Technical report TZ692/2023

PRECONCEPTUAL DESIGNS ASSESSMENT

Ikonen Antti

Saanio Timo

Koskinen Lasse

Kemppainen Kimmo

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SÚRAO

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RESEARCHERS:

Posiva Solutions[1], AINS Group[2]

TEAM OF AUTHORS: Ikonen A.[1], Saanio T.[2], Koskinen L. [1], Kemppainen K. [1]

Lucie Mareda	**Timo Saanio**
Project manager (SÚRAO)	Project manager (AINS Group)
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SÚRAO

Content

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List of abbreviations:

C	Conventional drill and blast excavation method
DGR	Deep Geological Repository
D1	Vertical disposal, alternative 1
D2	Vertical disposal, alternative 2
D3	Horizontal disposal, alternative 1
D4	Horizontal disposal, alternative 2
D&B	Conventional drill and blast excavation method
HD	Horizontal disposal
HVAC	Heating, ventilation and air conditioning
M	Mechanical excavation method
NNS	New nuclear source(s)
NPP	nuclear power plant
RAW	Radioactive waste
R&D	Research and development
SKB	Swedish Nuclear Fuel and Waste Management Co
SNF	Spent nuclear fuel
SÚRAO	Radioactive Waste Repository Authority
TBM	Tunnel boring machine
VAT	Value added tax
VD	Vertical disposal
VVER	Water-water energetic reactor
WDP	Waste disposal package

Explanation of terms:

Concrete container

A waste disposal package for disposal of RAW from decommissioning and of other RAW unacceptable by surface repositories.

Deposition holes/ deposition drifts/ disposal boreholes

Short vertical boreholes bored from charging corridors/ deposition tunnels or sub-horizontal TBM boreholes carried out from DGR main tunnels in which disposal sets/ spent fuel canisters with SNF will be disposed. WDP are protected by the individual engineering barriers.

Foreign materials

Materials that are not designed to contribute to the long-term safety but introduced in the underground construction by virtue of occupational safety (e.g., shotcrete) or concrete structures, pre-grouting or otherwise (oil spills, blasting residues, exhaust fumes from diesel engines) and scrutinized for their potential detrimental long-term safety. It is noted that pre-grouting, while is seen as essential to limit groundwater inflows could contain additives (organics, sulfur) that are seen detrimental either because they either promote corrosion or facilitate transport of (otherwise sorbing) radionuclides.

Horizontal disposal method = 3H

Method of permanent waste disposal package WDP deposition in sub-horizontal boreholes, assuming the deposition of multiple WDP into one borehole when separated by other engineering barriers.

Host rock

Bedrock surrounding the repository serving as a natural barrier.

Radioactive waste

An item that is a radioactive substance or an article or a device containing or contaminated with the substance, for which no further use is expected and that does not meet the conditions laid down by the Atomic Act for the release of radioactive material from the workplace.

Safety function

The safety function refers to operations of the system, structure, components, or another part of the nuclear equipment that are important for ensuring nuclear safety in all states of the nuclear installation.

Spent nuclear fuel

Irradiated nuclear fuel that was permanently removed from the nuclear reactor’s core.

Supercontainer

Supercontainers are assemblies consisting of a canister surrounded by bentonite clay buffer and a surrounding perforated shell.

Vertical disposal method = 3V

Method of permanent WDP deposition in the DGR into vertical boreholes, assuming the deposition of always one WDP into one borehole, including its protection by other engineering barriers.

Abstract

This report introduces a comparison of four design alternatives for deep geological repository. In two alternatives (D1 - VD, M and D2 - VD, C) canisters are deposited in vertical boreholes and in two alternatives (D3 - HD, M and D4 - HD, C) canisters are deposited in horizontal boreholes. On the other hand, alternatives D2 - VD, C and D4 - HD, C are supposed to be excavated mainly conventionally using drill & blast. Tunnel boring machine (TBM) is used for the excavation of most of the tunnels in alternatives D1 - VD, M and D3 - HD, M.

The comparison focuses on items affecting concepts suitability to all sites of the current site selection process. The report also contains a study of pros and cons of different excavation methods (Drill and blast vs TBM) and the most relevant arguments for vertical and horizontal deposition holes/ drifts. Comparing solutions are done for technical properties, technical readiness, long term safety, major operational differences and economics.

The horizontal disposal alternative (D3 - HD, M and D4 - HD, C) introduces several benefits in comparison to the vertical concept (D1 - VD, M and D2 - VD, C), for example, the total excavated volume is smaller, the operational costs are smaller (for example, because no deposition tunnel backfill is needed) and the production process of supercontainers would be more industrial than the separate emplacement of buffer and canister in vertical disposal. On the other hand, the horizontal concept is far less mature than vertical and requires a larger underground footprint. Also, horizontal disposal is potentially much more sensitive to chemical erosion than vertical, which makes the infiltration of dilute groundwater a risk for long-term safety, unless more erosion-resistant clay barriers are developed or new information on bentonite erosion behavior becomes available. Reducing the uncertainties related to long-term safety and demonstrating a sufficient safety level is a key issue if horizontal disposal development is continued in SÚRAO. Chemical erosion and the related potential domino effect are probably the most important topics to address. Solving them would allow the focus to be shifted from long-term safety uncertainties to other decision points, such as costs.

Technical readiness for the excavation using both drill and blast method or tunnel boring machines worldwide is high. However, drill and blast method has been used also for several disposal openings for radioactive waste e.g., low- and intermediate level waste repositories in Loviisa, Finland and in Kyungju, Korea. Therefore, technical readiness from the excavation point of view for the alternative D2 - VD, C is slightly higher than technical readiness of the other alternatives.

Supporting area needed above ground for TBM alternatives is large. Supporting area above ground covers area that is needed for the contractor e.g., to assemble machines that will be used for excavation and to store all equipment and material that is needed. Most of the tunnels in alternatives D1 - VD, M and D3 - HD, M are excavated by TBM, so in these cases large supporting area above ground is needed to store the excavated rock which cannot be used for other purposes. Horizontal disposal boreholes are bored with TBM in alternative D4 - HD, C but with a smaller machine and therefore smaller supporting area will be enough. Smallest supporting above ground area is needed for the alternative D2 - VD, C.

Total costs for horizontal alternatives (D3 - HD, M and D4 - HD, C) have been estimated to be remarkable lower than the costs for vertical alternatives (D1 - VD, M and D2 - VD, C). Main reason for this is the big difference in the volumes between horizontal and vertical alternatives. This has a strong impact on excavation and backfilling costs. Remarkable cost savings for D1 - VD, M and

D2 - VD, C are possible by developing these alternatives, e.g., by reducing the cross-section size of the transfer corridor which would shrink the cost difference. The cross-section size of the transfer corridor in alternative D2 - VD, C is 25 m^2 but corresponding cross-section size of the deposition tunnel in Posiva's repository is almost 10 m^2 smaller.

Due to the great differences in the volumes of the alternatives also environmental impacts have been estimated to be largest for the alternative D1 - VD, M while impacts of the alternatives D3 - HD, M and D4 - HD, C will be smallest.

In all there are no known exclusionary items that would prevent the implementation of the facility with either of the alternative concepts - they are all suitable for all different sites at this stage of SÚRAO development work.

Keywords

Deep geological repository, horizontal disposal, vertical disposal, drill and blast, tunnel boring machine, TBM, site selection

1 Introduction

The assignment is based on the framework contract number SO2016-120-22_ID3 and a partial contract No. 22 assignment ID3 issued by the SÚRAO, “Preconceptual designs assessment”.

The main purpose of the partial contract 22 and this task ID3 is to analyse all aspects of design alternatives that SÚRAO has so it could choose which one of the alternatives or their optimization could be suitable for all different sites at this state-of-the-art. After that, the above part of the repository and the environmental impact will be discussed with communities at localities in one version only. Also, all research and development activities will be influenced by this decision since then. SÚRAO has to focus on one variant at this stage, but this report will also be the report to come back for future evaluations. Site for the Deep Geological Repository (DGR) is not selected yet. Currently, four sites are in the site selection process, Březový potok, Horka, Hrádek and Janoch. Geological information from the sites is still limited and characteristics have not been taken into account in this report. This report supports SÚRAO for the selection of the site for Deep Geological Repository.

This evaluation is based on the following reports:

- Grunwald, L., Bures, P., Spinka, O., Porizek, J., Nohejl, J., Fiedler, F., Kobylka, D., Bittnar, Z., Zahradnik, O. 2018. "Optimisation of the underground parts of the DGR of the reference project - final report", SÚRAO Technical report No. 134/2017, Prague, May 2018.
- Saanio, T., Gerlander, J., Ikonen, A., Palmu, J. & Palomäki, J. 2020. Costs estimation for a deep geological repository for radioactive waste in Czech Republic. SÚRAO Technical report No. 529/2020, Prague.
- Ikonen, A. et al. 2020. Review and recommendations for the Design of the Underground Section of the Czech DGR. SÚRAO Technical report No. 467/2019, Prague.

In this report, a comparison of design alternatives is done and Posiva’s experiences of different conceptual solutions are shared. The comparison focuses on items affecting concepts suitability to all sites of the current site selection process. The report also contains a study of pros and cons of different excavation methods (Drill and blast vs TBM) and the most relevant arguments for vertical and horizontal deposition holes. Comparing solutions are done for technical properties (e.g., volumes, room types, equipment, machines), technical readiness, long term safety, major operational differences and economics. A summarizing table is also included as an Annex 1.

SÚRAO has designed four different alternatives for deep geological repository following the principals of KBS-3H and KBS-3V (Grunwald et al. 2018). In two alternatives (D1 - VD, M and D2 - VD, C) canisters are deposited in vertical boreholes and in two alternatives (D3 - HD, M and D4 - HD, C) canisters are deposited in horizontal boreholes. On the other hand, alternatives D2 - VD, C and D4 - HD, C are supposed to be excavated conventionally using drill & blast technique as is assumed in Posiva also. Tunnel boring machine (TBM) is used for the excavation of most of the tunnels in alternatives D1 - VD, M and D3 - HD, M. Alternatives and corresponding excavation methods are presented in Table 1-1.

Table 1-1. Arrangement variants of the design of the underground premises of the DGR (Grunwald et al. 2018). VD – vertical disposal, HD – horizontal disposal, C – conventional excavation method, M – mechanized method of excavation using tunnel boring machines; Note: A cross indicates the excavation technology preferred for the respective variant.

Arrangement	**D1 – VD, M**		**D2 – VD, C**		**D3 – HD, M**		**D4 – HD, C**	
Method of SNF disposal	Vertical		Vertical		Horizontal		Horizontal	
Preferred method of excavation	C D&B	M TBM	C D&B	M TBM	C D&B	M TBM	C D&B	M TBM
Transfer tunnel		x	x			x	x	
Backbone corridors		x	x			x	x	
Interconnecting tunnels, tech. facilities	x		x		x		x	
Transfer corridors/ deposition tunnels		x	x		---		---	
Disposal boreholes/ drifts		x		x		x		x

KBS-3H is an abbreviation from the Swedish term KärnBränsleSäkerhet 3 Horisontell, which means nuclear fuel safety 3 horizontal. KBS-3H developed by Posiva and the Swedish Nuclear Fuel and Waste Management Company (SKB), is the horizontal alternative to the reference KBS-3V disposal variant for the disposal of spent nuclear fuel in Finland. In the KBS-3H design alternative, canisters are emplaced in long horizontal holes called deposition drifts (Figure 1-1). Disposal is implemented using supercontainers, which are assemblies consisting of a canister surrounded by bentonite clay buffer and a perforated shell. Posiva’s reference design for KBS-3H is the so-called DAWE (Drainage, Artificial Watering and air Evacuation) design. The artificial watering used in the DAWE design guarantees that a certain amount of water is accessible for initial buffer swelling (Posiva 2013a) and heat removal from the buffer to the rock will not be delayed. In the KBS-3H DAWE design, the empty space in the annulus between the deposition drift wall and the supercontainer, distance block and filling components inside a sealed compartment will be artificially filled with water in each drift. (In KBS-3V the small gap between buffer and rock wall is filled with granular bentonite with the aid of gravity, but in KBS-3H this cannot be done - only DAWE water or equivalent can be used.)

