlist are provided in the following Sections VII.1 and VII.2.

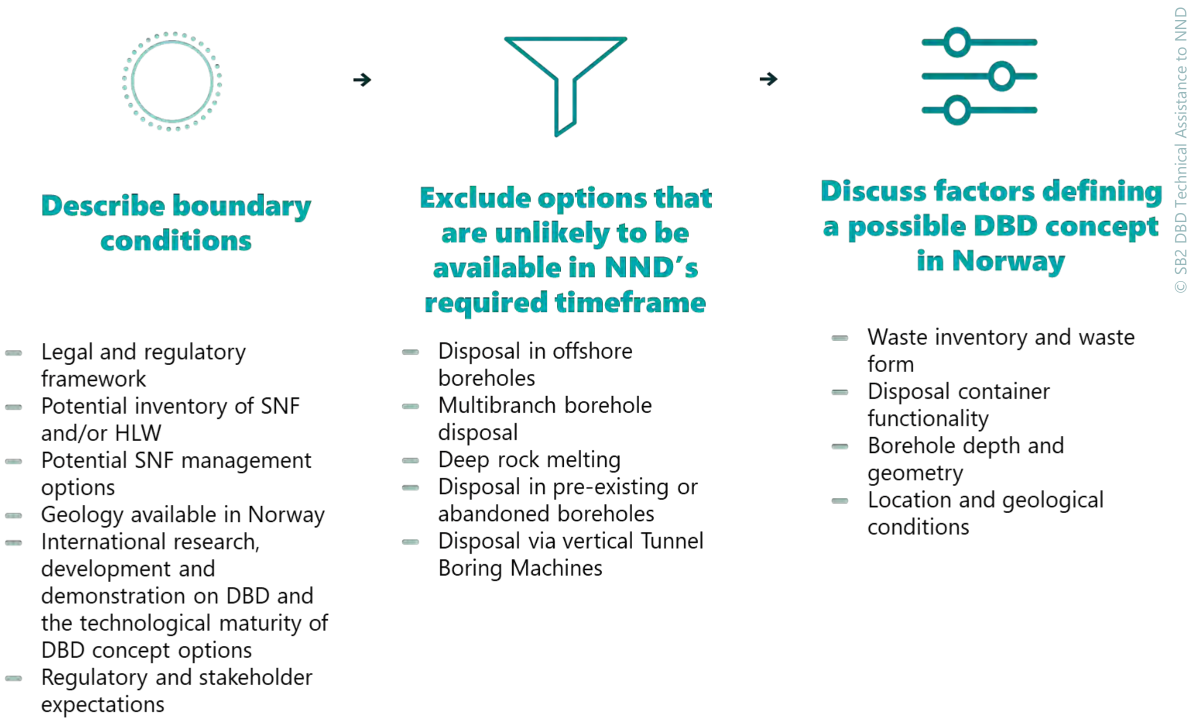
This shortlist has been further adapted in light of new information from other frameworks, which emerged after the shortlist was generated. The update to the shortlist is explained in Section VII.3. Finally, Section VII.4 outlines the assumptions, constraints and exclusions that were considered during the development of the DBD options lists.

1. Longlist of DBD options

The generation of a longlist of DBD options involved the following steps (Figure 11):

- The boundary conditions that apply to the DBD options were identified and described. These conditions set the requirements and constraints for the potential DBD options.
- Those DBD options that are unlikely to be available within NND's required timeframe were excluded. This avoids that options are considered that may be theoretically viable, but that are not practically achievable within that timeframe.
- The design factors that define a possible DBD project in Norway were discussed and a range of options was specified.

Figure 11: Process to generate the longlist of DBD options



The generation of the longlist of DBD options is discussed in detail in [22].

1.1. Boundary conditions

The development of a DBD concept for Norway's SNF and/or HLW is framed by:

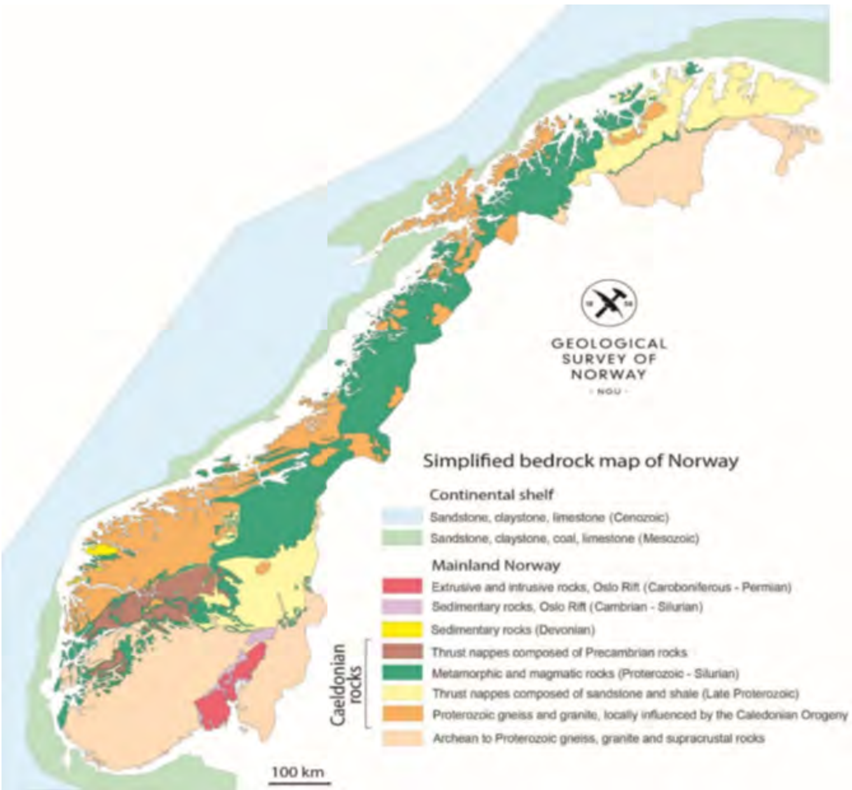
- The legal and regulatory framework.
- Regulatory and stakeholder expectations.
- The potential inventory of SNF and/or HLW.
- The potential SNF management options.
- The geology of Norway.
- The international research, development and demonstration on DBD and the technological maturity of particular DBD concept options.

The legal and regulatory requirements that apply to waste disposal in Norway are summarised in Section IV. A disposal option can only be successfully implemented if it has the support of stakeholders, including local communities. This highlights the need for stakeholder engagement and understanding the expectations of different stakeholders. Section II.1 provides a mapping of the main stakeholders and their responsibilities in the optioneering study. Further details about the potential waste inventory and the management options are given in Section III.

A description of the geology of Norway in the context of geological disposal and DBD can be found in [23] and [24]. Three main geological zones can be identified (Figure 12):

- The Precambrian basement (Archean to Proterozoic gneiss, granite and supracrustal rocks).
- The Oslo rift zone.
- The Caledonides.

Figure 12: Simplified bedrock map of Norway [24]



The international research, development and demonstration on DBD and the technological maturity of particular DBD concept options are discussed in the following section VII.1.2. Those options that were not considered to be sufficiently mature were excluded.

1.2. Excluded options

For more than 40 years, many organisations and institutions worldwide have been conducting research, development and demonstration (RD&D) into the geological disposal of radioactive waste. Today, mature geological disposal concepts exist and there is confidence that they can provide a safe and feasible long-term management solution for radioactive waste. This confidence is based on the extensive amount of RD&D, which provides the scientific and technical foundation for the design and safety demonstration of a range of geological disposal concepts.

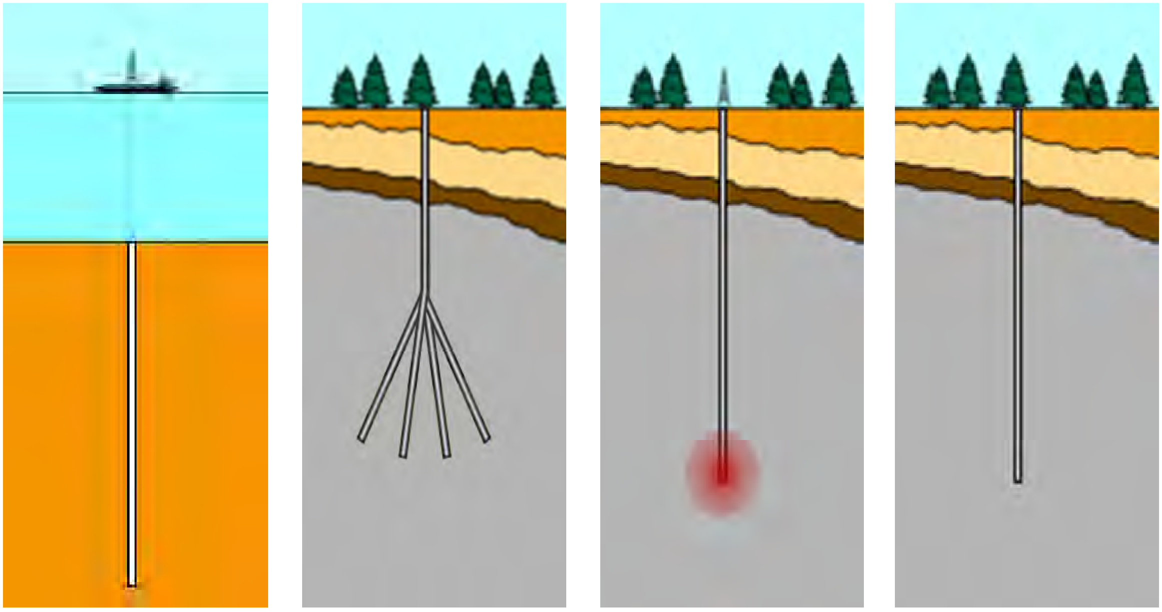
Most RD&D in the area of geological disposal concerns disposal in a mined underground repository. There is less experience and expertise available with regard to disposal in deep boreholes. Nevertheless, several countries have been conducting RD&D into DBD for decades. A review of the findings of deep borehole disposal studies outside Norway was conducted as part of Task C002 [17].

Some DBD options have been proposed, but have not been extensively studied (Figure 13):

- **Disposal in offshore boreholes**. An offshore borehole is drilled from a platform above the seabed within Norwegian territorial waters. Offshore disposal would increase complexity, may pose legal challenges and has not been studied to date.
- **Multibranch borehole disposal** [25]. Multibranch disposal could lower surface area and disposal costs, but it also increases complexity and the risk of canisters getting stuck. Due to the small amount of SNF in Norway, the added complexity and risks do not justify the potential cost savings.
- **Deep rock melting** [26,27]. The deep rock melting concept would involve disposing of wastes in sufficient concentrations to partially or completely melt the surrounding host rock. However, the safety and feasibility of these concepts have never been properly investigated and the low burnup and long cooling time of the majority of the SNF would in any case preclude this option unless the SNF was reprocessed.
- **Disposal in pre-existing or abandoned boreholes**. Using pre-existing or abandoned boreholes could lower construction costs, but the presence of residual resources and potential damage to the host rock may compromise their suitability for radioactive waste disposal. These challenges make it unlikely that cost savings would outweigh the risks.
- **Vertical Tunnel Boring Machine.** Drilling of very wider diameter openings to depth using vertical shaft sinking machines or other technology, as used for example in the construction of shafts to order 1 km depth in Germany. However, it is not clear if such technology could be deployed to the depths considered necessary for deep borehole disposal, so the TRL for that application must be regarded as low.

The TRL of these options is not comparable to the TRL level of DBD in a purpose-built vertical or sub-horizontal borehole. This conflicts with the requirement to use proven and tried materials and technologies. They were therefore not considered further in this study.

Figure 13: Less conventional or less studied DBD concepts: (a) disposal in an offshore borehole, (b) multibranch borehole disposal, (c) deep rock melting and (d) disposal in a pre-existing or abandoned borehole



(a) (b) (c) (d)

1.3. Factors defining the longlist

A longlist of DBD options was generated based on a combination of the following defining factors [22]:

- Waste inventory and waste form.
- Overpack type.
- Borehole depth and geometry.
- Geological conditions.
- Location.

Waste inventory and waste form

As part of a parallel task outside the scope of this study, Amentum-Multiconsult is conducting an analysis to identify preferred SNF management options. The absence of a defined management route for the SNF introduces a significant uncertainty in the DBD optioneering. The following three scenarios were selected as representative for the purposes of further consideration in this study, as they are widely applied and based on proven and tested technologies:

- Direct disposal of the SNF.
- PUREX reprocessing of most fuel assemblies resulting in the return of 8 CSD-V canisters with vitrified HLW and direct disposal of remaining un-reprocessed fuel assemblies.
- Dry oxidation of the metallic fuel, decladding of all UO_2 fuel with aluminium cladding and direct disposal of remaining non-oxidised fuel.

All three options include any SNF that has been processed into metal alloy ingots through MMC.

The SNF management strategy and its implementation schedule will impact the characteristics of the SNF and/or HLW inventory, such as radionuclide content, chemical composition, thermal output, total waste volume and the dimensions, weight and shape of the waste form. This will in turn influence the required bottom borehole diameter and length of the disposal section.

Overpack

Two main options for overpack longevity were considered:

- Long-lived overpacks that remain intact beyond the thermal phase.
- Very long-lived overpacks that remain intact for long enough for the radiotoxicity of the waste inventory to reduce to levels comparable to that of the uranium ore used to produce the fuel.

At this stage the diameter of the MMC ingots was not well defined and two different sizes were considered:

- A narrow-diameter overpack (outer diameter around 27-32 cm) for waste from direct disposal, dry oxidation and narrow-diameter MMC ingots.
- A wider-diameter overpack (outer diameter around 52-60 cm) for waste from PUREX reprocessing and wider-diameter MMC ingots.

Indicative disposal lengths for the three SNF management options were derived at the option longlist generation stage:

- Direct disposal: 2000 m.
- PUREX reprocessing: 100 m.
- Dry oxidation: 1000 m.

This indicates that a single borehole could potentially accommodate all Norwegian SNF. Even if the top of the waste emplacement zone is deeper than 1500 m, the required borehole depth remains within a feasible range.

Borehole depth and geometry

There are three basic options for borehole inclination: vertical, inclined and sub-horizontal. An inclined borehole would increase the length of the disposal section for a given disposal depth. However, given the limited length required for the disposal of the Norwegian SNF/HLW inventory, an inclined borehole is unnecessary and was therefore not considered further.

The inner diameter of the borehole at the disposal depth (i.e., the inner diameter of the smallest casing) is determined by the outer diameter of the overpack and the required annular clearance between the overpack and the casing. This clearance must be sufficient to account for any irregularities or distortions in the casing (such as ovality from downhole pressures and any irregularities in the overpack itself) to prevent the overpack from becoming stuck in the borehole.

A 4 cm clearance was assumed resulting in an inner casing diameter that is 8 cm larger than the outer diameter of the largest overpack. (ACE 7)

The estimated inner casing diameters for the three selected SNF management options were:

- Direct disposal: inner casing indicative diameter 35-40 cm.
- PUREX reprocessing: inner casing indicative diameter 60-65 cm.
- Dry oxidation: inner casing indicative diameter 35-40 cm (due to the direct disposal of some SNF assemblies).

The borehole diameter may need to be approximately 10 cm larger than these indicative diameters to accommodate the thickness of the casing and the annular space around it. For sub-horizontal disposal, a slightly larger diameter would be required to allow the overpack to pass through the curved part of the borehole.

These diameters are indicative and these boreholes are hereafter referred to as “narrow-diameter” (610 mm) boreholes and “wide-diameter” (990 mm) boreholes. The exact diameter will be determined by the dimensions of the overpacks, site characteristics and borehole design parameters (e.g., depth and casing thickness).

The minimum depth for the top of the disposal section will be influenced by the site characteristics at the selected location. DBD targets a zone with very old, stagnant and saline groundwater conditions without any meteoric water isotopic (O^{18}/O^{16}, D/H) component. The assumed minimum depth for DBD was 1500 m, based on the expectation that such conditions are found at a depth of at least 1000 m, with an additional 500 m added to account for uplift, erosion and provide a safety margin (ACE 18).

DBD at greater depths may also be considered. This could be the case if a site at 1000 m does not meet the required characteristics, but offers other advantages, such as proximity to other waste management facilities or community support. Although exploring various SNF and siting strategies is beyond the scope of this study, the possibility of DBD at depths significantly greater than 1500 m was assumed. A depth of 3000 m was used as an indicative figure (ACE 18).

Geological conditions

For the purposes of long-list option generation, it was assumed that host rock properties align with the geoscientific target properties defined by Hagros et al. [24], which are based on crystalline rock at depth (ACE 2). One target property is the topography of the site, which should ideally be relatively flat. This is because flat topographies lack hydrostatic gradients that could drive groundwater flow, are more likely to contain old brines, and therefore exhibit extremely slow water movements at depths below 1000 m. This observation was also made by SNL [28]. In Norway such topographies are predominantly found in the southeastern part of the country.

Location

Locations can be identified considering either (1) community-led (volunteerism) or (2) siting criteria-led processes. A criteria-led process would consider a range of topics, such as geological setting, safety, cost, proximity to waste storage, as well as community interest.

In terms of location, the following options were considered (ACE 18):

- A location for DBD in crystalline rock that meets predefined siting criteria, including suitability for DBD at a depth of 1000 m. This could be a site co-located with other disposal facilities as part of the Norwegian National Disposal Facility, or an independently selected site. To account for potential erosion, a 500 m margin is added, targeting a disposal zone depth of 1500 m.

- A location for DBD in crystalline rock where DBD is only feasible at depths significantly greater than 1000 m (with 3000 m used as an indicative depth) and/or where a greater disposal depth is desired, for example to increase stakeholder acceptance (3000 m is used here as an indicative figure). This could also be a site co-located with other disposal facilities as part of the Norwegian National Disposal Facility or an independently selected site.

In both cases, a suitable site would also require geological conditions and characteristics of formations overlying the disposal zone to be suitable for construction of a borehole to the required depth and for sealing after completion of disposal operations.

1.4. Resulting longlist

Based on the factors discussed above, a longlist of 24 options was developed [22] (Table 6). All options are for disposal in crystalline rocks. There is confidence that all of these options could provide a safe and secure disposal solution that could be implemented in Norway within the required timeframe (i.e., by 2050) and that these options could meet regulatory, safeguards and stakeholder requirements.

Table 6: Longlist of DBD options in Norway

(NOTE 1)

	Location	**Depth to top of disposal zone** [m]	**Borehole inclination**	**Disposal container**	**SNF management option** (NOTE 2)	**Borehole diameter**	**Length of disposal section** [m]
1	DBD at a location with suitable site characteristics at a depth of 1000 m	1500 (NOTE 3)	vertical	long-lived	direct disposal	narrow	2000
2					PUREX reprocessing	wide	100
3					dry oxidation	narrow	1000
4				very long-lived	direct disposal	narrow	2000
5					PUREX reprocessing	wide	100
6					dry oxidation	narrow	1000
7			sub-horizontal	long-lived	direct disposal	narrow	2000
8					PUREX reprocessing	wide	100
9					dry oxidation	narrow	1000
10				very long-lived	direct disposal	narrow	2000
11					PUREX reprocessing	wide	100
12					dry oxidation	narrow	1000
13		3000	vertical	long-lived	direct disposal	narrow	2000
14					PUREX reprocessing	wide	100
15					dry oxidation	narrow	1000
16				very long-lived	direct disposal	narrow	2000
17					PUREX reprocessing	wide	100
18					dry oxidation	narrow	1000
19			sub-horizontal	long-lived	direct disposal	narrow	2000
20					PUREX reprocessing	wide	100
21					dry oxidation	narrow	1000

	Location	Depth to top of disposal zone [m]	Borehole inclination	Disposal container	SNF management option (NOTE 2)	Borehole diameter	Length of disposal section [m]
22	DBD at a location where the site characteristics at a depth of 1000 m are not suitable and/or a greater disposal depth is desired to increase stakeholder acceptance			very long-lived	direct disposal	narrow	2000
23					PUREX reprocessing	wide	100
24					dry oxidation	narrow	1000

Note 1: All numerical values are indicative.
Note 2: All options include Mobile Melt Consolidated (MMC) ingots.
Note 3: An additional 500 m is added to the minimum depth of 1000 m to account for uplift and erosion during the assessment timeframe and to provide a safety margin.

2. Shortlist of DBD options

The long-listed options were then assessed based on the following criteria (see Section VI.2) [7]:

- Further evaluation of the technical feasibility of the DBD option.
- Screening out of sub-optimal DBD options.

The following design parameters were screened:

- Borehole inclination.
- Borehole depth and diameter.
- Overpack lifetime.

Borehole inclination

The construction of sub-horizontal boreholes in crystalline rock was considered to be impractical for the diameters required for DBD. Also, waste emplacement and possibly borehole backfilling and sealing are more complicated in sub-horizontal boreholes than in vertical ones. Disposal in sub-horizontal boreholes offers no readily identifiable advantages compared to disposal in vertical boreholes that would outweigh the uncertainties and complexity regarding the implementation of disposal in such boreholes. Therefore, the options involving disposal in a sub-horizontal borehole were not retained on the short list.

Borehole depth and diameter

Narrow-diameter (610 mm) vertical boreholes in crystalline rock could be drilled to a depth of 5000 m with current drilling technology. Wide-diameter (990 mm) boreholes have to date not been drilled in crystalline rock to the required maximum depth considered in the deeper options (3100 m). However, it was considered that such wider and deeper boreholes are feasible and could be drilled with sufficient investment in further R&D. The higher uncertainty about the technical feasibility of wider boreholes and possible differences in terms of safety, siting flexibility, cost, security, safeguards, criticality safety and stakeholder acceptance were not such as to rule out the wider and deeper vertical DBD option at this stage. All the narrow and wide vertical DBD options were therefore retained for further characterisation and evaluation.

Overpack lifetime

It is highly uncertain whether a very long-lived (100,000 years lifetime) overpack can be designed for DBD due to the expected high salinity in the disposal horizon and the limited space available to include a buffer material to protect the overpack. It also seems very difficult to demonstrate that the overpack would provide containment for the intended period. Moreover, given the level of isolation and containment provided by the host rock as the depths of interest, the added safety value of using a very long-lived overpack may be marginal. Therefore, the options using very long-lived overpacks were discarded.

Resulting shortlist

This resulted in the shortlist of DBD options presented in Table 7 and Figure 14. All options consider vertical DBD in crystalline rock using a long-lived overpack that would ensure waste containment at least during the thermal phase (1,000 years).

Table 7: Short list of DBD options (all with a vertical borehole)

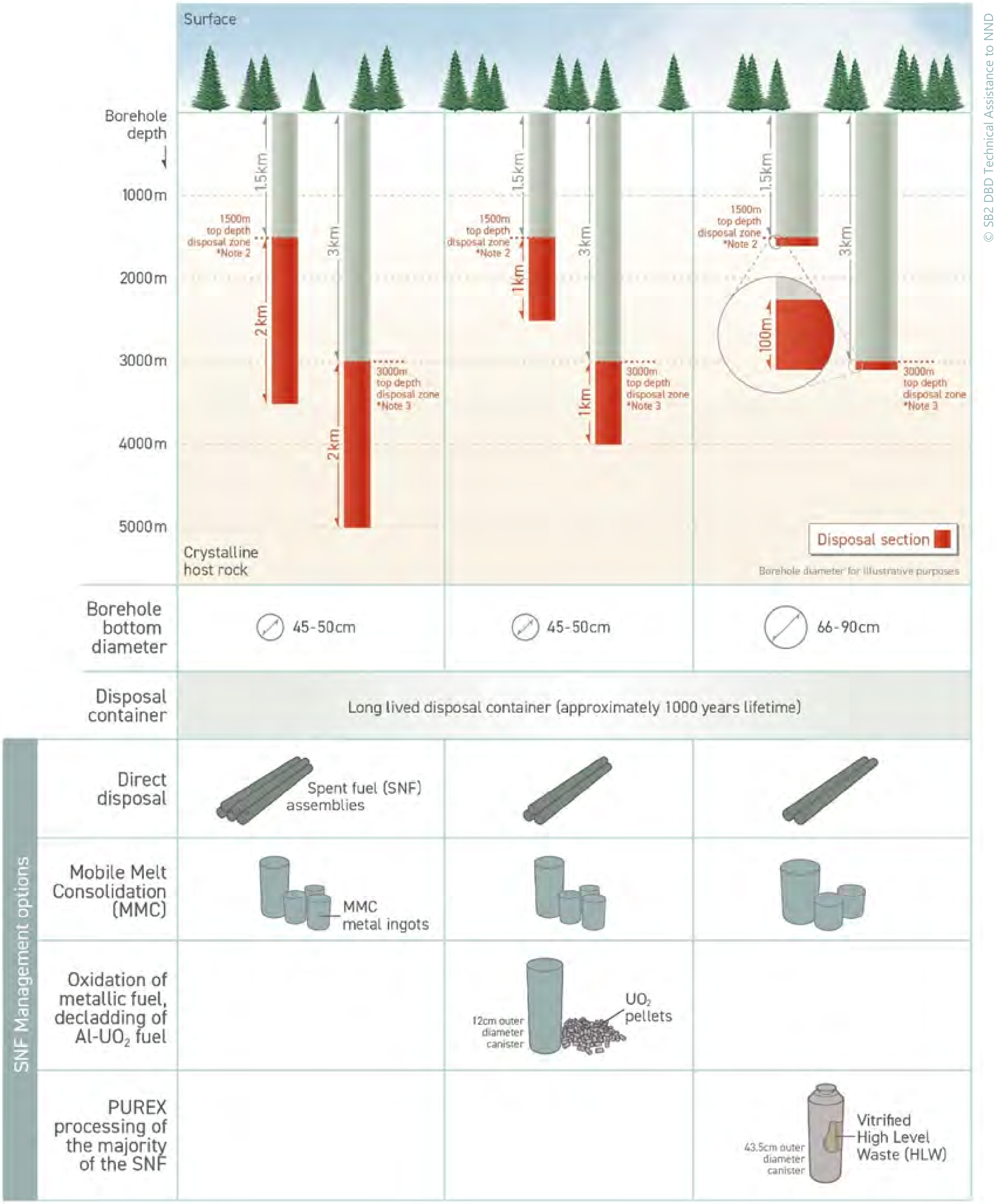
(NOTE 1, NOTE 2)

Option	Location	Depth to top of disposal zone [m]	SNF management option (NOTE 3)	Borehole diameter	Length of disposal section [m]
1	DBD at a location with suitable site characteristics at a depth of 1000 m	1500 (NOTE 4)	direct disposal	narrow	2000
2			PUREX reprocessing	wide	100
3			dry oxidation	narrow	1000
4	DBD at a location where the site characteristics at a depth of 1000 m are not suitable for DBD and/or a greater disposal depth is desired to increase stakeholder acceptance	3000	direct disposal	narrow	2000
5			PUREX reprocessing	wide	100
6			dry oxidation	narrow	1000

Note 1: All numerical values are indicative.
Note 2: All options use a long-lived overpack that ensures waste containment during the initial thermal transient (about 1,000 years).
Note 3: All options include Mobile Melt Consolidated (MMC) ingots.
Note 4: An additional 500 m is added to the minimum depth of 1000 m to account for uplift and erosion during the assessment timeframe and to provide a safety margin.

Figure 14: Short list of DBD options

(NOTE 1)



Note 1: All numerical values are indicative.

Note 2: If suitable host rock conditions are found at a depth of 1000m.

Note 3: If the site characteristics at a depth of 1000m are not suitable for DBD and/or a greater disposal depth is desired to increase stakeholder acceptance.

Assumptions, constraints and exclusions

Assumptions, Constraints and Exclusions (ACEs) underlying the development of the long-listed and short-listed options are summarised in [**Erreur ! Signet non défini.**]. They include assumptions in terms of potential inventory of SNF and/or HLW, geology, regulatory and stakeholder expectations, potential SNF management variants and DBD design.
The updated list of ACEs underlying the further characterisation and evaluation of shortlisted options is provided at the beginning of the report and indicates where the ACEs have been updated.

3. Adapted shortlist based on input from other frameworks

Within their Framework Agreement, GeoReN defined 4 possible variants for managing spent fuel before its disposal (ACE 4):

- SNF management variant 1: Direct disposal of all SNF
- SNF management variant 2a: Oxidation of the metallic uranium fuel and direct disposal of the rest of the SNF
- SNF management variant 2b: MMC treatment of metallic uranium fuel and direct disposal of the rest of the SNF
- SNF management variant 3: PUREX reprocessing of all fuel assemblies.

It is assumed that the MMC process will be used to treat Norwegian HEU plus ThO_2 fuel corresponding to about 120 kg of heavy metal in the fuel, and additional SNF could be treated. Hence, in all the SNF management variants it is assumed that 1 tonne of uranium is treated in the MMC facility (ACE 4).

SNF management variants 1, 2a and 2b all require a narrow-diameter borehole while SNF variant option 3 requires a wide-diameter borehole. Therefore, SNF management variants 1, 2a and 2b were considered as variants of the same DBD geometry option. This results in the options and variants presented in Table 8. These were further characterised and assessed, as specified in the following sections VIII and IX. The length of the disposal section for each of these options and variants is discussed in section VIII.1.

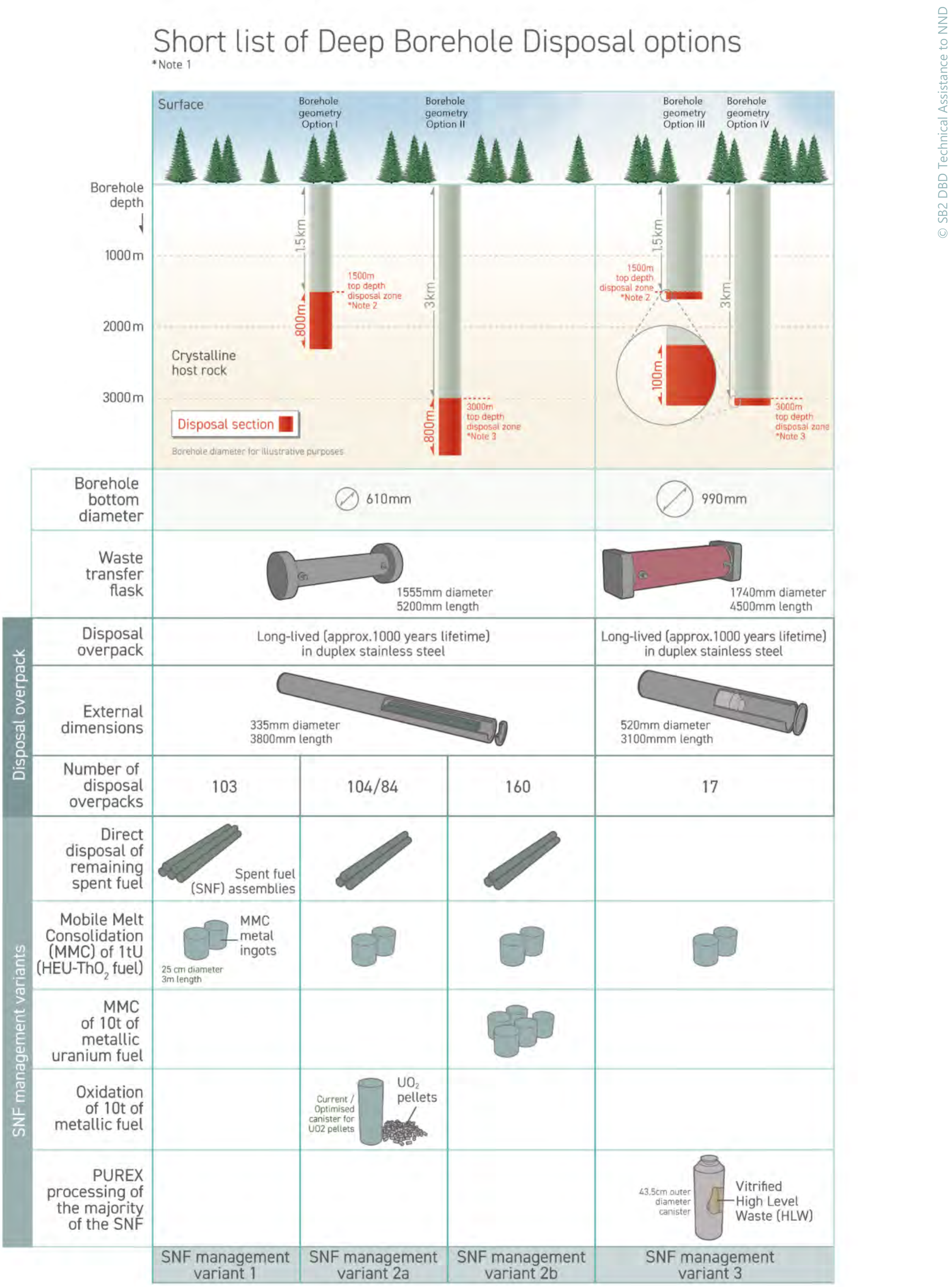
Table 8: Adapted shortlist of DBD options considered in the further characterisation and option assessment (all with a vertical borehole)

(NOTE 1, NOTE 2)

Borehole geometry option	SNF management variant (NOTE 3)		Depth to top of disposal zone [m]	Borehole diameter
I	SNF 1	Direct disposal of all SNF	1500 (NOTE 4)	Narrow
	SNF 2a	Oxidation of the metallic uranium fuel and direct disposal of the rest of the SNF		
	SNF 2b	MMC treatment of metallic uranium fuel and direct disposal of the rest of the SNF		
II	SNF 1	Direct disposal of all SNF	3000 (NOTE 5)	
	SNF 2a	Oxidation of the metallic uranium fuel and direct disposal of the rest of the SNF		
	SNF 2b	MMC treatment of metallic uranium fuel and direct disposal of the rest of the SNF		
III	SNF 3	PUREX reprocessing of all fuel assemblies	1500 (NOTE 4)	Wide
IV	SNF 3	PUREX reprocessing of all fuel assemblies	3000 (NOTE 5)	

Note 1: All numerical values are indicative.
Note 2: All options use a long-lived overpack that ensures waste containment during the initial thermal transient (about 1,000 years).
Note 3: All options include Mobile Melt Consolidated (MMC) ingots.
Note 4: If suitable host rock conditions are found at a depth of 1000 m.
Note 5: If the site characteristics at a depth of 1000 m are not suitable for DBD and/or greater disposal depth is desired to increase stakeholder acceptance.

Figure 15: Adapted list of DBD options considered in the further characterisation and option assessment



Note 1: All numerical values are indicative.
Note 2: If suitable host rock conditions are found at a depth of 1000m.
Note 3: If the site characteristics at a depth of 1000m are not suitable for DBD and/or a greater disposal depth is desired to increase stakeholder acceptance.

VIII. CHARACTERISATION OF THE SHORTLIST OF DEEP BOREHOLE DISPOSAL OPTIONS

The characterisation of the DBD options is structured as follows:

- The design basis for DBD.
- Conceptual designs for the DBD options.
- Assessment of the DBD options.

Any knowledge gaps or assumptions were identified. This provides a roadmap for further research and development on DBD. The next steps for implementing DBD in Norway are discussed in Section X.

1. The design basis for DBD

The design basis provides the set of criteria, assumptions and requirements that serve as the foundation for the design of the DBD concept. It serves as a reference throughout the design process, providing a clear and consistent framework that guides decision-making and ensures that all aspects of the project are aligned with the initial objectives and requirements.

The design basis for DBD consists of the following components:

- Regulatory and stakeholder requirements.
- Waste characteristics.
- Site characteristics.

1.1. Regulatory and stakeholder requirements

A note was prepared to set out a list of requirements for DBD in Norway [4] (see also section IV). There are currently no requirements regarding waste retrievability in Norway. However, to err on the side of caution, DBD optioneering considered the implications of waste retrievability (ACE 3).

1.2. Waste characteristics and forms

Ten groups of spent nuclear fuel assemblies (SNFA) have been categorised based on their properties:

- JEEP I in Kjeller.
- HBWR in Halden.
- 1st charge JEEP II in Kjeller.
- HBWR driver 2nd charge.
- HBWR driver 3rd charge.
- HBWR driver 4th charge.
- HBWR driver 5th charge.
- HBWR booster.
- HBWR Experimental 1 (early).
- HBWR Experimental 2 (late).