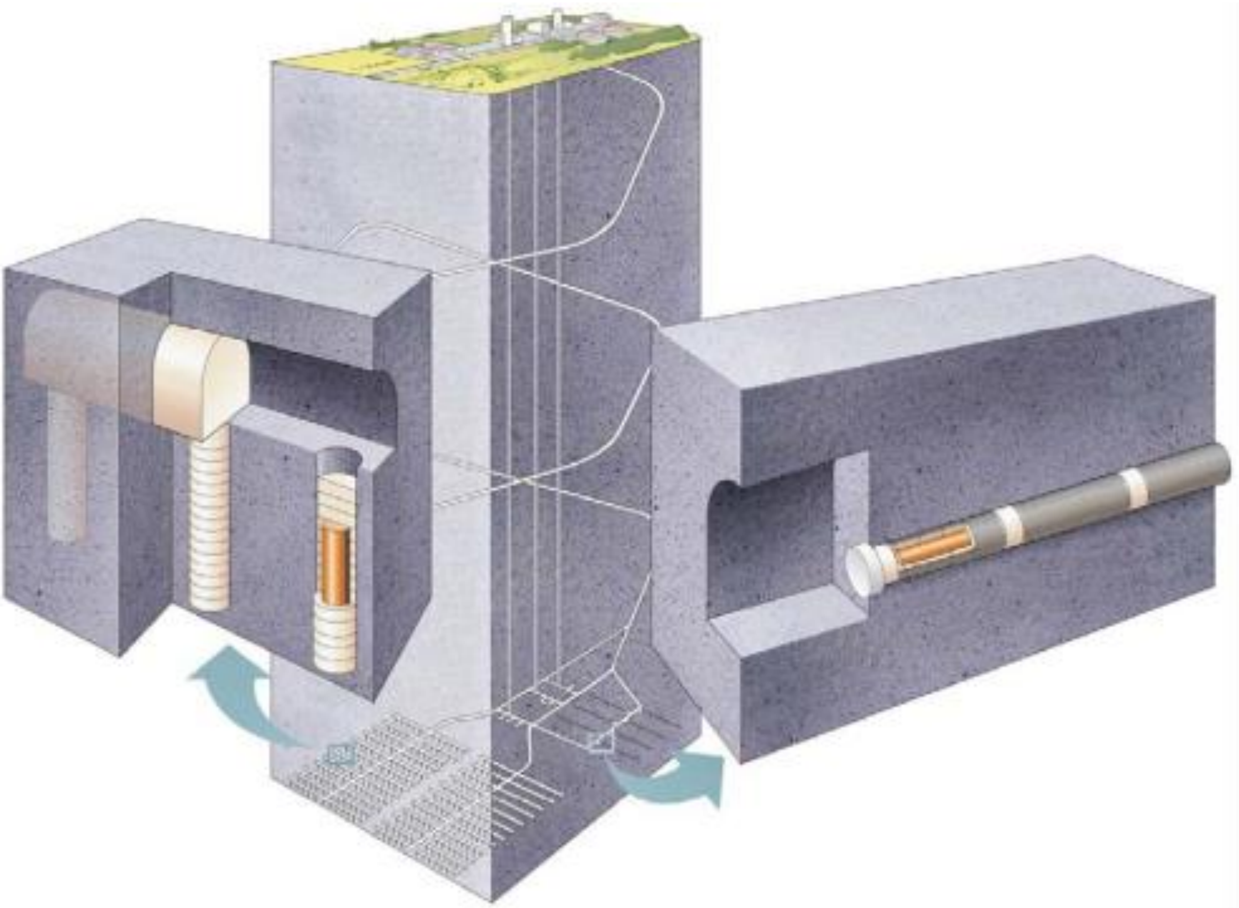

Figure 1-1. Schematic drawing of the KBS-3V reference design (to the left) and the KBS-3H alternative (to the right). All tunnels are excavated with drill and blast method. Figure 1-1 of Posiva (2017a). Courtesy of SKB, Illustrator: Jan Rojmar.

The whole SÚRAO disposal concept and engineering barrier designs are naturally on a very general level in this design stage (see Figure 1-2). Actual site characterization data, further technology and design development will bring remarkable changes in the coming years (Ikonen et al. 2020).

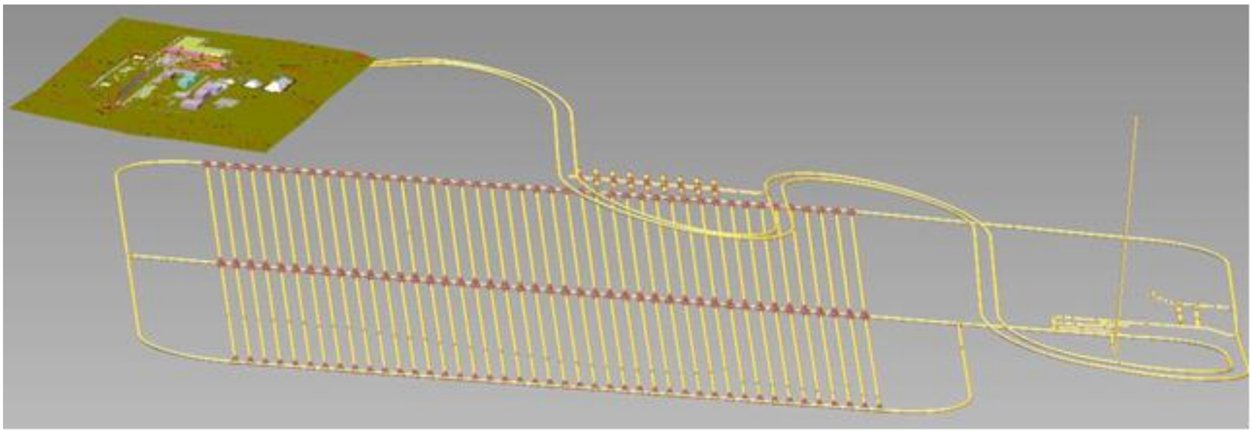

Figure 1-2. DGR layout principle according to the 3D-model by SÚRAO (not fully consistent with the D1-D4 layouts). Above ground facilities are shown in the upper left corner. The SNF disposal panel/ section is in the middle. The down-cast inlet air shaft and technical facilities are on the right.

This technical report is compiled and written by Antti Ikonen, Timo Saanio, Lasse Koskinen and Kimmo Kemppainen. Antti Ikonen and Timo Saanio have checked and approved this report.

Design alternatives are introduced in Chapter 2 of this report. Technical comparison of 3H-method vs. 3V-method is presented in Chapter 3 as well as comparison between Drill & Blast method and Tunnel Boring Method for the excavations of the repository.

Chapter 4 concentrates on technical readiness. Evaluation has been done both 3H-method and 3V-method and on the other hand for both excavation techniques: Drill & Blast and Tunnel Boring Method.

Major operational differences between all alternatives have been collected in Chapter 5. Long-term safety related issues of the alternatives are assessed in Chapter 6.

Overall costs including R&D, site preparation, construction, operation and closure of alternatives have been shown in Chapter 7. Other aspects identified for this evaluation including environmental are collected in Chapter 8. Finally, summary of the report can be found in Chapter 9.

2 Design alternatives D1…D4

2.1 Spent nuclear fuel disposal

SÚRAO has designed four different alternatives for deep geological repository following the principals of KBS-3H and KBS-3V (Grunwald et al. 2018). In two alternatives (D1 - VD, M and D2 - VD, C) canisters are deposited in vertical boreholes and in two alternatives (D3 - HD, M and D4 - HD, C) canisters are deposited in horizontal boreholes. On the other hand, alternatives D2 - VD, C and D4 - HD, C are supposed to be excavated conventionally using drill & blast technique as Posiva will do. Tunnel boring machine (TBM) is used for the excavation of most of the tunnels in alternatives D1 - VD, M and D3 - HD, M (Saanio et al. 2020).

Principle of vertical disposal alternative is introduced in Figure 2-1 and correspondingly principle of horizontal disposal alternative in Figure 2-2.

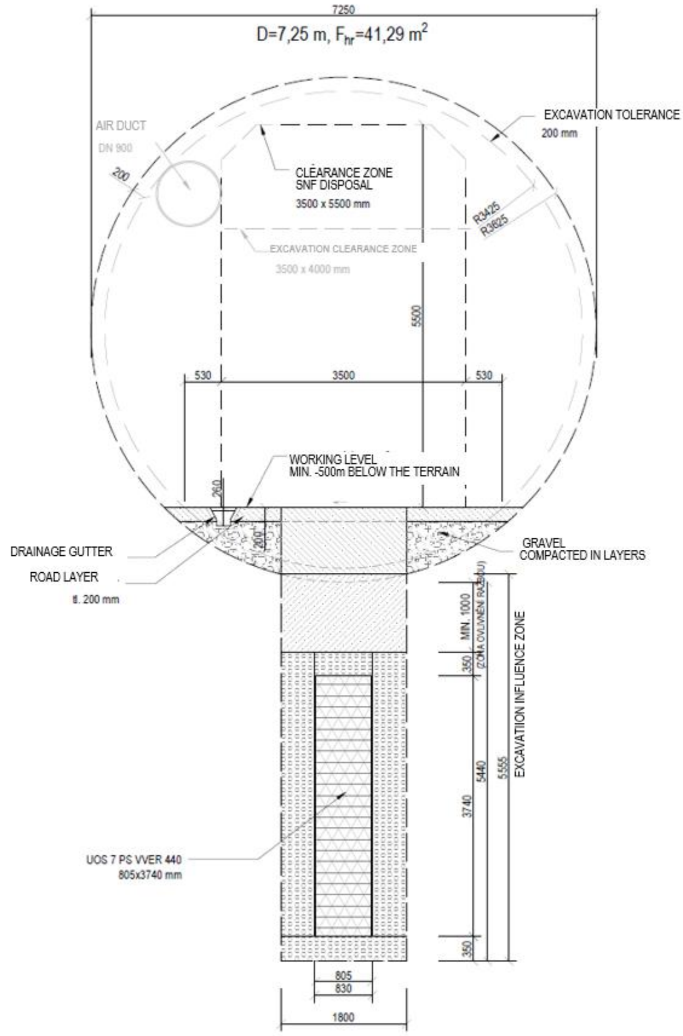

Figure 2-1. An example of vertical disposal of WDP (VVER 440) from the transfer corridor (deposition tunnel) – D1 - VD, M (Grunwald et al. 2018).

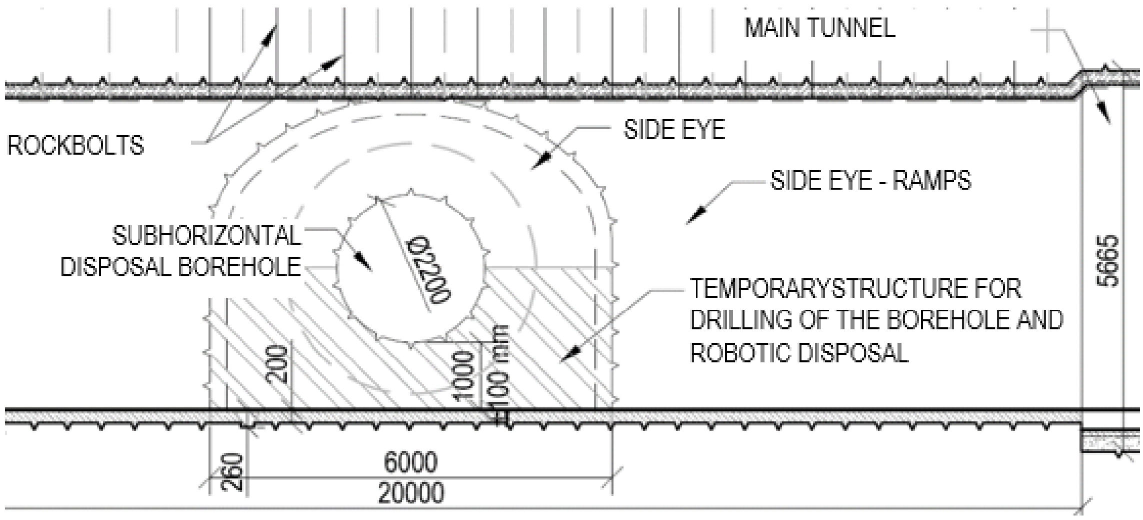

Figure 2-2. An example of horizontal disposal. Cross-section view from main tunnel – variant D4 – HD, C (Grunwald et al. 2018).

Table 2-1 shows the four layout variants (of two basic alternatives) and states the majority representation of the two basic excavation types. Regarding the rock excavation method, there are two alternatives (Grunwald et al. 2018):

- Mechanised boring method based on full-profile boring machines –hard rock TBM
- Conventional drill and blast (D&B) method

Table 2-1. Arrangement variants of the design of the underground premises of the DGR (Grunwald et al. 2018). VD – vertical disposal, HD – horizontal disposal, C – conventional excavation method, M – mechanized method of excavation using tunnel boring machines; Note: A cross indicates the excavation technology preferred for the respective variant.

Arrangement	D1 – VD, M		D2 – VD, C		D3 – HD, M		D4 – HD, C	
Method of SNF disposal	Vertical		Vertical		Horizontal		Horizontal	
Preferred method of excavation	C D&B	M TBM	C D&B	M TBM	C D&B	M TBM	C D&B	M TBM
Transfer tunnel		x	x			x	x	
Backbone corridors		x	x			x	x	
Interconnecting tunnels, tech. facilities	x		x		x		x	
Transfer corridors/ deposition tunnels		x	x		---		---	
Disposal boreholes/ drifts		x		x		x		x

The vertical method (Figure 2-3 and Figure 2-4) deals with disposal of WDP with SNF into vertical boreholes one by one, where each borehole with WDP with SNF will be filled and sealed with bentonite on each side. It is supposed that always a single type of fuel will be disposed in one transfer corridor (deposition tunnel). In principle different fuel types can be disposed in the same transfer corridor. Change of fuel type causes some modifications in the encapsulation station. Therefore, it will cause extra costs and it is not economic to change fuel type of the disposal process too often. Two disposal sections for vertical disposal are delineated within the potentially usable rock block. Each section comprises individual transfer corridors (deposition tunnels) with disposal boreholes.

The horizontal method (Figure 2-5 and Figure 2-6) of disposal deals with disposal of WDP with SNF into horizontal boreholes (drifts) in a row; the individual WDP in the boreholes will be surrounded and sealed with bentonite. It is supposed that al-ways a single type of fuel will be disposed in one horizontal borehole (drift). Four disposal sections for horizontal disposal are delineated within the potentially usable rock block. Each section comprises the individual main tunnels with drilled disposal boreholes (drifts). The dimensions of the cross-profiles are given by the method of disposal, the dimensions of the conveyance mechanisms, the dimensions of the WDP, and the method of excavation (Grunwald et al. 2018).

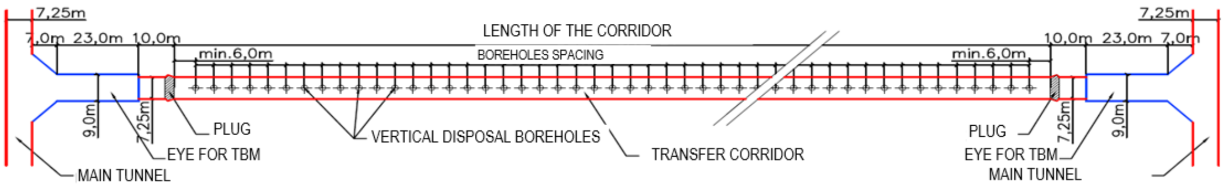

Figure 2-3. Schematic plan of vertical disposal, prevailingly mechanised excavation (D1 - VD, M) (Grunwald et al. 2018). Red lines = TBM tunnels, blue lines = D&B tunnels.

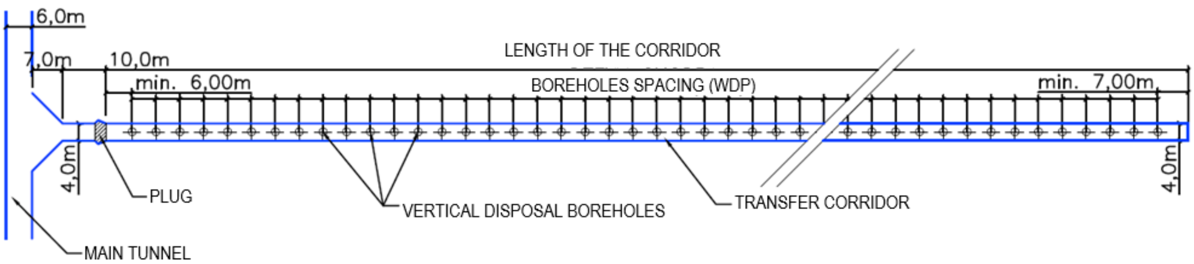

Figure 2-4. Schematic plan of vertical disposal, prevailingly conventional excavation (D2 - VD, C) (Grunwald et al. 2018).

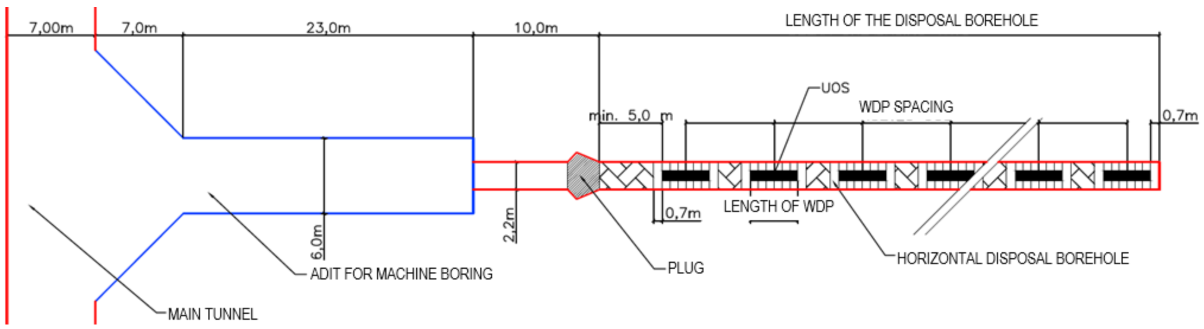

Figure 2-5. Schematic plan of horizontal disposal, prevailingly mechanised excavation (D3 - HD, M) Grunwald et al. 2018). Red lines = TBM tunnels, blue lines = D&B tunnels.

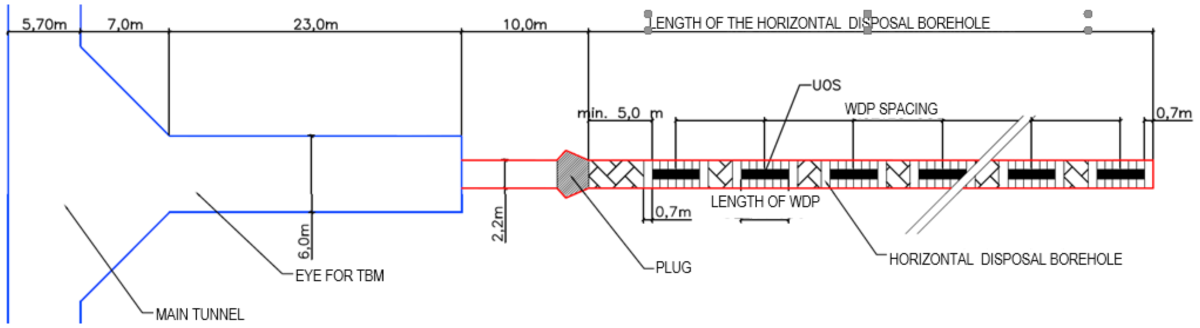

Figure 2-6. Schematic plan of horizontal disposal, prevailingly conventional excavation (D4 - HD, C) Grunwald et al. 2018). Red lines = TBM tunnels, blue lines = D&B tunnels.

2.2 Radioactive waste disposal

Radioactive waste disposal method is the same for all alternatives D1…D4 and is not in the scope of this report. RAW storage does not affect the comparison between alternatives D1…D4. RAW storage chambers (Figure 2-7) are conventionally excavated and connected to the transfer tunnel. The floor is levelled with concrete. Concrete containers outer dimensions are 1,7 x 1,7 x 1,5 m. Due to the fault zones, the storage positions for 3600 containers (20% increase compared to the RAW inventory 3000) is assumed. Eighteen storage chambers (Figure 2-8) with a total length of 55 m, a width of 10,5 m, and a height of 4,8 m (Profile area = 48,29 m^2) is designed (Figure 2-9). One chamber will hold 204 concrete containers (Spinka et al. 2018).

RAW storage chambers will be excavated with Drill & Blast method. Transfer tunnel will also be excavated with the same method in the alternatives D2 - VD, C and D4 - HD, C and therefore excavation of RAW storage chambers can be started smoothly from the transfer tunnel. TBM is used for the transfer tunnel in the alternatives D1 - VD, M and D3 - HD, M. If concrete or steel lining is installed in the transfer tunnel, star-up of the excavation of RAW storage chambers must be coordinated with the assembly oor construction of the lining. However, this is normal procedure also for other tunnels crossing with TBM tunnels.

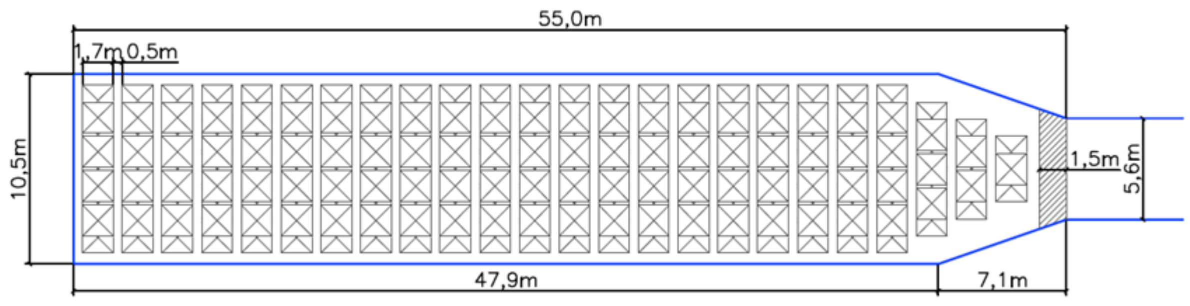

Figure 2-7. RAW storage chamber (Spinka et al. 2018).