The characteristics of these categories are given in Table 3 (see Section III.1.1, page 38).

SB2 has derived estimates for burnup and thermal power of the various SNFA categories at the time of disposal, as well as for the vitrified HLW generated through PUREX reprocessing. According to the timeline for developing the Norwegian National Facility [29], disposal of spent fuel is scheduled to begin in 2050. By then, the minimum cooling time for the spent fuel will be 30 years, with some fuel assemblies cooling for nearly 90 years. It was assumed that all spent fuel will have a 30-year cooling period following discharge from the reactor (ACE 15) (Table 9). This assumption will be revisited and confirmed at a later stage, following the outcomes of SNF treatment optioneering study, noting a shorter cooling period means that the waste could be more radioactive at the time of disposal.

Table 9: Estimated burnup and thermal power of the ten SNFA categories

Fuel category	Mass of uranium [kg]	Burnup [MWd/tHM]	Thermal power after 30 years [W/tHM]
JEEP I	3000	1000	25
HBWR 1st charge	7000	25	0.63
JEEP II	1500	20000	500
HBWR driver 2nd to 5th charges	3600	50000	1260
HBWR booster	1000	80000	2190
HBWR Experimental 1 (early)	400	100000	2740
HBWR Experimental 2 (late)	400	100000	2740

IFE and NND have recommended to treat approximately 120 kg HEU-ThO_2 fuel of the HBWR reactor using the MMC Facility developed by Savannah River National Laboratory. In MMC, the spent fuel is melted together with stainless steel (and depleted uranium in some cases) to create an ingot with a reduced concentration of uranium. The ingots produced through the MMC process are cylindrical, with a diameter of 25 cm and a length of 3 m (ACE 6). It was estimated that the treatment of 1 tonne of uranium in the MMC facility will result in 9 ingots, with a volume of 0.147 m^3 each. Based on the density of stainless steel (8 g/cm^3), the estimated weight is approximately 1180 kg per ingot. To estimate the thermal power of the MMC ingots, it is assumed that 85% of the ingot mass is stainless steel, with the remaining 15%, or 177 kg, consisting of heavy metals such as uranium, plutonium or thorium (ACE 15). The estimated thermal power per ingot after 30 years of cooling is 485 W.

In addition to MMC of the HEU-ThO_2 fuel, GeoReN defined 3 possible variants for managing spent fuel before its disposal, which were consistently adopted by SB2 (ACE 4):

- SNF management variant 1: Direct disposal of all SNF
- SNF management variant 2a: Oxidation of the metallic uranium fuel (fuel from JEEP I and HBWR 1st charge) and direct disposal of the rest of the SNF
- SNF management variant 2b: MMC treatment of metallic uranium fuel and direct disposal of the rest of the SNF
- SNF management variant 3: PUREX reprocessing of all fuel assemblies.

The MMC treatment of the metallic uranium fuel would produce 86 MMC ingots (cylinders with a diameter of 25 cm and a length of 3 m) with very low thermal power (i.e., less than 5 W per ingot by 2050).

The dry oxidation of metallic uranium fuel would result in UO_2 pellets that would be placed in 5 mm-thick stainless steel canisters that are 12 cm wide and 140 cm long (ACE 5). Dry oxidation of the 10 tonnes of metallic uranium fuel would result in 120 canisters, which would require 30 disposal overpacks. The thermal power per overpack would be very low, with less than 9 W per overpack in 2050.

PUREX reprocessing of the majority of the spent fuel would result in 8 CSD-V canisters containing vitrified HLW. These are stainless steel canisters that are 5 mm thick, 43 cm wide and 134 cm long. The initial thermal power of these canisters will be less than 2000 W each. If produced in 2040, the CSD-V canisters will undergo 10 years of decay before potential disposal (ACE 15). Since the thermal power is mainly influenced by Cs-137 and Sr-90, which have half-lives of about 30 years, the thermal power is expected to decrease to 1600 W per canister by 2050.

Further details on the SNF and other waste forms are included in Complementary Note 1 [3]. Note 1 provides estimates for the number of overpacks needed for disposal of the different SNF types and waste forms generated in the 4 four SNF management variants considered. Estimates of the thermal power per overpack in 2050 for the different SNF/HLW forms are included as well.

In Complementary Note 3 [3], thermal calculations are performed to estimate the maximum temperature increase at the overpack surface and the borehole wall for the disposal overpacks loaded with different SNF and/or HLW forms. The only waste form that leads to high maximum temperature increases over the ambient (close to 200ºC) is the CSD-V canister with vitrified HLW from the PUREX reprocessing. MMC ingots produce maximum temperature increases at the overpack surface below 50ºC and the fuel assemblies and consolidated fuel rods can be mixed within an overpack to limit its thermal power so that the maximum temperature increase at the surface of the overpack remains below 40ºC.

1.3. Site characteristics

The study is limited to consideration of disposal into crystalline rock formations (ACE 2). Target host rock properties for a DBD concept in the Norwegian context are defined in [24]. These target properties are:

- The DBD site should not contain significant or exceptional deposits of exploitable natural resources.
- The DBD site should not contain significant groundwater resources.
- The disposal zone should be more than a thousand metres below the ground surface.
- The DBD host rock should not contain large fractures or faults that form a potential flow path to the ground surface.
- The DBD host rock should have a rock volume large enough to provide a containment rock zone (CRZ).
- Rock temperature in the sealing zone should correspond to the chemical stability conditions of the sealing material.
- The DBD host rock should be located in a tectonically stable and quiescent region (no tectonically active zones, no volcanism).
- The DBD host rock should have good mechanical properties to ensure the long-term stability of the rock surrounding the borehole.

- The DBD host rock should have no or minimal groundwater flow and the general groundwater regime should be such that discharge cannot take place through the borehole or in its immediate vicinity.
- The chemical conditions at the depth of the disposal zone should be reducing and favourable for the engineering of the DBD concept, including any possible engineered barriers.

These are the properties of the host rock that will ensure that a DBD facility can fulfil its safety functions and provide long-term isolation and containment of the waste. Since no site for deep borehole disposal has been proposed or selected at this stage, this study assumes that the host rock properties align with the geoscientific target properties outlined above (ACE 2).

The temperature in and around the disposal borehole will influence the corrosion of the overpacks, the performance of backfilling and sealing materials, and the dissolution and migration of released radionuclides. Assuming an average surface temperature of 5°C and a geothermal gradient of 15°C per kilometre, the ambient temperatures at depths of 1500 m, 3000 m and 5000 m were estimated to be 27.5°C, 50°C and 80°C, respectively (ACE 16). The heat from the radioactive waste will cause a temporary increase in the temperature around the overpack and in the host rock. A literature search to identify representative temperatures at the depths relevant for DBD is presented in Complementary Note 3 [3].

2. Conceptual designs for the DBD options

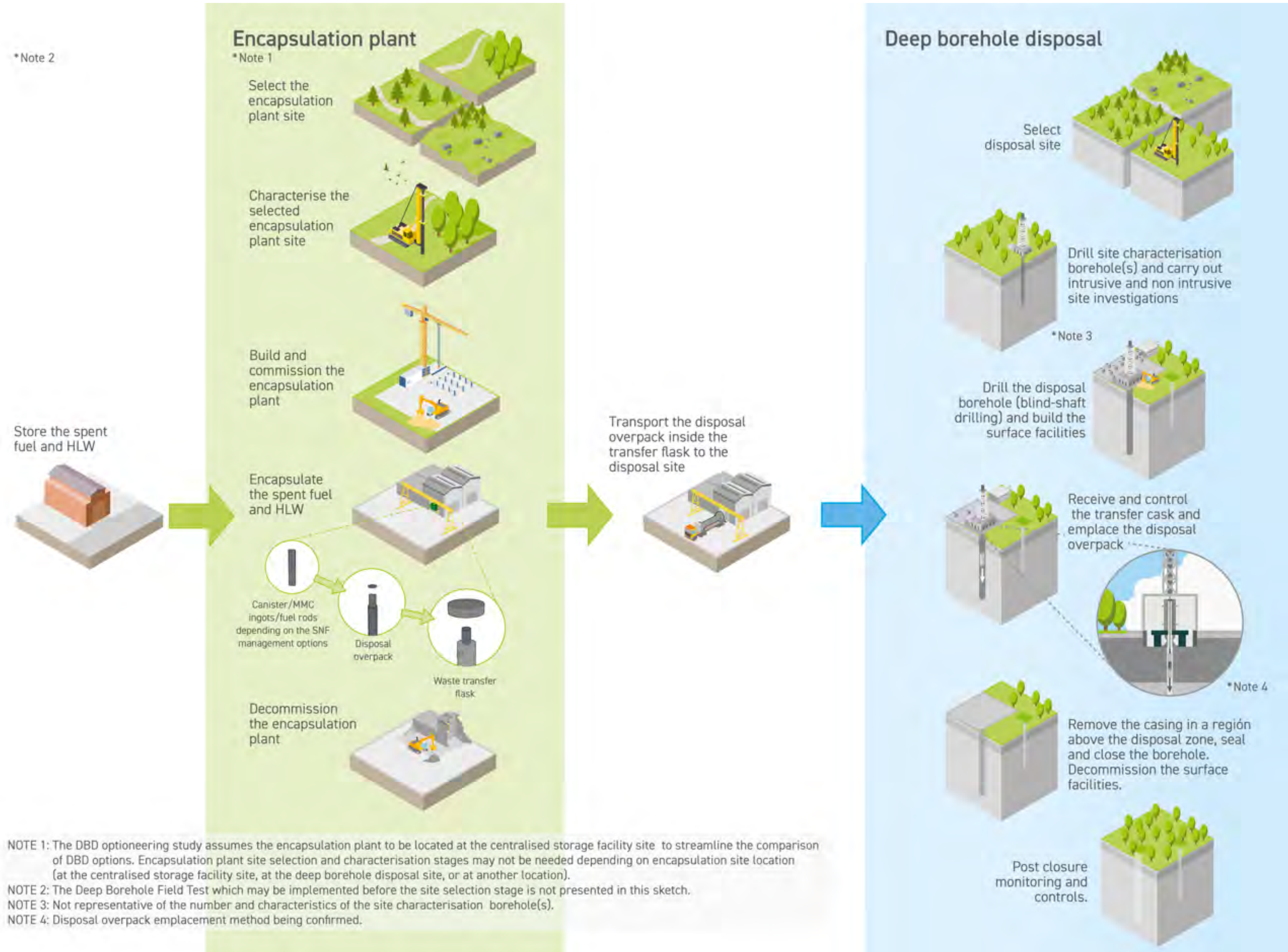
The conceptual design broadly outlines the main design features, such as material choices, technology selection and dimensions of the DBD options. The conceptual design for the four principal deep borehole geometry options includes the following components:

- Disposal overpack and encapsulation features.
- Disposal borehole.
- Borehole backfill.
- Borehole seal.
- Waste emplacement technology.
- Surface infrastructure at the repository site, including reception area for disposal packages and facilities to provide radiation shielding when transferring and emplacing the waste.

Figure 16 presents the preliminary Concept of Operations (CONOPs) of the Norwegian DBD concept considering each lifecycle stage (site characterisation, construction, operations, post-closure). The CONOPs is defined within the ISO 2018 Standard on Systems and Software Engineering — Lifecycle Processes — Requirements Engineering [30] as a user-oriented document that describes system characteristics for a proposed system from the users' viewpoint. It describes the mission of the system and its operational and support environments, and underpins the capture and structuring of systems requirements.

The process begins with SNF and/or HLW being transferred from the storage facility to the encapsulation plant, where the waste is sealed in disposal overpacks. It is assumed that the encapsulation plant is co-located with the storage facility (ACE 9). The overpacks are then transported to the disposal site and placed into the disposal borehole.

Figure 16: Preliminary CONOPs for DBD options in Norway



If the encapsulation plant is not located at the storage facility, there are two alternatives:

- **Encapsulation at the disposal borehole site**. If so, there will still be a requirement for transport casks, but the internal geometry will be different and various internal basket arrangements will be required to facilitate the loading of the various different types of unencapsulated fuel rod or fuel assembly to transport them to the encapsulation facility.

  In the case of direct disposal, the process of loading the SNF into the transport casks, and unloading it at the encapsulation plant, will be more onerous than if all encapsulation is done at the storage site. The details of what will be required will be dependent on the processing option that is defined and the design of the new storage facility for SNF.

  For the SNF to be treated by MMC, the MMC ingots would need to be transported to the storage facility, and from the storage facility to the encapsulation site.

  Where the fuel is assumed to be sent to Studsvik for conversion to pellets and placed in stainless steel containers, the return shipment will either go directly to the encapsulation plant and if so there will be no additional steps required, or to the centralised storage facility. If the fuel is sent to Orano La Hague for reprocessing and vitrification, then the return shipment will either go to the encapsulation plant and if so there will be no additional transportation, or to the centralised storage facility (ACE 4). The result of all the processed waste options is that if the return shipment is to go directly to the encapsulation plant, it will reduce the distance for transport from the encapsulation plant.

- **Encapsulation at a third site.** If encapsulation takes place at a third site, the transport casks to move the waste from the storage facility to the encapsulation plant will need to be transported on public roads. The form of the waste will be different when transporting in this stage to the stage from the encapsulation plant to the borehole, so although similar transport casks could be used, the internal basket arrangements will need to be different. In theory it could be possible to use the same transport casks for the additional movements; however, this would make the overall design slower and less adaptable to the needs of the project. Therefore, it should be assumed in the first instance that double the number of transport casks would be required. Development of an optimised multi-purpose transport casks to minimise the number of transport casks required could be carried out at a later stage.

2.1. Overpack

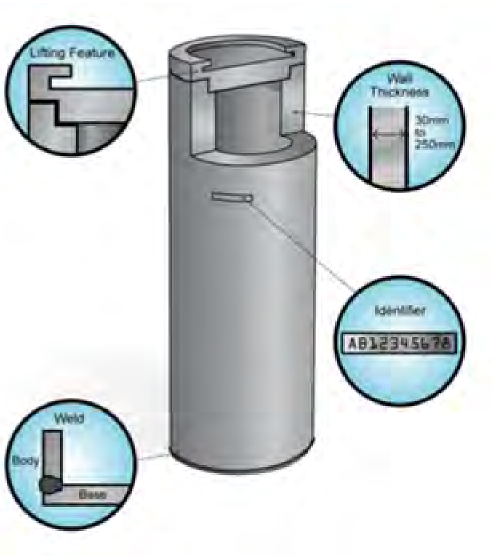
The SNF and/or HLW will first need to be packaged in an overpack. To fulfil the expected functions[3], the overpacks in a DBD concept need to meet the following requirements:

- The overpacks need to have sufficient size to contain the SNF and/or HLW but be sufficiently narrow to enable their disposal in a borehole.
- The overpacks need to be leakproof after welding.
- The overpacks need to be sufficiently strong to ensure their mechanical integrity during transport and emplacement and for a given period after closure of the borehole.
- Corrosion of the overpacks needs to be sufficiently slow and uniform to ensure they are not breached for a given period after closure of the borehole.

[3] The engineered barriers shall provide containment until radioactive decay has significantly reduced the hazard posed by the waste. In addition, containment shall be provided while the waste is still producing thermal energy in amounts that could adversely affect the performance of the disposal system.

The overpack consists of three basic elements: the base, the body, and the lid.

Figure 17: Basic overpack design
(Source: Nuclear Decommissioning Authority, UK)



The lid will include a lifting feature. A detailed design for this feature is outside the scope of this report, noting that a coiled tube attached to the overpack is the preferred deployment system (see Section VIII.2.3).

The base and body are welded together at the overpack manufacturing facility. The lid is added after the SNF and/or HLW is loaded into the overpack at the encapsulation facility. The lid is remotely welded in a shielded cell. Several welding processes have been proposed for this application. Electron Beam Welding (EBW) is assumed for all options because of the scale of the weld to be produced and the need for high quality of weld to ensure resistance to corrosion (ACE 7). The encapsulation plant will be equipped to accept the waste at the facility and conduct all necessary radiological controls.

Two sizes of overpacks were proposed (see section VII.1.3):

- **A narrow-diameter overpack** for waste from direct disposal, dry oxidation and MMC ingots. This overpack is designed to be long enough to contain the longest SNF assembly, and wide enough to contain the MMC ingot.
- **A wider-diameter overpack** for waste from PUREX reprocessing and MMC ingots. This overpack is designed to be long enough to contain the MMC ingots, and wide enough to contain the CSD-V canister. It is assumed that one CSD-V canister is contained per overpack to limit the maximum temperature at the overpack surface (ACE 10). Determining whether to include 2 CSD-V canisters in an overpack is an optimisation issue that can be addressed at a later stage.

Figure 18: Dimensions of the narrow-diameter and wider-diameter overpacks

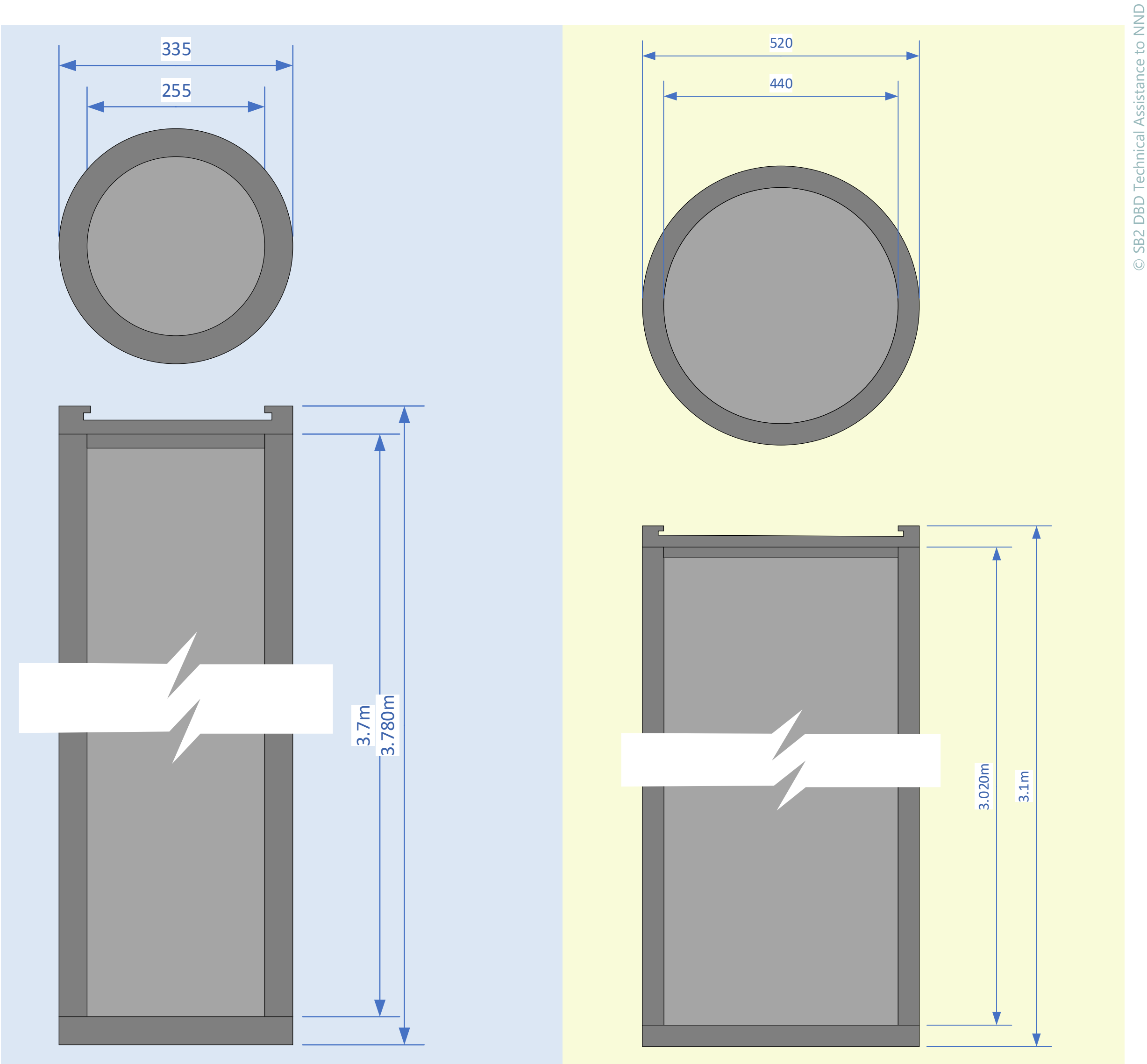


Figure 19, Figure 20 and Figure 21 show how single-sized narrow and wide overpack could hold various waste forms for disposal.

Figure 19: Illustration of how a single-sized narrow overpack could hold various waste forms for disposal

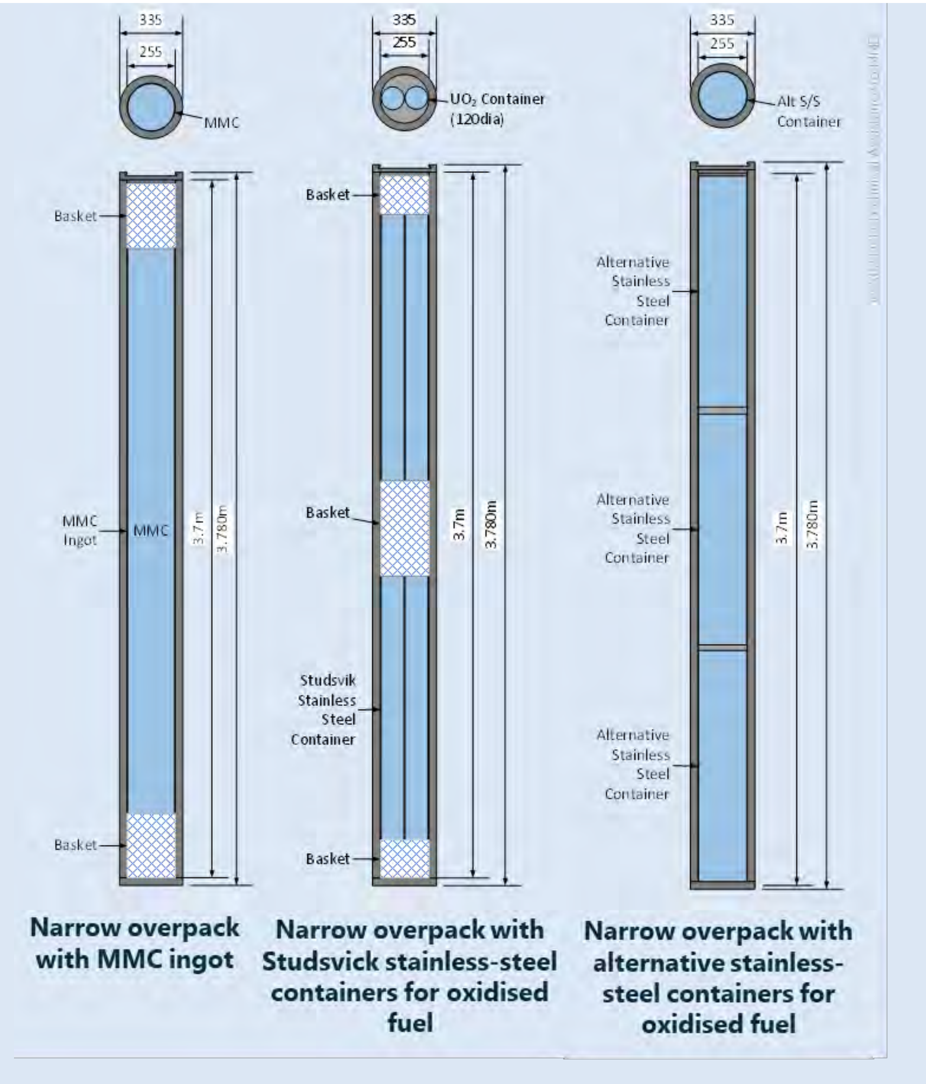


Figure 20: Illustration of how a single-sized wide overpack could hold various waste forms for disposal

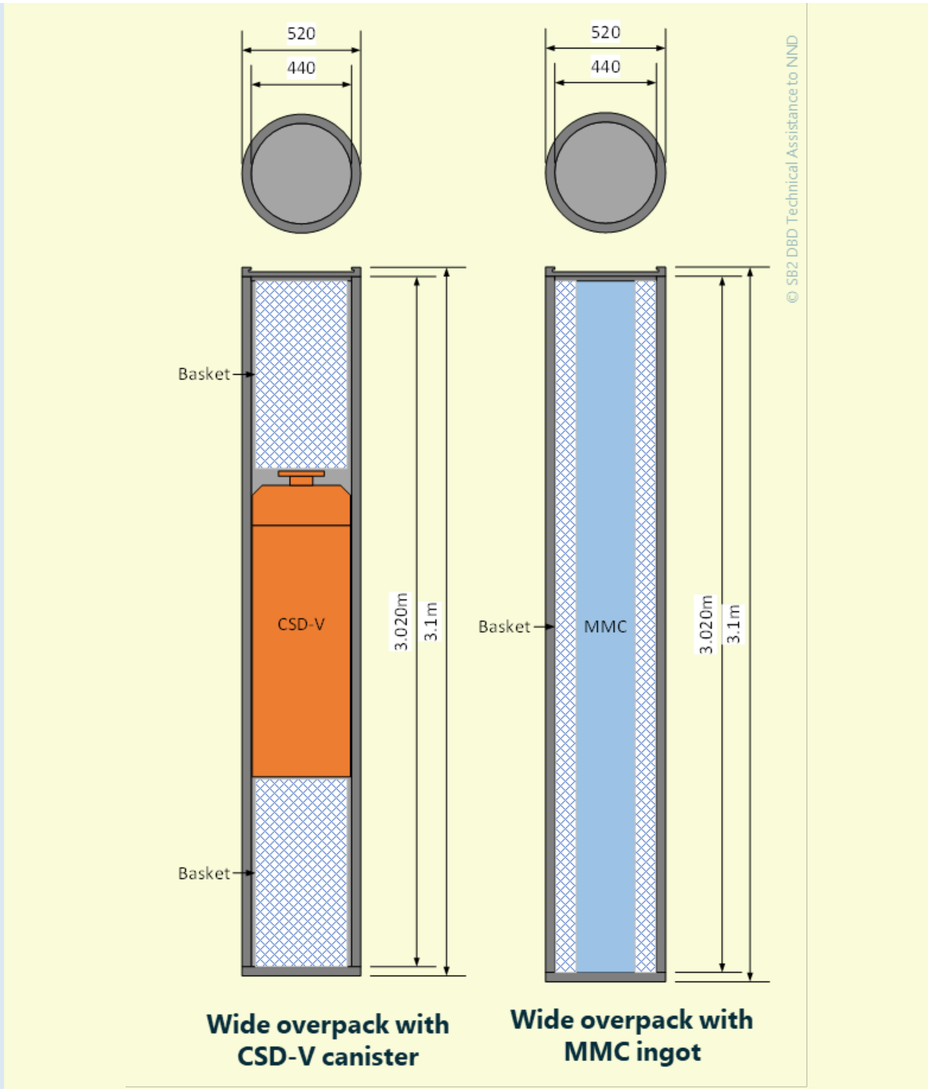
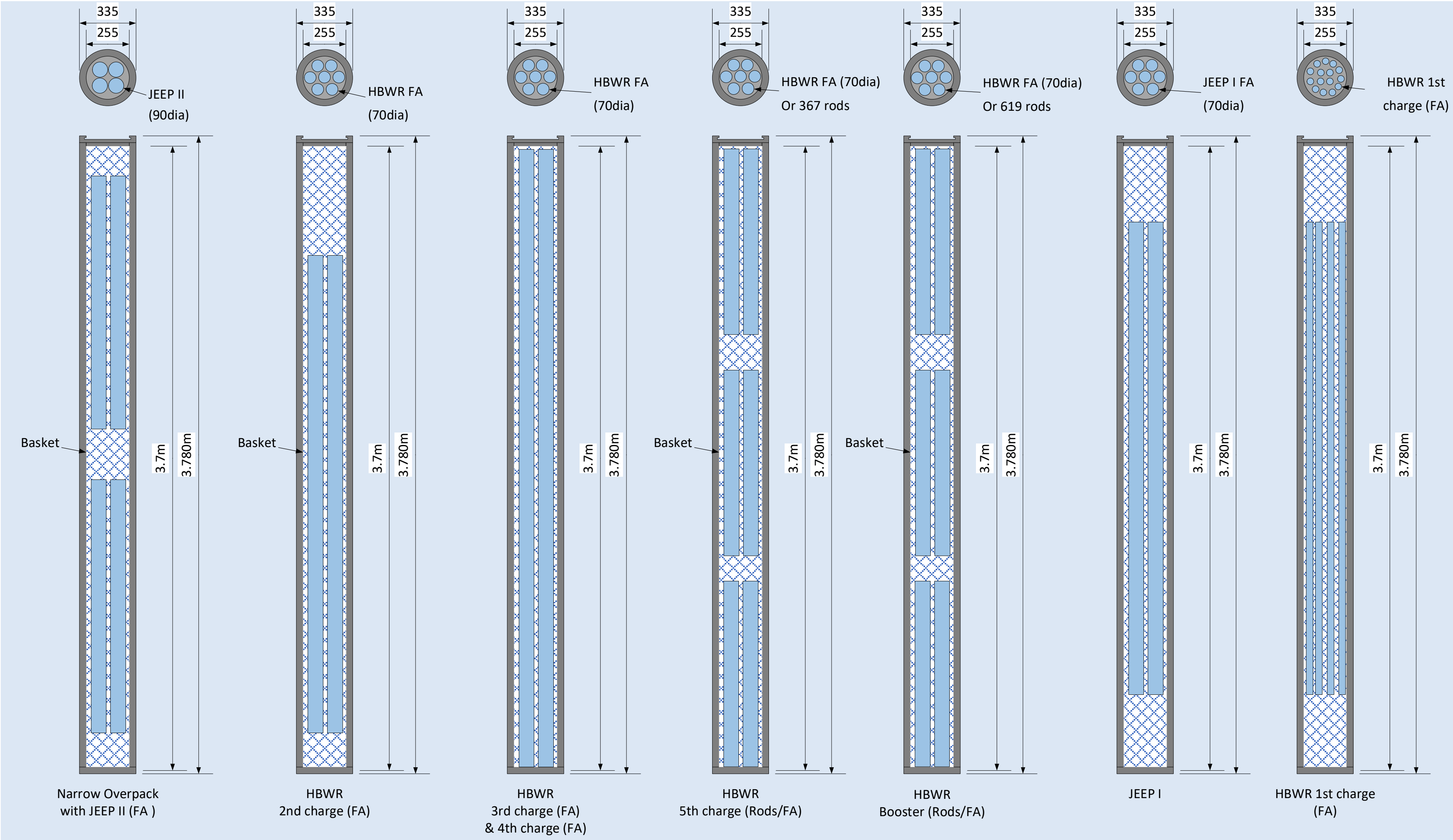


Figure 21: Illustration of how a single-sized narrow overpack could hold various SNF assemblies for direct disposal



The internal dimensions of these overpacks are determined by the size of the largest waste form that needs to be inserted. For the narrow-diameter overpack, the largest waste form is the SNFAs from the HBWR 3rd and 4th charge, which measures 3.66 m in length. The MMC ingots are 3 m long and have a diameter of 250 mm, much greater than the maximum diameter of the SNFAs, which is 90 mm. The outer length and diameter are assumed to be the same for all overpacks (ACE 7). Shorter overpacks could be used for shorter SNFAs or the MMC ingots, but it may be advantageous to use the same overpacks as those for the longest SNFAs to standardise manufacturing and handling processes. Determining whether to develop shorter overpacks or continue with the standard size is an optimisation issue that can be addressed at a later stage.

An internal diameter of 255 mm is assumed for the narrow-diameter overpack to allow for the insertion of the MMC ingots. It was then estimated how many SNF assemblies and/or rods of each category can be fitted inside this overpack (Table 10). Some rods are sufficiently short to allow more than one layer of rods to be placed inside one overpack. It is also assumed that a 10 mm wide basket is used for emplacing the SNF assemblies in the overpack. This results in a total of 94 overpacks loaded with SNF in the case of direct disposal of the whole inventory.

Table 10: Estimated number of SNF rods that can be fitted into the narrow-diameter overpack

Fuel category	Number of SNF of rods (R) or assemblies (A)	Rod or assembly diameter [mm]	Number of rods or assemblies per overpack [number of layers x number of rods or assemblies in one layer]	Number of overpacks
JEEP I in Kjeller	85 (R)	70[1]	1 x 7	13
HBWR in Halden	136 (R)	90[1]	2 x 4	17
1st charge JEEP II in Kjeller	300 (R)	40[1]	1 x 19	16
HBWR driver 2nd charge	7 (R)	70[1]	1 x 7	1
HBWR driver 3rd charge	59 (R)	70[1]	1 x 7	9
HBWR driver 4th charge	12 (R)	70[1]	1 x 7	2
HBWR driver 5th charge	3600 (R)	12.25	3 x 367	4
	90 (A)	70[1]	1 x 7	13
HBWR booster	1200 (R)	9.5	3 x 619	1
	30 (A)	70[1]	1 x 7	5
HBWR Experimental 1 (early)	720 (R)	14.3	2 x 268	2
	18 (A)	70[1]	1 x 7	3
HBWR Experimental 2 (late)	1440 (R)	14.3	5 x 268	2
	36 (A)	70[1]	1 x 7	6
Total				94

Note 1: A margin of 10 mm is to be added on top to the diameter of the FAs to account for the use of a basket for proper placement inside the overpack.

In addition, there are the 9 ingots from the MMC treatment of HEU-ThO_2 fuel. These cylindrical ingots are 3 m long and 25 cm wide, allowing one ingot to fit per overpack.

If the metallic uranium fuel from JEEP I and HBWR 1st charge is treated through MMC, it would result in 86 additional ingots or 57 additional overpacks compared with the total shown in Table 10. If metallic uranium fuel is oxidised instead, the UO_2 pellets would be placed in 12 cm wide and 140 cm long canisters. This means that four such canisters can fit in one narrow-diameter overpack, resulting in just 1 additional overpack compared with Table 10. The design of the stainless canisters could be adjusted to fit the internal dimensions of overpacks, potentially reducing the number of overpacks needed. Estimates done in Complementary Note 1 [3] point to a potential reduction of 20 overpacks. However, this is an optimisation issue that can be addressed at a later stage.

In the case of PUREX reprocessing, a total of 8 CSD-V canisters containing vitrified HLW would be produced. These canisters are 43 cm wide and 134 cm long, requiring a wider-diameter overpack. An internal diameter of 44 cm was assumed for the wider-diameter overpack. Due to the high thermal power of the CSD-V canisters, it is recommended that only one CSD-V canister is placed in each overpack. The exact dimensions and layout of the wider-diameter overpacks can be optimised at a later stage. For now, it was estimated that eight wider-diameter overpacks with an internal length of 3.02 m would be used for the CSD-V canisters, and nine wider-diameter overpacks would be needed for the MMC ingots.

More details about the number of overpacks required for each waste treatment option are given in Complementary Note 1 [3]. As explained above, Complementary Note 3 [3] presents the thermal calculations to estimate the maximum temperature increase at the overpack surface and the borehole wall for the disposal overpacks loaded with different SNF and/or HLW forms.

The next step was to select the material for the overpacks and define the wall thickness, as these determine the outer dimensions of the overpacks. Several materials were evaluated, considering the mechanical and chemical conditions the overpacks will encounter in the borehole, as well as potential ageing mechanisms. Given that the specific site characteristics, waste characteristics and overpack and borehole designs are not yet known, several assumptions were made. A preliminary assessment of the materials was conducted based on the functional requirements. This assessment and the underlying assumptions are detailed in Complementary Note 4 [3] .

For the material of the overpack, duplex stainless steels and Ni-Cr-Mo alloys were proposed, owing to their resistance to uniform and localised corrosion, although site-specific data will be needed for a proper evaluation of uniform and localised corrosion rates. Depending on the host rock pore fluid chemistry and expected evolution of pH, cheaper alternatives such as carbon steel, which also has good corrosion resistance at elevated pH, may also be considered.

The overpacks must be able to withstand both dynamic and static loads encountered during the emplacement process. Static loads are of two main types: hydrostatic arising from the pressure experienced at depth, and that due to the weight of any overlying overpacks in the disposal stack (axial stacking loads). Dynamic loads could also be encountered as a result of accidentally dropping a package during the emplacement process.