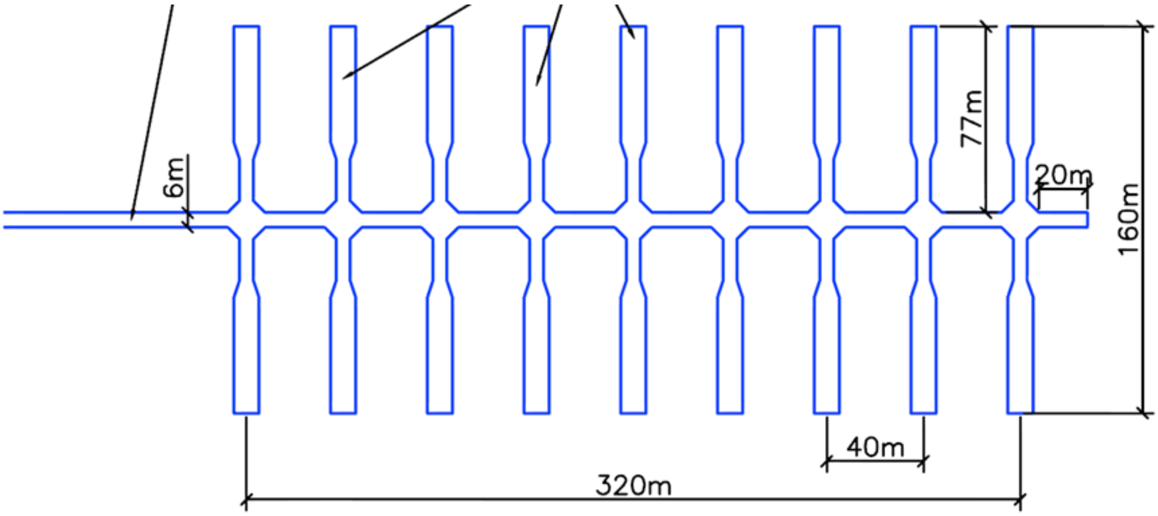

Figure 2-8. RAW storage level (Spinka et al. 2018).

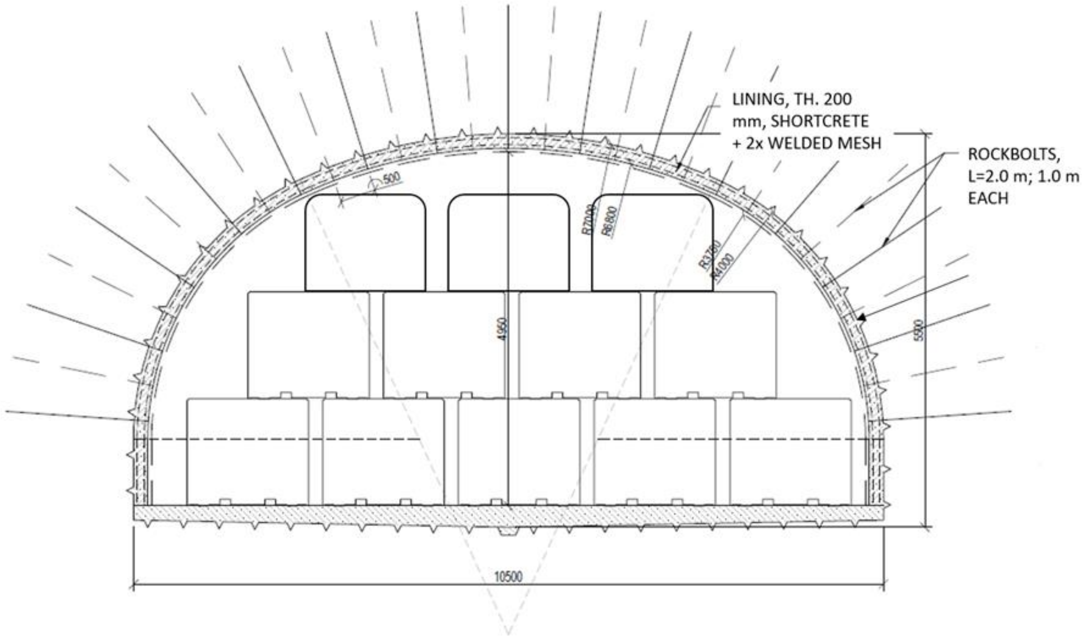

Figure 2-9. RAW storage chamber cross-section (Spinka et al. 2018).

2.3 Layout description

Waste inventory for the Deep Geological Repository is presented in Table 2-2.

Table 2-2. WDP balance for SNF (cooling time assumption 65 years) and RAW (Grunwald et al. 2018).

WASTE	AMOUNT
VVER 440	3100 WDP
VVER 1000	1800 WDP
NNS (New Nuclear Source)	2700 WDP
FUEL TOTALLY	7600 WDP
RAW	3000 concrete containers

Layout of the repository is based on waste amount presented in Table 2-2. Due to the possible fault zones, the length of the transfer corridors in the layout is 20% more than theoretically needed.

The storage / disposal areas and their transfer corridors are implemented in usable rock blocks (examples in Figure 2-10, Figure 2-11, Figure 2-12 and Figure 2-13). The underground technical facilities are placed near these blocks. The horizontal disposal (Figure 2-12 and Figure 2-13) requires different sizes and character of the storage/ disposal areas, compared to the vertical disposal (Figure 2-10 and Figure 2-11). The SNF storage/ disposal method impacts on mechanisation, WDP transportation, storage/ disposal, machinery for boring and dimensioning of underground openings. The varying storage/ disposal methods bring varying electric power and other media necessary to operate, maintain and repair the facility (Spinka et al. 2018).

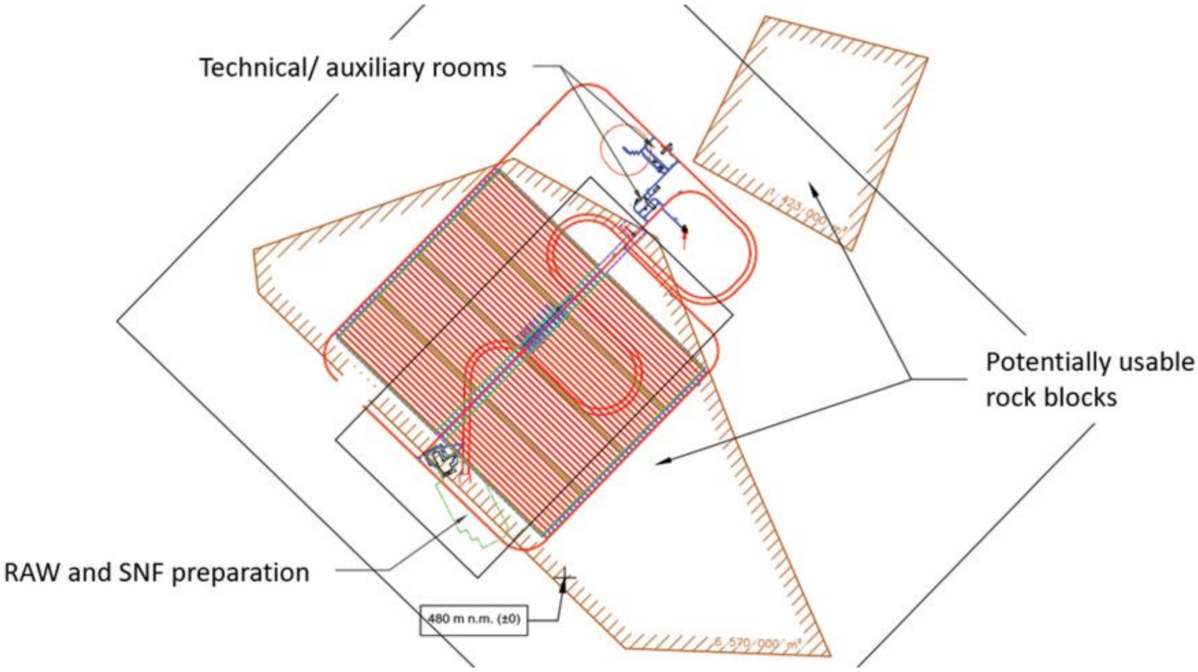

Figure 2-10. Vertical disposal, prevailing mechanised TBM boring (D1 - VD, M) (Spinka et al. 2018). Red lines = TBM tunnels, blue lines = D&B tunnels.

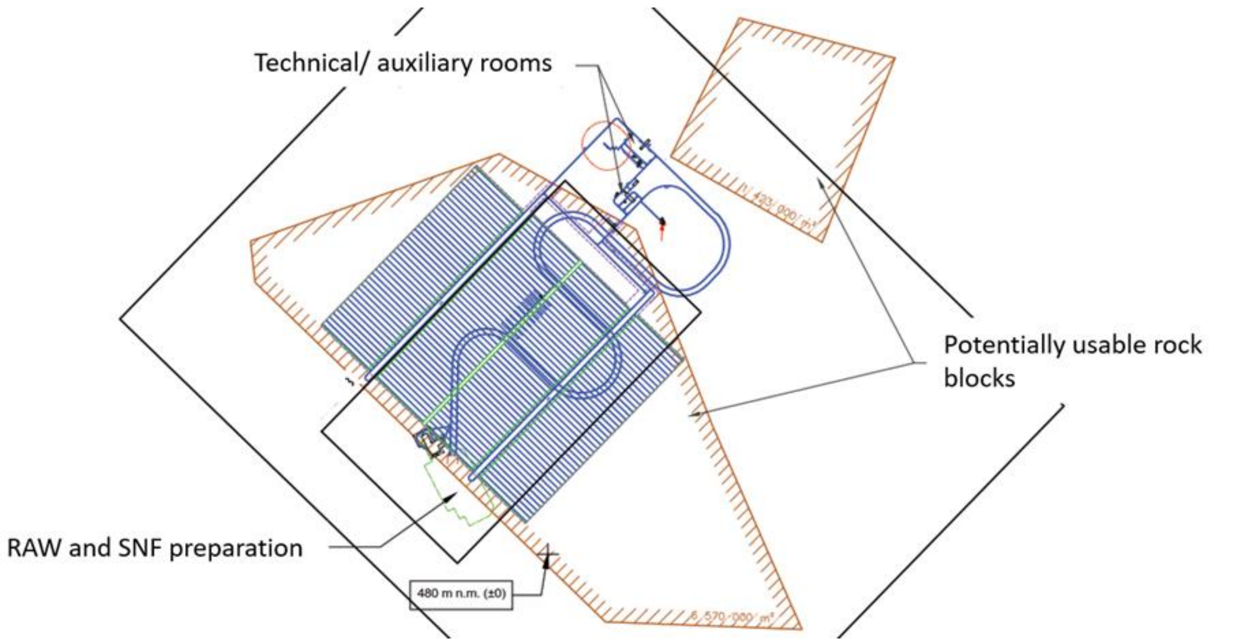

Figure 2-11. Vertical disposal, prevailing conventional drill and blast method (D2 - VD, C) (Spinka et al. 2018).

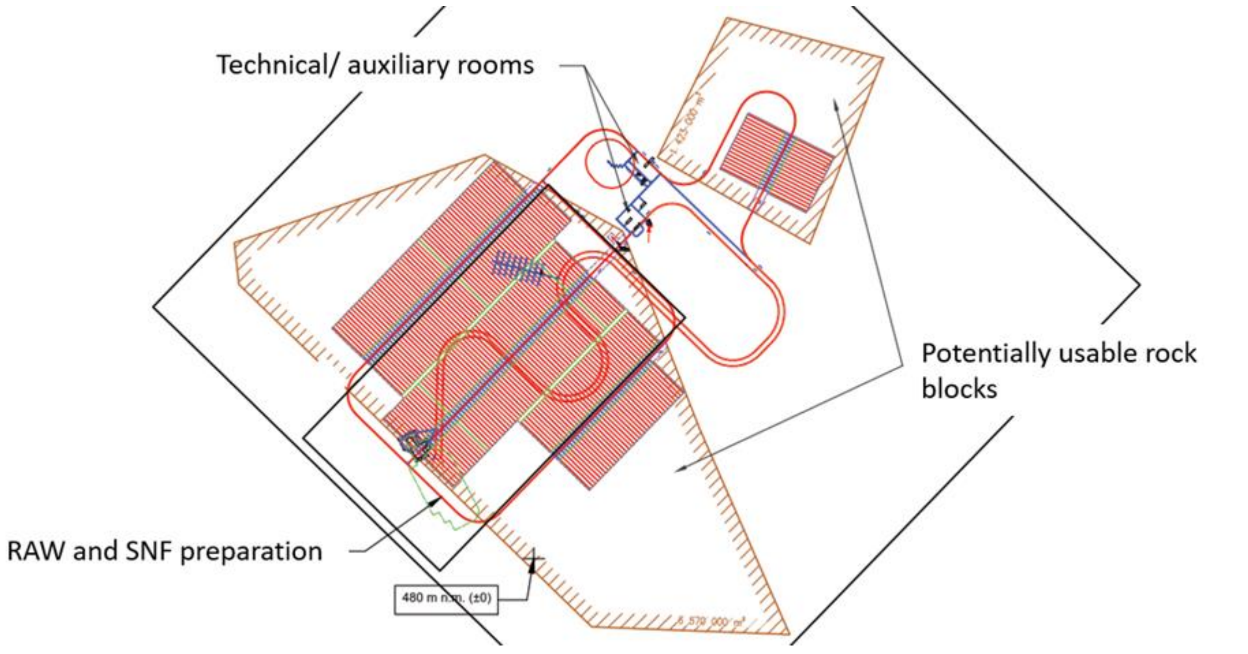

Figure 2-12. Horizontal disposal, prevailing mechanised TBM boring (D3 - HD, M) (Spinka et al. 2018). Red lines = TBM tunnels, blue lines = D&B tunnels.