Complementary Note 5 [3] provides an initial estimate of the magnitude of these loads. Complementary Note 4 [3] calculates the minimum wall thickness needed to withstand the expected stresses. It was determined that the overpack requires a wall thickness of 40 mm. This means that the narrow-diameter and wider-diameter overpacks have an outer diameter of 335 mm and 520 mm, respectively.

As a result of the comparative advantages of Duplex stainless steels and Ni-Cr-Mo alloys presented in the stress calculations, the material selected for the options assessment process, and to define the mass and the costs of the overpacks, is duplex stainless steel.

2.2. Transport cask

For the purpose of this report, it is assumed that the encapsulation plant will be located at the NND storage facility (ACE 9). This means the disposal overpack will need to be transported from the encapsulation plant to the borehole site and then to the borehole platform. This transport could be done via a rail system, but most likely road transport will be required. For the purposes of the options study, road transport is assumed (ACE 10).

The overpacks are not suitable for transport on their own. It is therefore necessary to place them inside a transport cask that complies with international transportation standards as well as national regulations. Because the overpacks do not provide radiological shielding, the transport cask must also offer shielding against gamma and neutron radiation.

Several methods have been proposed for transporting overpacks with radioactive waste from an encapsulation plant to a borehole, with examples detailed in Complementary Note 4 [3] .

These examples illustrate conceptual ideas for waste transport systems that could be employed to move the overpacks above the borehole and potentially lower them into it. There is confidence that this can be accomplished with existing technology, as the handling and transport of radioactive waste packages have been routinely conducted in many countries for decades. The challenge lies in designing transfer equipment for this specific case, but there is no doubt that it is technically feasible.

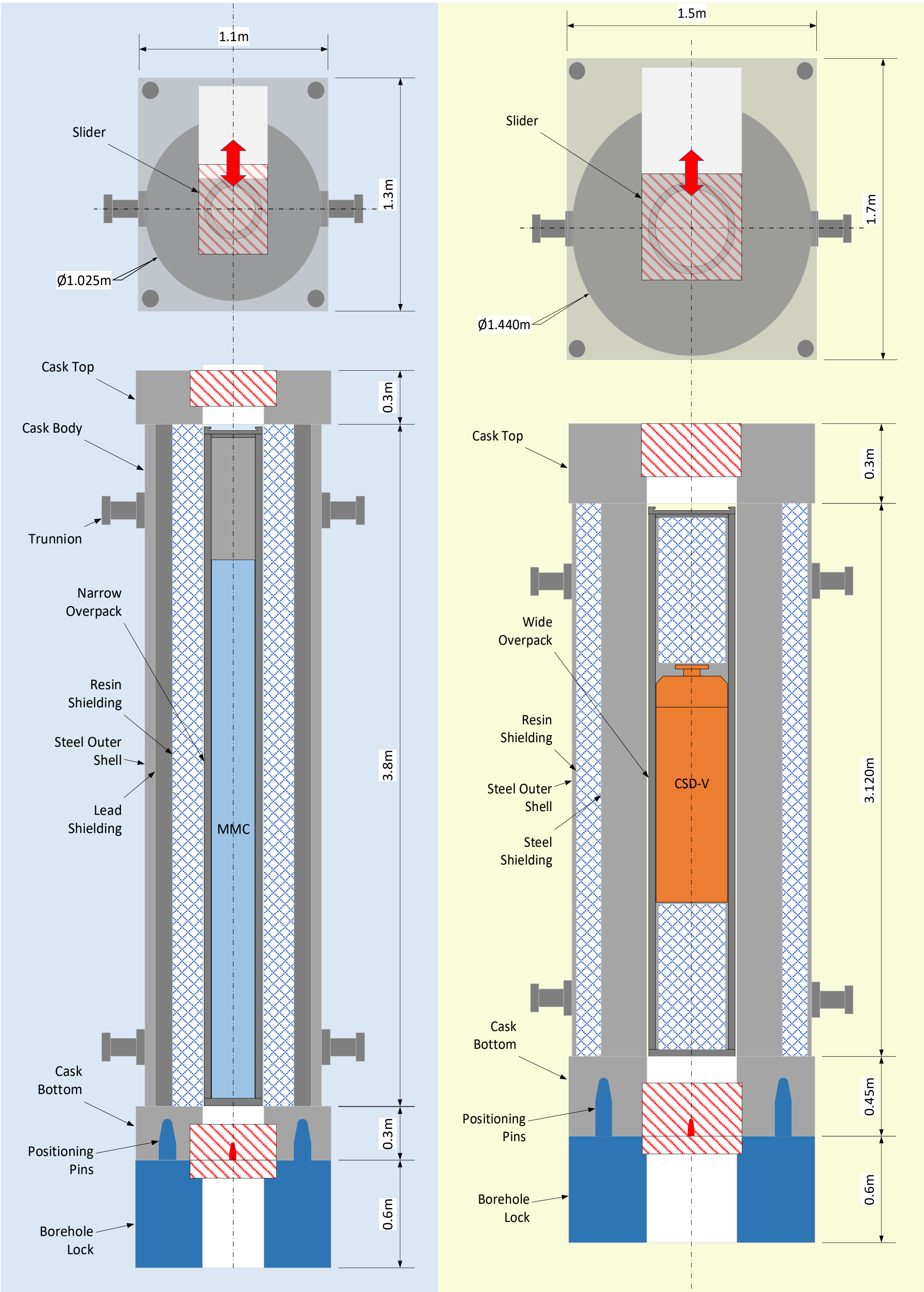
The transport cask will need to have an internal space that is sufficient to contain the overpack that is used in the chosen treatment solution either the narrow overpack (ø335 mm x 3800 mm high) or the wide overpack (ø520 mm x 3100 mm high).

For the purpose of this study, an estimated wall thickness of 600 mm is assumed for the transport cask for shielding purposes (ACE 10). This would result in a cylindrical shape with overall dimensions, dependent on the treatment solutions, of:

- Narrow transport cask: 1555 mm external diameter and 5200 mm in length.
- Wide transport cask: 1740 mm external diameter and 4500 mm in length.

To facilitate the loading of the transport cask, a gamma gate will be required on the top of the cask so the overpack can be loaded. A gamma gate will also be required on the bottom end of the cask to allow the overpack to be lowered into the borehole using a coiled tube.

Figure 22: Transport cask for narrow (left) and wide (right) overpack



2.3. Disposal borehole

The dimensions and estimated number of overpacks for each considered waste treatment option are summarised in Table 11, along with an estimate of the required length of the disposal zone. The results are obtained assuming that there is 1 metre of separation (filled with a cementitious sealing and support matrix) between overpacks in the disposal zone (ACE 7). Details about these estimated are given in Complementary Note 1 [3] .

Table 11: Estimated number of overpacks required for the different waste treatment options

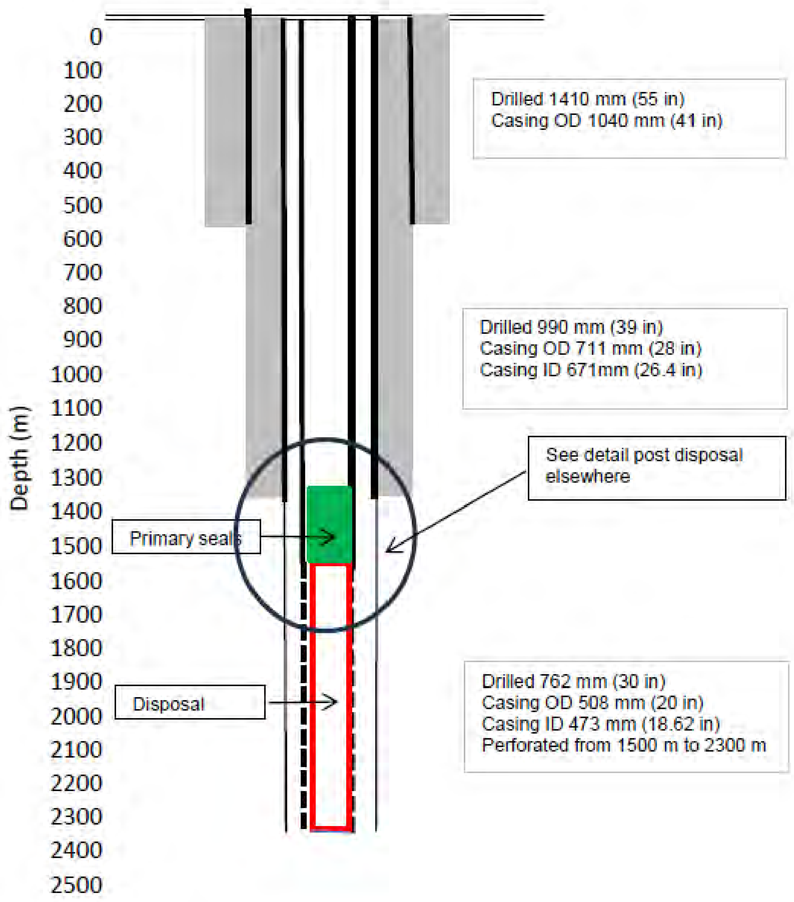
SNF Management Variant		Number of overpacks	Length of the overpacks + 1 m spacing between the overpacks [m]	Total length [m]
1. Direct disposal of all SNF				
	Spent fuel rods and assemblies	94	4.8	451
	MMC ingots	9	4.8	43
			Total:	**494**
2a. Oxidation of the metallic uranium fuel and direct disposal of the rest of the SNF				
	Canisters with UO_2 pellets	30	4.8	144
	Spent fuel rods and assemblies	65	4.8	312
	MMC ingots	9	4.8	43
			Total:	**499**
2b. MMC treatment of metallic uranium fuel and direct disposal of the rest of the SNF				
	MMC ingots	86	4.8	353
	Spent fuel rods and assemblies	65	4.8	267
	MMC ingots	9	4.8	37
			Total:	**768**
3. PUREX reprocessing of most fuel assemblies and direct disposal of the remaining unreprocessed fuel assemblies				
	CSD-V canisters	8	4.1	33
	MMC ingots	9	4.1	37
			Total:	**70**

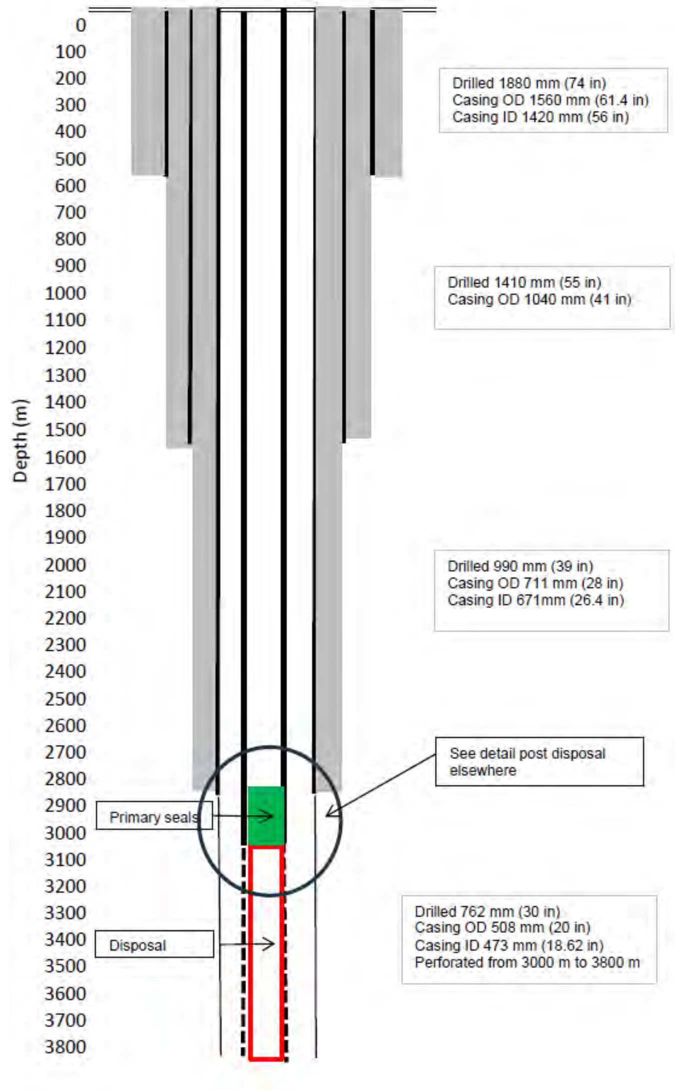
Since the dimensions of the SNF management variants 1, 2a and 2b are similar, they were merged into a single borehole layout. This means that the following borehole dimensions are required for the different DBD options (Table 12).

Table 12: Required borehole dimensions for the different waste treatment options

DBD Borehole Geometry option	SNF Management Variant	Top of the disposal zone [m]	Bottom of the disposal zone [m]	Borehole bottom diameter [cm]
I	Direct disposal of all SNF, or oxidation or MMC treatment of metallic fuel	1500	2268	61
II		3000	3768	61
III	PUREX reprocessing of most fuel assemblies	1500	1570	99
IV		3000	3070	99

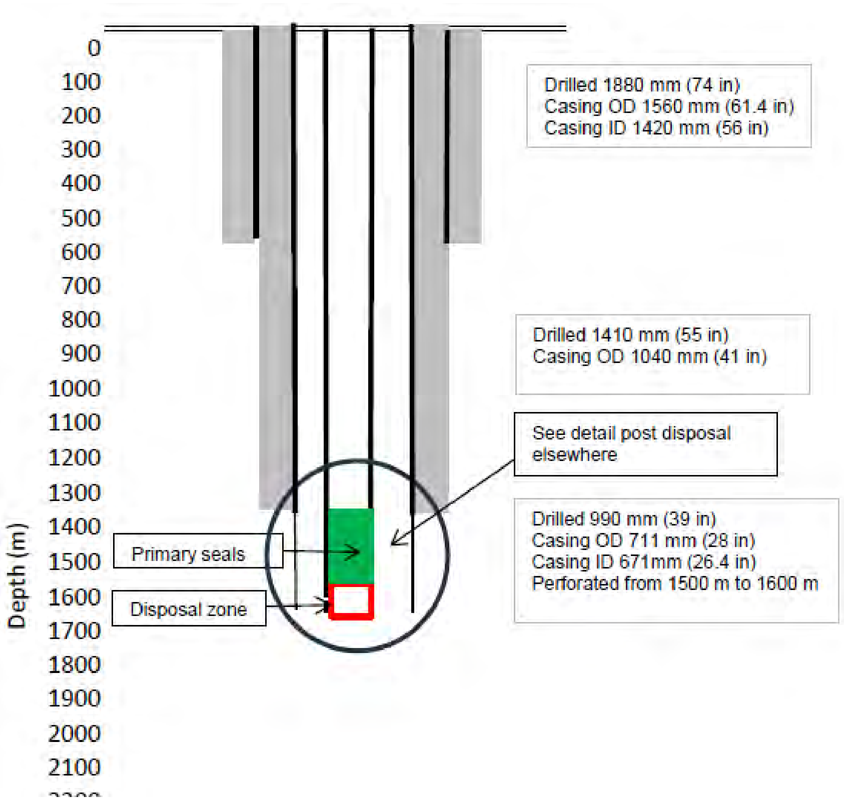
Figure 23: Options for the narrow DBD geometries

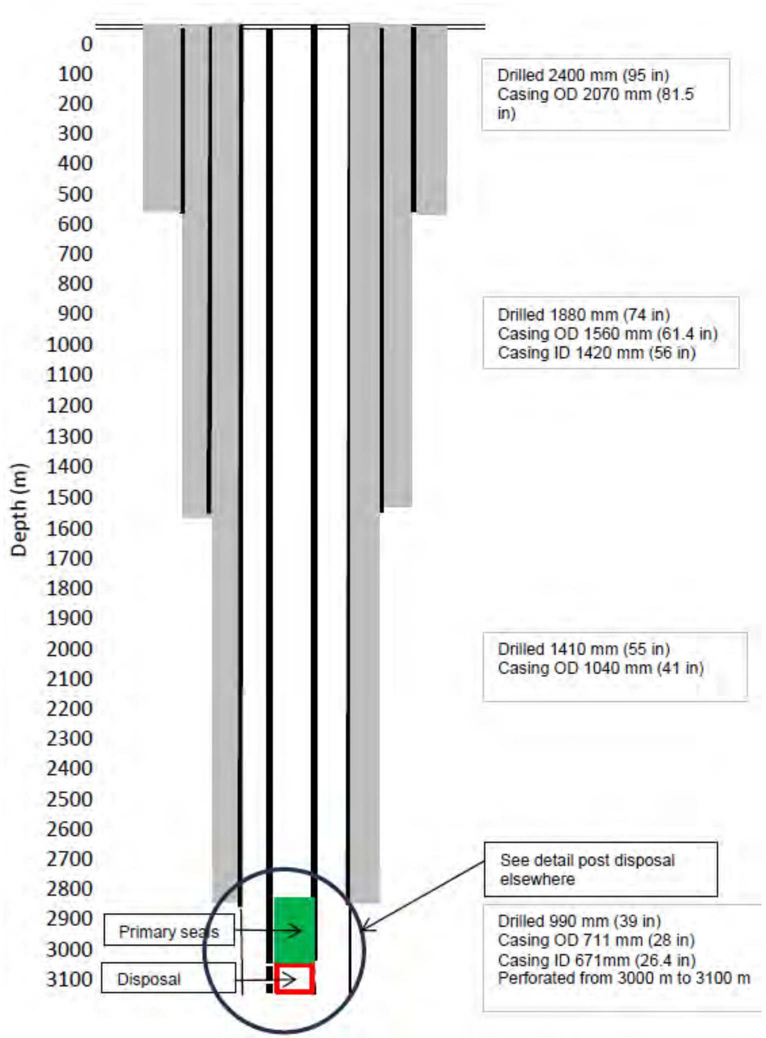




Drilled: Drilled borehole diameter
Casing OD: Borehole casing outer diameter
Casing ID: Borehole casing inner diameter

Figure 24: Options for the wide DBD geometries





Drilled: Drilled borehole diameter
Casing OD: Borehole casing outer diameter
Casing ID: Borehole casing inner diameter

All of these borehole geometries have a diameter larger than typical oilfield drilling requirements and smaller than those commonly used for mining access and ventilation shafts. The feasibility of drilling a 90 cm diameter, 3500 m deep borehole was assessed. The logic is that the other borehole options would be similar or easier to drill. Some adjustment may be required in terms of the length of the disposal zone, but modest changes can be accommodated without significant changes to the proposal set out here.

Complementary Note 6 [3] presents a conceptual design for this wide-diameter, deep borehole. It provides details about the drilling method, borehole plan, casing and grouting and a rationale for the design choices proposed. This design is not site-specific. Once a disposal site is selected, at least one and possibly several investigation boreholes will need to be drilled to obtain the necessary geotechnical site characteristics needed to develop a detailed borehole design. It is then also important to assess the site accessibility – can the heavy drilling equipment be mobilised on the site? – and the presence or possibility to install the necessary utilities (water, electricity, communication, etc.).

Drilling method

Experience with drilling large-diameter deep injection wells in South Florida during the 1980s provides confidence in reaching the required depths and diameters. These boreholes were over 1000 m deep with casing diameters ranging between 406 mm (16 inch) and 610 mm (24 inch). This was achieved with smaller equipment than what is available today. This historical context suggests that modern rigs and tools should be more than capable of drilling a 3500 m deep and 99cm wide borehole. There is no known record of similar boreholes failing, indicating that such drilling has not been attempted due to a lack of demand rather than owing to technological limitations.

The proposed drilling approach for the optioneering approach considers the two distinct phases of the construction and later completion of the boreholes using the **blind shaft drilling approach** illustrated in Figure 25. The blind shaft drilling approach involves the following:

- Shafts are bored and lined entirely from the surface.
- Bores remain full of fluid during drilling, with the lining and grouting process providing stability to the shaft and balance through aquifers.
- Cuttings are carried to the surface in high-velocity fluid flow through the centre of the drill pipe using reverse circulation.
- Smooth, fully watertight shaft lining options are available for any ground conditions.

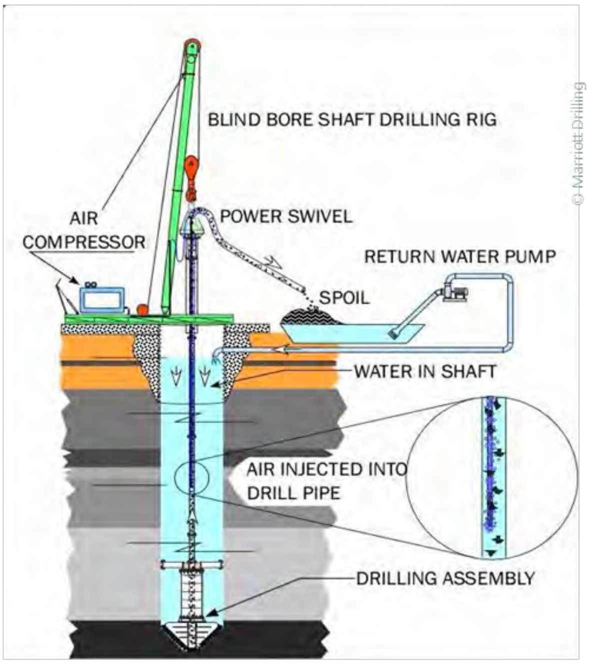
It is believed that no significant advancements in drilling technology are required, and Complementary Note 6 [3] discusses different drilling rigs that could be used. For the borehole geometries considered in the optioneering study, a 3000 hp class oilfield drilling rig with modifications to cater for the reverse circulation system required for larger diameters. Land-based oilfield rigs of that capacity are not uncommon. The primary challenge lies in ensuring the drill pipe is strong enough to handle the weight of the large-diameter drill string, but this appears to be within manageable limits.

Unloading and positioning the various rig components will require one or two heavy cranes with a forklift for the lighter loads. On completion of drilling of each interval, the borehole will be flushed and callipered ready for installation of the casing, which will be installed using the rig or a casing jack.

Figure 25: Illustration of proposed drilling technique

Typical heavy duty drilling rig

Catwalk machine to lift pipe for the ground racks



Reverse circulation drilling

Casing jack

Borehole plan

In the absence of specific geological data, it seems reasonable to base the borehole plan on publicly available descriptions of the prevalent geological conditions in the south of Norway. In this region, the expected geology consists of sediments overlying the Fennoscandian Shield of hard Precambrian granitoid rocks and crystalline granitic gneisses. Complementary Note 6 [3] presents two possible options for the borehole plan.

By starting with a significantly larger initial diameter than the required final diameter, successively smaller and deeper intermediate casings can be installed to address any challenging ground conditions that may arise. In plan A, surface sediments, including weathered rocks and near-surface aquifers, are isolated behind surface casing set deep into the basement rock. The remainder of the borehole to 3000 m is then drilled in a single section. Plan B includes an additional intermediate casing to provide temporary support to the upper parts of the borehole until the final casing is installed. The necessity of an intermediate casing depends on site-specific conditions and should be evaluated when developing a site-specific design. Records from the Kola (USSR), KTB (Germany) and Gravberg (Sweden) very deep boreholes in granitic rock suggest that an intermediate casing may not be required.

The drilling tools such as mud swivel, an air swivel, drill pipe elevators, elevators links and a make-up/break-out device would all have to be matched to the nominated drill pipe size and bore.

As there has previously been no demand for boreholes at the widths and range of depths considered appropriate for DBD holes, suitable drill pipe, elevators, kelly bars, swivels and make/breakout tools are not likely to be available "off-the-shelf". This is typical of most large diameter drilling tools which are usually designed and produced only for specific applications.

In the estimate of the cost of the different DBD options, the costs for Option IV (the wider and deeper option), are based on Plan B with the additional intermediate casing. The other option costs are based on the cutting rates and casing for the different sizes and depths of borehole without the intermediate casing.

Casing

It is recommended to case the boreholes over the entire length. The casing supports any weak strata at risk of collapse and provides a smooth, unimpeded path for emplacement of waste. The annulus between the casing and the borehole wall is cemented to stabilise the casing and keep it centralised. This can also contribute to sealing the excavation disturbed zone around the borehole.

The casing needs to be sufficiently strong and reinforced to withstand the hydrostatic pressures from both the drilling fluid and the cementing process. It is assumed that the borehole will remain filled with brine during the emplacement phase, and will eventually be displaced by the backfill (ACE 17). As a result, the casing will not be exposed to atmospheric pressure, eliminating the need to design the casings to withstand collapse from external hydrostatic pressure. A carbon steel casing reinforced with stiffener rings made from solid rectangular steel bars is proposed. These reinforcements provide enough strength to resist collapse under 5 MPa of external pressure.

The weight of such deep, heavy casing strings exceeds the capacity of current drilling rig hooks. It may therefore be necessary to assist the controlled lowering movements, for example with a customised hydraulic jacking system. To keep loads within the rated capacity of the drilling rig, a part of the casing could be floated in, using buoyancy to reduce the load. The tension load on the upper sections of the smallest diameter casing strings reaches about 75% of the yield strength of mild steel. Stronger steel grades, like 350 or 400 MPa, may be worth considering, along with careful attention to weld joint integrity.

The casing corrosion needs to be sufficiently slow to avoid the creation of a free gas phase. A corrosion-resistant material could therefore be considered. However, it is important to keep in mind that the potential for a free gas phase depends not only on casing corrosion but also on the gas dissolution and dissipation rates. It is therefore important to consider the potential for gas to dissolve and dissipate and assess the risk of a free gas phase when designing the casing and considering the need for corrosion-resistant casing materials.

Grouting

The casing-rock annulus in the part below the borehole seal (see next section VIII.2.6) will be cemented or grouted to support the casing prior to drilling the next interval. The section of casing above the seal will be removed after the seal is installed, so grouting is not required for this part.

The borehole plan foresees a relatively generous annular space around the outside of each casing. This allows for smooth casing installations and space to run a grout tremie pipe. Grouting wide diameter casings is typically done in stages rather than in one continuous pour. These stages consist of pumping a volume of grout into the annulus through the day and allowing the mix to solidify overnight.

Recent research indicates that neat cement grout, commonly used to seal casings and create plugs in oil and gas wells, is susceptible to continuing degradation over time, particularly in aggressive chemical environments. Considering the long service life and desired mechanical properties that the grout is expected to exhibit in a DBD hole, the casings should be grouted with 50 MPa concrete in preference to a neat cement and water mix.

The cement grout could possibly serve a chemical function by creating an alkaline environment that slows overpack corrosion and reduces the mobility of released radionuclides. However, due to the relatively small volume of this grout, its buffering capacity (i.e. its ability to resist pH changes within the surrounding environment) may be limited.

2.4. Waste emplacement technology

There are several methods for emplacing the overpacks into the boreholes, including drill pipe, wireline, coiled tubing and drop-in emplacement. Using drill pipe is a slow process: a round trip in a 3000 m borehole could take around 15 hours. Wireline is faster: a round trip in a 3000 m borehole could be done in 2 to 3 hours. However, wireline carries the risk of a hangup and the formation of what is called a “bird’s nest”, which is difficult to remove.

The preferred method is coiled tubing. Coiled tubing is a continuous metal pipe with no joints. A 3000 m round trip could be made in about 80 minutes, plus additional time for latching and unlatching of the overpack. As with traditional wireline, the coiled tubing can incorporate an electrical cable for monitoring and controlling a downhole tool. But unlike wireline, it has the advantage that fluids can be pumped through the tube.

Finally, drop-in emplacement relies on the free-fall release of the overpack into a borehole filled with water or another fluid. The speed at which the overpack falls is controlled by the fluid’s viscosity, the overpack’s weight and the clearance between the overpack and casing. Studies indicate that the expected velocities are unlikely to damage the overpacks [31, 3224].

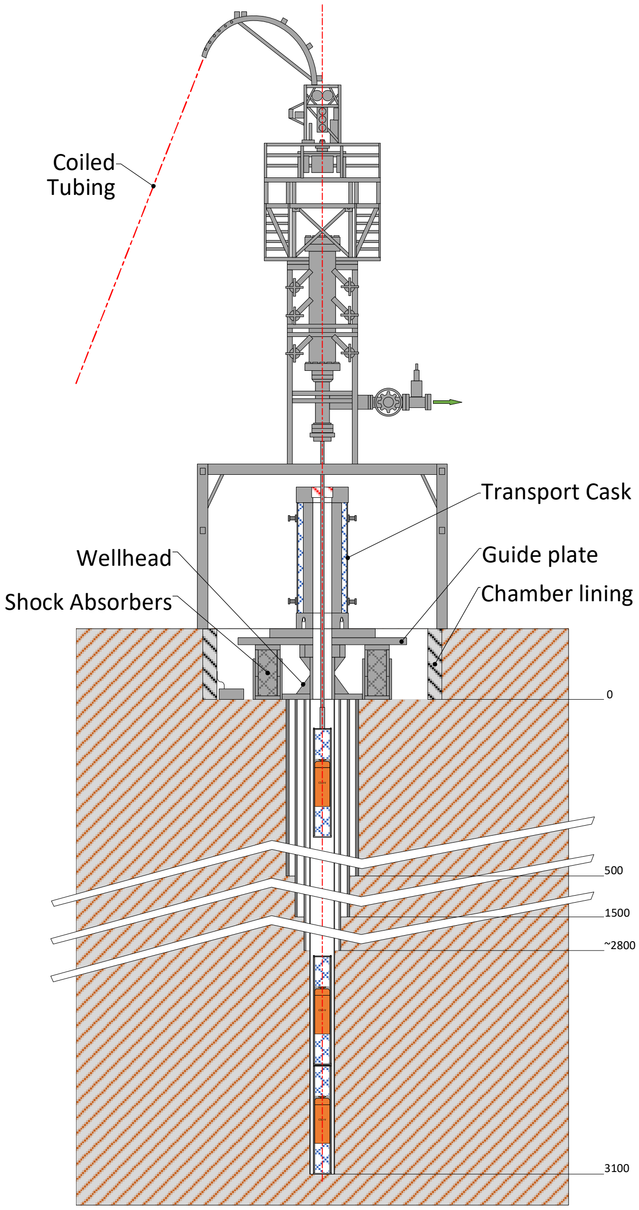
Additionally, waste emplacement requires a reliable method for connecting and releasing the overpack in the borehole. A typical latching mechanism is shown in Figure 26. The overpack designs should incorporate a pickup connector at the top of the package.

Figure 26: Internal catch latching tool
(Source Limar and Baker Hughes)

Complementary Note 4 [3] discusses different waste emplacement methods. During the emplacement of overpacks in the borehole it will be necessary to maintain the radiation protection of operators of the drilling rig/emplacement equipment. In conclusion, there is confidence that modern drilling technology can effectively handle the emplacement of overpacks in boreholes. However, a full-scale demonstrator may be necessary to increase confidence in the performance of the proposed waste emplacement equipment.

For the optioneering assessment, the simplest and most appropriate method to use as the baseline, similar for all options, is shown in Figure 27. It includes a chamber (called a "cellar") at the top of the borehole, but air-filled rather than water-filled. The concept design is based on the proposed transport cask with sliding doors top and bottom. The transport cask is engaged with the well head and remains in position for the duration of the emplacement. There would need to be adequate shielding in place to protect operators, and the cellar would be below ground level so that no infrastructure from the borehole would project above ground, thereby facilitating operations at the wellhead.

Figure 27: Emplacement with solid shielding (borehole geometry option IV is shown for illustration)



2.5. Borehole backfill

After waste emplacement, the borehole will be backfilled. This involves:

- Filling the voids around the overpacks below the seal. A Sealing and Support Matrix (SSM) will be emplaced **around the overpacks**, and through the perforations in the casing **in the disposal zone**, to form the adjoining casing-rock wall annulus.
- Backfilling the entire borehole section above the seal. In the area above the seal, the borehole casing will first be removed, which can be accomplished using either a mechanical cutter or a radial plasma cutter.

The backfill mainly fulfils mechanical and hydraulic functions. It provides mechanical support to the borehole ensuring it remains stable and to the overpack keeping them in place and reducing stacking loads. In addition, it acts as a hydraulic barrier limiting the water flow in the borehole. The backfill should be compatible with the overpacks and not contain components that could enhance the corrosion of the overpacks.

Like the grout surrounding the casing, the cement backfill can also serve a chemical function by creating an alkaline environment that slows overpack corrosion and reduces the mobility of released radionuclides. While the exact buffering capacity could be calculated once the specific backfill cement and site characteristics are determined, the contribution of this chemical barrier is generally considered minimal due to the relatively small volume of backfill.

A different cement backfill composition could be considered for the section below and above the borehole seal. Non-cementitious backfill materials, such as the use of a special alloy emplaced as a fine shot, have been proposed. However, cement is a preferred option due to its low cost, wide availability and extensive industrial experience gained from its use in hydrocarbon, geothermal and scientific boreholes.

The high temperatures and hydrostatic pressures to which the cementitious backfill will be subjected in a deep borehole will accelerate the cement setting process. Therefore, specialised retarders may be needed. The maximum temperature is estimated to reach 80°C (Complementary Note 3 [3]) and the hydrostatic pressures could reach up to 50 MPa in boreholes as deep as 5 km. The geothermal industry regularly conducts cementing jobs in boreholes with temperatures in excess of 300°C.

Emplacing the backfill can be done by pumping the cement through flexible tubing or by using a dump bailer. The SSM amount should fill only approximately two thirds of the volume of the annulus if retrievability is required or could fill all void space if there is no need for retrievability.

Regardless of which method is used, the cement must arrive *in situ* and fill the annular space without prematurely setting, noting trip times of the order of four hours can be achieved with modern coiled tubing methods. This can be challenging, but can be addressed by additives which include super plasticisers and anti-thickening agents. Unlike in mined repositories where addition of superplasticisers may enhance radionuclide transport, there should be little concern for DBD because little advective radionuclide transport is expected.

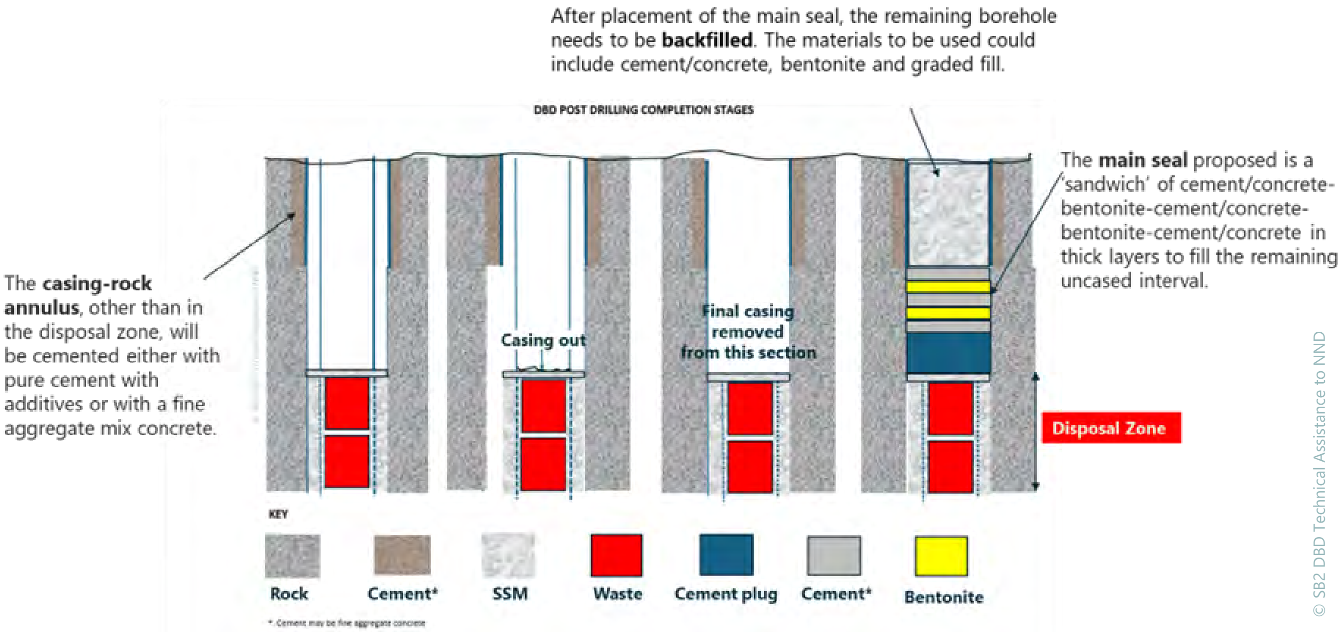
More information about the backfill material is given in Complementary Note 7 [3] . In addition, Complementary Note 6 [3] includes considerations for backfill emplacement. There is confidence that backfilling boreholes is achievable with current technologies and expertise. However, further RD&D is required to specify the backfill material and to select or develop an appropriate emplacement method. Most importantly, demonstration tests are essential to prove that the backfilling process can be carried out repeatedly, consistently and with verifiable outcomes.