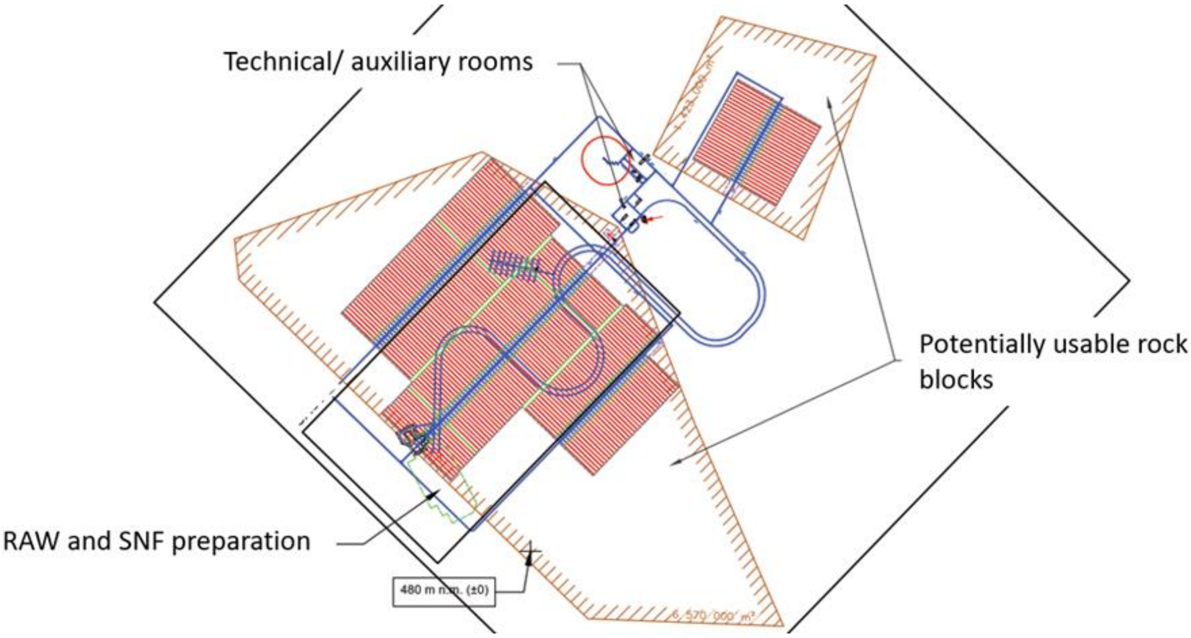

Figure 2-13. Horizontal disposal, prevailing conventional drill and blast method (D4 - HD, C) (Spinka et al. 2018). Red lines = TBM tunnels, blue lines = D&B tunnels.

Main differences in the volumes between the alternatives are collected in Table 2-3.

Table 2-3. Volumes of the main components in different alternatives.

	D1 – VD, M (m^3)	D2 – VD, C (m^3)	D3 - HD, M (m^3)	D4 – HD, C (m^3)
Transfer corridors	3 800 000	2 100 000	440 000	440 000
Vertical disposal boreholes	126 000	126 000		
Horizontal disposal boreholes			445 000	445 000
Main tunnels	400 000	132 000	390 000	287 000
Total	**4 800 000**	**2 753 000**	**1 710 000**	**1 550 000**

2.4 Closure

The transfer corridors (deposition tunnels) are plugged close to the main tunnel. The plug is located 7,5 m from the borehole/ tunnel mouth. The designed plug thickness is 2,5 m, and it is wedged into the rock. All the openings outside transfer corridors (deposition tunnels) will be filled with suitable backfill material. Bentonite is considered as the backfill material for the SNF section. The boreholes themselves are to be filled with prefabricated bentonite. Closure and WDP installation work must be separated from each other by physical barriers between closure section and storage / disposal section (Spinka et al. 2018).

Closure in the case of vertical disposal includes (Spinka et al. 2018):

1. Filling the disposal boreholes with prefabricated bentonite
2. Filling the transfer corridors/ deposition tunnels
3. Securing the filled transfer corridors/ deposition tunnels with plugs
4. Filling the handling niches and corridor parts
5. Filling the main tunnels

Closure in the case of horizontal disposal includes (Spinka et al. 2018):

1. Filling borehole sections
2. Securing the chamber entrance with plug
3. Closing the chamber access corridors

The free space between the containers in RAW chambers will be filled with suitable material. Closure of chambers with RAW includes the following activities (Spinka et al. 2018):

1. Filling the free space
2. Securing the chamber entrance with plug
3. Closing the chamber access corridors

Closure of the entire repository will take place once the closure of all the disposal sections is completed and after the specified in-situ monitoring period. The DGR will be filled up with suitable backfill material. For economic assessment of the design, conservative consideration is given to the use of pure bentonite. Activities during DGR closure (Spinka et al. 2018):

1. Removal of equipment, and material
2. Reinforcement removal
3. Filling all the remaining underground openings

Current plan in Posiva's repository is to remove most of the structures (e.g., floors and walls) from all underground tunnels. Some reinforcement must be left because of safety e.g., rock bolts and possibly nets in the deposition tunnels. Operational safety must be guaranteed also during the removal of the reinforcements.

3 Technical comparison

3.1 3H versus 3V

The spent nuclear fuel and canisters (WDPs) are the same ones for horizontal disposal as would be used in vertical disposal. The size and shape of the canisters have been derived based on the space needed for the actual spent nuclear fuel assemblies and on the requirements for e.g. mechanical resistance, corrosion resistance, radiation shielding and cooling capability.

Closure refers to the backfill and plugs in openings other than deposition drifts/deposition tunnels. Host rock is the natural barrier that surrounds the repository to a distance of some tens of metres. Closure and host rock are the same for both horizontal and vertical disposal concepts.

Other repository components have horizontal- and vertical-specific modifications (e.g. the buffer) or are completely specific to the either design − the supercontainer shell, for example (Posiva 2017a). For example, vertical KBS-3V does not have any titanium components as horizontal KBS-3H does. The main differences between horizontal and vertical are summarised in Annex 1.

The most notable differences in the underground openings of the disposal facility are the horizontal deposition drifts, which are used instead of horizontal deposition tunnels with vertical deposition holes. Most parts of the disposal facility (e.g. the access tunnels and shafts) will be almost identical for both alternatives.

In the KBS-3H design, the canister and the buffer are emplaced into the bedrock as one unit rather than in the KBS-3V case, where the buffer and the canister are installed in separate steps. The KBS-3H canister-buffer unit including an outer perforated shell is called a supercontainer (Figure 3-1). The design and assembly of the Posiva supercontainer is described in detail in the Design Description 2007 (Anttila et al. 2008). The supercontainer is designed to withstand unfavourable load conditions induced by variations in the excavation of the deposition drift (Posiva 2012a).

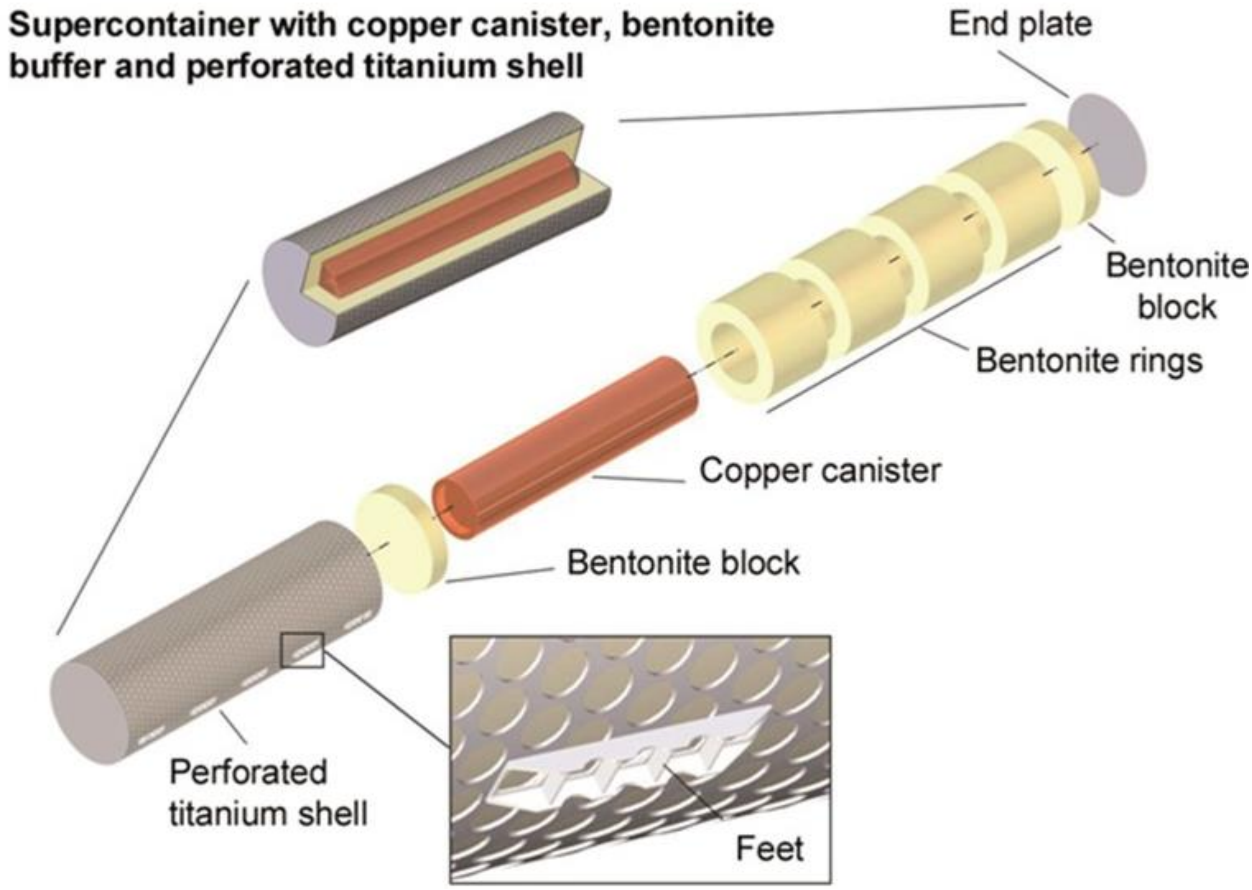

Figure 3-1. Detailed illustration of the KBS-3H supercontainer (Posiva 2017a, Posiva 2012a). The diameter of the supercontainer is 1761 mm (length depends on fuel type).

SÚRAO's version of the supercontainer components are illustrated in Figure 3-2 and it follows main characteristics of Posiva's supercontainer.