2.6. Borehole seal

A borehole seal must create a low-permeability barrier to prevent the borehole from acting as a preferential pathway. Complementary Note 6 [3] presents possible design and installation phases of the borehole seal, which is illustrated in Figure 28. The seal is composed of layers of cement/concrete and bentonite. The installation process involves first removing the casing locally and then placing the various layers of cement/concrete and bentonite. Cement/concrete can be introduced using a tremie pipe, while bentonite placement may utilise a specialised tool for inserting pre-compacted bentonite sticks or pellets. Such a tool, developed by Marriott Drilling for the Wood Group (now Amentum), was successfully tested in the laboratory and in field trials, including a 2000 m deep borehole drilled entirely in granite in Cornwall, UK.

As for the backfill, there is confidence that sealing boreholes can be done using current technologies and expertise. However, further RD&D is required to specify the sealing material and to select or develop an appropriate emplacement method. Demonstration tests will be required to prove that the sealing process can be carried out repeatedly, consistently and with verifiable outcomes.

Figure 28: Schematic showing the design and installation phases of the SSM, the borehole seal and the backfill



2.7. Surface facilities at the DBD repository site

Various surface facilities and installations are needed at a disposal site. For example in the IAEA report *Design Principles and Approaches for Radioactive Waste Repositories [33]*, the following list of functions is provided:

- **Waste reception control**. Waste shipments arriving on site must be confirmed for acceptance. A control area allows inspection of the arriving shipment to confirm contents and allow visual inspection and radiological surveys.
- **Buffer storage**. Inclusion of a buffer store provides flexibility in the rate of waste package receipt and disposal. This feature would probably not be required given the small size of the Norwegian inventory.

- **Waste processing and transport on-site**. As previously noted, most processing would be expected to be carried out at the encapsulation plant, prior to shipment. If the encapsulation plant were to be located at or near the DBD site, this would be an additional facility to consider in siting.
- **Physical security**. Engineered security features ensure control of access to the site, including personnel, vehicle control, control of supplies and materials and management of waste.
- **Radiation protection and monitoring**. Standard methods for radiological protection of workers and the public.
- **Administrative support facilities**. As with any large-scale industrial activity, administrative support will be needed.
- Limited **on-site analytical capabilities** may be required depending on WAC and disposal system requirements.
- **Other auxiliary functions** could include equipment repair and maintenance facilities, garages and parking facilities for equipment, road vehicles, internal roadways, electricity, water and sanitary facilities, heating, ventilation and air conditioning and communication facilities, data management and computing services.
- **A visitor reception and visitor centre**. Such facilities are proven to be effective for public outreach and education, particularly in the surrounding communities

A site typically some 300 m x 200 m will be required to house **the drilling package**, allow the access and manoeuvrability for **heavy trucks** and **cranes,** and provide space for **ancillary buildings and store areas.** The surface of the site should be tailored for the drilling package, including construction of access roads. The blind shaft drilling method usually requires the **excavation of a pit or pits for water and other fluid supply** for the reverse circulation process. In a remote location, consideration may also be given to a camp for personnel to minimise travel times to a suitable area for accommodation.

A **water supply** would be necessary either from a mains supply or by the construction of a water well(s) or at worst supply by tanker. The access to the site area should be suitable for heavy trucks for the mobilisation and demobilisation of the drilling equipment and for the delivery of casing and other services and equipment that will be required during the borehole construction and the removal of drill cuttings from the site.

Some form of **cellar or surface chamber at the borehole location** will be required, the detail depending on the arrangement and method of introducing the waste package to the borehole. Further details about the disposal process including transfer of overpacks from the transfer cask and into the borehole are provided in Complementary Note 4 [3]**.**

Definition of specific surface facilities will be considered at a later stage of optimisation of the DBD system design. In the options assessment it is assumed that there is no differentiation between the costs of surface facilities to support the different options, and an indicative cost of €3M is assigned to all options, to include the specific DBD facilities mentioned above (ACE 11). In the cost assessment, indicative fixed costs are also provided for a crane for manipulation of the overpacks and for construction of a cellar.

IX. ASSESSMENT OF THE DBD OPTIONS

The conceptual designs of the DBD options have been evaluated against the following criteria:

- Safety / Health.
- Socio-Economic Impacts.
- Site Characteristics.
- Technical Implementation.
- Flexibility.
- Security and Safeguards.
- Environment/Sustainability.
- Lifetime Cost.

The methodology to evaluate and rank the DBD options is explained in section VI. This section identifies parameters underpinning the comparison and scoring of the DBD options for each sub-criterion (text in blue box). The scores for the different sub-criteria are turned into an overall score and ranking of the DBD options, and a sensitivity analysis is carried out. Finally, the conclusions from the MCA are presented.

1. Assessing and scoring the options

1.1. Safety/Health

Safety refers to the protection of people against risks caused by the DBD facility. It encompasses both radiological and conventional risks during the operational phase, as well as long-term radiological risks after closure of the borehole. These latter risks persist as long as the radioactive waste remains hazardous, i.e., hundreds of thousands of years. The DBD options were evaluated against this criterion by considering the protection of people under both expected evolution and alternative scenarios, including fault conditions and accident scenarios.

Main criteria		Sub-criteria
!	**Safety / Health**	• Post-closure safety • Conventional safety of workers • Conventional safety of the public • Radiological safety of workers and of the public

1.1.1. Post-closure safety

All four DBD options can provide adequate post-closure safety and allow the development of a robust safety case that meets regulatory requirements and applicable safety standards. However, there are differences between the options that may influence the level of waste isolation and containment they offer. These differences include:

- **Disposal depth**. Deeper boreholes (options II and IV) offer a higher degree of isolation from the biosphere and surface processes.
- **Thermal disturbance caused by the waste**. The thermal output of PUREX reprocessed waste (options III and IV) is higher than that of the waste in options I and II. Additionally, the host rock temperature at the disposal zone is higher for the deeper options.

- **Radiotoxicity of the inventory**. Options I and II contain many more long-lived actinides than Options III and IV, resulting in a higher long-term radiological impact compared to options III and IV. Furthermore, Options I and II contain a greater inventory of the highly mobile I-129. Noting in Options III and IV, some SNF (1 tU) is treated using MMC, thus these options will contain some long lived actinides and some I-129.
- **Overpack failure time**. Corrosion and failure of the overpack by localised corrosion could occur in shallower or deeper boreholes. Generation of aggressive chemical species through radiolysis is more likely to occur in Options III and IV owing to the higher gamma radiation dose from the reprocessed options. Deeper boreholes (options II and IV) may experience higher temperatures at the overpack surface during the thermal pulse, potentially reducing overpack lifespan.
- **Travel time to the biosphere**. Deeper boreholes (options II and IV) offer longer travel times for any potential radionuclide migration and are less vulnerable to various risks or fault conditions.

Complementary Note 9 [3] provides further details on post-closure safety considerations.

Assessment by the OAP

Options III and IV were viewed as providing a higher degree of post-closure safety due to the lower radiotoxicity of the waste inventory. The radiotoxicity of this inventory also decreases more rapidly over time compared to options I and II. While the thermal output of the waste in options III and IV is greater, which could result in enhanced corrosion, it is assumed that the overpack will ensure containment of the waste during this thermal phase (ACE 7).

Nonetheless, a safety case must account for the possibility of a breached overpack, which could lead to an earlier release of radionuclides. In such an event, in Options III and IV the temperature within the host rock would be elevated during the thermal phase leading to some radionuclide migration dissolved in the water that moves due to thermal expansion. Despite this, the increase in temperature is expected to be limited in both time and space. This restricted impact is not seen as significant enough to outweigh the advantages of reduced radiotoxicity provided by options III and IV.

The deeper DBD options offer a higher level of isolation and result in longer radionuclide travel times to the biosphere. However, greater disposal depth comes with some disadvantages: the temperature in the host rock around the disposal zone will be higher, which could potentially increase overpack corrosion rates, and uncertainties associated with deeper disposal may also be greater. Nevertheless, the benefits of deeper disposal were considered to outweigh the disadvantages.

Borehole geometry options	I	II	III	IV
Score for post-closure safety	4	5	4	5

1.1.2. Conventional safety to workers

In terms of conventional safety to workers, relevant parameters are:

- The number of waste types to be encapsulated.
- The number of overpacks to be produced in each option.
- The number of transports to the borehole site.
- The number of truck loads for spoil removal (which is linked to the drilled borehole volume).
- The number of working days at the disposal site.

These data are provided in Table 13.

Table 13: Number of waste form types and overpacks

Borehole geometry option	I	II	III	IV
Number of waste form types	8-10	8-10	2	2
Number of overpacks	84-160	84-160	17	17
Number of transports to the borehole site	84-160	84-160	17	17
Drilled borehole volume [m^3]	1700	4250	2910	7340
Number of truck loads for spoil removal	290	720	490	1240
Number of working days at the disposal site:	401	575	421	571
Borehole drilling	287	395	394	534
Waste and SSM emplacement	104	160	17	17
Borehole closure	10	20	10	20

Assessment by the OAP

Options III and IV were preferred from a conventional safety perspective because they involve a smaller variety of waste types to be encapsulated and require fewer overpacks to be produced compared to options I and II. Between these two, option III was favoured over option IV, as it demands fewer working days and involves a lower number of truck loads for spoil removal. Consequently, option III was assigned a score of 5, while option IV received a score of 4.

Option I involves more waste types and encapsulation operations compared to option IV, but it requires fewer working days in the borehole site and fewer truckloads for spoil removal. Determining which of these factors is more significant is not possible at this stage, as it depends on various factors, such as the distance between the disposal site and the designated spoil removal location (ACE 14). Because it is not possible to prioritise one aspect over the other, both options I and IV were assigned an equal score of 4.

Similar to the distinction between options III and IV, option II received a lower score compared to option I. This is because option II requires more working days and involves a greater number of truck loads for spoil removal.

Borehole geometry options	**I**	**II**	**III**	**IV**
Score for conventional safety to workers	4	3	5	4

1.1.3. Conventional safety to the public

In terms of conventional safety to the public, relevant parameters include the number of transports to the borehole site and the number of truck loads for spoil removal, presented in Table 14. The total number of transports is also presented in Table 14.

Table 14: Number of transports

Borehole geometry option	I	II	III	IV
Number of transports to the borehole site	84-160	84-160	17	17
Number of truck loads for spoil removal	292	733	494	1257
Mobilisation and demobilisation of drilling equipment	120	120	120	120
Total number of transports	496-572	937-1013	631	1394

Assessment by the OAP

The conventional safety to the public is assessed based on the number of transports involved. This includes the transportation of the overpacks from the encapsulation plant to the borehole site, as well as the number of truck loads required to remove spoil from the borehole. The significance of each transport type will largely depend on the distances between the encapsulation plant and the borehole site, and between the borehole site and the spoil removal location. These distances are currently unknown (ACE 9).

Option I requires the fewest transports (overpack and spoil transports combined), which earned it the highest score. Option III includes only slightly more transports, so it was given the same maximum score as option I. In contrast, Option II requires roughly double the number of transports, which resulted in a score of 4. Option IV, with approximately three times as much transports as option I, was given a score of 3.

Borehole geometry options	I	II	III	IV
Score for conventional safety to the public	5	4	5	3

1.1.4. Radiological safety to workers and the public

Finally, in terms of radiological safety of workers and the public, there are no significant differences between the DBD options during waste transport and emplacement operations. This is because during these operations, all waste is placed in standardised overpacks, which are transported using a transfer cask designed to provide the necessary radiological shielding. Similarly, waste emplacement operations are carried out in a manner that ensures adequate radiological shielding. Any differences between the options in terms of radiological hazards during transport and emplacement would only affect the potential cost of providing enhanced shielding or specialised equipment. Therefore, all options present the same level of radiological safety during transport and waste emplacement.

However, the radiological hazards to workers during waste encapsulation can vary. This is linked to the number of waste types to be encapsulated and the number of overpacks to be produced in each option. These figures are presented in Table 13. Additionally, the vulnerability of the waste form to handling accidents is considered lower for options III and IV. The vitrified HLW in these options provides a stable waste form with a low risk of releasing airborne particulates if impacted. In contrast, options I and II involve fuel rods or assemblies, which may perform less effectively in the event of an accident.

Assessment by the OAP

As explained above, there are no significant differences between the DBD options during waste transport and emplacement operations in terms of radiological safety of workers or the public. However, the radiological hazards to workers during waste encapsulation depends on the number of waste types to be encapsulated and the number of overpacks to be produced in each option. Therefore, options III and IV were given a score of 5 because they involve a smaller variety of waste types to be encapsulated and require fewer overpacks to be produced compared to options I and II. In addition, the vitrified HLW in options III and IV was considered less vulnerable to handling accidents than spent fuel assemblies and rods. Options I and II were given a lower score of 3.

Borehole geometry options	I	II	III	IV
Score for radiological safety to workers and the public	3	3	5	5

Complementary Note 8 [3] provides further details on operational safety considerations.

1.2. Socio-economic impacts

The socio-economic impact of the DBD options encompasses the impact on the local community and economy. This includes aspects such as job creation, economic development, local infrastructure and services, local benefits payments and potential changes in property values.

Main criteria		Sub-criteria
	Socio-Economic Impacts	• Impact on the local community and economy

Assessing the socio-economic impacts of a DBD project is challenging without a specific project site. In addition, there are currently no regulations in place specifying how socio-economic effects are to be managed, or whether incentives might be offered to potential host communities.

In the absence of a site and regulations, socio-economic impacts can therefore only be considered in broad terms by identifying those factors that may influence community perception of a DBD project. One such factor is the profile of the community itself, as communities can vary widely. For instance, it could be a small rural area reliant on tourism or a single industry, or a large urban community with a diversified economic base. Certain characteristics may influence community attitudes toward a DBD project, including:

- **Community dependence on local industries**. Communities with existing industries may be more sceptical with regards to competition for existing services, area utilisation, etc. Local businesses may suffer due to requirement for limited local services.
- **Pressure on social infrastructure**. Increased demands on social infrastructure (health, education, etc.) may put strains on municipal budgets.
- **“Not In My Backyard” (NIMBY) sentiment**. Areas of lower population density may be less likely to exhibit NIMBY sentiment.
- **Openness to new industry**. Traditional industrialised communities are generally more open to establishing new industry with regards to overall growth of the community (private and public sector).
- **Increased local income**. The influx of labour can lead to increased local spending, along with potential growth in local tax revenue, skill development and, possibly, future clustering of related industries as a result of the project.

- **Support for community development goals**. The project can build momentum for community development goals by attracting investment, enhancing local infrastructure, creating job opportunities, and supporting long-term economic growth.

Another factor is the impact the project may have on the attractiveness of the host community. The DBD project could lead to:

- Changes in property values.
- Increased demand for external labour, which could influence the local workforce.
- Traffic impacts from project logistics.
- Shifts in land use patterns, potentially affecting the community's appeal and growth.

When evaluating various DBD options in terms of socio-economic impacts, the following distinctions could be relevant:

- Options that generate more traffic may cause greater community disruption.
- Options requiring more labour over extended periods may boost local spending, but also increase the demand on local services.
- Longer construction and operational timelines could impact community perceptions, positively through sustained economic benefits and negatively through prolonged disruption.
- Deeper boreholes may prove more acceptable to risk-averse communities since the waste would be farther from the surface, potentially lessening concerns.

In conclusion, using potential socio-economic impacts to differentiate between DBD options remains challenging without a specific site and specific socio-economic regulations. The general considerations outlined here provide a preliminary understanding, but a detailed analysis will be needed once a site is chosen and relevant regulations are in place. Until then, distinguishing between DBD options on socio-economic grounds remains difficult.

Assessment by the OAP

As explained above, using potential socio-economic impacts as a way to differentiate between DBD options is challenging without a specific site and specific socio-economic regulations. It was concluded therefore that there is no basis currently to use such impacts as a means to differentiate between the options. A detailed analysis of this aspect should be undertaken once a site is chosen, and relevant regulations are in place.

Borehole geometry options	I	II	III	IV
Score for socio-economic impacts	5	5	5	5

1.3. Site characterisation

This criterion evaluates both the feasibility of finding an appropriate site and the complexity of the subsequent site characterisation work.

Main criteria		Sub-criteria
	Site Characteristics	• Feasibility of finding an appropriate site • Complexity of the subsequent site characterisation work

As explained in Section VIII.1.3, it is assumed that the disposal site meets the target host rock properties defined in [2424] (ACE 2). It is anticipated that the required site characteristics for DBD will be present in Norway, so there is confidence that a suitable site can be identified.

A preliminary assessment of groundwater composition in crystalline basements rocks below 1.5 km depth was done based on publicly available data from the following deep drilling projects in the crystalline basement of Germany, Finland and Sweden:

- German Continental Drilling Program KTB.
- Outokumpu Deep Drilling Project (Finland).
- DGE-1 borehole (Sweden).
- KLX02 borehole in Laxemar (Sweden).

Groundwater in the crystalline basement below 1.5 km often exhibits high salinity, with chlorine, calcium and sodium being the most abundant elements in solution. Salinity generally increases with depth. Reducing conditions are expected and pH values have been found to range from 5.3 to 9.3. However, the higher values may not accurately represent *in situ* conditions and might need to be adjusted downward.

Fisher et al. [2323] concluded that the area of Norway where Precambrian basement crops out and is present to great crustal depth appears ideal for borehole disposal (see Section VII.1.1). The Caledonides appear more challenging because of structural complications and lithological heterogeneity. Borehole disposal in the Oslo rift zone is assumed to be even less feasible because this area has been most recently tectonically active and is close to population centres.

Site characterisation for deep borehole disposal will require one or more site investigation boreholes. While theoretically the disposal borehole itself could be used for site investigation, this approach has some important disadvantages:

- The borehole would need to remain open for the period between site characterisation and the start of disposal operations, which could last years or even over a decade.
- The site characterisation itself might disturb the host rock around the borehole.
- Regulatory approval for this approach is uncertain [34].

Additionally, using the disposal borehole for site investigation poses a significant cost risk. Investigation boreholes can be drilled with a smaller diameter, whereas the disposal borehole requires a larger diameter. Drilling wider site investigation boreholes significantly increases their cost. Although the intention would be to offset these costs by using the same borehole for disposal, it is uncertain at the site investigation stage whether the site would be suitable and whether a license for the disposal operations would be obtained. Furthermore, the geotechnical parameters required to design the disposal borehole would not yet be known, complicating borehole design. Expanding a small-diameter investigation borehole into a larger disposal borehole is considered impractical due to difficulties in following the original borehole path. This may also significantly disturb the host rock.

Therefore, it is expected that one or more separate investigation boreholes will be needed. The exact number of boreholes will depend on regulatory requirements and the specific site characteristics. The investigation boreholes should be far enough from the disposal borehole to avoid interference but close enough to represent the conditions around disposal borehole. The optimal distance will depend on the site characteristics and the DBD design. For now, an indicative distance of 500 m is assumed (ACE 11). This distance is deemed sufficiently far to avoid interference while still being representative given the assumption that the disposal site will exhibit minimal lateral heterogeneity.

When comparing the different DBD options, there is little difference in the required site characterisation efforts between narrow-diameter and wide-diameter boreholes. Investigation boreholes are typically around 10 cm wide or slightly larger. This is sufficient for taking core samples and performing borehole logging. As a result, the choice of borehole diameter does not impose significant additional challenges or benefits in terms of site characterisation.

In contrast, borehole depth may play a more substantial role in determining the scope of the site characterisation work. Shallower boreholes generally will require less subsurface investigations compared to deeper boreholes because the volume of rock to be analysed is smaller and existing petrophysical data may be more readily available. Furthermore, deeper boreholes may present technical challenges: increased temperature and pressure at greater depths can affect the accuracy and functionality of measuring instruments. However, deeper boreholes may result in increased containment and isolation which could, in turn, reduce the site characterisation requirements to establish a robust safety case. Nevertheless, in the absence of a specific site, it remains speculative whether a borehole at 3 km or 5 km depth would provide a substantial advantage in terms of overall characterisation efforts, as the requirements for site characterisation and safety case development will depend on the local geological conditions. There is therefore no solid basis for favouring one option over the other in terms of site characterisation efforts.

As part of the site characterisation assessment, and for costing purposes, it is assumed that a small investigation borehole, approximately 10 cm in diameter, will be required. (ACE 11)

Additionally, it is likely that as part of the early stages of DBD implementation, it is likely that a field test demonstration would be needed. Such a field test would be a demonstration borehole, matching the diameter of the disposal borehole, drilled to test and demonstrate borehole construction, waste emplacement and borehole closure technologies. There are no constraints on the design, location or timing of the field test demonstration and it has been excluded from consideration in the cost assessment.

Assessment by the OAP

Feasibility of finding an appropriate site

As explained in section VIII.3.3, it is assumed that the disposal site meets the target host rock properties defined in [2424] (ACE 2). The likelihood of finding suitable site conditions is considered to be higher at greater depth. Therefore, the deeper DBD options II and IV were given a score of 5, while the shallower options I and III were given a lower score of 4.

Borehole geometry options	I	II	III	IV
Score for the feasibility of finding an appropriate site	4	5	4	5

Complexity of site characterisation work

As explained in section VIII.3.3, the choice of borehole diameter does not impose significant additional challenges or benefits in terms of site characterisation. Furthermore, there was no justification for favouring either the shallower or deeper options based on site characterisation efforts.

Borehole geometry options	I	II	III	IV
Score for complexity of site characterisation work	5	5	5	5

1.4. Technical implementation

The 'Technical Implementation' criterion refers to the difficulty associated with implementing the DBD option.

Main criteria	Sub-criteria
Technical Implementation	• Maturity of borehole technology (borehole drilling, casing, waste emplacement, sealing) • Maturity of waste encapsulation technology

1.4.1. Maturity of waste encapsulation technology

As shown in Figure 16 the DBD project consists of the encapsulation of the waste in overpacks, the transport of these overpacks to the disposal site and the disposal of the overpacks at the disposal site. These operations are described in section VIII.2. Regarding the maturity of these technologies, a distinction is made between waste encapsulation and borehole technology.

The transport of waste from the encapsulation plant to the borehole disposal site is not factored into the assessment of technological maturity, as this type of transport is routinely conducted worldwide and does not introduce any technological uncertainty.

The technological maturity of waste encapsulation is regarded as high. Similar overpacks to those proposed in the DBD options are currently being considered, designed, and manufactured in other waste disposal programmes. Electron beam welding is considered a viable method for welding the overpacks. This requires a vacuum chamber around the weld area, which could incur significant development costs. Nevertheless, this is a well-established and widely used welding technique.

Assessment by the OAP

As explained above, there are few uncertainties regarding the technological maturity of waste encapsulation. While the larger diameter of the overpacks in options III and IV introduces slightly more demanding requirements on the welding process, this is not significant enough to warrant differentiating the scores of the various options. A more substantial distinction lies in the greater variety of waste forms present in options I and II. These differing waste forms necessitate the use of various types of internal baskets to adequately fill the space around the waste within the overpacks. As a result, the technological maturity of options I and II was assigned a lower score of 4, while options III and IV received the highest score.

Borehole geometry options	I	II	III	IV
Score for the maturity of waste encapsulation technology	4	4	5	5

1.4.2. Maturity of borehole technology

A preliminary review of technical maturity for the different operations at the borehole site is included below[4]. Whilst the drilling challenge falls between traditional relatively small diameters of the oil, gas and geothermal wells and the much larger diameter boreholes now drilled commonly for mine shaft access and ventilation, the process still demands a high technical maturity. The development of large-diameter tools to place the SSM in a dump bailer and the bentonite in a downward placement systems (DPS) for the main seal, will need some further design work.

Table 15: Technical maturity of different operations at the borehole disposal site

Component	Technical Maturity	Comments
Site development	High	
Drilling rig	Medium to high	Rigs would need minor modification
Mobilisation	High	
Well control	Medium to high	
Drilling and casing	Medium	Outside current experience
Waste package emplacement	Medium	Latching system needs development
SSM emplacement	Lower to medium	Dump bailer upscaling required
Cut and pull casing	Medium	Larger casing than normal
Placement of plug above disposal zone	Medium	Tremie for large quantities
Primary seal emplacement	Low to medium	DPS upscaling required
Borehole backfilling	Medium	Uncertainty about backfill material

When comparing the different DBD options, there is mainly a difference in the technical maturity of constructing the boreholes. The dimensions of the different boreholes are summarised in Table 16.

Table 16: The dimensions of borehole options

Borehole geometry options	I	II	III	IV
Borehole depth [m]	2300	3800 m	1600	3100
Borehole diameter at the bottom of the borehole [mm]	610	610	990	990

The narrow boreholes can be drilled with modern technology. No examples exist of wider boreholes in crystalline rock to 3 km depth, but this is not due to technical limitations, but rather a lack of demand. The existing technology can likely be scaled up to larger diameters if needed.

There are no differences between the options concerning the TRL of waste emplacement and casing installation. Also the technical maturity for casing, backfilling and sealing is the same for all options. However, it is important to note that the emplacement of SSM at a depth of 3 km has not yet been conducted or demonstrated. Additionally, the higher host rock temperatures in the deeper options

[4] At a later stage, a detailed review of the Technology Readiness Level (TRL) of the different components of the Norwegian shortlisted DBD options will be carried out, implementing a bespoke TRL assessment framework in line with the recommendations of the IAEA CRP on DBD Implementation.

could lead to a quicker hardening of the cementitious materials, which could complicate their proper emplacement.

Assessment by the OAP

The feasibility of constructing boreholes was scored based on the diameter and depth of the boreholes. The shallow borehole with a narrow diameter (option I) was considered the easiest to construct and therefore received the highest feasibility score of 5. The deeper borehole with a narrow diameter (option II) and the shallow borehole with a wide diameter (option III) are more challenging. These options received a lower score of 4. Option IV – the deep borehole with a wide diameter – is technically the most demanding to construct and received a score of 3.

Apart from borehole construction, there is the technological challenge of SSM emplacement. This is more difficult for deeper boreholes. However, it is believed that these difficulties are already adequately accounted for in the feasibility scores assigned to borehole construction and there is no need to further reduce these scores.

Borehole geometry options	I	II	III	IV
Score for the maturity of borehole technology	5	4	4	3

1.5. Flexibility

The 'Flexibility' criterion addresses how well the DBD option can handle changes, for example in the predisposal management or the inventory of the radioactive waste. The assessment under this criteria focuses on the ability of the DBD system to respond to changes in waste volumes or characteristics, operational or regulatory changes, and/or strategic changes.

Main criteria		Sub-criteria
	Flexibility	• Adaptability to respond to changes in programme or regulatory changes

Options involving a wider borehole, such as options III and IV, provide greater flexibility because the overpacks and borehole in these options can accommodate all SNF and/or HLW generated in the different spent fuel management options under consideration by NND. This flexibility allows for deferred decision-making regarding the SNF treatment method.

Currently, the DBD options are limited to the borehole disposal of SNF and/or HLW, excluding long-lived (LL) ILW. However, should the consideration of co-disposal of LL-ILW and SNF/HLW arise, the wide borehole options would again prove more flexible because they provide less stringent dimensional constraints and an increased disposal volume per unit length of borehole compared to narrow borehole options. Additionally, deeper boreholes also provide more flexibility because LL-ILW could be emplaced above the SNF/HLW without increasing the total depth of the borehole.

Currently, there is no regulatory requirement in Norway for the retrievability of SNF or HLW disposed of in a DGR or a deep borehole. Should future regulations introduce such a requirement, retrieval operations would generally be easier in shallower boreholes than in deeper ones. Retrieving the waste from the borehole could be done by overcoring. To facilitate any potential retrieval of the overpacks, the annulus between the overpacks and the casing could be made greater than necessary for emplacement operations. This would increase the bottom diameter of the borehole, which would be easier in the narrow boreholes than in the wide ones.

Assessment by the OAP

The 'Flexibility' criterion addresses how well the DBD option can handle changes, such as the complexity of implementing the option and its ability to respond to changes (e.g., in waste volumes or characteristics, regulatory requirements or strategic choices). Complexity of implementation was addressed within the operational safety element (i.e., the number of process steps). Therefore, only the adaptability of the options was assessed.

In this assessment, the deeper and wider boreholes were found to offer greater flexibility due to their increased disposal volume, enabling them to accommodate a larger waste volume and/or wider waste forms. Therefore, option IV received the highest score of 5. Options II (narrower and deeper) and III (shallower) were assigned lower scores of 4. Option I, which is both shallower and narrower, was given the lowest score of 3.

In contrast, when retrievability is taken into account, the shallower and narrower options perform better. However, the ability to maximise disposal volume was prioritised over retrievability in this evaluation.

Borehole geometry options	**I**	**II**	**III**	**IV**
Score for adaptability	3	4	4	5

1.6. Security and safeguards

Security refers to the prevention, detection and response to theft, sabotage, unauthorised access, illegal transfer or other malicious acts involving the radioactive waste. Safeguards refers to the measures to ensure that the IAEA can supervise or prevent fissile materials in the SNF or HLW being diverted for military purposes.

Main criteria	**Sub-criteria**
Security and safeguards	• Operational security and safeguards • Post-closure security and safeguards

During the operational phase, the borehole site will be secured. These security measures may remain in place, possibly in a reduced form, during the institutional control phase after borehole closure. The same level of security can be applied for all DBD options, meaning there is no difference in security between them during the operational phase.

Once the active security measures are lifted, the security of the disposal site will depend on passive features intrinsic to the DBD concept. The main feature is the disposal depth which provides a high degree of isolation. Additionally, the small footprint of the borehole minimises the risk of inadvertent human intrusion. The disposal site can further enhance security, as a remote site with limited or no resources reduces the likelihood of intrusion.

When comparing the different DBD options, only the disposal depth represents a significant distinction. The footprint remains negligibly small for all options and the option of selecting a remote site with no or limited resources is possible for each option.

The IAEA safeguards are a set of technical measures implemented to verify that fissile materials are not diverted from peaceful uses to the development of nuclear weapons. These safeguards are designed to monitor and account for fissile material. Since IAEA safeguards apply only to fissile materials, the vitrified

HLW in options III and IV is not subject to safeguards. However, because some SNF will be treated using MMC and the ingots disposed of in the borehole, safeguards measures will still be required for options III and IV, just as they are for options I and II.

Currently, the IAEA does not have specific standards or guidelines for safeguarding SNF that is placed in geological repositories, including DBD. Nevertheless, there does not seem to be a reason to differentiate safeguards requirements between the different DBD options.

Assessment by the OAP

There are no differences in the security measures that need to be implemented for the four DBD options, nor is there a notable variation in the level of security they provide during either the operational or post-closure phases. While the deeper options might be perceived as offering a greater degree of security, both disposal at depths of 1.5 km and 3 km are considered extremely secure. Therefore, there is no justification for distinguishing between the shallower and deeper DBD options in terms of security.

From a safeguards perspective, there is no clear basis to distinguish between the options. Although options 3 and 4 will involve less waste subject to safeguards compared to options 1 and 2, all options will require safeguards measures, like maintaining continuity of knowledge, verifying the final design or ongoing site surveillance. The specifics of these measures cannot be defined without a licensed design that has undergone evaluation by the IAEA Department of Safeguards (ACE 14). Therefore, it is not possible to rank the options based on potential safeguards obligations. However, any differences in safeguard requirements between the options are expected to be minimal. Consequently, all options receive the same score for safeguards.

Borehole geometry options	**I**	**II**	**III**	**IV**
Score for security and safeguards during the operational phase	5	5	5	5
Score for security and safeguards during the post-closure phase	5	5	5	5

1.7. Environment/sustainability

The criterion 'Environment/Sustainability' addresses the potential environmental impact and long-term sustainability of the full life cycle of the DBD option and considers four sub-criteria as defined in the table below.

Main criteria		**Sub-criteria**
	Environment/Sustainability	• Material requirements • Energy requirements • Secondary waste • Carbon footprint

It is recognised that some overlap exists among these sub-criteria. For example, higher material and energy demands will contribute to a larger carbon footprint. Nevertheless, carbon footprint is included as a distinct sub-criterion due to its frequent use as an indicator of a project's environmental impact and because it is frequently scrutinised by authorities and NGOs. Further, the carbon footprint of materials and activities is not necessarily directly proportional to their quantification against the other sub-criteria, for example, the carbon footprint of cement relative to clay is greater than the simple weight ratio of the two materials.

The following environmental factors are either the same for all options, are considered not to be significant, or are considered elsewhere in the analysis, so are not considered further here:

- **Biodiversity and footprint**. The infrastructures above ground and in the upper layers of soil, where most life exists, are similar for each option. Consequently, the impacts on biodiversity are expected to be similar for each option. The footprint is also assumed to be the same for each option (ACE 19).
- **Climate change adaptation**. Surface and shallow installations, as well as construction and transport operations, will be exposed to climatic hazards and may be sensitive to flooding, strong winds, extreme temperatures, etc. However, the options are very similar in this regard. All of the deeper installations are not sensitive to climatic hazards.
- **Water usage**. Water is necessary for drilling the borehole and extracting the cuttings. This water will be managed through treatment and reuse in borehole operations, which is why it is not included in the secondary waste sub-criterion. Additionally, the volume of water used is assumed to be incorporated into the material requirements.
- **Noise**. The impact of noise depends on the duration of the works, the site machinery and the off-site transportation. However, it is assumed that the borehole site will be located in a remote area (ACE 19). Therefore, noise and vibrations are not expected to be a significant issue.
- **Air**. Except for emissions from diesel generators (if chosen as the power solution) and vehicle traffic (if internal combustion engine vehicles are used), drilling and emplacement operations are not associated with air pollution. Diesel use and traffic are accounted for under energy requirements.

Complementary Note 10 [3] describes further how the “'Environment/Sustainability” criterion has been broken down into a set of sub-criteria to best represent the environmental characterisation of the DBD options for the purposes of this options assessment. This takes into account the generic (i.e. not site-specific) stage of the assessment and the scope with it being largely focused on the options for different depths and diameters of the disposal boreholes.

The estimated material requirements for the four DBD options are presented in

Table 17. This estimate includes the materials required for manufacturing the overpacks and for constructing and closing the borehole. It is assumed that the material requirements for the construction of the encapsulation plant and other surface facilities will be similar for all DBD options and they have not been included (ACE 19). There may be some differences related to the overpack designs, but these are expected to be minimal compared to the materials needed for the construction of the encapsulation plant and other surface facilities. There is no design on which to base estimates of the material requirements for the encapsulation plant and, since the numbers would be the same for each option, their inclusion would only dilute the differences calculated for other activities. Material requirements associated with drilling site investigation boreholes are not included, as there is no basis to differentiate the number of investigation boreholes needed for each option. For comparison with the numbers, a single LLW disposal vault at Dounreay (United Kingdom) used around 3900 m^3 of reinforced concrete [35].

Table 17: Estimated material requirements of the DBD options

Borehole geometry options	I	II	III	IV
Overpack steel [m^3]	22.4	22.4	3.2	3.2
Drilling steel casing [m^3]	295	800	517	1404
Cement/concrete in casing [m^3]	841	2544	1358	3870
Cement for SSM and unfilled disposal zone [m^3]	73	73	123	123
Bentonite for main seal [m^3]	18	18	31	31
Cement/concrete for plug and seal [m^3]	307	307	84	84
Backfill [m^3]	1001	2156	2030	4373
Total	**2557**	**5920**	**4146**	**9888**

The energy consumption for drilling, operating and closing the borehole is estimated based on the amount of diesel consumed – roughly 10 m^3 per day [36]. This energy consumption can is converted to kWh on a basis of 10 kWh per litre of diesel (see Table 18). However, use of renewable energy sources can be a strong mitigating factor in these calculations. The energy requirements for the manufacture of the overpacks has been approximated by the energy requirements for the manufacture of rolled steel (around 20 GJ/tonne [37]). Again this energy use can be mitigated by use of renewable energy sources and/or recycled materials. The number of transport operations is given in Table 14, but the differences in transport cannot be scaled to energy requirements without site-specific information. Additionally, variations in energy requirements associated with the construction and operation of the encapsulation plant are not included in this analysis, as these differences are highly uncertain without specific design details.