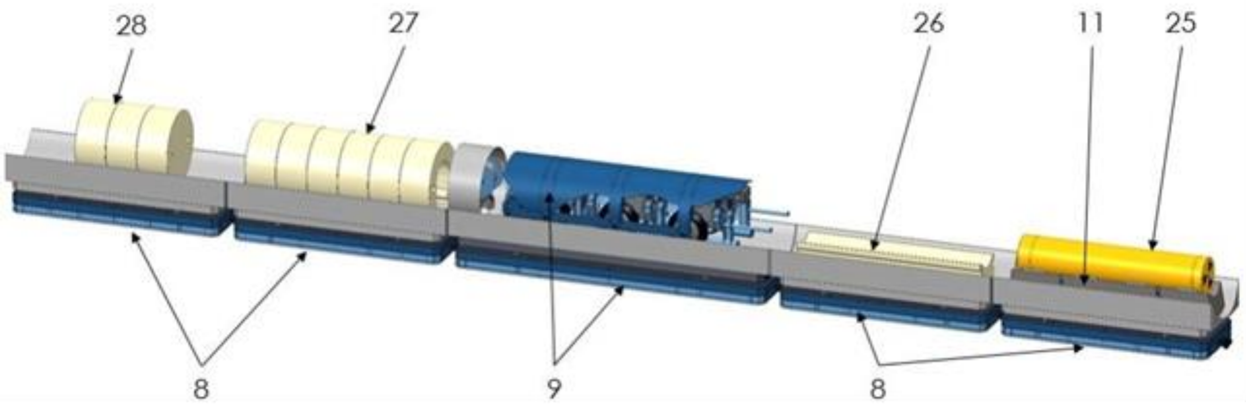

Figure 3-2. Set of robotic vehicles for transporting WDP and bentonite prefabricates for one super container (Grunwald et al. 2018). 8: Transport carriage, 9: Carriage with turntable and disposal robot, 11: Platform with anchoring elements, 25: Canister/ waste disposal package WDP, 26: Bentonite bed, 27: Bentonite circle sector, 28: Round bentonite filling.

The supercontainer is needed only in the horizontal disposal concept (Figures 3-1 and 3-2). The supercontainer shell is perforated to allow the bentonite in the supercontainer to become wetted and to swell and to fill the void spaces between the supercontainers and the drift rock wall. The supercontainer shell will be provided with metal feet to elevate it from the drift floor (Posiva

2017a). In one deposition drift, there will be approximately 10,000 kg of titanium in the supercontainer shells (Posiva 2018a). As the supercontainer shell is not a barrier, it does not have safety functions or performance targets. This is because it is needed during the installation phase and early evolution only with no long-term purpose in itself. However, it is a very important component due to its proximity to the canister and the surrounding buffer. The shell must not impair the safety functions of these barriers, and this requirement is relevant also in the long term (Posiva 2017a).

The buffer components in the supercontainer comprise ring-shaped bentonite blocks around the canister and solid bentonite blocks at both ends of the supercontainer (Figures 3-1 and 3-2). In KBS-3H, the term buffer also covers the distance blocks (also made of bentonite) placed between supercontainers (Figure 3-3). Both the buffer in the supercontainer and the buffer in the distance blocks are needed to provide the functions of the buffer as in KBS-3V, but they may have slightly different dimensions, dry densities and initial water contents. The dimensions of the distance blocks and the buffer segments in the supercontainers depend on the canister/WDP type, the layout and the thermal conductivity and heat capacity of the host rock and the drift components. The KBS-3H distance blocks will also be standing on feet (Posiva 2013a; Posiva 2017a). There are also other KBS-3H specific components of which part are illustrated in Figure 3-4.

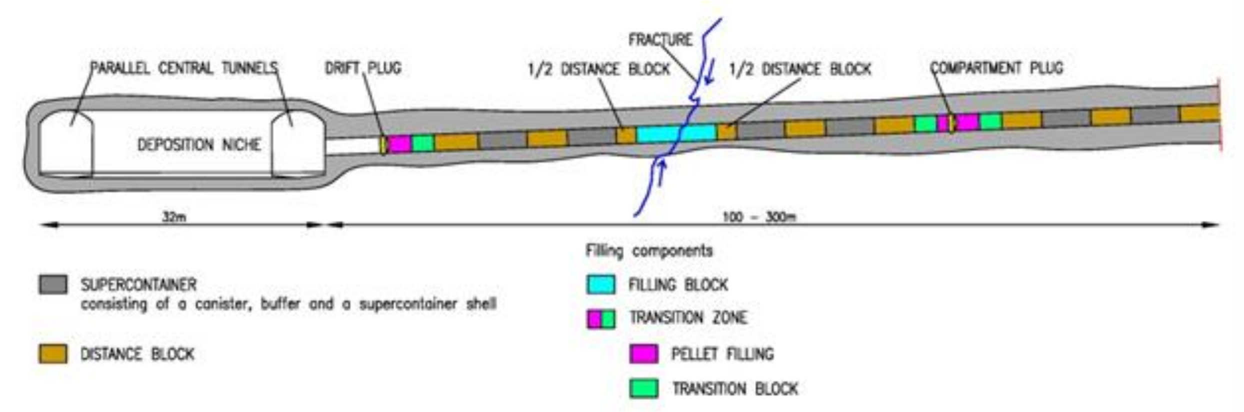

Figure 3-3. The deposition drift and its main components (Posiva 2017a, Posiva 2013a). There is buffer both inside in the supercontainers (grey colour) and as distance blocks (brown colour).

In the KBS-3H DAWE (drainage, artificial watering and air evacuation) design, the empty space in the annulus between the deposition drift wall and the supercontainer, distance block and filling components inside a sealed compartment will be artificially filled with water in each drift. (In KBS-3V the small gap between buffer and rock wall is filled with granular bentonite with the aid of gravity, but in KBS-3H this cannot be done - only DAWE water or equivalent can be used.) This will ensure initial swelling of the buffer and filling components (all made of bentonite), the development of counter pressure against drift surface, the locking of canisters in place and the prevention of axial displacement and excessive buffer erosion (Posiva 2013a). Water filling will be done by pumping water through the plug with short wetting pipes. During the water filling, air will be compressed and accumulate at the end of the drift compartment due to its slightly upward inclination, and this trapped air will be evacuated from the compartment through a long pipe to allow complete filling with water (Posiva 2012a; Posiva 2013a). The watering and air evacuation pipes are located in the lower part of the plug (Figure 3-4). DAWE has been tested in full scale in Multi Purpose Test (MPT).

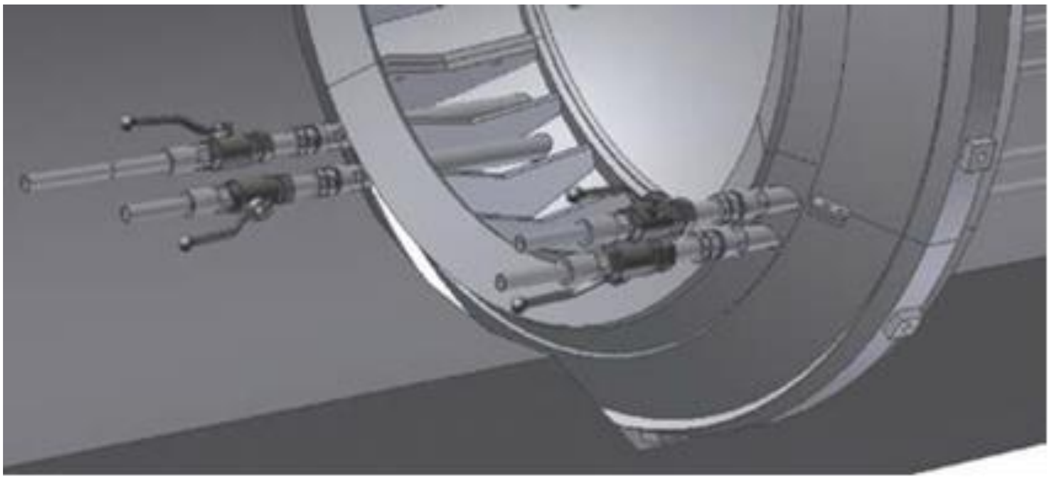

Figure 3-4. Watering and air evacuation pipes, which are located in the lower part of the plug (Posiva 2018e).

In the case of vertical disposal, the buffer and the canister are installed in separate steps direct to the deposition hole. The buffer components also in vertical alternative comprise ring-shaped bentonite blocks around the canister and solid bentonite blocks at the bottom and top end of the deposition hole (Figures 1-1 and 3-5). No artificial filling with water is needed in vertical disposal.

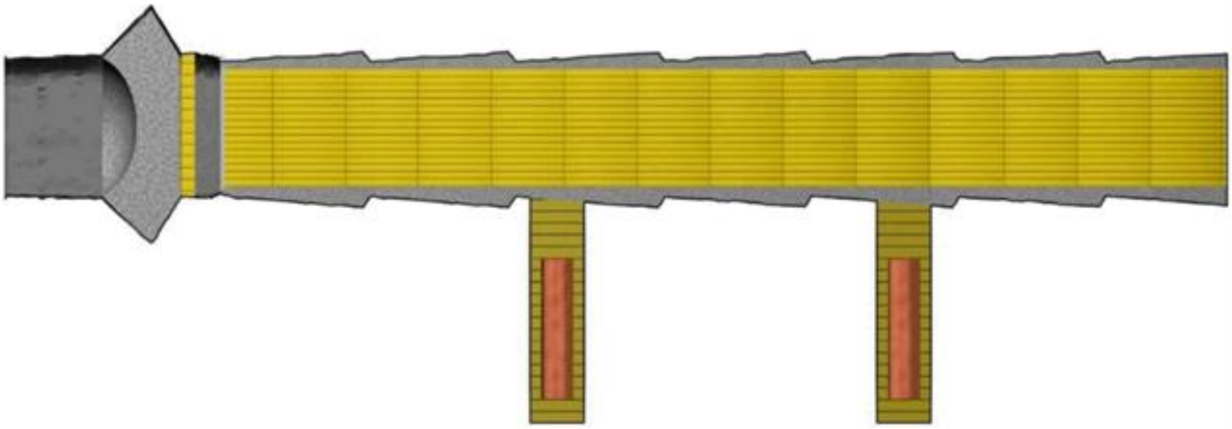

Figure 3-5. The principal of the deposition tunnel and its main components. There are dark yellow buffer bentonite blocks around the red canisters/WDPs and light-yellow granular bentonite clay backfill in the tunnel. The grey deposition tunnel plug is on the left. Figure Posiva Oy.

The horizontal mechanical excavation (full-face reaming of the pilot holes by push reaming) of deposition drifts will be more consistent than the drill and blast excavation of deposition tunnels, although it should, of course, be mentioned that the vertical deposition holes are also made by means of mechanical excavation (Posiva 2012a). On the other hand, in the case of KBS-3H the technology should allow for drilling of 300-m-long, slightly upward-inclined pilot holes with strict straightness requirements (Posiva 2018a), see also Section 4.2.2. The pilot holes and deposition drifts are upward inclined in order to run the seepage water out from the drift with gravity (there is no room for pump lines during installation of supercontainers and other components with the small margin related to the drift profile). If inclined downwards, the accumulated water would prevent successful installation of supercontainers and other drift components. The boring equipment for vertical deposition holes is shown in Figure 3-6 and for horizontal deposition holes in Figure 3-7.

Figure 3-6. Posiva final vertical deposition hole boring machine for operating phase was completed in 2022 (Figure Posiva). This was developed according to experiences gained when boring numerous deposition holes in ONKALO with earlier prototype machine.

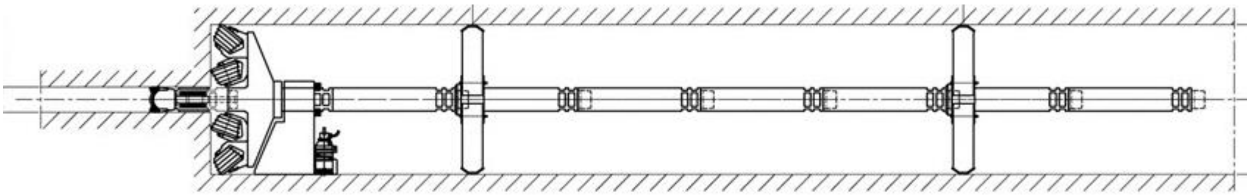

Figure 3-7. Principal illustration of horizontal push-reaming for KBS-3H deposition drift boring. From the left: pilot hole, reamer head and two stabilisers in the already excavated drift. Courtesy: Atlas Copco (Posiva 2018f). The actual boring machine is not shown in the figure.

The horizontal disposal requires different sizes and character of the disposal areas, compared to the vertical disposal. The SNF disposal method impacts on mechanisation, canister/ WDP transfers, disposal, machinery for boring and dimensioning of underground openings. The varying disposal methods bring varying electric power and other media necessary to operate, maintain and repair the facility (Spinka et al. 2018).

The drainage is gravitational in all cases. In SÚRAO's case the mining water runs through channels in the floor. In case of horizontal disposal, careful drainage is needed since the contact line feeding the robotic transfer and installation mechanisms on rail bogies is also located on the floor. For this reason, a pair of troughs are outside the tracks to drain the floor under the contact wire level (Spinka et al. 2018).

The vertical method of disposal requires a smaller underground footprint (area) of the potentially usable rock block. Smaller underground footprint is enough for the vertical disposal D1 - VD, M and especially D2 - VD, C layouts. Bigger footprint is needed for the horizontal disposal D3 - HD, M and D4 - HD, C layouts (Spinka et al. 2018).

In Posiva's design there is no remarkable difference between 3H and 3V footprint in theory. In practice there would be some difference in the footprints according to the Olkiluoto specific host rock data depending on the potential host rock volume length between the layout determining features (fracture zones). Despite the smaller excavate volume, e.g. in Olkiluoto KBS-3H may require a larger underground footprint than KBS-3V. In KBS-3H, the areal extent of the Olkiluoto repository was approximately 2.5 km in the E-W direction and 1.8 km in the N-S direction, when a fuel amount of 9000 tU was assumed (Posiva 2018f), whereas in KBS-3V, the corresponding extents were approximately 2.3 km and 1.7 km for the same fuel amount (Posiva 2012d). Note that, in theory, the 3H footprint is only slightly larger, and in the examples above, the difference is mainly caused by the position of two major (layout-determining) fracture zones at Olkiluoto; the area between them is more efficiently used up by 350-m-long deposition tunnels than 300-m-long 3H deposition drifts.

The extent or the size of the excavation damaged zone and the excavation disturbed zone of the rock mass primarily follows from the technology of excavation and blast works used. Generally, the mechanical method (TBM) is gentler regarding the formation of these zones (Grunwald et al. 2018). The mechanical excavation of the horizontal deposition drifts may be assumed to correspond to the boring of vertical deposition holes, which is related to the formation of an insignificant excavation damaged zone (Posiva-SKB 2017).

It should be noted that when Posiva compared the vertical and horizontal methods, the underlying assumption was that the Olkiluoto site would be suitable for both. There is no published comparison report available, but the most relevant issues are documented in this report. The bedrock fracturing is generally rather minor at the planned disposal depth (about 400–450 m) at Olkiluoto, and the locations of more pronounced fracture zones are quite well known, as shown by the experiences during the underground excavation. At sites where the occurrence of faults or other fracture zones is higher and their locations are more unsure, it may be more practical to employ the vertical method, as in a deposition tunnel it is easier to carry out more detailed investigations and use the acquired information to select locations for deposition holes, avoiding the lower-quality parts of the rock mass for full profile boring. In KBS-3H, supercontainer emplacement may be difficult if a major fracture zone has been unexpectedly intersected by a deposition drift, resulting, on the one hand, in potential irregularities in the rock surfaces and, on the other hand, large drift sections that may not fulfil the requirements for supercontainer locations. In that case a larger part of the full profile bored drift would be left unused (unused supercontainer positions).

3.2 Drill and blast versus TBM

Detailed technical comparison of the excavation methods must be based on design requirements and design bases for the tunnels. Because design requirements for SÚRAO DGR are not defined yet, technical comparison is still in more generic level. More detailed comparison can be made when more information about the geology exists and when design requirements for the tunnels are defined.

For both tunneling methods, clients and decisions makers understanding of geology and rock mechanical behavior is very important. From technical point of view, it is important to understand tunneling methods, their benefits, limitations and requirements.

For setting the design requirements, targets for the tunnels should be clear including the tunnel geometry, requirements for the rock staying around the tunnel and for the structures to be constructed and the materials to used and left in the tunnels. For example, possible use of concrete and/or steel in the floor structure or requirement for the floor shape should be defined. Should the floor be even or is it not obligatory. Tolerances for the tunnel excavation and requirements for excavation damage zone disturbed zone need to be decided. Typically, most of the requirements are different for the deposition tunnels compared to the mining tunnel and transfer tunnel.

For the technical comparison it should be remembered that DGR includes a lot of tunnels and caverns that will be excavated by drill and blast method in all alternatives. Technical facilities, RAW storage chamber, intersection areas etc. will be drilled and blasted.

Factors that should be considered in the final comparison of the excavation methods are effect on the long-term safety, environmental aspects, operation and construction safety, quality, schedule and costs.

3.2.1 Drill and blast

Typical and relevant features of the drill and blast method for the comparison of the excavation methods are:

- Excavation method is flexible for the changes regardless of the reason for possible change. Direction of the tunnel can be changed during the excavation quite easily. Cross-section, wide and high of the tunnel can be changed. New pits and channels can be excavated along the tunnel. Above mentioned flexibilities mainly apply to other tunnels than transfer corridors / deposition tunnels which are usually parallel.
- In drill and blast method the whole tunnel face and profile is open for the free choice of pre-grouting hole drilling geometry (See Figure 3-8). This partly improves the grouting result.
- Site preparations before excavations can be started are not demanding.
- Excavations can be stopped with reasonable costs for example for mapping or other surveys. Excavation equipment can be moved to another tunnel and continue excavations there. Mobilization to continue the excavations is not tremendous.
- Use of the excavated rock is possible. It can be used quite easily in above ground infrastructure projects and e.g., for concrete. Likely excavated rock could be used also for the backfilling of the mining, transport and deposition tunnels and other facilities in the DGR. This should be the goal since using excavated rock in the same facility would decrease transfers of the rock and would increase impacts to the environment a lot.
- Use of explosives requires extra procedures to secure people and to storage explosives safely against accidents and sabotage.
- Use of explosives causes some explosive residuals in the rock around the tunnel and in blasted rock (recycling or reuse). Amount and properties of explosive residuals must be analyzed detailed and take account in the long-term safety assessments. Posiva's tunnels are washed systematically after excavation and properties in the rock around the tunnels have been acceptable.
- Use of explosives causes need to ventilate the tunnel always after explosion. Usually, 1-2 hours are needed, and this slows down the excavation. However, this is always a normal procedure in the drill and blast tunnels and time for the ventilation is always noted.
- Explosion causes shock waves (positive and negative) in the tunnels. Structures, equipment, and installations must be protected against the shock waves. Some of equipment close to the tunnel end are moved for the duration of the blast. The effects of the blasting lead also greater damage to the host rock environment e.g., EDZ.
- Electricity and water for the drilling must be arranged.
- More manpower is needed compared to the TBM method.

Figure 3-8. If pre grouting is neglected for technical or other reasons, the seepage water can remain too big, water chemistry can be totally changed and the risk that site will be spoiled as unsuitable for disposal grows. Figure SKB-report R-08-116 (SKB 2009).

3.2.2 TBM

Considering TBM excavations, it should be remembered that also Drill & Blast method will be used in all variants to excavate interconnecting tunnels, technical rooms etc. Typical and relevant features of the TBM method for the comparison of the excavation methods are:

- Tunneling method is very fast during boring without interruptions.
- Method is highly automated.
- Explosives, blasting and ventilation of explosive gases after blasting are not needed.
- Instead, energy consumption is high.
- Tunnel boring machine is massive and a lot of prework is needed always before the boring can begin. Therefore, interruptions are expensive and should be avoided.
- Alignment of the tunnel can't be changed quickly. Lay-out of the tunnels is not so flexible to change. Geology and fracture zones should be investigated in more detail to be sure where the deposition tunnels can be adopted.
- Extent and focus of engineering geological survey is wider.
- TBM reduces flexibility to rapidly change the layout of the tunnels and avoid water conductive fracture zones. This means that special attention is needed for the pre (and post) grouting of the penetrated water conductive fractures and fracture zones. Grouting is important for long term safety to avoid lowering the local ground water table and reducing disturbances to the hydrogeochemistry (Ikonen et al. 2020). Larger inflow rates are expected for the cases where more TBM is used due to the TBM equipment limited

drilling geometry for grouting holes. Tunnel boring machine typically fills the end of the tunnel and there is no room and bare rock surfaces for grouting.

- Grouting may be challenging. Some limitation for grouting hole locations in the TBM's cutterhead. Grouting limits water inflow into the tunnels. Large inflow into the tunnels can change water chemistry and open more water bearing fractures and fracture zones. This may affect the long-term safety of the deep geological repository.
- Tunnel shape is typically round.
- Ground vibration is low.
- Procedure for authorities' inspections may cause challenges especially if the shield will be constructed immediately during the boring process. Rock surface of the tunnels behind the shield should be mapped and documented before or after shielding. E.g., radiation and nuclear safety authority may want to verify and document the rock surface e.g., because of the safeguards. Also, occupational safety authority may want to check the rock surface before shielding or other structures.
- Use of the excavated rock may be challenging because of the shape and size of the rock. Possible use in the backfilling should be studied and tested.
- Tunneling boring machines are always designed and constructed for specific projects. This should be done in close cooperation between client, designer and TBM contractor. Enough time should be reserved for the design and construction of the machine.
- Supporting area needed above ground is wide and should be designed and communicated with local residents. Wide supporting area is needed to assemble the tunnel boring machine and to store the excavated rock. Use of the excavated rock may be difficult and therefore larger storage area is needed. Assembly area is needed also in case of drill and blast method and difference in the size of the assembly area size may be minor but probably difference in the storage area size is larger. Blasted rock can be used for many purposes and is easier to sell and therefore smaller storage area for the rock is needed.
- Tunnel boring machine is more expensive. Since the capital cost is high, machine should be used 24/7 to excavate tunnels economically. Energy consumption is very high, and it needs to be arranged to the site.

4 Technical readiness

4.1 3H versus 3V

Development history

In 2001, Posiva and SKB decided jointly to carry out a Research, Development & Demonstration (RD&D) programme for a KBS-3 repository with horizontal emplacement (SKB 2001). KBS-3H development was launched because it was assumed that it would have potential of providing a more resource-efficient disposal solution. The name of the horizontal alternative was initially MLH (Medium Long Hole) but was changed at that point from MLH to "KBS-3H alternative" (Posiva 2012a). This RD&D programme provided a basis for the development of the KBS-3H design.

During 2002−2003, the development of KBS-3H was initiated with the Feasibility Study phase, which dealt mainly with technical matters such as rock excavation techniques and design of the supercontainer (SKB 2004). The Demonstration phase in 2004–2007 aimed at using practical trials to demonstrate that the horizontal deposition alternative was technically feasible and that it fulfilled the same long-term safety requirements as the reference design KBS-3V (Posiva 2008, 2013a). The following phase, Complementary Studies of Horizontal Emplacement KBS-3H, 2008–2010 (Posiva 2013a), included critical issues on design and material selection and plans for the KBS-3H System Design phase (2011−2016). The objective of the System Design phase was to develop a system design level of KBS-3H and to accomplish a long-term safety evaluation for the Finnish site Olkiluoto, which has been used as the reference site for long-term safety activities (Posiva 2017a).