Table 18: Estimated energy consumption of the DBD options

Borehole geometry options	I	II	III	IV
Energy (drilling)	2.8E+07	4.3E+07	4.0E+07	5.8E+07
Energy (operations and closure)	2.0E+07	2.2E+07	6.1E+06	8.1E+06
Energy (fabrication)	1.4E+06	1.4E+06	2.0E+05	2.0E+05
Total [kWh]	**5.0E+07**	**6.7E+07**	**4.6E+07**	**6.6E+07**

The estimated amount of secondary waste generated is based on the spoil volume produced during the borehole drilling operations, as detailed Table 19. Wastes related to the encapsulation plant, surface facilities or investigation boreholes are excluded from this estimate, as these quantities are either assumed to be similar for all DBD options or cannot be accurately assessed with the available information (ACE 19).

Table 19: Estimated amount of spoil generated in the DBD options

Borehole geometry options	I	II	III	IV
Spoil volume [m^3]	1719	4267	2904	7348

The estimated carbon footprint in the equivalent kilogrammes of carbon dioxide emissions for the different DBD options is given in Table 20. These estimates are based largely on the materials and energy requirements for fabrication of the overpacks and drilling of the boreholes. The different transport requirements are included, but their impact is minimal in this analysis, as they cannot be scaled for distance without site-specific information. Impacts related to the encapsulation plant, surface facilities or investigation boreholes are excluded from this estimate, as these quantities are either assumed to be similar for all DBD options or cannot be accurately assessed with the available information (ACE 19). For comparison, the total carbon emissions equivalent in Norway in 2022 were estimated at 4.1e10 kg CO_2e [38].

Table 20: Estimated material and energy requirements, secondary waste generation and carbon footprint of the DBD options

Borehole geometry options	I	II	III	IV
Material	7.6E+06	2.2E+07	1.5E+07	4.3E+07
Fuel	1.4E+03	2.5E+03	1.6E+03	3.5E+03
Waste	5.8E+03	1.4E+04	9.8E+03	2.5E+04
Energy	1.1E+07	1.5E+07	1.1E+07	1.5E+07
Total carbon emission [kg CO_2e]	**1.9E+07**	**3.7E+07**	**2.6E+07**	**5.9E+07**

Assessment by the OAP

The paragraph above presents the estimated material and energy requirements, secondary waste generation and carbon footprint of the DBD options. These estimates are summarised in Table 21.

Table 21: Estimated material and energy requirements, secondary waste generation and carbon footprint of the DBD options

Borehole geometry options	I	II	III	IV
Material requirements [m^3]	2557	5920	4146	9888
Energy requirements				
Energy consumption [kwH]	5.0E+07	6.7E+07	4.6E+07	6.6E+07
Number of transports	496-572	937-1013	631	1394
Spoil volume [m^3]	1719	4267	2904	7348
Carbon footprint [kg CO_2 e]	1.9E+07	3.7E+07	2.6E+07	5.9E+07

These numbers formed the basis for scoring the various options, which are detailed in the table below. It was not possible to weight or assess the importance of the number of transports, as this depends on the distance from the borehole site to the spoil removal location.

Borehole geometry options	I	II	III	IV
Score for material requirements	5	4	5	3
Score for energy requirements	5	3-4	5	3-4
Score for secondary waste	5	3	4	2
Score for carbon footprint	5	4	5	3

It was noted that while there are clear differences between the different options, the absolute values reflect limited material and energy requirements, spoil volumes and carbon emissions. This is all the more relevant considering that the construction of the encapsulation plant, surface facilities and investigation boreholes are not included in the assessment, as these factors are assumed to be comparable or cannot be estimated at this time (ACE 19). Consequently, the differences in scoring, although grounded in the factual basis presented in Table 21 above, may exaggerate the distinctions between the options, particularly when compared to the differences observed in the assessment of other criteria. This observation has been taken into account in the sensitivity analysis that follows.

1.8. Lifetime cost

Lifetime cost evaluates the financial costs associated with a DBD option.

Main criteria		Sub-criteria
	Lifetime Cost	• Base cost and contingency cost (NOTE 1) • Cost risk

NOTE 1: Because contingency varies in the same way as base cost, it was decided in the Optioneering workshop to combine the sub-criteria for base cost and contingency cost into a single score based on the total of both cost elements.

A cost estimate of the DBD options was developed (see Complementary Note 11 [3]). The purpose of the cost estimate is to obtain a preliminary and high-level estimate of the cost of the borehole disposal of Norway's SNF and/or HLW and to assess whether there are substantial differences in costs between the different options.

It is important to note that it is not a full lifecycle cost analysis and does not include the cost of SNF treatment or reprocessing. The scope of the estimate includes the costs for developing a license application for DBD, including site characterisation costs, and the cost of implementing the DBD option. The following costs are not included (ACE 11):

- Costs associated with stakeholder involvement, including potential benefits to local communities.
- Costs associated with regulatory review.
- Generic R&D costs such as development of a demonstration borehole or field test elsewhere in Norway. It is assumed at this stage that generic R&D costs would be similar across the options (ACE 8). The demonstration borehole or field test may be planned in the Programme initiation stage before the site characteristics of the disposal borehole are known and the spent fuel treatment option is selected.
- Costs for spent fuel treatment and interim storage.

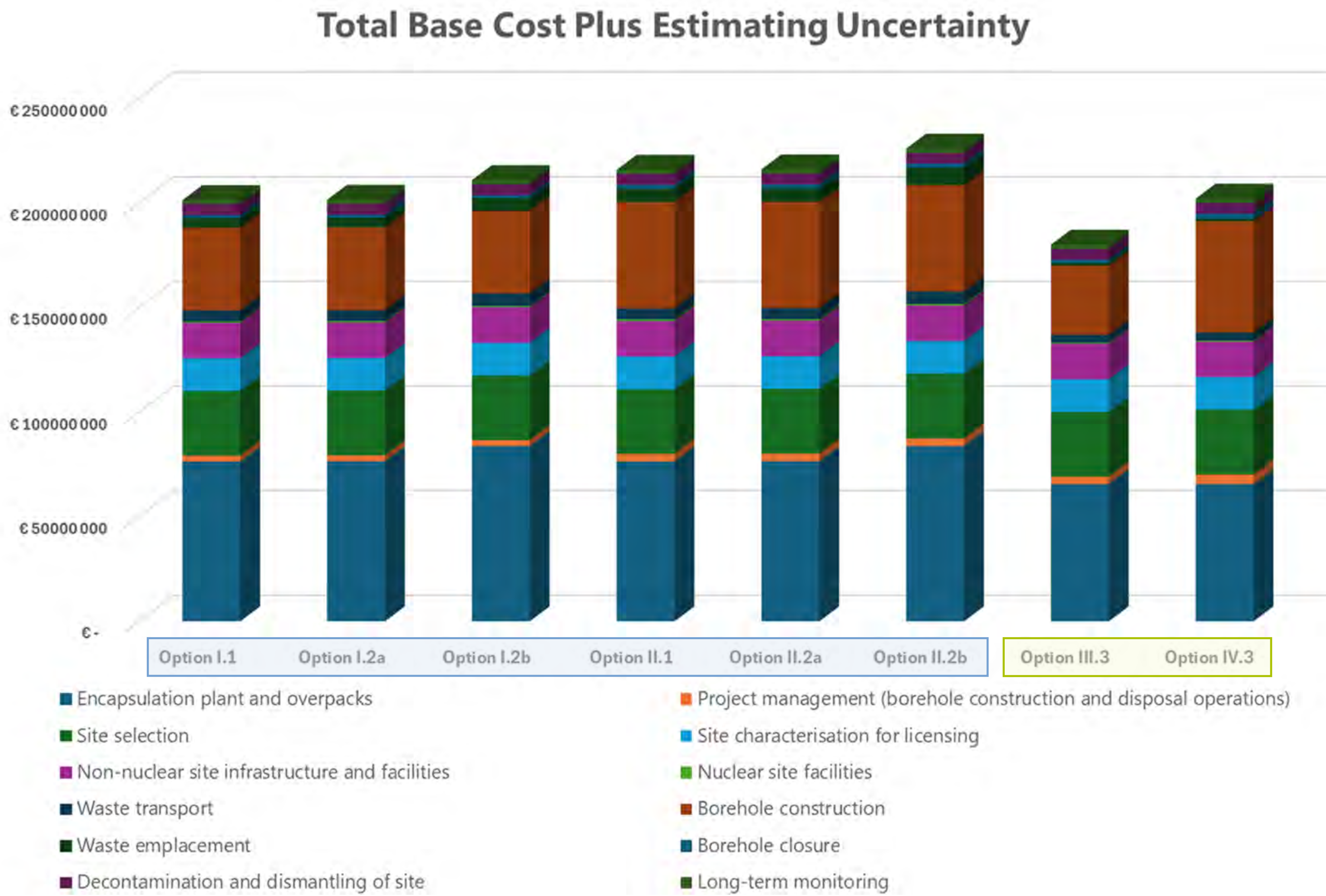
The estimate consists of the following elements:

- The base cost of the options.
- An allowance for estimating uncertainty (contingency).
- A preliminary analysis of risks and opportunities that may have an impact on the cost estimate.

Figure 29 presents a summary diagram of the base cost, plus estimating uncertainty (contingency) for each of the DBD options. The base costs for the options show only about 20% variation with the main cost components being the encapsulation facility and overpacks, the characterisation activities leading to site selection and the cost of drilling the borehole and emplacing the overpacks. The total cost varies from €180M for option III (1500 m disposal, full reprocessing) to €226M for option II (3000 m disposal, SNF management variant 2b). This cost difference largely reflects the shorter timescales needed to drill a 1500 m borehole and the smaller number of overpacks to dispose of in the reprocessed options and means that options III and IV are respectively cheaper or of similar cost to option I.

To provide a preliminary estimate of the provisions that could be needed to cover potential future project risks, an indicative set of risks and opportunities has been identified for the DBD options (refer to Complementary Note 11 [3]). Based on assumed risk probabilities, impacts and risk appetite, a risk provision in the order of €10 to €20M was estimated (ACE 11). This provision was not greatly different between the different options indicating that the options were mostly considered to be equally susceptible to risks, with deeper disposal options involving a longer drilling time only being slightly more vulnerable.

Figure 29: Stacked bar chart showing the total cost of the DBD options, including both base cost and estimating uncertainty (contingency)



Assessment by the OAP

The scoring for lifetime cost was based on the preliminary cost estimate of the DBD options (see Section VIII.3.8 and Complementary Note 11 [3]). It is important to reiterate that the cost estimate is not a full lifecycle cost analysis but focuses on those cost elements that could differ between the DBD options.

Contingency costs are estimated to be a fixed percentage (30% or 40%) of the base costs. Because contingency varies in the same way as base cost, it was decided to combine the sub-criteria for base cost and contingency cost into a single score based on the total of both cost elements. Table 22 presents the estimated costs of the DBD options. As can be seen, there are variations in the score of the different variants for options I and II. The total estimated cost for option I ranges from €201M to €211M and for option II from €216M to €226M. As a result, a score of varying from 3 to 4 was given to options I and II. Options III (€180M) and IV (€202M) were allocated scores of 5 and 4, respectively.

Table 22: Estimated cost of the DBD options, including both base cost and estimating uncertainty (contingency)

Borehole geometry options	**I**			**II**			**III**	**IV**
	1a	**2a**	**2b**	**1a**	**2a**	**2b**		
Base cost [€M]	151	152	159	163	163	170	135	202
Contingency cost [€M]	50	50	52	53	53	56	45	50
Total [€M]	**201**	**201**	**211**	**216**	**216**	**226**	**180**	**202**

Table 23 presents the estimated risk probability x cost impact for each DBD option. It is important to note that these estimates are based on assumed risk probabilities and impacts (ACE 11). They are not intended to guide future decisions regarding risk provisions, which would necessitate a more comprehensive and substantiated analysis. The sole purpose of these estimates is to provide indicative figures that may help identify any significant differences between the options in terms of risk provisions.

Table 23: Estimated risk probability x impact for the DBD options. Depending on risk appetite, the risk provision could be set as a fraction of these values

Borehole geometry options	**I**	**II**	**III**	**IV**
Preliminary estimate of the risk probability x impact [€M]	36	41	36	41

Since these differences in risk provision relative to the overall cost are minimal, each option was given an equal score of 5.

Borehole geometry options	**I**	**II**	**III**	**IV**
Score for base cost and contingency cost	3,5 (3-4)	3,5 (3-4)	5	4
Score for cost risks	5	5	5	5

2. Qualitative evaluation of pros and cons

The main value of the MCA lies in its ability to highlight the various pros and cons of each option, providing insight into why certain options may be preferred over others. Ultimately, which options are deemed preferable will depend on the relative importance assigned to different aspects. That relative importance is influenced by individual preferences and is subjective. The MCA offers a valuable tool for clarifying how these preferences shape the selection of a DBD option.

The shallow DBD options perform better than the deeper options in several key areas:

- Conventional safety for workers and the public as they require fewer working days and truckloads for spoil removal.
- Technological maturity.
- Environmental impact as material and energy demands and carbon footprint are lower.
- Cost.

The deeper options score better in the following areas:

- Post-closure safety as they offer greater isolation and result in longer radionuclide travel times to the biosphere.
- Flexibility as they provide a larger disposal volume, although waste retrievability may be more complex in deeper boreholes.
- Ease of finding a suitable site as suitable site characteristics are more likely to be found at greater depths.

It is essential to note that shallow options would only be implemented at a site that meets the required characteristics for borehole disposal.

Next, the different spent fuel treatment options can be compared based on their implications for borehole disposal of the resulting SNF and/or HLW. In this case, a clearer and less ambiguous picture emerges than with the comparison between shallower and deeper options. The DBD options for PUREX reprocessed HLW perform better in several key areas:

- Conventional and radiological safety to workers as they involve a smaller variety of waste types to be encapsulated and require fewer overpacks.
- Maturity of the encapsulation process as the greater variety of waste forms in the other options necessitates the use of various types of internal baskets to adequately fill the space around the waste within the overpacks. This is believed to outweigh the slightly more demanding requirements on the welding process for the wider overpacks for PUREX reprocessed HLW.
- Flexibility as the wider boreholes in these options provide a larger disposal volume, although waste retrievability may be more complex in wider boreholes.
- Cost because fewer overpacks are needed.

However, the DBD options for PUREX reprocessed HLW require wider overpacks and wider boreholes, leading to lower scores in the following areas:

- Technological maturity of the drilling technology.
- Environmental impact as material demands, secondary waste generated and carbon footprint.

Based on this analysis, and solely from the viewpoint of borehole disposal of the waste, PUREX reprocessing of spent fuel emerges as the preferred option. However, selecting a spent fuel treatment strategy encompasses a wide range of factors beyond disposal considerations. Nevertheless, the optioneering approach has shown that none of the DBD options constrains the optioneering of the spent fuel treatment strategy.

3. Ranking at criteria level and sensitivity analysis

Based on the scores assigned to the different options for the different (sub)criteria, a ranking of options can be established. This is presented in Table 24 and without applying any weighting. The overall scores differ, but not by significant amounts because all of the options were considered credible and most of the scores were 3 or above. However, it is important to see if weighting causes there to be greater differences between the options and if so, which criteria are most sensitive to weighting.

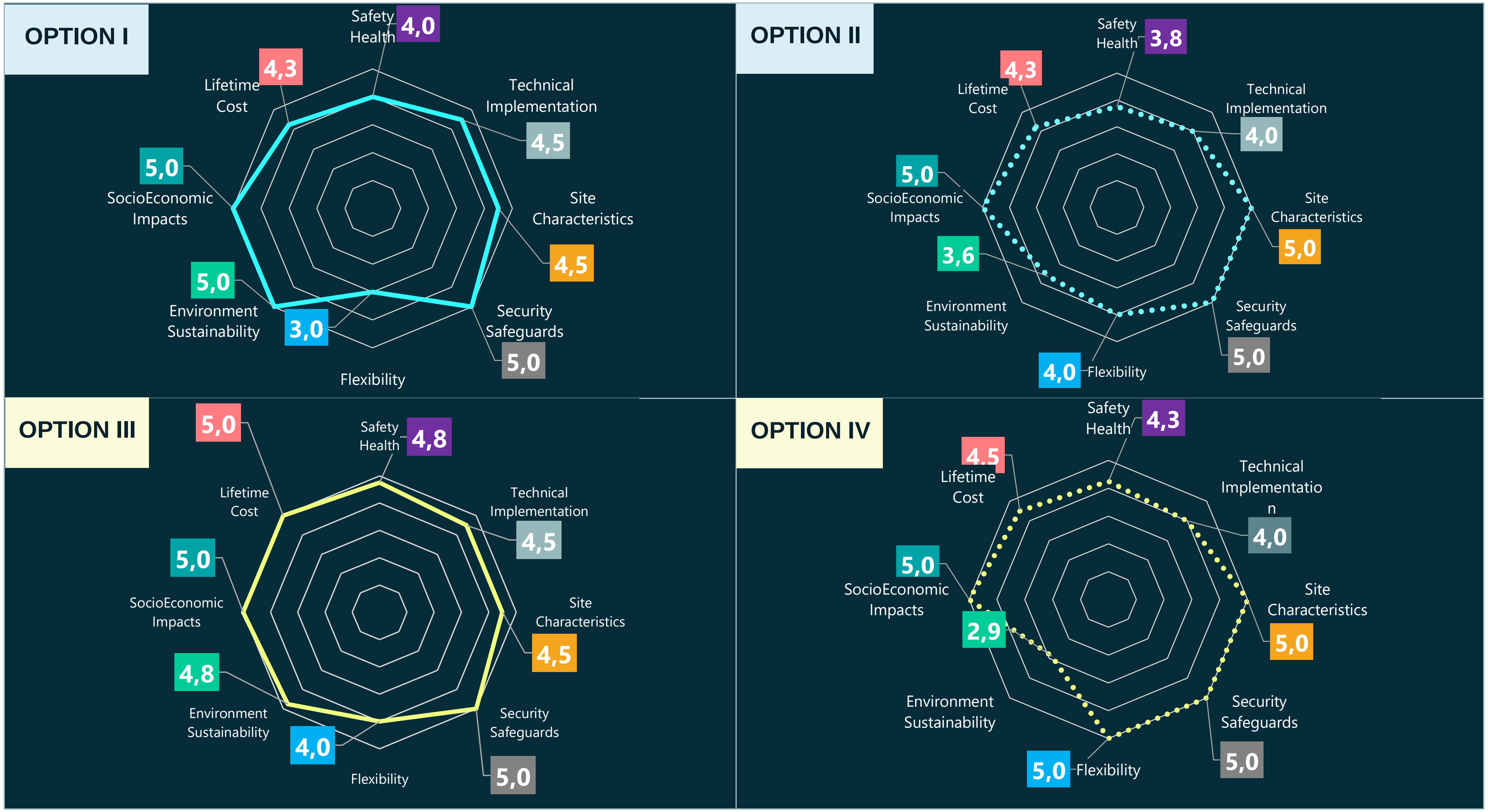
The Option Assessment Panel agreed in the workshop to apply the same weight among the sub-criteria within a criteria, which results in the scores at criteria level highlighted in Table 25.

Table 24: Overall scoring for the different options (unweighted)

Borehole geometry options	I	II	III	IV
Safety Health				
Post-closure safety	4	5	4	5
Conventional safety to the **workers**	4	3	5	4
Conventional safety to the **public**	5	4	5	3
Radiological safety to the workers and public	3	3	5	5
Socio-Economic Impacts				
Impact on the local community and economy	5	5	5	5
Site Characteristics				
Ease of finding a site in Norway	5	5	5	5
Difficulty/complexity to characterise a potential DBD site	4	5	4	5
Technical Implementation				
Maturity of technology (**drilling, casing, waste emplacement, sealing**)	5	4	4	3
Maturity of technology (**waste treatment and packaging**)	4	4	5	5
Flexibility				
Complexity and adaptability	3	4	4	5
Security/ Safeguards				
Operational security and safeguards	5	5	5	5
Post-closure security and safeguards	5	5	5	5
Environment Sustainability				
Material requirements	5	4	5	3
Energy requirements	5	3	5	3
Secondary waste	5	3	4	2
Carbon footprint	5	4	5	3

Borehole geometry options		I	II	III	IV
	Lifetime Cost				
	Base and **contingency** cost	3,5	3,5	5	4
	Cost **risk**	5	5	5	5
	Overall score (unweighted)	**80,5**	**75**	**85**	**75,5**

Figure 30: Radar diagrams showing scoring for the different options at criteria level



As mentioned in section VI.3.2, assigning weights to different criteria is inherently subjective. Different stakeholders have differing values and priorities and will assign different weights to the criteria. Therefore, a sensitivity analysis was conducted by considering different weight sets and checking to see the impact on the overall score and ranking of the options. In particular, this analysis seeks to identify trade-offs in weighting and seeks to understand which options could be sensitive to changing the weight on specific criteria.

The OAP discussed the impact on scoring of an alternative location of the encapsulation plant to the disposal site or a third site (see VIII.2). The OAP considered that the differences in terms of transportation (from storage to encapsulation plant and/or to disposal site) would impact similarly all options, not changing their relative ranking.

A series of four alternative weighting scenarios were considered in order to evaluate their impact on the overall result – baseline weighting and Scenarios 1, 2 and 3, respectively reflecting potential interests of local communities, waste owners, and regulators. (ACE 3)

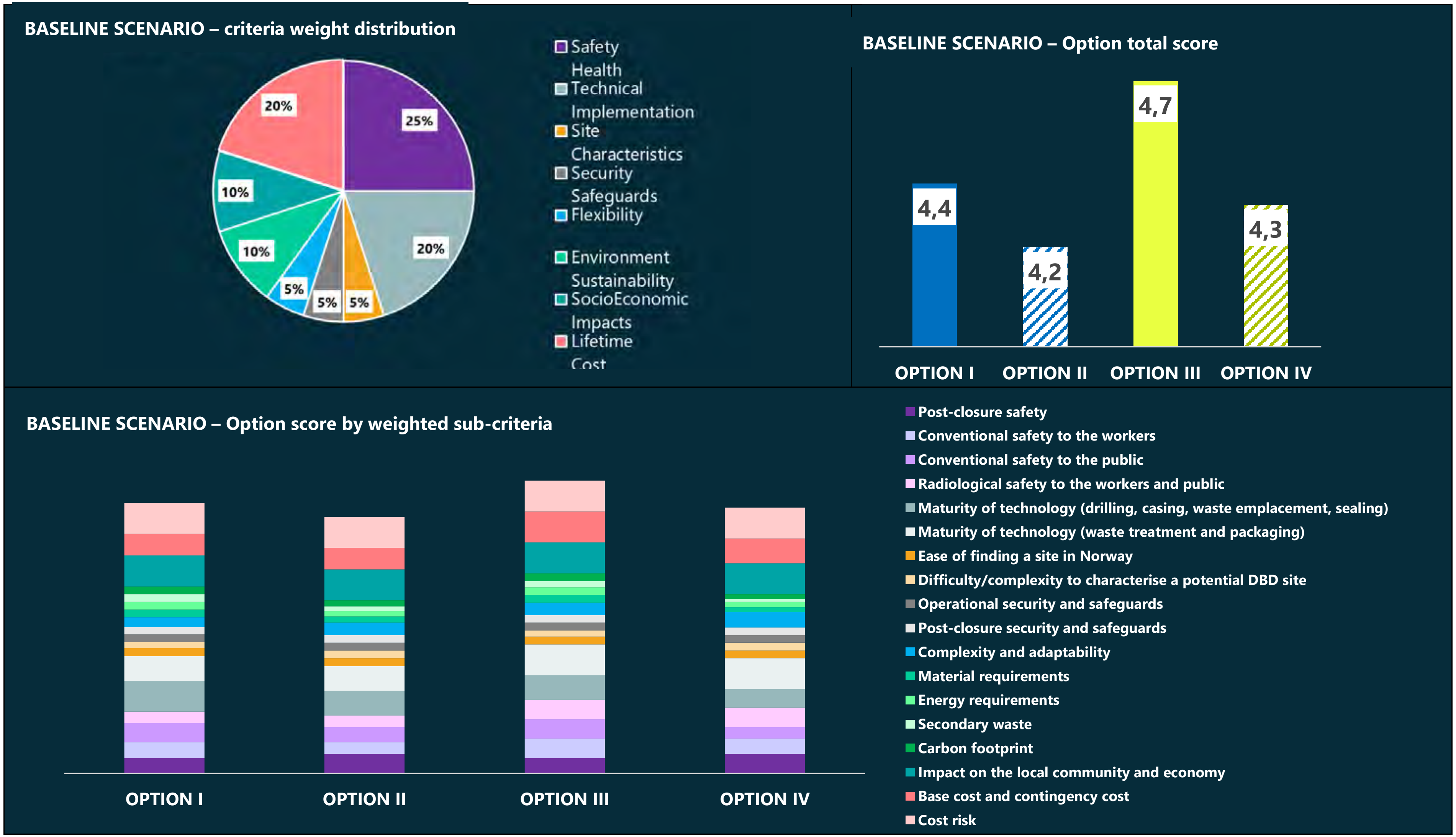
Baseline weighting representing a set of weights that is aligned with those used in related options assessment of SNF management options carried out by Jacobs (now Amentum) and GeoReN.

Table 25: Overall scoring for the different options

Assessment criterion		Baseline weighting factor	Maximum score	Option I	Option II	Option III	Option IV
	Safety/Health	25%	1,2	1,0	0,9	1,2	1,1
	Socio-Economic Impacts	20%	0,9	0,9	0,8	0,9	0,8
	Site Characteristics	5%	0,3	0,2	0,3	0,2	0,3
	Technical Implementation	5%	0,3	0,3	0,3	0,3	0,3
	Flexibility	5%	0,3	0,2	0,2	0,2	0,3
	Security/ safeguards	10%	0,5	0,5	0,4	0,5	0,3
	Environment/ Sustainability	10%	0,5	0,5	0,5	0,5	0,5
	Lifetime Cost	20%	1,0	0,9	0,9	1,0	0,9
	Overall score(weighted) – maximum score 5			4,4	4,2	4,7	4,3

The assessment scores and baseline weighting results are plotted in Figure 31 where it can be seen that Option III has the highest weighted score, but all of the scores for the other options are within 0.5 of each other, which equates to only about 12% of the lowest score, so the differences in total score of the options is not great. The two deeper options score lowest for environment owing to the greater environmental impact of drilling a deeper hole. The highest performing Option III, which is one of the shallower options, performs better than the other options on all criteria except Flexibility. As well as having better environmental and safety impacts, it contains a smaller, less radiotoxic waste inventory as a result of reprocessing.

Figure 31: Comparison of option performance when applying baseline scenario weighting



Scenario 1 involves a weight set reflecting potential priorities of local communities, with a stronger emphasis on safety, socio-economic impacts and environment/sustainability.

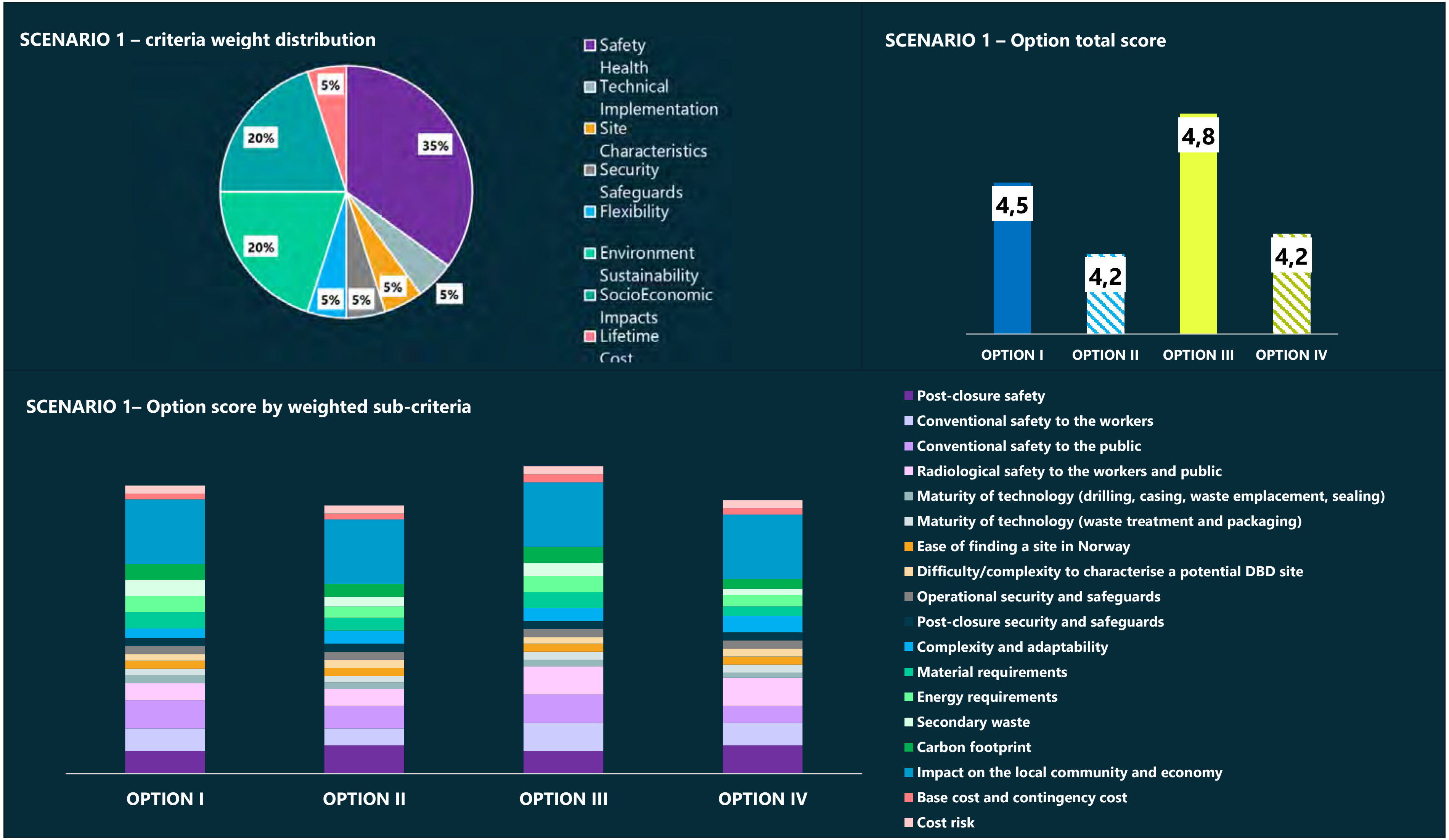
The weights of Technical Implementation and Lifetime Cost are reduced to 15%, while the weights for Safety/Health, Socio-Economic Impacts and Environment/Sustainability are increased by 10% each (Table 26).

Table 26: Overall scoring for the different options using weights that reflect potential priorities of local communities

Assessment criterion		Scenario 1 weighting factor	Maximum score	Option I	Option II	Option III	Option IV
	Safety/Health	35%	1,7	1,4	1,3	1,7	1,5
	Socio-Economic Impacts	20%	0,2	0,2	0,2	0,2	0,2
	Site Characteristics	5%	0,3	0,2	0,3	0,2	0,3
	Technical Implementation	5%	0,3	0,3	0,3	0,3	0,3
	Flexibility	5%	0,3	0,2	0,2	0,2	0,3
	Security/ safeguards	5%	1,0	1,0	0,7	1,0	0,6
	Environment/ Sustainability	20%	1,0	1,0	1,0	1,0	1,0
	Lifetime Cost	5%	0,3	0,2	0,2	0,3	0,2
	Overall score (weighted) – maximum score 5			4,5	4,2	4,8	4,2

The assessment scores and local community weighting results for Scenario 2 are plotted in Figure 32, where it can be seen that Option III again has the highest weighted score, and all of the scores for the other options are still within 0.6 of each other, representing only about 14% of the lowest score. The increased weighting for the Socio-economic criterion has no impact on the final result because all options are scored the same. The two deeper options again score lowest for environment and the highest performing Option III performs better than the other options on all criteria except Flexibility. The option scores are now shown as a stacked bar chart. The higher weights placed on Safety/Health, Socio-Economic Impacts and Environment/Sustainability are not enough to change significantly the overall total weighted scores.

Figure 32: Comparison of option performance when applying potential local community weighting (Scenario 1)



Scenario 2 involves a set of weights reflecting potential priorities of waste owners, with a stronger emphasis on flexibility and lifetime cost

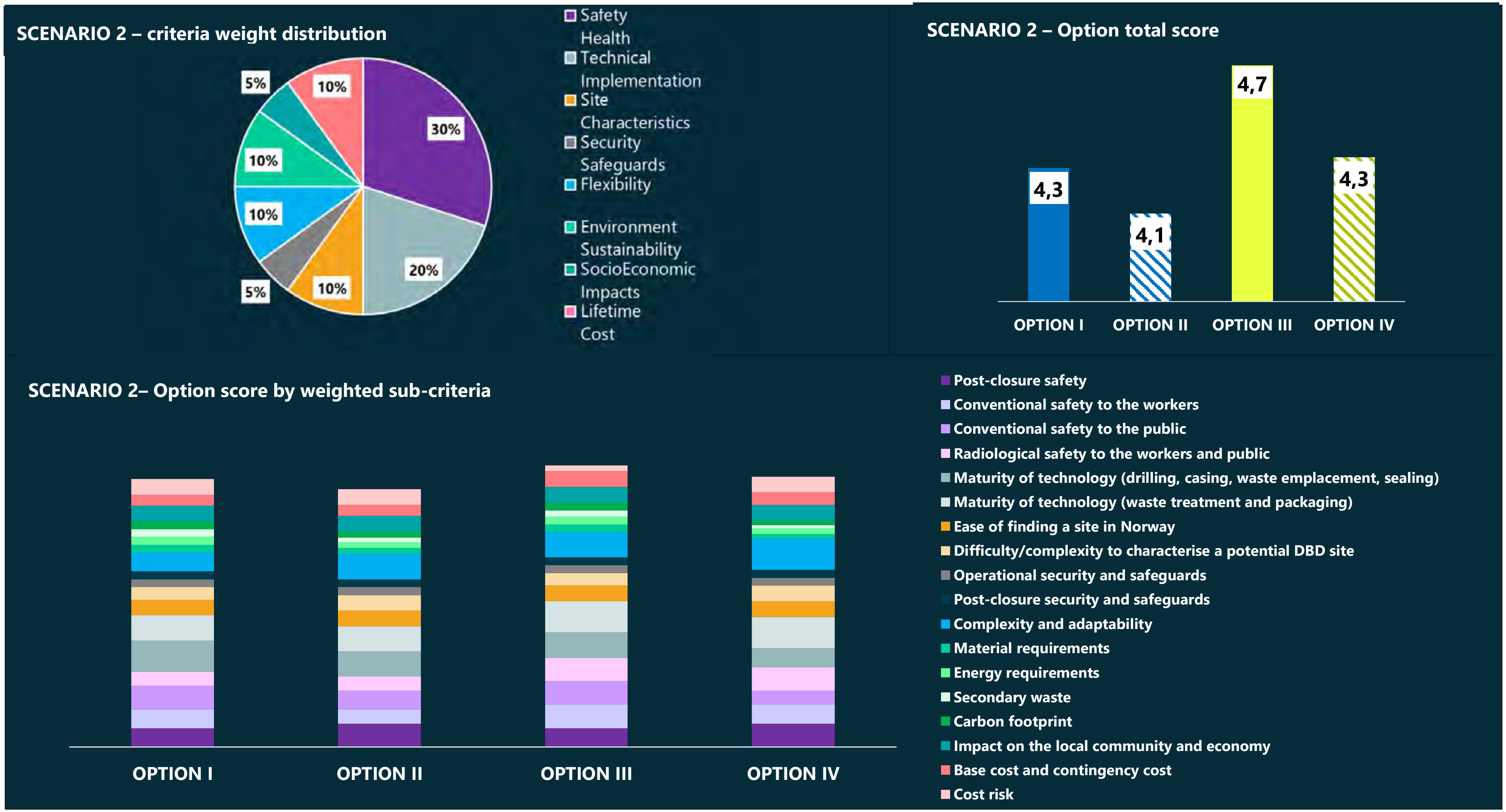
The weights of Safety/Health and Technical Implementation are reduced by 10% each, while the weights for Flexibility and Lifetime Cost are increased by 10% each (Table 27).

Table 27: Overall scoring for the different options using weights that reflect priorities of waste owners (Scenario 2)

Assessment criterion		Scenario 2 weighting factor	Maximum score	Option I	Option II	Option III	Option IV
	Safety/Health	30%	1,4	1,2	1,1	1,4	1,3
	Socio-Economic Impacts	20%	0,9	0,9	0,8	0,9	0,8
	Site Characteristics	10%	0,5	0,5	0,5	0,5	0,5
	Technical Implementation	5%	0,3	0,3	0,3	0,3	0,3
	Flexibility	10%	0,5	0,3	0,4	0,4	0,5
	Security/ safeguards	10%	0,5	0,5	0,4	0,5	0,3
	Environment/ Sustainability	5%	0,3	0,3	0,3	0,3	0,3
	Lifetime Cost	10%	0,5	0,4	0,4	0,5	0,5
	Overall score(weighted) – maximum score 5			4,3	4,1	4,7	4,3

The results for Scenario 2 with waste owner weighting are shown in Figure 33 and again show minimal difference from the baseline weighting results. Option III again has the highest weighted score, and all of the scores for the other options are still within 0.6 of each other, representing only about 15% of the lowest score. The option scores are now shown as a stacked bar chart. The higher weights placed on Cost and Flexibility are not enough to change the overall total weighted scores.

Figure 33: Comparison of option performance when applying potential waste owner weighting (Scenario 2)



Scenario 3 involves a weight set reflecting potential priorities of the regulatory authorities and the public at large, with a stronger emphasis on technical implementation (i.e., demonstrating the feasibility of the concept)

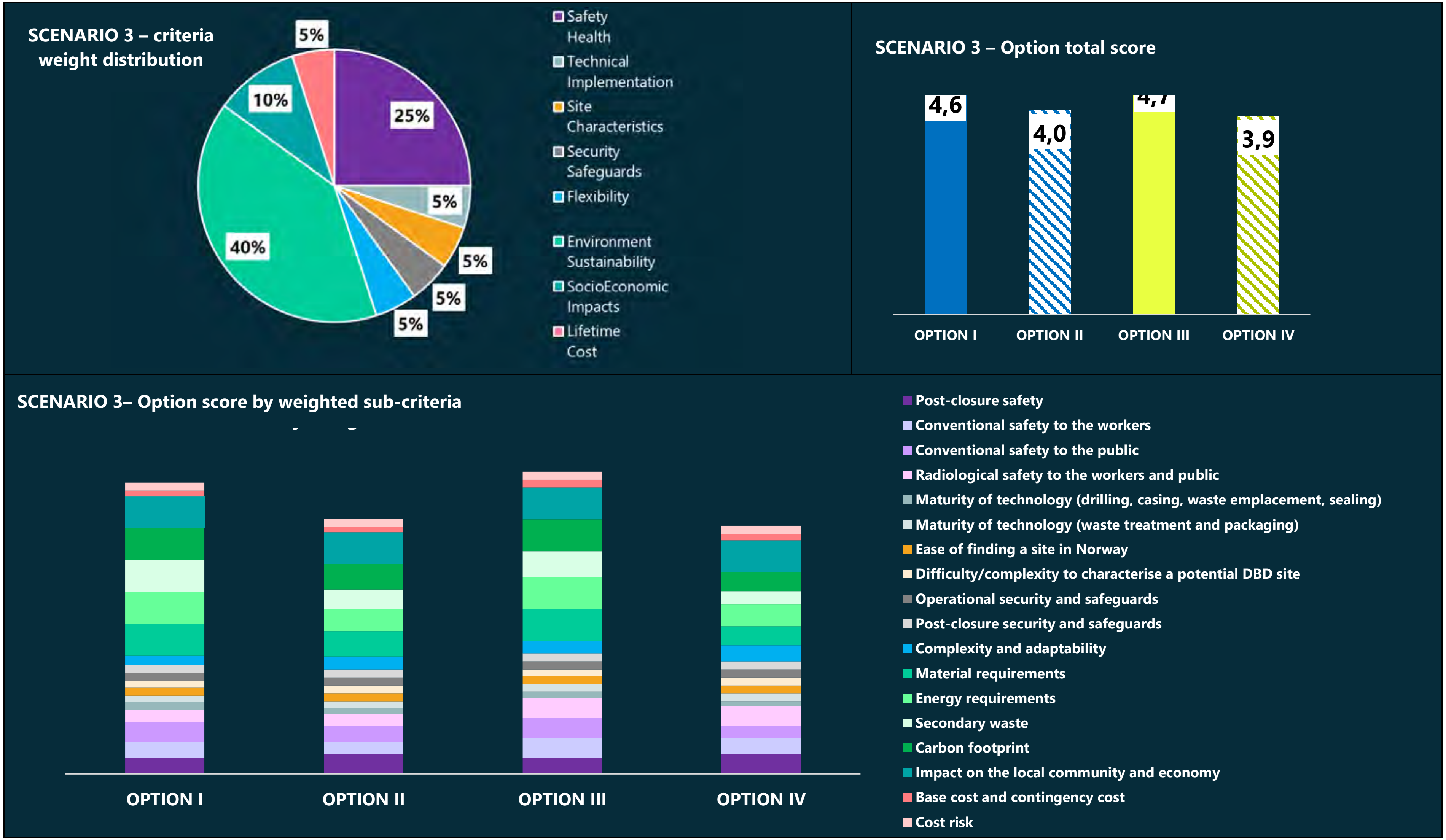
The weight of Lifetime Cost is reduced by 10%, while the weight for Technical Implementation is increased by 10% (Table 28).

Table 28: Overall scoring for the different options using weights that reflect potential priorities of regulators

Assessment criterion		Scenario 3 weighting factor	Maximum score	Option I	Option II	Option III	Option IV
	Safety/Health	30%	1,2	1,0	0,9	1,2	1,1
	Socio-Economic Impacts	20%	0,2	0,2	0,2	0,2	0,2
	Site Characteristics	10%	0,3	0,2	0,3	0,2	0,3
	Technical Implementation	5%	0,3	0,3	0,3	0,3	0,3
	Flexibility	10%	0,3	0,2	0,2	0,2	0,3
	Security/ safeguards	10%	2,0	2,0	1,5	1,9	1,2
	Environment/ Sustainability	5%	0,5	0,5	0,5	0,5	0,5
	Lifetime Cost	10%	0,3	0,2	0,2	0,3	0,2
	Overall score(weighted) – maximum score 5			4,6	4,0	4,7	3,9

The results for Scenario 3 with regulator/public weighting are shown in Figure 34 and again show minimal difference from the baseline and Scenario 1 and 2 results. Option III again has the highest weighted score, and the scores for the other options are within 0.9 of each other, representing about 18% of the lowest score. The option scores are shown as a stacked bar chart. The higher weights placed on Safety and Technical Implementation are not enough to change the overall total weighted scores.

Figure 34: Comparison of option performance when applying potential regulator/public weighting (Scenario 3)

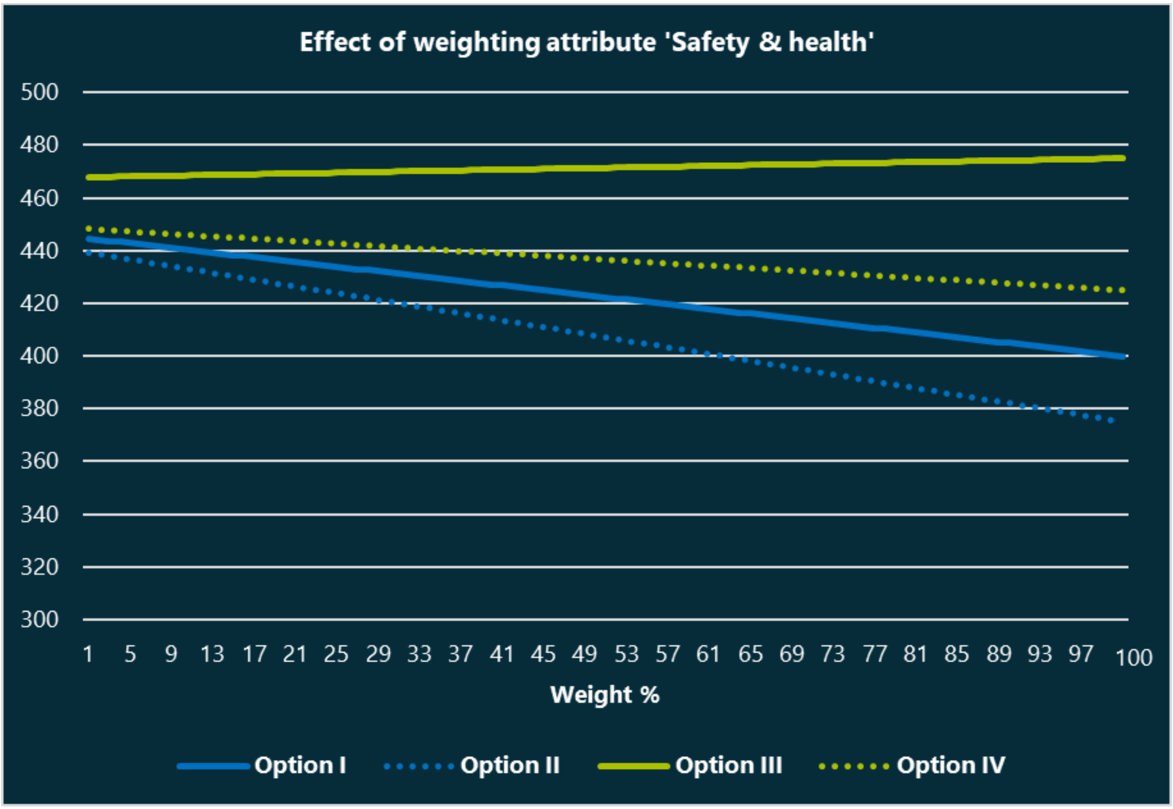


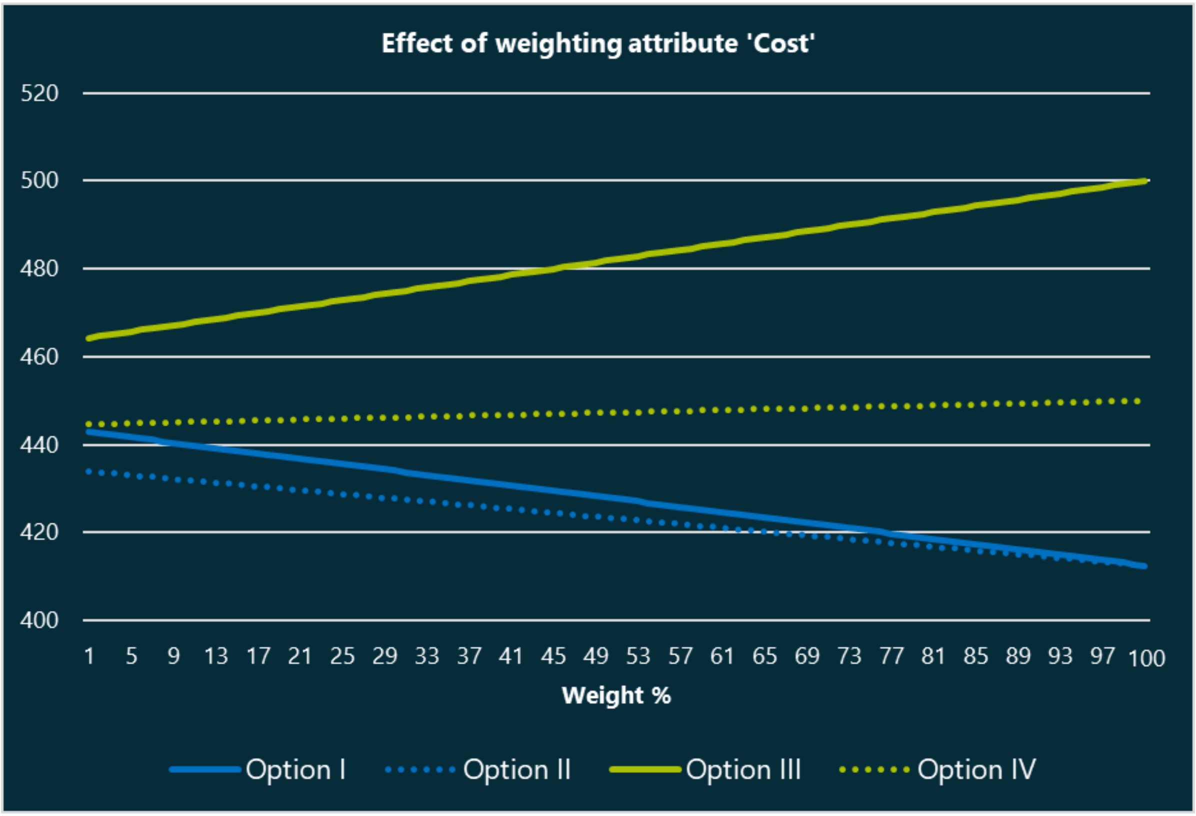
The results for the Baseline and Scenario 1, 2 and 3 weight sets show that alternative weights have little impact on the overall performance of the different options. The sensitivity to weighting can be tested further by considering more extreme weightings. This has been done for the criteria Safety, Cost and Environment with the results shown in Figure 35 For Safety and Cost, the difference in scores is relatively small, so that the overall ranking of each option does not change, even with very high weights. This is because the ranking order for Safety is the same as the overall result considering all criteria, so that the lines for the different options have a low gradient and do not cross. For cost it is the same story with Option 3 performing best regardless of the weight on this criterion.

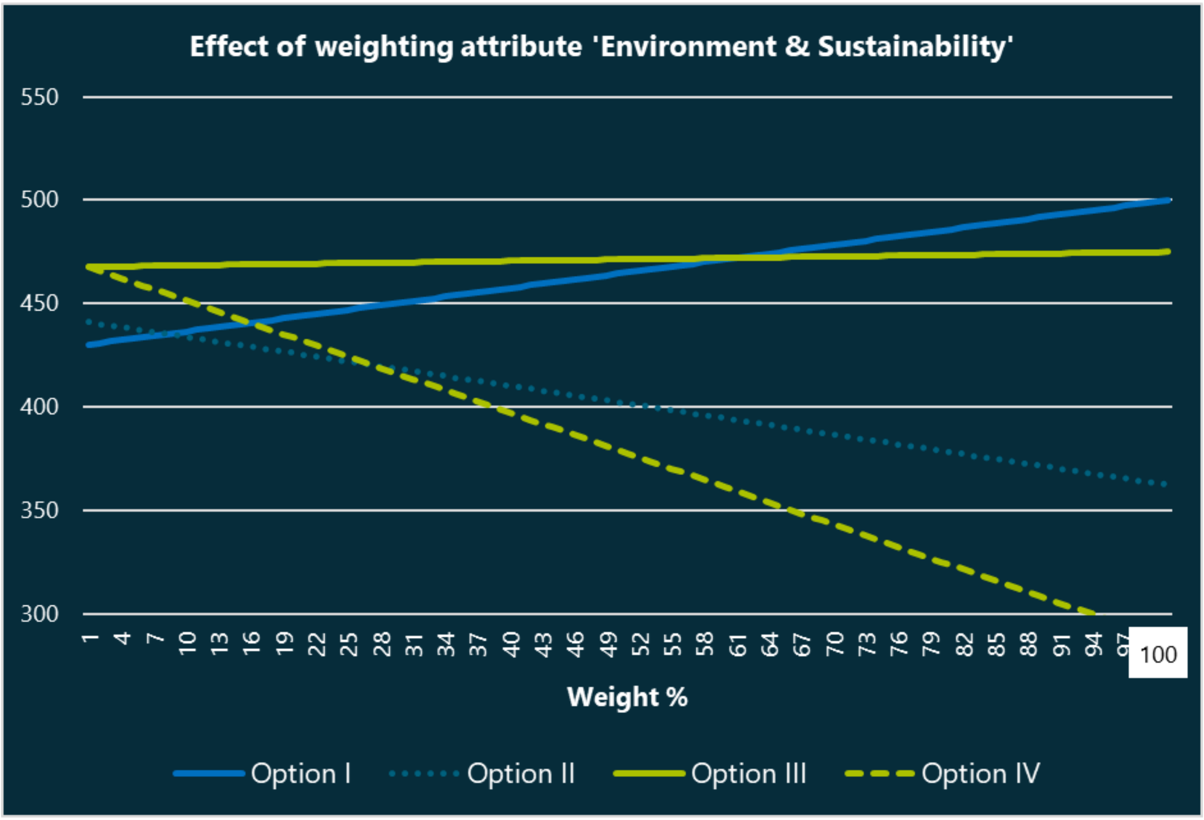
Only for the Environment criterion does varying the weight have a significant impact. Here, the deeper options (Options II and IV) become the worst performing overall for Environment weights above 25%, because of their lower scoring resulting from higher secondary waste (spoil), material and energy consumption. At Environment weights below about 15%, Options III and IV are best performing overall but at high Environment weightings (above about 60%) Option I becomes best performing overall.

Note, however, that there was some uncertainty around the scoring of the various Environment sub-criteria with Options II and IV scored as 3 or 4. Moreover, Environment was not able to consider the impact of encapsulation or overpack fabrication in detail, which would have favoured Options III and IV owing to the smaller number of overpacks needed for these options. Consequently, although Environment is identified as the criterion with the biggest impact on the overall results as weighting is varied, because it tends to favour the shallower borehole options, at more realistic weight sets represented by Scenarios 1, 2 and 3 and the Baseline, it does not change the overall score and relative ranking of the options.

Figure 35: Three swing weighting diagrams for the criteria Safety, Cost and Environment, showing how the overall score of each option varies as the criterion weight changes







The sensitivity analysis shows that the overall result obtained from the workshop scoring of the different DBD options is quite robust to alternative weightings. The main reason for this is that all options are credible and the differences in scoring against the various criteria and sub-criteria are sufficiently small that the result is relatively insensitive to weighting.

4. Assumptions, Constraints and Exclusions (ACEs)

Any assumptions, constraints and exclusions identified during the characterisation, assessment or comparison of the options are identified at the beginning of the report and grouped in the table below.

If the conditions of an ACE were not met, the conclusions of the study could differ, and it could be easier to narrow the choice of options, for instance if SNF management variants are excluded following the outcomes of the SNF treatment study. In other cases, the ACE is not likely to be important to assessment outcomes but may vary the design, planning and/or cost of the DBD concept, for instance if LL-ILW is included in the inventory to be disposed of by DBD.

Table 29: Grouped Assumptions, Constraints and Exclusions

Category	ACEs	Comment
NND holistic radioactive waste management strategy and scope of the study	Assumed inventory: only legacy Norwegian SNF and/or HLW (ACE 1)	The impact on assessment of a change to the inventory to be disposed of by DBD is discussed under the flexibility criterion. The design of the DBD concept would be significantly impacted.
	SNF treatment strategy (ACEs 4, 5, 6)	The DBD MCA study highlights that DBD could be implemented as a disposal route for the four SNF management variants considered. If the SNF treatment study recommends another treatment variant, then the DBD optioneering study would need to be revisited.
	SNF and/or HLW storage strategy (ACE 13).	A revised SNF and/or HLW Storage strategy with no development of a new facility may induce further waste forms degradation and impact the boundary conditions of the optioneering study. However, further waste forms degradation is unlikely to affect option preference at the level of granularity considered in this study. A revised SNF and/or HLW Storage facility with different new storage facilities instead of a consolidated storage facility would impact the transport of the waste forms to the encapsulation plant. See below impact of ACE 9.
	DBD programme timeline (ACE 12)	A significant delay to the start date of disposal operations would mean the thermal output of the waste was lower at the time of disposal, which could increase the amount of waste in each overpack and reduce constraints on the backfill material. However, a later disposal date is unlikely to affect option preference at the level of granularity considered in this study.
	NND siting strategy for the borehole site (ACE 2)	A revised siting strategy for the borehole site may result in different host rocks, both crystalline and non-crystalline, being considered as part of the site selection process. If credible non-crystalline sites are found, the long list of DBD options may change, along with the rationale for shortlisting the options. The selection of preferred options in a crystalline host rock environment will not be impacted, and assuming the sites selected are suitable for DBD, it is not believed that a non-crystalline host rock will confer significant advantages or disadvantages. However, this analysis is yet to be confirmed. Two indicative depths have been considered to account for potential siting and stakeholder requirements. These depths are intended to bound the likely real range of disposal depths, and any intermediate depths can be considered by reference to the bounding options.

Category	ACEs	Comment
	Encapsulation plant location (ACE 9)	The potential impacts of an alternative encapsulation location at the disposal site, or on a third site, is discussed in Section VIII.1. The OAP concluded that an alternative encapsulation location would impact the transport of the waste forms and disposal overpacks (from the centralised storage facility to the encapsulation plant and from the encapsulation plant to the borehole). Even if the reprocessed wastes, whether oxidised or vitrified, are to be sent to the centralised storage facility and not directly to the encapsulation plant, the impact on the assessment outcome would be minimal.
	Boundaries of the study, from termination of storage of HLW/SNF to borehole construction, operation and closure (ACE 9)	Changes in study boundary could impact the DBD assessment outcomes: for instance, excluding transport of the waste from the encapsulation plant to the disposal site would impact option comparison against operational safety, environment and cost (sub)-criteria. However, the conclusions of the assessment are unlikely to be significantly impacted.
Regulatory and stakeholder expectations	Regulatory and safeguards requirements and stakeholder expectations (ACE 3, ACE 14)	The impact on assessment of a potential retrievability requirement is discussed under Flexibility criteria. A potential revision of IAEA safety standards related to safeguards may differentiate options under the Security and safeguards criterion, but the impact on the overall assessment outcome should be minimal. A deeper indicative disposal depth has been considered to account for potential stakeholder requirements around an enhanced level of confidence in post-closure safety. The sensitivity analysis discusses the impact of potential weight sets that may be applied by different stakeholders. Refining these weighting assumptions based on actual dialogue with stakeholders could shift the balance, making either shallow or deeper options more favourable.
Uncertainty in data and data gaps	Inventory data gaps and uncertainties (ACEs 5, 6, 7, 15)	The potential impact of changes in inventory data on assessment outcomes would be limited by the relatively small inventory and the conservative assumptions made, for instance regarding design of the disposal overpacks and the length of the disposal section.
	Absence of site-specific data (ACEs 7, 16, 17, 18, 19)	The unavailability of suitable ground conditions near potentially interested host communities would represent a significant difficulty for any disposal option. The availability of site-specific data, combined with a better understanding of stakeholder expectations and the siting process, would allow for better understanding of the pros and cons of shallower and deeper options. Site-specific data would allow confirmation and refinement of the design options for the disposal overpacks and the disposal borehole, and reduced uncertainty. It would improve option comparison against all criteria.

Category	ACEs	Comment
Maturity of the DBD options and future RD&D needs	Knowledge gaps (ACE 8)	The assessment has taken into account an initial review of the technical maturity of the DBD concepts considered under the Technical implementation criterion and has identified knowledge gaps to be addressed. A more detailed review of the Technology Readiness Level of DBD system components - and the definition of the desired or necessary TRL for each component of the concept at the major decision points in taking DBD forward - would confirm the timing of RD&D needs and support the more detailed definition of the different design options and their safety assessment. Further staged RD&D is needed to increase the Technology Readiness Level and safety demonstration of DBD concepts, including such things as evaluation of requirements on container lifetime, waste emplacement technique and borehole closure. Such work would reduce uncertainty, impact the design of the different options, and potentially their differentiation against various criteria.
Maturity of design and safety assessment	Design of overpack, transport cask and borehole (ACEs 7, 8, 10, 17)	Further design work can be carried out to optimise the design, for instance to confirm the stacking loads, or to determine whether to include 2 CSD-V canisters in an overpack. Further design work would reduce uncertainty, and allow for more detailed cost estimates to support programme planning. However, no major impact on the assessment conclusion is expected.
	Preliminary safety, cost and environment assessment (ACEs 8; 11, 17, 19)	The assumptions made at this stage of the optioneering study serve the purpose of differentiating the options. Development of more quantitative generic and, in due course, site-specific safety assessment and lifecycle cost models would help to confirm the potential for DBD to provide a safe and viable disposal solution, and more detailed environmental assessment would be needed to inform local planning studies.

X. CONCLUSION AND NEXT STEPS

It is important to emphasise that the ranking of DBD options should not be seen as a definitive or absolute conclusion. There are many inherent uncertainties and assumptions made during this optioneering exercise, all of which have been documented and can be found in Section IX.4.

The overall preference for an option depends on the relative importance, or weight, assigned to each of these areas. A different weighting could shift the balance by magnifying the differences between options, making either shallow or deeper options more favourable depending on the priorities set for safety, technological maturity, flexibility, ease of finding a suitable site, environmental impact and cost. However, as noted in the sensitivity analysis in Section IX.3, the differences in scoring against the various criteria and sub-criteria are sufficiently small that the overall result is relatively insensitive to weighting.

The decision regarding which DBD option to pursue will largely be influenced by factors beyond this optioneering exercise, including the spent fuel management strategy, the site selection process, the characteristics of the chosen site (such as the minimum depth at which disposal is deemed safe), and the design and research outcomes from possible future demonstrator tests.

As a result, there is no justification for excluding any options at this stage. This should not hinder NND in developing an RD&D programme on DBD. Most RD&D efforts will be relevant for all options and research focused on one specific option will not exclude or diminish the value of the others.

It is recommended that NND revisits the scoring in the future when more information is available. This could include data from a selected site, additional RD&D findings, clearer stakeholder and regulatory expectations, or a more detailed cost assessment.

To inform NND's decision on whether to pursue a DBD programme, further work could be carried out where the outcome can best build confidence in the DBD concept and the capability to achieve it, and where the information can most usefully inform the KVU and demonstrate compliance with safety requirements. Examples of activities which could be launched by NND in the short and medium term and their interdependency with the optioneering ACEs are highlighted in the Table below. They are further discussed in the Roadmap for DBD programme implementation in Norway, being developed under a separate Task under SB2 Framework Agreement [39].

Table 30: Examples of activities which could be launched by NND in the short and medium term to build confidence in the DBD concept and the capability to achieve it whilst addressing planning and safety requirements (HOLD 4)

Category	Examples of activity	Related ACE(s)
Overall programme management and stakeholder engagement	Should a DBD project be further explored, it would be necessary to integrate it with the other activities ongoing within NND regarding its wider waste management responsibilities. In particular, further work would be needed to establish a clear understanding of the requirements and expectations, and their future development. Although it is not NND's role to develop the regulatory framework, it would be helpful to consider the kinds of regulatory criteria that could make sense for DBD, and to provide a technical basis for interacting with the regulator as they work to define any such criteria. At the programme level, it would also be necessary to develop the approach to capturing and reviewing what assumptions need to be re-examined or work potentially redone if there is a change in the programme. Another key activity in parallel to stakeholder engagement and the review of regulatory requirements for DBD outlined above is planning for all of the regulatory interactions that would be needed for the project, including construction of the storage and encapsulation facilities, field tests, site investigations, surface infrastructure, etc. An essential part of taking the concept of DBD forward successfully would be to take stakeholders along with the programme as it develops. It is therefore important to inform stakeholders about DBD and create opportunities for them to express their opinions and expectations. This would ensure that the project aligns with regulatory and stakeholder expectations. A more detailed cost assessment of the DBD options would be valuable for planning, as it would help identify the key cost drivers and the main cost uncertainties and risks. This would also support a comparison between DBD and other disposal options considered for the SNF and/or HLW. The cost assessment and its content could be guided in the near-term by the requirements of the KVU.	ACEs 3, 12; 14
Disposal system development	This work in the near-term could be focused on those areas where the outcome can best build confidence in the DBD concept and the capability to achieve it, and where the information can most usefully inform the KVU and the decisions therein. In the case of the latter, the information might distinguish more clearly between the options considered in this assessment. In the longer-term, undertaking work would be balanced against factors such as cost and the likelihood or risk that the outcome will not prove effective in helping the project move forward. The focus below is on the nearer-term tasks.	
	Strategy and waste acceptance. It is essential that a possible DBD programme is integrated into a comprehensive radioactive waste management strategy. That strategy should define the spent fuel management strategy, and the disposal plans for all radioactive waste. The wastes that could be accepted by DBD should also be considered; this will link to the safety assessment and design areas of work. Placed in this section is an ongoing review of the TRL of the DBD design concept and the desired or necessary TRL for each component of the concept at the major decision points in taking DBD forward as one of, or the only, chosen strategy. This piece of work could equally be placed under design or overall programme management.	ACEs 1, 4, 8, 9 and 13

<table>
<tr><th>Category</th><th>Examples of activity</th><th>Related ACE(s)</th></tr>
<tr><td></td><td> Site selection and characterisation strategy. A site suitable for implementing a DBD project must:

Meet technical and scientific criteria regarding the safety and feasibility of the DBD facility at that site.
Gain political and social acceptance.

There are various possible processes to select a suitable site. Some countries conduct a national screening based on technical criteria to propose candidate sites. Then, political and social acceptance is sought for these candidate sites. Other selection processes start with sites within willing or volunteering communities and the technical suitability of those sites is subsequently investigated. A generic strategy for siting new nuclear facilities in Norway is currently under development by NND. Two separate near-term tasks could be undertaken to consider the application of this strategy to finding a site for DBD informed by a review of the approaches in other countries.
One of the first steps in the site selection process for DBD would be for NND to establish, in consultation with all stakeholders, a clear decision-making framework for selecting the DBD site. Thereafter, a detailed site selection plan would be needed. The planned process would proceed through the stages of site identification, where several potential sites might be identified and investigations might be conducted at several sites to the selection of a final site for the DBD operation. The site selection process would necessitate collecting data of diverse nature and scope – such as geological, hydrogeochemical, geotechnical, geographic, socio-economic and other relevant data – for each site being evaluated.
Once a site has been selected as the DBD site, the site characterisation work could start. In this phase, one or several characterisation boreholes would be drilled to a depth greater than the bottom of the proposed disposal borehole to obtain the information necessary to plan the construction of the disposal borehole and build the safety case. Such work must be requirements-driven, focusing on collecting data necessary to:

Build the safety case and conduct safety assessments.
Develop the borehole design.
Conduct an environmental impact assessment.
Satisfy any other specific needs formulated by the regulatory authorities, the public, or other stakeholders.

A strategy for the site characterisation phase could start to be developed now, well ahead of its actual implementation. This would be necessary because there is a wide range of views on the extent of any characterisation required for DBD and a strategy for resolving differences of opinion is needed. Issues include how the approach could differ from site characterisation for a mined GDF, any special considerations specific to DBD, and whether the required effort might differ for different geological environments and different concepts. </td><td>ACEs 2, 3, 18, 19</td></tr>
</table>

Category	Examples of activity	Related ACE(s)
	Design. Further RD&D would be necessary to advance the design and technology of the DBD concept. In the first instance, it would be necessary to confirm the safety strategy and design concept based on this options assessment. Several other near-term tasks could be undertaken to build confidence and support the KVU. These include: • Collation of geological information (lithology, temperature, groundwater age and salinity, etc.) available to support applicability of the DBD concept(s) in Norway. • The information gathered as part of this options assessment allows the trade-off between borehole depth and diameter to be set out clearly. For example, questions such as what reduction in borehole length would justify increasing the diameter to be addressed. Another factor is that a larger diameter borehole could allow for the installation of a more extensive engineered barrier system. • Carbon footprint analysis consistent with the methodology expected as part of Norway's concept development framework. • Clarify emplacement procedures and the associated overpack design. This should set out operational lifetime and the associated risks and stakeholder (regulatory) requirements. Evidence for borehole stability and the ability to keep boreholes open for the required time should be compiled. The potential for dropping overpacks and the possible impact of damage to dropped overpacks on mechanical integrity and subsequent corrosion behaviour (e.g., stress corrosion cracking, hydrogen embrittlement) should be explored. • What would be a suitable design for the disposal container and how can it be demonstrated that the design can provide the required containment (i.e., containment for at least 1,000 years)? • Better define the design for the borehole backfill and seals. The design should consider how to emplace the sealing material and ensure their performance under downhole conditions. • What might be the impact of gas generation on the post-closure safety of a DBD concept and how can this impact be mitigated? It would then be necessary to undertake R&D to address key knowledge gaps remaining including: • Waste acceptance criteria. • Overpack design. • Borehole construction and stability over the operating period. • Operating and emplacement procedures. • Sealing and closure.	ACEs 7, 8, 10, 11, 16, 17, 18, 19

Category	Examples of activity	Related ACE(s)
	Safety case development and safety assessment. A template for the DBD safety case needs to be considered; this can preferably be undertaken in dialogue with the regulators and in tandem with work on the regulatory requirements and the timings of key project milestones. There is a need to develop a generic safety assessment capability for DBD. Such an assessment could help to confirm the potential for DBD to provide a safe and viable disposal solution. Additionally, it would also play an important role in guiding future site characterisation work as it would identify which specific site data are required for a future site-specific safety assessment. NND is currently developing a safety assessment methodology. It would be necessary to review this methodology in the context of conducting both operational and post-closure assessments for DBD. A generic safety assessment could include: • Definition of expected evolution and alternative scenarios. • Development of a conceptual safety assessment model, using (a range of) generic site data. • Conducting safety assessment calculations. • Evaluation of the results, including identifying the main parameters. • Identifying the main site-specific parameters that need to be part of the site characterisation programme. In the first instance, a functional analysis would be needed to support the scenario development, TRL assessment and setting of design requirements for components. This work could be undertaken in parallel with NND's international collaboration programme.	ACEs 7, 8, 10, 11, 15, 16, 17 18
Deep Borehole Field Test.	In support of all of the above activities, there would be a need for a comprehensive Deep Borehole Field Test (DBFT) that demonstrates the entire process from site characterisation, borehole construction, waste emplacement, and sealing and backfilling. Such a full-scale demonstrator needs to provide evidence that the DBD technology can be safely and effectively implemented. Without such a demonstration, it would be difficult to convince regulatory authorities that the technology meets the standard of being "tried and proven". Planning for the DBFT could be started immediately and could be undertaken in parallel with development of the site selection plan and site characterisation strategy. The planning should consider the implications of siting the field test at the same location as the ultimate disposal borehole, and the associated stakeholder (regulator and public) viewpoints should plans change or develop in this direction.	ACEs 3, 7, 8, 10, 11, 17, 18, 20

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APPENDIX 1

PROGRAMME RISK AND OPPORTUNITY REGISTER

Rev	Written by	Reviewed by	Approved by	Date	Description
B	S. Prasad	L.Prévot	L.Prévot	03/03/2025	Accepted version
A2	L.Prévot	S. Wickham	L. Prévot	04/02/2024	Second revision following answers to NND comments on the Final Report Revision B
A	S. Wickham S. Prasad L.Prévot	M. Crawford C. Herbert	L. Prévot	26/11/2024	

NND 361 SB2 |FINAL REPORT – MULTI-CRITERIA ANALYSIS TO IDENTIFY PREFERRED DEEP BOREHOLE DISPOSAL CONCEPT OPTIONS IN NORWAY

APPENDIX 1: PROGRAMME RISK & OPPORTUNITY REGISTER

		ASSESSMENT						
Risk /Opportunity	**Risk Description**	**Probability**	**Proposed Impact level**	**Veracity Level**	**Programme stage** (note: for this MCA study, risks to a potential Deep Borehole Field siting, drilling, testing and closure stages are not included)	**R&O ID within the MCA cost comparison of options where applicable**	**Comments (Impact Insight)**	**Mitigation Strategy**
DBD Implementation Risk / Opportunity - NND Programme Risk / Opportunity		***(Without mitigation)*** *5 = High probability* *4 = Medium probability* *3 = Uncertain* *2 = Low probability* *1 = N/A*	*(Impact if the risk materialises)* *1 =Negligible* *2 = Low* *3 = Medium* *4 = High* *5 = Showstopper*	*(Confidence V Impact)*	*Programme Initiation* *Site(s) identitification & selection* *Specific site(s) characterisation* *Construction & commissioning* *Operation* *Closure* *Post-closure*	*Cost comparison of options consider key quantifiable R&O from specific site(s) characterisation stage onwards, assuming DBD is the selected option*		
DBD Implementation Risk	There is a risk of SSM emplacement difficulties, casing removal difficulties.	4	4	**16**	Operations and closure	**R03**	If the risk materialises, this may result in waste emplacement being interrupted or slower than expected leading to a delay to disposal operations, leading to programme delays and surface storage lifetime needs may be prolonged. This could also lead to an increase in costs (costs of a new store & additional RD&D).	Develop a RD&D programme to adress SSM, casing removal TRL needs, adapt the design accordingly. Develop emergency operating procedures, train operators, and ensure availability of spare parts and recovery equipment.
DBD Implementation Risk	There is a risk of stuck waste packages.	4	4	**16**	Operations	**R04**	If the risk materialises, this may result in waste emplacement being interrupted or slower than expected leading to a delay to disposal operations, leading to programme delays and surface storage lifetime needs may be prolonged. This could also lead to an increase in costs (costs of a new store & additional RD&D).	Develop a RD&D programme to adress waste emplacement TRL needs, adapt the design accordingly. Develop emergency operating procedures, train operators, and ensure availability of spare parts and recovery equipment.
NND Programme Risk	Risk that DBD is not the selected option.	3	5	**15**	From programme initiation to site identification and selection	Not applicable	If the risk materialises, DBD will not be the option implemented in Norway and another disposal option will be implemented.	Mined disposal is considered in paralllel with DBD. Regular engagement with regulators and authorities to anticipate any programmatic change.
NND Programme Risk	Risk that DBD TRL is not demonstrated.	3	5	**15**	From programme initiation to site identification and selection	Not applicable	If the risk materialises and TRL can't be demonstrated another option must be considered or further DBD RD&D must be carried out.	Mined disposal is considered in paralllel with DBD. Development of a RD&D programme to adress TRL needs.
DBD Implementation Risk	There is a risk of the rock being more resistant to drilling than expected	3	4	**12**	Site characterisation	**R05**	Drilling proceeds more slowly and is more costly, leading to programme delays and surface storage lifetime needs may be prolonged. This could also lead to an increase in costs (costs of a new store & additional RD&D)	Ensure robust site characterisation and adopt conservative margin in drilling design to manage uncertainties on the design assumptions (e.g. strength, discontinuities and permeability/transmissivity/porosity). Develop an operating procedure should the risk arise on site. Ensure the risk is accounting for in the drilling and supervision contracts.
DBD Implementation Risk	There is a risk that the site is more difficult to characterise than expected, or encounters material requiring specialised management when excavated.	3	4	**12**	Site characterisation	**R12**	If the risk materialises, this will result in additional scope to support site investigations, which will lead to a schedule delay for site investigations.	Develop a robust site characterisation programme, including non intrusive, instrusive characterisation and desktop studies. Consider RD&D and testing of siting equipment if needed. Account for the risk when defining the siting contract.
DBD Implementation Risk	There is a risk that poor underground rock conditions are encountered.	3	4	**12**	Site characterisation	**R16**	If the risk materialises, this will result in the borehole having to be abandoned and a new site needing to be found, causing programme delays and increased costs.	Development of a staged and sound site characterisation programme, with a combination of desktop studies, intrusive and non intrusive techniques. Account for uncertainties in design and safety assessment margins.

Risk /Opportunity	Risk Description	Probability	Proposed Impact level	Veracity Level	Programme stage (note: for this MCA study, risks to a potential Deep Borehole Field siting, drilling, testing and closure stages are not included)	R&O ID within the MCA cost comparison of options where applicable	Comments (Impact Insight)	Mitigation Strategy
DBD Implementation Risk	There is a risk around Norwegian and international regulatory, safety standards and safeguards, changes/lack of applicability to DBD. For instance for there is a risk of the regulator requiring full retrievability of all disposed packages pre-closure of DBD, or of an evolution of permitting and planning	2	5	**10**	Throughout the programme	**R10**	If the risk materialises, this will result in the deep borehole disposal system needing to be redesigned, leading to programme delays and surface storage lifetime needs may be prolonged. This could also lead to an increase in costs (costs of a new store & additional RD&D).	A potential requirement for retrievability has been considered under Flexibility criterion in the MCA. The design will consider the implications of waste retrievability. Participate in regular stakeholder engagement. Involvement in international forums to review applications of safety standards to DBD.
DBD Implementation Opportunity	There is an opportunity that a good site is identified and quickly proven to be suitable for DBD.	3	3	**9**	Site characterisation	**OO2**	If the opportunity materialises, this will result in a reduction in site selection and characterisation for licensing costs.	Development of a staged and sound site characterisation programme, withupfront desk studies and review of existing data, building of Site Descriptive Model to target the area.
NND Programme Opportunity	Leverage DBD RD&D programme overseas, to increase DBD TRL.	3	3	**9**	From programme initiation to site identification and selection	Not applicable	This could lead to optimisation of Norwegian DBD RD&D programme.	Keep engaging in international collaborative research programmes on DBD such as the IAEA CRP to keep abreast of DBD initiatives worldwide.
DBD Implementation Risk	There is a risk of there being a poor safety audit.	2	4	**8**	From site characterisation to closure (excluding potential Deep Borehole Field Test)	**R06**	If the risk materialises, this will result in poor safety audit results or safety incidents can result in temporary project shut down leading to programme delays.	Ensure robust testing and rehearsal of disposal facilities. Ensure all safety precautions, measures, requirements, procedures and training are considered and implemented at each phase.
DBD Implementation Risk	There is a risk that the DBD system does not evolve as planned (e.g. heat source induces hydrothermal flow, or post closure monitoring indicates facilities not performing as expected.).	2	4	**8**	From operations to post closure	**R11**	If the risk materialises, for instance hydrothermal flow is induced by the heat output of the HLW, this will potentially increase the duration of surface storage needed so that the thermal perturbation of deep borehole disposal is reduced.This could also lead to programme delays and also to an increase in costs (costs of a new store & additional RD&D).	Keep engaging in international collaborative research programmes on DBD such as the IAEA CRP to keep abreast of DBD initiatives worldwide to enable anticipation of the risk impact on the programme.
DBD Implementation Risk	There is a risk of there being a failure to achieve positive community support.	2	4	**8**	From site selection and identification to closure	**R14**	If the risk materialises, this will result in a new site being needed, icreasing the cost for site characteristion activities.	Develop a sound stakeholder management plan and DBD siting strategy. Engage regularly with potential host site communities, incentivise hosting the DBD site.
DBD Implementation Risk	There is a risk of site characterisation activities causing damage to site.	2	4	**8**	Site characterisation	**R15**	If the risk materialises, this will result in a new site being needed, icreasing the cost for site characteristion activities.	Develop a robust site characterisation programme, including non intrusive, instrusive characterisation and desktop studies. Specific training for drilling operators, development of operating and emergency
DBD Implementation Risk	There is a risk of severe winter weather during borehole drilling.	3	2	**6**	From site characterisation to construction and commissioning	**R01**	If the risk materialises, this will result in borehole site operations proceeding slowly.	Optimise the planning of the drilling operations avoiding winter if feasible. If not, design and procure drilling rig and ancillary equipment suitable for cold weather operations, for instance adding weather curtains to the rig substructure and heaters.
DBD Implementation Risk	There is a risk of an economic downturn.	2	3	**6**	From site characterisation to closure	**R02**	If the risk materialises, this will result in the procurement of specialist equipment becoming difficult, leading to programme delays and surface storage lifetime needs may be prolonged. This could	Stockpile relevant equipment. Anticipate impact to procurement, adapt financial and contractual modalities, explore alternative procurement route (in case of economic failure of a supplier)
DBD Implementation Risk	There is a risk of equipment design not meeting performance expectations.	2	3	**6**	From site characterisation to post-closure	**R07**	If the risk materialises, this will result in equipment needing to be replaced and some of the construction and waste emplacement work may need to be redone.	Develop a robust RD&D and equipment testing programme. Ensure back up equipment is readily available, and conduct risk studies. Take this risk into account when developing design and equipment procurement contracts.
DBD Implementation Risk	There is a risk of the Suitably Qualified and Experienced Personnel workforce being unavailable and that that unforseen/unplanned absences may cause disruption to work, due to staff conflicts/illness/departure.	2	3	**6**	Throughout the programme	**R08**	If the risk materialises, this may result in slow down of programme development leading to programme delays and surface storage lifetime needs may be prolonged. This could also lead to an increase in costs	Ensure there are no single points of failure. Knowledge management within NND to build capacity internally. Develop Deep Borehole Disposal capacity among the different stakeholders on the long term. Engage with universities.
DBD Implementation Risk	There is a risk of delay to production of a robust safety case for permit	2	3	**6**	From site identification and selection to closure	**R09**	If the risk materialises, this may result in borehole site operations needing to stop or proceed slowly, leading to programme delays and surface storage lifetime needs may be prolonged. This could also lead to an increase in costs (costs of a new store & additional	Development of a RD&D programme to adress TRL needs.

Risk /Opportunity	Risk Description	Probability	Proposed Impact level	Veracity Level	Programme stage (note: for this MCA study, risks to a potential Deep Borehole Field siting, drilling, testing and closure stages are not included)	R&O ID within the MCA cost comparison of options where applicable	Comments (Impact Insight)	Mitigation Strategy
DBD Implementation Risk	There is a risk of rig and other drilling equipment mobilisation and modifications take longer than expected.	2	3	**6**	From site characterisation to site closure	**R13**	If the risk materialises, this will result in more time being needed for rig mobilisation, which will delay the start of drilling and increase the costs.	Early engagement with drilling supply chain. Anticipate rig mobilisation and earlier rig sourcing
DBD Implementation Risk	There is a risk that borehole closure activities run into difficulties.	2	3	**6**	Site closure	**R17**	If the risk materialises, this will result in closure being more costly than anticipated.	Increase TRL of site closure activities, with a robust RD&D, design and testing programme. Anticipate the risks building on lessons learned from siting, construction and operating phases to further anticipate the risks
DBD Implementation Opportunity	There is an opportunity that production of the overpacks is optimised.	2	3	**6**	From programme identification to operation	**OO1**	If the opportunity materialises, this will result in a significant reduction in overpack cost.	Explore RD&D and design optimisation to design the overpack and the encapsulation plant. Ensure proper requirements and design change management.
NND Programme Risk	There is a risk that the information requirements relating to design or safety parameters cannot be met, due to a lack of available data.	2	2	**4**	Throughout the programme (difficult to quantify)	Not applicable	This will result in delay to refine the information requirement needs, of the management of uncertainty.	Track assumptions made where information is not available. Engage and manage interfaces with stakeholders, safety, design and site characterisation team to ensure requirements-driven information data gathering.
NND Programme Risk	There is a risk during the site(s) identification and selection stage that unquantifiable uncertainties make it impossible to establish a baseline understanding for down selection of sites.	2	2	**4**	Site(s) identification and selection	Not applicable	If the risk materialises,this will result in technical impacts including a reduction in the confidence of conclusions, or the selection of another site.	Track assumptions made where information is not available. Engage and manage interfaces with stakeholders, safety, design and site characterisation team to ensure requirements-driven information data gathering.
NND Programme Risk	There is a risk that Norway's ILW or LLW and any potential waste associated with future new build activities will need to be disposed of by DBD.	2	2	**4**	From programme initiation to site(s) identification and selection	Not applicable	If the risk materialises, additional design, safety and optioneering assessment work will be needed to vary the inventory. For instance, a supplementary BH or a deeper BH may be needed.	Evolution of inventory considered under flexibility criterion at the MCA stage. NND to engage with stakeholders, and ensure a holistic radioactive waste management approach, from cradle to grave, to ensure consideration of all wastes arisings.
NND Programme Risk	There is a risk the centralised storage programme being developed in parallel impacts the DBD programme in terms of disposability of the HLW/SNF to be disposed of, or in terms of schedule. For instance, if the fuel is further degraded in the actual storage conditions, or if several storage facilities are developed.	2	2	**4**	From programme initiation to site(s) identification and selection	Not applicable	If the risk materialises, DBD programme schedule may be delayed, and boundary conditions on the design and safety requirements on the overpack / transfer flask / borehole casing and backfilling may vary. Transportation to the encapsulation plant may also vary. A buffer storage may be necessary.	Track design assumptions, uncertainty and safety margin. Manage interface with centralised storage facility programme. Development of an overarching radioactive waste management summary option study, with a cradle to grave approach.
NND Programme Opportunity	There is an opportunity that the MMC ingot diameter may be optimised.	2	2	**4**	From programme initiation to site identification and selection	Not applicable	This could give more flexibility to optimise the borehole geometry.	Explore design optimisation, confirm MMC process modalities and outputs. Track design assumptions, uncertainty and safety margin.
NND Programme Risk	There is a risk that there will inconsistency between the different optioneering studies in terms of outputs (spent fuel management options, overall disposal options, DBD	2	1	**2**	Programme initiation	Not applicable	If the risk materialises, there will be inconsistencies in approaches taken to produce deliverables between SNF, SB1 And SB2 resulting in issues when comparing	Implementation of interfaces management modalities discussed and agreed between NND and the Technical Assistance Teams. Development of an overarching radioactive waste management summary option study, with
NND Programme Risk	There is a risk that the siting process impacts the DBD optioneering approach and underlying host rock assumption, for instance if siting identifies a different host	2	1	**2**	From programme initiation to site(s) identification and selection	Not applicable	If the risk materialises, additional optioneering assessment work might be needed to vary the host rock properties, impacting level of effort, scope and	NND to anticipate the development of the siting strategy and criteria, and to engage with corresponding stakeholders.
NND Programme Risk	Uncertainty in spent fuel inventory, impacting the design options.	2	1	**2**	From programme initiation to site(s) identification and selection	Not applicable	If the risk materialises, additional design, safety and optioneering assessment will be needed to vary the inventory, impacting level of effort, scope and	Track design assumptions, uncertainty and safety margin. Carry out waste characterisation programme to inform the inventory characteristics.
NND Programme Risk	Evolution of NND priorities (for instance prioritisation of NND storage programme), leading to delays in implementation of the disposal programme.	1	2	**2**	From programme initiation to site identification and selection	Not applicable	If the risk materialises, disposal programme may slow down, impacting the start date of disposal operations.	Holistic review and implementation radioactive wastr and decommissioning management programme and strategy, with a full lifecycle perspective.
NND Programme Risk	There is a risk that information flow may break down between NND and its stakeholders.	2	1	**2**	Throughout the programme (difficult to quantify)	Not applicable	If the risk materialises, this will result in an increase in cost as a result of data flowing too slowly which will impact quality assurance and increased complexity.	Develop a sound stakeholder engagement plan. Participate in regular stakeholder engagement. Implement document, change, requirements management capture and tracking.
NND Programme Risk	There is a risk that there could be an information breach, due to release of Official Sensitive information.	2	1	**2**	Throughout the programme (difficult to quantify)	Not applicable	If the risk materialises, this will result in reputational damages relative to the content of the information breach.	Ensure all staff involved have completed NND security induction. Ensure refresh trainings.

Risk /Opportunity	Risk Description	Probability	Proposed Impact level	Veracity Level	Programme stage (note: for this MCA study, risks to a potential Deep Borehole Field siting, drilling, testing and closure stages are not included)	R&O ID within the MCA cost comparison of options where applicable	Comments (Impact Insight)	Mitigation Strategy
NND Programme Opportunity	There is an opportunity for a more important cooling time for the vitrified SNF, for instance if NND horizon to start emplacement of wastes is delayed.	2	1	**2**	From programme initiation to site(s) identification and selection	Not applicable	If the opportunity materialises, the thermal output of the waste forms to be disposed of will decrease. Design of the overpack, transport cask and borehole may be optimised, reducing cost of the Deep Borehole Disposal Programme, whilst adding storage	Explore design optimisation, confirm vitrified reprocessing schedule and modalities, refine thermal modelling. Track design assumptions, uncertainty and safety margin.

APPENDIX 2

MINUTES OF THE OPTION ASSESSMENT PANEL – SESSION 1

Rev	Written by	Reviewed by	Approved by	Date	Description
D	S. Prasad	L. Prévot	L. Prévot	24/02/2025	Accepted version
C2	S. Prasad	L. Prévot	L. Prévot	28/01/2025	Answer to NND comments received on 17/01/2025
C	S. Prasad	S. Wickham J.L. Cormenzana D.A. Galson	L. Prévot	09/01/2025	

Note: Revision A and B correspond to the transmission of brief material ahead of the meeting to NND and to OAP Panelists.

DEVELOPMENT OF SOLUTIONS FOR DISPOSAL OF SPENT FUEL AND OTHER RADIOACTIVE WASTE INCLUDING BOREHOLE DISPOSAL SUBCONTRACT 2

OAP MEETING MINUTES: MULTICRITERIA ANALYSIS OF SHORTLISTED OPTIONS – SESSION 1

TASK C004 - OPTIONEERING

22 October 2024 On Teams

Reference 361-SB2-C004-MOM-EXT-004-D

Key: DBD: Deep Borehole Disposal; DSA; IAEA: International Atomic Energy Agency, ILW: Intermediate-Level Waste; MMC; Mobile Melt Consolidation, NND; Norwegian Nuclear Decommissioning, OAP; Option Assessment Panel, PUREX: Plutonium Uranium Reduction Extraction, RD&D: Research, Development and Demonstration; SB2: Subcontract 2 Framework Holder; SNF: Spent Nuclear Fuel; SSM: Sealing and Support Matrix; TRL: Technology Readiness Level.

ATTENDEES

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SNF Management Framework – Amentum-Multiconsult[1]	Cristiano Padovani Michelle Dickinson	SNF representatives – spent fuel and disposal specialists	cristiano.padovani@jacobs.com michelle.dickinson@jacobs.com	× ×

✓ Attending - × Not present SB2 experts not attending OAP Session 1 have participated in the preparation of the OAP

[1] *Jacobs Multiconsult now Amentum.*

Meeting objectives:

- To assess and score the shortlist of deep borehole disposal options against a first set of criteria, including safety and health, site characteristics, technical implementation and security.
- To capture key points of discussion, pros and cons of options, and note any uncertainties and assumptions made when scoring.
- To identify knowledge gaps that affect scoring, and highlight areas for potential future research, development or demonstration (RD&D).

MINUTES OF MEETING

1. Introduction

1.1 Overview of Shortlisted Options

This study compares four previously defined borehole geometry options being considered within the SB2 framework for Deep Borehole Disposal (DBD) of radioactive waste in Norway. Only DBD options are compared and not mined repositories. The borehole geometries include narrow and wide boreholes and shallower and deeper boreholes. They are designed to contain different spent nuclear fuel (SNF) management variants: direct disposal of all SNF, oxidation of the metallic uranium fuel and direct disposal of the rest of the SNF, mobile melt consolidation (MMC) treatment of metallic uranium fuel, and direct disposal of the rest of the SNF, and plutonium uranium reduction extraction (PUREX) reprocessing of most fuel assemblies and direct disposal of the remaining un-reprocessed fuel assemblies. All options include some MMC ingots, and all options consider vertical DBD in crystalline rock using a long-lived overpack that would ensure waste containment at least during the thermal phase (1,000 years).

1.2 Key Assumptions and Boundary Conditions

Uncertainties and assumptions used in this study to underlie the development of the shortlisted options include the following:

- The optioneering study only concerns DBD of Norwegian legacy SNF. The disposal of Norway's intermediate-level waste (ILW) or low-level waste by DBD is excluded, as well as any potential waste associated with future nuclear new build activities. The disposal of long-lived (LL)-ILW by DBD, increased waste arisings and impact of co-location with other types of radioactive waste repositories are assessed under the flexibility criterion in the Part 2 OAP workshop on 31 October 2024.
- There is currently no requirement regarding waste retrievability in Norway. However, to err on the side of caution, the potential implications of waste retrievability during and after operations are also considered within the flexibility criterion.
- The scope of the study starts from the disposal encapsulation process, including transport from the encapsulation plant to the repository site, and extends until closure. The reprocessed waste canisters/fuel rods/fuel assemblies are assumed to be encapsulated for disposal at a single location. The encapsulation plant is assumed in all cases to be located on the planned new long-term storage site, to ease the comparison of DBD options within this study. Alternative encapsulation plant locations are discussed under the flexibility criterion. Holistic SNF management and disposal options will be consolidated following the completion of three parallel optioneering studies – the second one considering SNF processing options (SNF Framework), and the third one comparing mined disposal options with DBD (GeoRen Framework).

- A demonstration of waste and Sealing and Support Matrix (SSM) emplacement and borehole closure has not yet been carried out. The current Technology Readiness Level (TRL) of the DBD concept options are considered under the Technical Maturity criterion.
- Only crystalline rock has been considered for the DBD host rock.
- Norway will pursue a disposal option for its own wastes independently of any multinational initiatives established by anyone else.
- As the SNF management strategy has yet to be decided, four scenarios of SNF management, including no treatment for the bulk of the SNF, are assumed. All four options include some SNF processed via MMC into metal alloy ingots.

1.3 Description of Shortlisted Options

The OAP Brief slides, describing the shortlisted options are included in Appendix 3.

TABLE 1: SHORTLISTED OPTIONS[2]

Borehole geometry option	Variant	SNF management variant (Note 4)	Depth to top of disposal zone (m)	Borehole diameter (mm)
I	I.1	Direct disposal of all SNF	1500 (Note 2)	610
	I.2a	Oxidation of the metallic uranium fuel and direct disposal of the rest of the SNF		
	I.2b	MMC treatment of metallic uranium fuel and direct disposal of the rest of the SNF		
II	II.1	Direct disposal of all SNF	3000 (Note 3)	
	II.2a	Oxidation of the metallic uranium fuel and direct disposal of the rest of the SNF		
	II.2b	MMC treatment of metallic uranium fuel and direct disposal of the rest of the SNF		
III	III.3	PUREX reprocessing of most fuel assemblies	1500 (Note 2)	990
IV	IV.3	PUREX reprocessing of most fuel assemblies	3000 (Note 3)	

There are two different disposal overpack designs - one for the direct disposal of SNF and the ingots from MMC, which is the narrow overpack, and one for the PUREX reprocessed waste, which requires a wider overpack and therefore a wider borehole. Duplex stainless steel is used for both types of overpack. It has been assumed that electron beam welding can be used to weld overpacks shut at the encapsulation facility, which is assessed under the 'Technical Implementation' criterion.

The term overpack refers to the secondary container of the waste, the item being emplaced into the borehole. There will be one or more waste packages per overpack. The waste forms considered include direct disposal SNF and waste already inside a primary canister (for processed SNF). Inside the overpack, different types of baskets may be required to organise the different canister/waste types.

[2] *Note 1: all numerical values are indicative.*

Note 2: if suitable host rock conditions are found at a depth of 1000 m.

Note 3: if the site characteristics at a depth of 1000 m are not suitable for DBD and/or greater disposal depth is desired to increase stakeholder acceptance.

Note 4: all options include Mobile Melt Consolidation of 1 tU.

The overpack will need to be transported from the encapsulation facility to the DBD site inside a standard transport cask that has been adapted for the Norwegian case. The concept design is based on an Orano transport cask.

The process of putting waste into a canister is considered to be outside the scope of this study.

The technique for emplacing waste into the borehole is assumed to be the same for all options. There are possible alternatives, such as emplacement in water, which have been considered, but not retained for this study.

An SSM, either cementitious grout or mortar, will be emplaced around the overpacks, and through the perforations in the casing in the disposal zone, the adjoining casing-rock wall annulus, to backfill the space surrounding the overpack in the borehole.

After placement of the main borehole seal, the remaining borehole needs to be backfilled. The materials to be used could include cement/concrete, bentonite and graded fill. The main seal proposed is a 'sandwich' of cement/concrete and bentonite in thick layers to fill the remaining uncased interval. The casing-rock annulus, other than in the disposal zone, will be cemented either with pure cement with additives or with a fine aggregate mix concrete.

2. Option Scoring

A list of criteria has been developed from the considering criteria used in the Amentum-Multiconsult and GeoRen interfacing option studies. Each criterion may also be split into sub-criteria. During the first OAP session, safety and health, site characteristics, technical implementation and safeguards and security criteria were discussed. Options were placed in relative order of performance against each individual sub-criterion and were compared against each other. There is no baseline option used for comparison. First, the option that performed best for each sub-criterion was identified and scored as a 5. The other options were given a score of 5 or lower depending on the degree to which they underperformed compared to the best-performing option. Criteria not discussed during the first OAP session were discussed during the second OAP session, when sensitivity analysis was also discussed.

1.4 Safety and Health

1.4.1 Sub-criterion: Post-closure safety

The analysis of options against the post-closure safety sub-criterion was predicated around the assumption that the right host rock conditions/site are available.

It is a requirement that the desired conditions for DBD are found, namely that any pore fluid is old, stagnant, and has not interacted with shallower active hydrogeological systems. For the shallower options, if these conditions are not found at 1.5 km depth, the borehole must be drilled to greater depths until such conditions are found.

For the deeper boreholes, there will be a greater thickness of host formation above the host facility, therefore providing greater isolation from the surface and increasing the radionuclide travel time to the biosphere. Human intrusion is very unlikely at the shallower depth, but the deeper borehole will decrease the likelihood further.

In all options, 1 tonne of SNF is assumed to be treated using MMC. The radiotoxicity of the waste in options III and IV, containing the PUREX reprocessing waste, is much lower than in options I and II since most of the long-lived actinides have been removed from the HLW but not from the MMC ingots. The inventory of highly mobile I-129 in options III and IV will also be much smaller. Therefore, in terms of radiotoxicity, although the PUREX reprocessing options still contain 1 tonne of SNF treated using MMC, options III and IV were viewed as providing a higher degree of post-closure safety due to the lower radiotoxicity of the waste inventory. However, these options have a higher thermal power per disposal overpack than options I and II.

The PUREX reprocessing options contain vitrified HLW in CSDV canisters, which have a thermal power output of 2 kW. It is assumed that the CSDV canisters will be received in 2040 and disposed of in 2050, at which point the thermal power will have decreased to 1.6 kW. The resulting maximum temperature increase at the overpack surface, for options III and IV, is greater than that for options I and II. For options I and II the thermal power can be limited by interchanging the combination of different spent fuel management variant components. The differing thermal pulse produced by the SNF variants is managed by the overpack lifetime, to provide protection.

Higher thermal output will lead to greater temperatures and will create greater disturbances in the host rock, potentially leading to hydrofracturing due to water expansion. Although damage to the host rock will be small and may not have a significant effect, minimum disturbance to the host rock is desired. In this regard, hotter borehole options perform worse than cooler ones.

Given the necessary conditions, the potential impacts of future glaciation will not affect safety, as the very old stagnant water will have experienced earlier glaciations and demonstrably not been affected. Additionally, the radiotoxicity levels of the waste will not be deemed hazardous by the time the next glaciation takes place (order 100,000 years). There is potential for faults to become more active, if there is post-glacial rebound. If the site is surrounded by mountains, there will be a higher near-surface hydraulic gradient, resulting in a more mobile fluid system to greater depths. This is a greater concern with the shallower options, but note that any connectivity between flowing groundwater and the disposal zone would result in the site being excluded for DBD. Analysing the potential disturbances to the host rock is a recommended area of RD&D for the future.

It may be easier to license deeper options. When drilling, if a fracture is intersected, the radionuclide travel time from disposal zone to biosphere will be shorter for the shallower options, but initial scoping calculations show in both cases that doses would be negligible.

A safety case must account for the possibility of a breached overpack before the end of the thermal transient in the borehole, which could lead to an earlier release of radionuclides leading to the potential for thermally induced water flows perpendicular to or along the borehole. For the overpacks to remain sealed for the same duration, the CSVD canisters will need to be thicker. The impact of varying overpack thickness is a potential topic for future analysis; for this study, an overpack thickness of 40 mm was assumed for all options. The reprocessing options (III and IV) have a higher thermal power; therefore, there is greater potential to drive hydrothermal movement in the early years after disposal. However, if the integrity of the overpack for the CSDV canisters can be guaranteed, then the case can be made that no radionuclides can escape while there is a significant thermal disturbance. The potential for localised corrosion is difficult to predict and rule out; therefore, there may be a need to increase the thickness of the overpack. This adds uncertainty to the options including reprocessed waste and risk to the early years after disposal. How likely it is for the overpack to fail early is another factor to be considered for future RD&D. It is assumed that the overpack can be designed to provide containment at least during the thermal phase (approximately 1,000 years).

Summary

Overall, differentiating post-closure safety between DBD options proved challenging without specific site conditions, as the depth factor tended to dominate, with the thermal power and radiotoxicity cancelling out for the options containing reprocessed and non-reprocessed waste. The deeper DBD options offer a higher level of isolation and result in longer radionuclide travel times to the biosphere. However, greater disposal depth comes with disadvantages; the temperature in the host rock around the disposal zone will be higher, which could potentially increase overpack corrosion rates, and uncertainties associated with deeper disposal may also be greater. Nevertheless, the benefits of deeper disposal were considered to outweigh the disadvantages and scored higher.

Option	I	II	III	IV
Score for Post-closure safety	4	5	4	5

1.4.2 Sub-criterion: Conventional safety to workers

A quantitative analysis was conducted to show the differences in the number of overpacks and waste form types for each option, which would affect the conventional safety of workers. The number of overpacks is the same for options I and II. However, the different waste forms introduce complexity and increase the risk to workers. Options III and IV only contain two waste types so complexity of operations in the encapsulation facility will be reduced. Options III and IV have fewer overpacks so the risk to workers is reduced.

It is assumed that there is one overpack per transport cask and there will be one transport to the DBD site per transport cask. The number of transports to the DBD site is therefore greater for options I and II than for options III and IV. Safety in relation to drilling operations and materials needing to be drilled and removed from site are considered by comparing the drilled borehole volumes. Deeper options have a greater rock volume. This affects the number of 16 tonne vehicle loads required to remove the drilling spoil offsite, which goes in increasing order from option I to III to II to IV.

The number of person days to operate the borehole differentiates slightly between options I & II and III & IV. The drilling and emplacement times vary across options, but overall, the total duration of operations on site is similar. A greater depth increases the total time of operations on site; however, it is assumed that the number of workers on site will be the same for all options.

Summary

Overall, options III and IV were preferred from a conventional safety perspective because they involve a smaller variety of waste types to be encapsulated and require fewer overpacks to be produced compared to options I and II. Between these two, option III was favoured over option IV, as it demands fewer working days and involves a lower number of truck loads for spoil removal. A longer duration of operations on site creates more risk to the workers safety even if all procedures are managed properly and safely. Consequently, option III was assigned a score of 5, while option IV received a score of 4. Similar to the distinction between options III and IV, option II received a lower score compared to option I. This is because option II requires more working days and involves a greater number of truck loads for spoil removal.

Option	I	II	III	IV
Score for Conventional safety to workers	4	3	5	4

1.4.3 Sub-criterion: Conventional safety to the public

Conventional safety to the public was assessed based on the number of transports involved. Due to the uncertainty around the site of the DBD, distances are unknown so only transport numbers were presented.

The scenario assumes that there will be two transport casks in rotation as the emplacement procedure occurs, one at the encapsulation site and another at the DBD site. It is assumed there will be a single overpack in each transport cask, to keep the design simple. No assumptions have been made regarding the destination of the spoil, as this would not differentiate between options.

The number of transports to the borehole site will be more dangerous to the public and is therefore weighted more heavily than the number of spoil transports off site. The risk for transporting spoil may be greater than transporting nuclear waste due to more care being taken by drivers when transporting waste.

Summary

Overall, option I requires the fewest transports (overpack and spoil transports combined), which earned it the highest score. Option III includes only slightly more transports, so it was given the same maximum score as option I. In contrast, option II requires roughly double the number of transports, which resulted in a score of 4. option IV, with approximately three times the number of transports than option I, was given a score of 3. The distance travelled and location in Norway where the transport will take place will have an impact and will be considered as part of the sensitivity analysis.

Option	I	II	III	IV
Score for Conventional safety to the public	5	4	5	3

1.4.4 Sub-criterion: Radiological safety to workers and the public during operations

There are no significant differences between the DBD options during waste transport and emplacement operations in terms of radiological safety to workers or the public. However, radiological hazards to workers during waste encapsulation depends on the number of waste types to be encapsulated and the number of overpacks to be produced for each option.

There is potential, though probably negligible, radiological risk when moving the overpack from the transport vehicle to the borehole, due to skyshine. The greater number of overpacks for options I and II increases the likelihood of issues occurring.

The only additional radiological risk when emplacing waste would be if radioactive gas could be released to the surface during emplacement operations, but this would be similar for all options.

Summary

Options III and IV were given a score of 5 because they involve a smaller variety of waste types to be encapsulated and require fewer overpacks to be produced and filled compared to options I and II. In addition, the vitrified HLW in options III and IV was considered less vulnerable to handling accidents than spent fuel assemblies and rods. Option I and II have a greater number of overpacks to be managed, leading to additional risk to operations, as well as greater risk due to the number of waste types to be encapsulated, and therefore scores of 3 were given.

Option	I	II	III	IV
Score for Radiological safety to workers and the public during operations	3	3	5	5

1.5 Site Characteristics

A disposal site has not yet been specified making it difficult to evaluate how site characteristics will differentiate between options. The volume of land needing to be characterised (area and rock) and number of characterisation boreholes required may differ between options. There may be differences in ease of taking water samples, and hydrogeological uncertainties related to characterisation.

1.5.1 Sub-criterion: Site characterisation effort for the disposal borehole

A key parameter for comparison is the extent of the volume that needs to be characterised. Shallow disposal options may require less investigation than deeper ones. On the other hand, the shortened distance between the disposal depth and near-surface system means a greater level of effort may be required to prove that there is no interaction between the disposal level and active hydrogeological systems at shallower depths. This could be counteracted due to the potential of having more readily available data at such depths.

There may be a need for one or more characterisation boreholes, depending on site but as this is not expected to be a differentiator between options, this is not considered further. In terms of macro-geological and hydrogeological issues, deeper options perform better. It could be simpler to characterise deeper sites, or there may be a need to drill several deep investigation boreholes. There is no obvious outcome favouring deep over shallow or wide over narrow DBD options.

Summary

Generally, requirements to make a safety case might be more stringent at shallower depths, but to characterise a deeper site the investigation boreholes may need to be twice as deep. Therefore, there was no justification for favouring either the shallower or deeper options based on site characterisation effort.

Option	I	II	III	IV
Score for Site characterisation effort for the disposal borehole	5	5	5	5

1.5.2 Sub-criterion: Ease of finding a suitable site

The conditions required for a suitable site include that regions must be found with sufficient crystalline rock to a depth of at least 1.5 km. There are regions of crystalline rock in Norway not affected by Caledonian faulting that provide such a crystalline basement. The likelihood of finding suitable site conditions is considered to be higher at greater depth. Therefore, the deeper DBD options II and IV were given a score of 5, while the shallower options I and III were given a lower score of 4.

Option	I	II	III	IV
Score for Ease of finding a suitable site	4	5	4	5

1.6 Technical Implications

The TRL was considered separately for each part of the disposal process:

- The TRL for waste emplacement is considered to be the same for all options.
- The TRL for borehole closure is also considered to be the same for all options, with the caveat that no tests have yet been carried out at 3 km depth.
- Sealing encompasses the SSM, main seals and backfilling material. The SSM has two functions, to support the stacking load stress of the overpacks and to slow ingress of groundwater. Neither are critical to the safety case. The main seals are emplaced at the top of the disposal zone, consisting of cement and bentonite layers, followed by a backfill. The SSM proposed for DBD is a cementitious matrix, which must be pumpable down a borehole, where it will encounter higher temperatures at depth. Cement may thicken or set faster at higher temperatures; however, additives can delay thickening. Overpacks may need to be emplaced through water/brine, which may complicate emplacement of SSM. Delivering a liquid cement grout down the hole via a steel tube requires preventing the cement from setting prematurely. Emplacement of cement grout at depth in wet environments has been previously done in the oil industry and for geothermal purposes. The deeper holes are more likely to cause issues with premature cement setting. However, the TRL is based on the availability of the additives rather than cement itself, so the differences between options are considered to be small.

1.6.1 Sub-criterion: Maturity of borehole technology

The feasibility of constructing boreholes was scored based on the diameter and depth of the boreholes. Wider holes have previously been drilled to 2000-m depth; therefore, there is confidence in the feasibility of drilling a narrower hole to 3000-m depth. The shallower borehole with a narrow diameter (option I) was considered the easiest to construct and therefore received the highest feasibility score of 5. The deeper borehole with a narrow diameter (option II) and the shallower borehole with a wide diameter (option III) are more challenging. These options received a lower score of 4. Option IV, the deeper borehole with a wide diameter, is the most technically demanding to construct and received a score of 3.

There are no differences between the options concerning the TRL of waste emplacement and casing installation. The technical maturity for casing, backfilling and sealing is the same for all options. However, there is the technological challenge of SSM emplacement. The increased difficulties for emplacing SSM at greater depths have not yet been explored and could potentially be an especially challenging part of the process. Additionally, the higher host rock temperatures in the deeper options could lead to a quicker hardening of the cementitious materials, which could complicate their proper emplacement, but in Norway small geothermal gradients are expected. Therefore, option IV, with highest temperatures at depth, scores the lowest. These difficulties are already adequately accounted for in the feasibility scores assigned to borehole construction and there is no need to further reduce these scores.

Option	I	II	III	IV
Score for Maturity of borehole technology	5	4	4	3

1.6.2 Sub-criterion: Maturity of encapsulation technology

The transport of waste from the encapsulation plant to the borehole disposal site is not factored into the assessment of technological maturity, as this type of transport is routinely conducted worldwide and does not introduce any technological uncertainty.

The overpack design is similar across options, and therefore there is no differentiation between the maturity of the technology used, as options have similar designs with slightly differing geometries.

The main difference is whether a narrow or wide overpack is required to suit the different SNF management variants. The material selection and production methods are the same. There will be differences in the cost and risk between the narrow and wide overpack. Therefore, the overpack diameter (circumference) is the key differentiator.

The larger diameter of the overpacks in options III and IV introduces slightly more demanding requirements on the welding process, though this is not significant enough to warrant differentiating the scores of the various options. Welds are the components of the overpacks most susceptible to corrosion, and therefore wider overpacks will have a greater risk to corrosion. Electron beam welding is considered a viable method for welding overpacks. This technique is relatively complex because it must be done in a shielded cell and requires a vacuum, which increases the complexity of production and lowers the TRL for the manufacturing process.

A more substantial distinction lies in the greater variety of waste forms present in options I and II. The differing waste forms necessitate the use of various types of internal baskets to adequately fill the space around the waste within the overpacks. All options include 1 tonne of SNF treated using MMC; each MMC ingot will go into an overpack. However, for options I and II, multiple fuel rods of different types will also go into an overpack, adding complexity, especially because some fuel assemblies may be damaged. There is more experience with encapsulating the CSDV canisters, as emplacement inside disposal overpacks has been done or is planned in several countries. However, encapsulation for options I and II will still be more complicated due to the SNF management variants included. As a result, the technological maturity of options I and II was assigned a score of 4, while options III and IV received the highest score.

Option	I	II	III	IV
Score for Maturity of encapsulation technology	4	4	5	5

1.7 Security and Safeguards

1.7.1 Sub-criterion: Operational phase security and safeguards

During the operational phase, the borehole site will be secured. These security measures may remain in place, possibly in a reduced form, during the institutional control phase after borehole closure. The same level of security can be applied for all DBD options, meaning there is no difference in security between them during the operational phase.

When comparing the different DBD options, only the disposal depth represents a significant distinction. The footprint remains negligibly small for all options and the option of selecting a remote site with no or limited resources is possible for each option.

The International Atomic Energy Agency (IAEA) safeguards are a set of technical measures implemented to verify that fissile materials are not diverted from peaceful uses to the development of nuclear weapons. These safeguards are designed to monitor and account for fissile material. Since IAEA safeguards apply only to fissile materials, the vitrified HLW in options III and IV is not subject to safeguards. However, because some SNF will be treated using MMC and the ingots disposed of in the borehole, safeguards measures will still be required for options III and IV, just as they are for options I and II.

Summary

For options III and IV, only the nine disposal overpacks containing MMC ingots will be subjected to safeguards. On the other hand, in options I and II the number of disposal overpacks will be between 84 and 160, and all will be subjected to safeguards. Therefore, safeguard checks may take more time for options I and II, but the difference will be minor so there does not seem to be a reason to differentiate operational phase safeguards requirements between the different DBD options.

Option	I	II	III	IV
Score for Operational phase security and safeguards	5	5	5	5

1.7.2 Sub-criterion: Post-closure phase security and safeguards

After closure, safety measures will remain in place in a reduced form, but this will be the same for all four options. Once active security measures are lifted, the security of the disposal site will depend on passive features intrinsic to the DBD concept. The main feature is the disposal depth, which provides an extremely high degree of isolation and reduces the level of safeguarding required. Additionally, the small footprint of the borehole minimises the risk of inadvertent human intrusion. The disposal site can further enhance security, as a remote site with limited or no resources reduces the likelihood of intrusion.

Post-closure safeguards would be intended to ensure that there is no intrusion to extract waste from the borehole and to monitor that waste remains within the borehole, which will be easier for the shallower options. Safeguards rely on geophysical methods and satellite images, which will be the same for all options but may be more relaxed for the deeper options. There are no differences in the security measures that need to be implemented for the four DBD options, nor is there a notable variation in the level of security they provide during either the operational or post-closure phases. While the deeper options might be perceived as offering a greater degree of security, disposal at depths of both 1.5 km and 3 km are considered extremely secure. Therefore, there is no justification for distinguishing between the shallower and deeper DBD options in terms of security.

Summary

From a safeguard's perspective, there is no clear basis to distinguish between the options. Although options III and IV will involve less waste subject to safeguards compared to options I and II, all options will require safeguards measures, such as maintaining continuity of knowledge, verifying the final design, or ongoing site surveillance. The specifics of these measures cannot be defined without a licensed design that has undergone evaluation by the IAEA Department of Safeguards. Therefore, it is not possible to rank the options based on potential safeguards obligations. However, any differences in safeguard requirements between the options are expected to be minimal. Consequently, all options received the same score for post-closure safeguards.

Option	I	II	III	IV
Score for Post-closure phase security and safeguards	5	5	5	5

NEXT MEETING

DATE	TITLE
31 Oct 24	OAP Workshop Session 2

Nota bene. Any comment on these Minutes to be provided within five working days following their transmission. Otherwise, attendees are deemed to accept these Minutes as accurate and complete.

Distribution: Meeting attendees

REVISION	PREPARED BY	REVIEWED BY	APPROVED BY	ISSUE DATE	NOTE
C	S. Prasad	S. Wickham J.L. Cormenzana D.A. Galson	L. Prévot	09/01/2025	
C2	S. Prasad	L. Prévot	L. Prévot	04/02/2025	Answer to NND comments received on 27/01/2025
D	S. Prasad	L. Prévot	L. Prévot	24/02/2025	Accepted version

Note: Revision A and B correspond to the transmission of brief material ahead of the meeting to NND and to OAP Panelists.

APPENDIX 3

MINUTES OF THE OPTION ASSESSMENT PANEL – SESSION 2

Rev	Written by	Reviewed by	Approved by	Date	Description
D	S. Prasad	L. Prévot	L. Prévot	24/02/2025	Accepted version
C2	S. Prasad	L. Prévot	L. Prévot	04/02/2025	Answer to NND comments received on 17/01/2025
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Note: Revision A and B correspond to the transmission of brief material ahead of the meeting to NND and to OAP Panelists.

DEVELOPMENT OF SOLUTIONS FOR DISPOSAL OF SPENT FUEL AND OTHER RADIOACTIVE WASTE INCLUDING BOREHOLE DISPOSAL SUBCONTRACT 2

OAP MEETING MINUTES: MULTICRITERIA ANALYSIS OF SHORTLISTED OPTIONS – SESSION 2

TASK C004 - OPTIONEERING

31 October 2024 On Teams

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Key: DBD: Deep Borehole Disposal; DSA; IAEA: International Atomic Energy Agency, ILW: Intermediate-Level Waste; MMC; Mobile Melt Consolidation, NND; Norwegian Nuclear Decommissioning, OAP; Option Assessment Panel, PUREX: Plutonium Uranium Reduction Extraction, RD&D: Research, Development and Demonstration; SB2: Subcontract 2 Framework Holder; SNF: Spent Nuclear Fuel; SSM: Sealing and Support Matrix; TRL: Technology Readiness Level.

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✓ Attending - × Not present: Any Norwegian socio-economic queries have been flagged to Phil Richardson. SB2 experts not attending OAP Session 2 have participated in the preparation of the OAP

[1] *Jacobs Multiconsult now Amentum.*

Meeting objectives:

- To assess and score the shortlist of deep borehole disposal options against a second set of criteria including, socio-economic impacts, flexibility, environment/sustainability impacts and lifetime cost.
- To capture key points of discussion, pros and cons of options and note any uncertainties and assumptions made when scoring.
- To identify knowledge gaps that affect scoring, and highlight areas for potential future research, development or demonstration (RD&D).
- To consider the impact of weighting scores through a sensitivity analysis.

MINUTES OF MEETING

1. Introduction

1.1 Description of Shortlisted Options

This study compares four previously defined borehole geometry options being considered within the SB2 framework for Deep Borehole Disposal (DBD) of radioactive waste in Norway. Only DBD options are compared and not mined repositories. The borehole geometries include narrow and wide boreholes and shallower and deeper boreholes. They are designed to contain different spent nuclear fuel (SNF) management variants: direct disposal of all SNF, oxidation of the metallic uranium fuel and direct disposal of the rest of the SNF, mobile melt consolidation (MMC) treatment of metallic uranium fuel, and direct disposal of the rest of the SNF, and plutonium uranium reduction extraction (PUREX) reprocessing of most fuel assemblies and direct disposal of the remaining un-reprocessed fuel assemblies. All options include some MMC ingots, and all options consider vertical DBD in crystalline rock using a long-lived overpack that would ensure waste containment at least during the thermal phase (1,000 years).

The Option Assessment Panel (OAP) Brief slides, describing the shortlisted options are included in Attachment1.

TABLE 1: SHORTLISTED OPTIONS[2]

BH geometry option	Variant	SNF management variant (Note 4)	Depth to top of disposal zone [m]	Borehole diameter (mm)
I	I.1	Direct disposal of all SNF	1500 (Note 2)	610
	I.2a	Oxidation of the metallic uranium fuel and direct disposal of the rest of the SNF		
	I.2b	MMC treatment of metallic uranium fuel and direct disposal of the rest of the SNF		
II	II.1	Direct disposal of all SNF	3000	

[2] *Note 1: all numerical values are indicative (applicable for the whole drawing)*

Note 2: if suitable host rock conditions are found at a depth of 1000 m

Note 3: if the site characteristics at a depth of 1000 m are not suitable for DBD and/or greater disposal depth is desired to increase stakeholder acceptance

Note 4: all options include Mobile Melt Consolidation of 1 tU

BH geometry option	Variant	SNF management variant (Note 4)	Depth to top of disposal zone [m]	Borehole diameter (mm)
	II.2a	Oxidation of the metallic uranium fuel and direct disposal of the rest of the SNF	(Note 3)	
	II.2b	MMC treatment of metallic uranium fuel and direct disposal of the rest of the SN		
III	III.3	PUREX reprocessing of most fuel assemblies	1500 (Note 2)	990
IV	IV.3	PUREX reprocessing of most fuel assemblies	3000 (Note 3)	

1.2 Key Assumptions and Boundary Conditions

Uncertainties and assumptions used in this study to underlie the development of the shortlisted options include the following:

- The optioneering study only concerns DBD of Norwegian legacy SNF. The disposal of Norway's intermediate-level waste (ILW) or low-level waste by DBD is excluded, as well as any potential waste associated with future nuclear new build activities. The disposal of long-lived (LL)-ILW by DBD, increased waste arisings and impact of co-location with other types of radioactive waste repositories are assessed under the flexibility criterion in the Part 2 OAP workshop on 31 October 2024.
- There is currently no requirement regarding waste retrievability in Norway. However, to err on the side of caution, the potential implications of waste retrievability during and after operations are also considered within the flexibility criterion.
- The scope of the study starts from the disposal encapsulation process, including transport from the encapsulation plant to the repository site, and extends until closure. The reprocessed waste canisters/fuel rods/fuel assemblies are assumed to be encapsulated for disposal at a single location. The encapsulation plant is assumed in all cases to be located on the planned new long-term storage site, to ease the comparison of DBD options within this study. Alternative encapsulation plant locations are discussed under the flexibility criterion. Holistic SNF management and disposal options will be consolidated following the completion of three parallel optioneering studies – the second one considering SNF processing options (SNF Framework), and the third one comparing mined disposal options with DBD (GeoRen Framework).
- A demonstration of waste and Sealing and Support Matrix (SSM) emplacement and borehole closure has not yet been carried out. The current Technology Readiness Level (TRL) of the DBD concept options are considered under the Technical Maturity criterion.
- Only crystalline rock has been considered for the DBD host rock.
- Norway will pursue a disposal option for its own wastes independently of any multinational initiatives established by anyone else.
- As the SNF management strategy has yet to be decided, four scenarios of SNF management, including no treatment for the bulk of the SNF, are assumed. All four options include some SNF processed via MMC into metal alloy ingots.

2. Option Scoring

A list of criteria has been developed from the considering criteria used in the Jacobs-Multiconsult and GeoRen interfacing option studies. Each criterion may also be split into sub-criteria. During the first OAP session, safety and health, site characteristics, technical implementation and safeguards and security criteria were discussed. Options were placed in relative order of performance against each individual sub-criterion and were compared against each other. There is no baseline option used for comparison. First, the option that performed best for each sub-criterion was identified and scored as a 5. The other options were given a score of 5 or lower depending on the degree to which they underperformed compared to the best-performing option. Criteria not discussed during the first OAP session were discussed during the second OAP session, when sensitivity analysis was also discussed.

1.3 Socio-Economic Impacts

1.3.1 Sub-criterion: Impact on the local community and economy

Assessing the potential socio-economic impacts of a DBD project is challenging without a specific project site. In addition, there are currently no regulations in place specifying how socio-economic impacts are to be managed, or whether or whether incentives might be offered to potential host communities. Therefore, socio-economic impacts can only be considered in broad terms by identifying those factors that may influence community perception of a DBD project.

One such factor is the profile of the community itself, as communities can vary widely. For instance, it could be a small rural area reliant on tourism or a single industry, or a large urban community with a diversified economic base. A small community with an existing industry may be more sceptical to hosting the DBD site, as they may not be receptive to the prospect of competing industries, and local businesses might feel they could suffer. Traditional industrialised communities are generally more open to establishing new industries with regards to overall growth of the community.

Options that generate more traffic may cause greater community disruption and might be more noticeable in a smaller or semi-urban community. Impacts from traffic will be greater for the deeper and wider borehole options, with longer durations for operations on site. They will, however, result in greater local spend.

Options requiring more labour over extended periods may boost local spending but also increase the demand on local services. The influx of labour will be over a shorter period for the narrower and shallower options. Smaller communities might not want an influx of external labour and may want workers to be located on an external camp.

There may be shifts in land use patterns, potentially affecting the community's appeal and growth for the duration of the project and sometime into the future. Longer construction and operational timelines could impact community perceptions positively through sustained economic benefits and negatively through prolonged disruption. However, disposal operations are expected to last 500-700 days, which is a relatively short period. Therefore, the duration of operations is not a strong differentiator between options.

Community reactions to a proposed DBD project are difficult to judge without consultation. Drilling a shallower borehole may be deemed better so that the community does not feel as impacted. However, deeper boreholes may prove more acceptable to risk-averse communities since the waste would be further from the surface, potentially lessening concerns.

A sceptical community may demand a full-scale field test to demonstrate the technology in real conditions elsewhere and/or to prove the ability to retrieve damaged overpacks, if necessary, which could increase project duration significantl. There is experience of recovery operations for shallower boreholes from other industries; however, there is less confidence with recovery for the wider and deeper borehole options. Proof of retrievability may be a regulatory requirement.

There could be an increased demand on social infrastructure, especially for a smaller community, putting a strain on municipal budget. Urban areas are more likely to exhibit a ‘Not In My Backyard’ (NIMBY) sentiment, whereas areas of lower population density may be less likely to exhibit this.

As the siting process is not yet defined, it was decided not to consider interactions with the Halden and Kjeller communities (sites of the research reactors that generated the SNF being considered in this project) - although it is noted that issues experienced with these two communities could be analogous to potential issues for DBD siting. New nuclear regulations may specify the kind of communities to target, and the presence of suitable geology at depth would be a key consideration. NND has completed a first draft of a siting strategy, which the Norwegian nuclear regulator has reviewed. The first use of the siting strategy will first be for a new long-term storage facility for SNF.

Summary

Overall, the most relevant negative socio-economic impacts are likely to relate to societal concern deriving from community perceptions of the project and any prejudices regarding the disposal of nuclear waste. These are difficult to assess without knowledge of the potential host community. The most relevant positive impact is likely to relate to increased spend in the local community, but it is difficult to differentiate the options on this basis.

In conclusion, using potential socio-economic impacts to differentiate between DBD options remains challenging without a specific site and specific socio-economic regulations. The general considerations provide a preliminary understanding, but a detailed analysis will be needed once a site is chosen, and relevant regulations are in place. Until then, distinguishing between DBD options on socio-economic grounds remains difficult, and all options are given the same score.

Option	I	II	III	IV
Score for Impact on the local community and economy	5	5	5	5

1.4 Flexibility

The 'Flexibility' criterion addressed how well the DBD option can handle change related to programme complexity. Complexity of implementation was addressed within the operational safety element (i.e., the number of process steps). Therefore, only the adaptability of the options was assessed here.

1.4.1 Sub-criterion: Adaptability

This sub-criterion focused on how easily options could adapt to unpredictable future changes and discussion led to the following considerations.

Options involving a wider borehole (III and IV) provide greater flexibility because the overpacks and borehole in these options can accommodate all SNF and/or HLW generated in the four SNF management options. This flexibility allows for deferred decision-making regarding the SNF treatment method.

Currently, the DBD options are limited to consideration of the borehole disposal of SNF and/or HLW, excluding LL-ILW. However, should the need for co-disposal of LL-ILW and SNF/HLW arise, the wide borehole options would again prove more flexible because they provide less stringent dimensional constraints and an increased disposal volume per unit length of borehole compared to narrow borehole options. Additionally, deeper boreholes could provide more flexibility because LL-ILW could be emplaced above the SNF/HLW without increasing the total depth of the borehole. Conversely, the depth of shallower borehole options could simply be extended to accommodate LL-ILW. Depending on the amount of LL-ILW to be disposed of, a new borehole design might also be needed or a second shallow borehole drilled, increasing costs. Rough estimates of the dimensions and volume of LL-ILW after conditioning for DBD would be needed to draw a clear conclusion.

After completion of the borehole, it would be difficult to restart drilling if it is decided that additional waste is to be disposed of. Therefore, this should be considered during the early design stage. It is expected that when drilling operations commence, the waste to be disposed of will be known and given the short timescale of drilling and emplacement, it is unlikely new waste would be included at that point.

All DBD options could be implemented at an independent site or could be co-located with other radioactive waste disposal facilities. If the other facilities have already been sited and there is a requirement to co-locate the DBD facility at a given site (i.e. there is no independent site selection process), the deeper options would offer more certainty / adaptability. Similarly, deeper options would have the advantage of greater siting flexibility for a purely community-led siting process (in which the availability of appropriate host rock at shallower depth was not a siting consideration).

Currently, there is no regulatory requirement in Norway for the retrievability of SNF or HLW disposed of in a geological repository. Should future regulations introduce such a requirement, retrieval operations would generally be easier in shallower boreholes than in deeper ones. Retrieving the waste from the borehole could be done by overcoring. To facilitate any potential retrieval of the overpacks, the annulus between the overpacks and the casing could be made greater than necessary for emplacement operations. This would increase the bottom diameter of the borehole, which would be easier in the narrow boreholes than in the wide ones. Retrieval operations would be easier in a shallower and narrower borehole.

Summary

Overall, the borehole designs for the deeper and wider options were found to offer greater flexibility due to their increased disposal volume, enabling them to accommodate a larger waste volume and/or wider variety of waste forms. Therefore, option IV received the highest score of 5. Options II (narrower) and III (shallower) were assigned lower scores of 4. Option I, which is both shallower and narrower, was given the lowest score of 3.

Note that the shallower and narrower options perform better against retrievability; however, the ability to maximise disposal volume was prioritised over retrievability..

Option	I	II	III	IV
Score for Adaptability	3	4	4	5

1.5 Environmental / Sustainability Impacts

Criteria from the Egis sustainability assessment system were used as a starting point to perform an environmental comparison of the different options. The criteria were mapped to the issues to be addressed in an Environmental Impact Assessment in Norway. The assessment focused on attributes considered to be of most importance to the assessment: material use, energy requirements, secondary waste and greenhouse gas (GHG) emissions. Note that there is overlap between the GHG sub-attribute and the other three attributes as material use, energy requirements and secondary waste all have the potential to impact GHG emissions. Nevertheless, the GHG sub-attribute was retained as a summary indicator given the importance of GHG emissions in achieving national strategies of Net Zero emissions.

The following issues were excluded – as it was more difficult at this stage to use them to distinguish between options:

- Biodiversity footprint and climate change adaption.
- Traffic noise and air quality – although note that traffic and diesel use were considered under energy requirements. However, it was not possible to assess the importance of the number of transports related directly to borehole drilling operations, as this depends in part on the distance from the borehole site to the spoil removal location, which is not known.

1.5.1 Sub-criterion: Material requirements

The material requirements sub-criterion is based on requirements for disposal packaging, and drilling, completing and sealing of the borehole. In absence of a design for an encapsulation facility, an assumption was made that the material requirements for construction of the encapsulation plant would be similar for all DBD options and were this not considered further in scoring. The surface facility footprint is assumed to be the same for all options, and material requirements would likely exceed and mask differences between the borehole options.

There is no basis to determine or differentiate between the number of characterisation boreholes required for each option. Though the material requirements can be estimated for one characterisation borehole, this was not included in the analysis as the number of boreholes for each option is uncertain and this uncertainty could inappropriately dilute the differences calculated for the disposal borehole itself.

Therefore, only the material requirements for drilling, casing, sealing, packaging and backfilling the disposal borehole were used to assess options. Option I uses the least material, and the main differences lie in increased amount of cement/concrete for casing and backfill required for options II, III and IV. There are mitigations that could be included, for example retrieving and recycling borehole casing, to reduce the increased impact but no assumptions were made for the assessment.

While there are clear differences between the options, the absolute values reflect limited material and energy requirements, spoil volumes and carbon emissions. This is relevant considering that the construction of the encapsulation plant, surface facilities and investigation boreholes are not included in the assessment, as these factors are assumed to be comparable or cannot be estimated at this time. Consequently, the differences in scores, may exaggerate the distinctions between options, particularly when compared to the differences observed in the assessment of other criteria. This observation was considered in the sensitivity analysis.

Option	I	II	III	IV
Score for Material requirements	5	4	5	3

1.5.2 Sub-criterion: Energy requirements

The energy consumption for drilling, operating and closing the borehole was estimated based on the amount of diesel consumed, which was equated to kWh. Renewable energy sources can be used as a mitigating factor, particularly in the carbon footprint calculations. It was assumed that one operating day per package will be required for emplacement. There will be differences between the options associated with the energy requirements for manufacture and welding of the disposal packages. However, differences are likely to be minimal compared to the overall energy requirements for running the encapsulation plant. Variations in energy requirements associated with the construction and operation of the encapsulation plant were not included, as these differences are highly uncertain without specific design details. The differences in transport cannot be scaled to energy requirements without site-specific information.

The energy required for drilling, operations and closure and fabrication were considered for each option. Options I and III required the least amount of energy and only differed slightly from each other. Options II and IV were also essentially the same. Overall, the energy requirements are relatively low. The energy required for fabrication of the overpacks is small, since a small amount of steel is required to manufacture the overpacks.

Option	I	II	III	IV
Score for Energy requirements	5	3/4	5	3/4

1.5.3 Sub-criterion: Secondary waste

The secondary waste sub-criterion was based on the volume of spoil from drilling the borehole, as the volume of spoil from overpack fabrication is insignificant. Wastes related to the encapsulation plant, surface facilities and characterisation boreholes were excluded from this estimate, as these quantities were either assumed to be similar for all DBD options or could not be accurately assessed with the available information.

A greater width and depth result in greater spoil volumes from drilling; therefore, as option I had the lowest spoil volume, it was assigned the highest score of 5. On the other hand, option IV had the largest spoil volume and scored the lowest.

There is no proposed destination for the spoil; therefore, it was assumed that the spoil material would go to landfill.

Option	I	II	III	IV
Score for Secondary waste	5	3	4	2

1.5.4 Sub-criterion: Carbon footprint and GHG Emissions

The assessment considered four carbon footprints associated with any industrial operation: these are associated with the materials used, fuel (transport), secondary waste, and direct use of energy. Norway has a carbon emission strategy, for which this sub-criterion could be used as a metric to assess options. Nevertheless, as noted above, the assessment here overlaps with the assessment of the other environmental criteria.

The direct GHG emissions from the drilling and emplacement operations are largely dependent upon the source of energy used. CO_2 emissions are also associated with transport to and from the site, for the mobilisation of the drilling rig, the rest of the site installations, and for transport of supplies during drilling and emplacement operations. These emissions will dependent upon the distance to the site, the tonnages to be transported, and the type of vehicles used. Considering the indirect GHG emissions, it can be noted that the materials to be used in the construction of the borehole (steel for the casing, cement for sealing) are significant sources of CO_2 emissions.

The GHG assessment outcome was based largely on the impact of drilling the boreholes and the energy required for fabricating overpacks. The impacts associated with the encapsulation plant were assumed to be similar for all DBD options and were not included in the analysis. Packaging differences were approximated using energy requirements for steel manufacture. The different transport requirements were included, but their impact was minimal in the analysis, as they cannot be scaled for distance without site-specific information.

It was assumed that renewable energy would not be used for the borehole. The drilling and emplacement machinery could in theory be supplied by overhead power and solar panels, which could change the assessment under this sub-criterion significantly. Therefore, differences in the carbon footprint associated with energy used to implement the borehole was not used in scoring, as this can be mitigated. Its potential importance was investigated further in the sensitivity analysis.

The carbon footprint calculation results showed that option I used the least amount of material and a similar amount of energy to fabricate overpacks as option III, and therefore scored the highest. Option IV used the most material and so scored the lowest.

Option	I	II	III	IV
Score for Carbon footprint and GHG emissions	5	4	5	3

1.6 Lifetime Cost

A preliminary and high-level estimate of the cost of the borehole disposal of Norway's SNF and/or HLW was made to assess whether there were substantial differences in costs between the different options. This was not a full lifecycle cost analysis, and the work focused on estimating costs for developing a license application for DBD, including site characterisation costs, and the cost of implementing the DBD option. The parts of the process that were costed are outlined in the Final report MCA to identify preferred DBD concept options[3]. The following costs were excluded from this preliminary analysis:

1. Costs for spent fuel treatment and interim storage.
2. Generic R&D costs such as development of a demonstration borehole or field test in Norway. It is assumed that generic R&D costs would be similar across the options. The demonstration borehole or field test may be planned in the Programme initiation stage before the characteristics/site of the disposal borehole are known and the SNF treatment option selected.
3. Costs associated with stakeholder involvement, including potential benefits to local communities.
4. Costs associated with regulatory review.

A cost estimate is generally composed of a number of discrete elements:

- **Base cost**: The base cost is the estimated cost to fulfil the base scope of a project. It may include the initial cost; provisions for known activities that are considered in the base cost but for which exact cost values are not presently known; and costs to mitigate against potential risks within the base cost estimate.
- **Estimating uncertainty:** Estimating uncertainty is a contingency primarily associated with events 'in the field' (routine variability). Such events include equipment reliability issues / breakdown, inclement weather; and logistical delays.
- **Funded risk**: Funded risk considers external events that are unpredictable, but whose discrete likelihood and impact can be assessed, such as natural disasters, regulatory changes, and scope changes.
- **Opportunities**: Opportunities are simply positive risks that may decrease the cost.
- **Unfunded risk**: Unfunded risks are risks for which funding is not necessarily provisioned – a supplement may be included depending on how risk tolerant the funding body is.

For this assessment only the baseline approach was costed. Delays to the programme can have a significant impact on the cost; this was accounted for in the risk analysis.

1.6.1 Sub-criterion: Base cost and contingency cost (estimating uncertainty)

Because contingency (or estimating uncertainty) is simply an uplift of the base cost, it was decided to combine the sub-criteria for base cost and contingency cost into a single score based on the total of both cost elements. Therefore, the total cost (base cost + contingency) was used to assess options. The data used for the assessment only included the major cost groups within the project. It was noted that under most groups the data could be broken down into several smaller categories of cost, if a more detailed bottom-up analysis were to be undertaken.

As noted above, the cost for setting up a demonstration/field test was not included within the cost base, as this was considered more of a generic RD&D activity and would not differentiate between options. However, a range of site characterisation activities, which will allow a site to be chosen were included.

There were three cost categories that dominated: costs associated with the encapsulation facility and overpacks, site characterisation, and the cost of drilling the borehole and emplacing the overpacks. When developing the cost data, it was assumed that site selection and characterisation costs would not differentiate between options. The costs associated with the encapsulation plant and overpacks were driven by the number of overpacks, which differentiates between options. The encapsulation plant design costs were assumed to be the same for all options but the number of overpacks required is far fewer for options III and IV and highest for option II. The other category

[3] *Van Marcke P., et al (2024). Final Report Multi-criteria analysis to identify preferred Deep Borehole Disposal concept options in Norway. (361-SB2-C004-REP-006-C). SB2 Deep Borehole Disposal Technical Assistance to NND.*

that distinguishes mostly strongly was the borehole construction cost - the deeper boreholes have the highest construction costs.

Summary

Overall, option III had the lowest cost, but there was little difference across options as the base costs showed only ~20% variation. The option I and II variants have different costs. The estimated total cost for option I ranges from €201M to €211M and for option II from €216M to €226M. As a result, a score varying from 3 to 4 was given to options I and II. Options III (€180M) and IV (€202M) were allocated scores of 5 and 4, respectively. The difference in cost largely reflects the shorter timescales needed to drill a 1500-m deep borehole (option III) and the smaller number of overpacks to dispose of in the reprocessed options. Option III has a lower cost than option I, and option IV has a similar cost to option I.

Option	I	II	III	IV
Score for Base cost and contingency cost	3/4	3/4	5	4

1.6.2 Sub-criterion: Cost risk

To provide a preliminary estimate of the provisions that could be needed to cover potential project risks, an indicative set of risks and opportunities was identified for the DBD options (Complementary Note 11[4])Many risks, if they were to materialise, would impact on the schedule of drilling and result in delays and extensions to the duration of drilling, disposal operations and closure.

Delays to the project are likely to influence cost. Based on assumed risk probabilities, impacts and risk appetite, a risk provision in the order of €10 to €20M was estimated. This provision was not greatly different between the different options, indicating that the options were mostly considered to be equally susceptible to risks, with deeper disposal options (options II and IV) involving longer drilling time, only being slightly more vulnerable to cost increases. It is not clear which of the SNF variants would be disposed of in the borehole resulting in uncertainty, which would influence the cost. It is important to note that the estimates were based on assumed risk probabilities and impacts.

The greatest cost risk is that once borehole drilling has started it is found that the rock at disposal depth is unsuitable, resulting in abandoning the site and starting the process again elsewhere, doubling some of the costs. However, as the differences in risk provision relative to the overall costs were minimal, each option was given an equal score of 5.

Opportunities that could result in cost decreases were also identified, e.g. if the production of overpacks is optimised or if site selection and characterisation effort can be reduced. However, these also do not significantly differ between options.

Option	I	II	III	IV
Score for Cost risk	5	5	5	5

[4] *Van Marcke P., et al (2024). Complimentary technical notes supporting characterisation and comparison of shortlisted DBD options. SB2 Deep Borehole Disposal Technical Assistance to NND.*

1.7 Sensitivity Analysis

The sensitivity analysis considered the impact of attribute weighting on total scores across all attributes. Microsoft Excel was used to develop a spreadsheet tool to automate such sensitivity analysis. The spreadsheet can be used to vary weights at sub-criterion level, but this was not attempted during the workshop.

Scores were assigned at criteria or sub-criteria level based on ranking option performance against specific criteria/sub-criteria. Ranges of scores were given during the optioneering, and as part of the sensitivity analysis, both scores in the range were considered. Weights should reflect the value judgements of stakeholders about the criteria/sub-criteria. Assigning weights to different criteria is therefore inherently subjective. Different stakeholders have differing values and priorities and will assign different weights to the criteria. The analysis sought to identify trade-offs in weighting and to understand whether option preference could be sensitive to changing the weight on specific criteria.

Four alternative weighting scenarios were considered in order to evaluate their impact on the overall result: baseline weights, and Scenarios 1, 2 and 3, respectively reflecting potential interests of local communities, waste owners, and regulators. The baseline represented a set of weights aligned with those used in related options assessment of SNF management options carried out by Jacobs (now Amentum) and GeoRen.

Considering unweighted scores, option III scored the highest followed by options I, IV and II respectively. After applying the baseline weights, option III remained the highest scoring option. The two deeper options scored lowest for environment owing to the greater environmental impact of drilling a deeper borehole. The highest performing option III, which is one of the shallower options, performed better than the other options on all criteria except Flexibility. As well as having better environmental and safety impacts, it contains a smaller, less radiotoxic waste inventory as a result of reprocessing of the SNF. It was noted that option III would only be feasible provided that competent rock is found at around 1.5-km depth. If this is not the case, then the borehole would need to be deeper or an alternative site found. The overall scores differed, but not by significant amounts because all of the options were considered credible, and all of the scores were 3 or above.

The impact on scoring of choosing an alternative location of the encapsulation plant, for example the disposal site or a third location, based on the transport requirements (from storage to encapsulation plant and/or to disposal site) was determined to be similar across all options, and did not change the relative ranking.

Scenario 1 involved a hypothetical weight set reflecting potential priorities of local communities, with a stronger emphasis on safety, socio-economic impacts and environment/sustainability. As the scores were similar against these criteria, the different weights of Scenario 1 did not change the result for baseline weighting.

Scenario 2 involved a set of weights reflecting potential priorities of waste owners, with a stronger emphasis on flexibility and lifetime cost. Option III again had the highest weighted score. The higher weights placed on Cost and Flexibility were not enough to change the overall total weighted scores.

Scenario 3 involved a weight set reflecting potential priorities of the regulatory authorities, with a stronger emphasis on Safety and Technical Implementation and safety. The results showed minimal difference from the baseline and Scenario 1 and 2 results. Option III again had the highest weighted score, and the higher weights placed on Safety and Technical Implementation were not enough to change the overall total weighted scores.

The sensitivity analysis showed that the overall results obtained from scoring of the different DBD options was quite robust to alternative weightings. The overall outcomes of the different applied weightings were similar between scenarios. The conclusion was that all options had pros and cons, but the scores were relatively close, so all options remain viable. The selected option will depend on the spent fuel management strategy, the site selection process, the characteristics of the chosen site (such as the minimum depth at which disposal is deemed safe), and the design and research outcomes from possible future field demonstration test. It is important to note that shallow options would only be implemented at a site that meets the required characteristics for borehole disposal.

Nota bene. Any comment on these Minutes to be provided within five working days following their transmission. Otherwise, attendees are deemed to accept these Minutes as accurate and complete.

Distribution. Meeting attendees

REVISION	PREPARED BY	REVIEWED BY	APPROVED BY	ISSUE DATE	NOTE
C	S. Prasad	S. Wickham J.L. Cormenzana D.A. Galson	L. Prévot	09/01/2025	Commented by NND on 17/01/2025
C2	S. Prasad	L. Prévot	L. Prévot	04/02/2025	Answers to NND comments
D	S. Prasad	L. Prévot	L. Prévot	24/02/2025	Accepted version

Note: Revision A and B correspond to transmission of preparatory material to NND and OAP Panelists before the workshop.

NND

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