A full-scale demonstration test called Multi Purpose Test, MPT, was included in the EC LucoeX project (2011–2014). The test was performed without heating and included the main KBS-3H components in a partial (95-m-long) deposition drift configuration at the Äspö HRL, KBS-3H test site at the −220 m level. The MPT utilises the innermost 19 m of the 95-m-long drift. This drift was previously used for testing the deposition machine (Posiva 2012a; Kronberg 2016; Pintado et al. 2017). The preparations and installation of the MPT were carried out during 2011–2013 (Kronberg 2016). The MPT has been instrumented with 227 sensors, and the monitoring phase has been ongoing since 7th December, 2013. The monitoring phase will continue until the dismantling of the MPT (SKB 2019). Currently, there is no plan to dismantle and retrieve the MPT (SKB 2021).

Overall differences

When comparing KBS-3H with KBS-3V from a demonstration perspective, both designs have run repetitive testing of the installation of dummy buffer made of concrete and the emplacement of the canister. Both designs have also performed installations with bentonite components, while far more extensive testing has been done for KBS-3V. However, one of the major differences is that the step from use of concrete dummies to bentonite buffer is greater for KBS-3H than for KBS-3V given the added complexity introduced by the feet to elevate it from the drift floor waters and air evacuation pipe during installations, see Figure 3-1), which add an entirely different type of mechanical strain imposed on the bentonite blocks. In the Multi Purpose Test at the Äspö Hard Rock Laboratory, test transportation of one horizontal distance block of clay and installation of three composite components was carried out successfully; however, a quite significant fracture was noted on the innermost distance block and the reliability of this procedure has to be further verified (Kronberg 2016).

After 2018 Grunwald et al. studies (2018) and Multi Purpose Test (2011–2014), vertical disposal and equipment has been strongly developed further and demonstrated with full-scale prototype equipment by Posiva. In addition, Posiva has already assembled, and the Finnish regulator (STUK) has controlled (e.g. Factory Acceptance Tests and Site Acceptance Tests), most of the final equipment that will be used in the real operating of the Posiva disposal facility, and the rest are under assembly and factory acceptance tests controlled by the regulator. So, regarding feasibility, the vertical method faces far less technical and technological problems than the horizontal method due to wider development work done by Posiva. E.g., transfer and manipulation with canister/ WDP – tilting to the drilled vertical disposal borehole and its subsequent filling with bentonite buffer as well as sealing/ shielding of the deposition hole (there is a realistic possibility of movement of persons and technology above the holes which have already been filled) has been demonstrated. Instead, no further development or reporting for horizontal equipment has been done neither at Posiva nor at SKB after 2018.

Automation of disposal is in some extent wider in the case of the horizontal disposal of canister/ WDP. According to Posiva and SKB experiences regarding the manipulation and robotic automation, it is obvious that further dealing also with the horizontal method of disposal with the use of supercontainers is a realistic approach, even it needs a lot of further development.

The horizontal disposal alternative is less mature than KBS-3V and would require several years of extensive studies before reaching the current maturity level of KBS-3V.

Remaining open issues and tests

A lot of technical development is needed to bring horizontal alternative 3H to the same maturity as vertical 3V. This primarily includes:

- the selection of materials for and the design of the supercontainer,
- detailed design of the underground reloading station,
- detailed design of the plugs in the deposition drift,
- the intended Mega-Packer grouting solution (post-grouting device consisting of a large tube of 48 mm thick steel, 1970 mm long with a grouting length of 1590 mm and a diameter of 1820 mm (Posiva 2018f; see also Posiva 2013a), and
- the design of a supercontainer deposition machine (e.g. to cope with the heavy canisters, cf. Posiva 2021a) (SKB 2016; Posiva 2018g; RWM 2017).

Furthermore, the current MPT experiments need to be supplemented with a full-scale heater test at actual repository depth, to show that the bentonite swells and homogenises as intended outside the horizontal supercontainer (SKB 2016; RWM 2017). The transportation and installation of bentonite components has not yet been demonstrated to be successful for horizontal disposal, and the reliability of this procedure has to be further verified during the future development work (Kronberg 2016). Also, the automation in titanium welding should be developed for horizontal plugs. Needs for future horizontal demonstration work are discussed in more detail in Kronberg (2016).

It should be noted that the long-term safety requirements defined for KBS-3H in Posiva (2017a) were based on Posiva's earlier TURVA-2012 safety case for KBS-3V (Posiva 2012b). Recently, Posiva has updated its long-term safety requirements (Posiva 2021b), and the requirements are significantly more detailed than in 2012. In case the KBS-3H work is continued by any nuclear waste management organisation, it is recommended that the 3H-specific requirements would be revised and utilized to consider the latest information gathered in Posiva's KBS-3V project and the newest long-term safety requirements. After the requirements update, it is possible to update the KBS-3H design to match the requirements, and the revised design can be used as a basis for updating the safety evaluation of Posiva (2017b) or creating a new one. A detailed design (including the supercontainer reloading/assembling station) and a full safety case (including radionuclide release and transport analysis and dose assessment) are still missing for the KBS-3H concept even for Posiva.

The main differences in the readiness between KBS-3H and KBS-3V are summarised in Annex 1. In addition to the 3H-specific open issues discussed above, there are many issues that are common to both 3H and 3V. For example, the canister design is still being optimised from the design given in Posiva (2021a) and even wider design is needed for SÚRAO's canister/ WDP. On the other hand, some issues are only related to KBS-3V, e.g. those related to the deposition tunnel backfill.

4.2 Drill and blast versus TBM

Technical readiness for the excavation using both drill and blast method or tunneling boring machines worldwide is high. Differences may rise when use of the methods especially for the nuclear waste repositories are discussed below.

4.2.1 Drill and blast

Excavation by drill and blast method has been used for a long time and is very conventional. In principle method includes following phases:

1. Drilling
2. Charging
3. Blasting
4. Ventilation
5. Mucking and scaling
6. Support

Grouting is not included in above mentioned phases and is usually done before and/or after excavation of tunnel section. Typically, the length of the grouting holes is 10…30 meters. Length of tunnel section to be excavated at a time is typically 3…5 meters. Support usually means rock-bolting and shotcrete.

During last 40 years, drill and blast method has been used in several nuclear waste repositories e.g., a) low- and intermediate level waste repository in Olkiluoto, Finland, b) low- and intermediate level waste repository in Loviisa, Finland and c) low- and intermediate level waste repository in Kyungju, Korea. Tunnels, silos and shafts have been excavated by D&B method.

Drill and blast method has also been used to excavate the first repository for the spent fuel in the world. The construction work of ONKALO started roughly twenty years ago. ONKALO is located in Olkiluoto, Finland. A spiral-shaped access tunnel, central tunnels, deposition tunnels and technical rooms are excavated by this method. Rock surface of the deposition tunnel excavated by drill and blast method and floor leveled using grinding method is shown in Figure 4-1. Wire cutting method to level the floor could be used as well but because the amount of the floors is huge it would take long and would be quite expensive.

Figure 4-1. A deposition tunnel in ONKALO, picture Timo Saanio.

Technically, deposition tunnels could be very long, meaning several kilometers. However, the maximum length of deposition tunnels in ONKALO will be 350 meters to guarantee occupational safety, secure fire safety and feasible ventilation.

By definition technical readiness is very high when technology or system is tested and proven in operational environment. The drill and blast method has been used a lot for conventional excavations, 40 years for LILW-repositories which are in operation and almost 20 years for the spent fuel repository in Finland. Therefore, it can be deduced that the technical readiness of the drill and blast method for the DGR in Czech Republic is very high.

4.2.2 TBM

Excavation by Tunnel Boring Machine is also called as mechanized excavation method. The name already indicates that most of the work steps are mechanized compared to the D&B method. TBM method is widely used technology in public transportation tunnels. An example of Tunnel Boring Machine is shown in Figure 4-2.

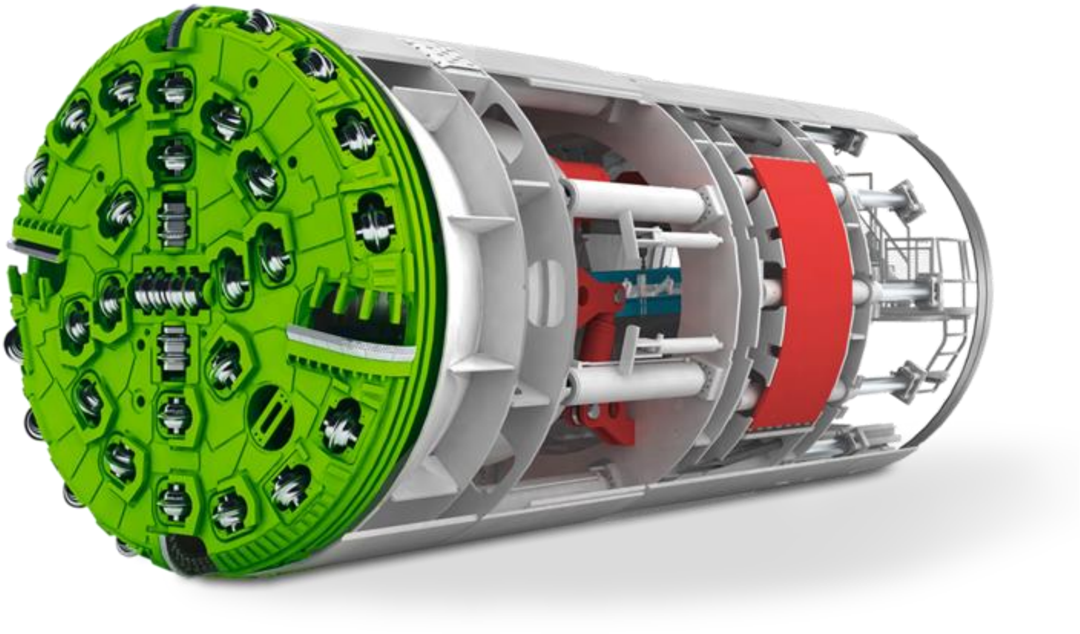

Figure 4-2. An example of double shield TBM (Herrenknecht 2023).

However, TBM has been used for decades also for tunneling in hard rock. Recently technology to excavate larger and larger tunnels in hard rock has been developed. The Caucasia tunnel boring machine (TBM), a full cross-section hard rock TBM with the world's largest diameter, has dug more than 5,000 meters at the Kvesheti-Kobi highway tunnel project in Georgia. Jointly developed by China Railway Tunnel Group Co., Ltd. and China Railway Hi-Tech Industry Co., Ltd., both subsidiaries of China Railway Group Limited, the machine is 182 meters long, weighs 3,900 tons and has a diameter of 15.08 meters. Its maximum power is 9,900 kilowatts (SASAC 2013).

In Finland the maximum horizontal deposition hole/drift length in for 3H-alternative is assumed to be maximum 300 m (Saanio et. al 2013), because the deposition drift/ hole length needs to be feasible from a construction point of view. Longer than 300 m long pilot hole filling the straightness (geometrical) requirements is not seen to be feasible. The most uncertainties relate to the horizontal disposal variant (D3 - HD, M), mainly due to the low-profile drilling of disposal boreholes (Grunwald et al. 2018).

Since TBM method has been used a lot for conventional excavations worldwide, it can be deduced that the technical readiness of the method for the mining tunnel and transport tunnel of DGR in Czech Republic is very high. Anyway, technology is not tested and proven in operational environment meaning in the disposal rooms. Therefore, it can be deduced that the technical readiness of the method for the deposition tunnels of DGR in Czech Republic is high instead of very high.

5 Major operational differences

Canister/ WDP handling, transfer and installation methods on the SNF Disposal level depends on the chosen method of disposal – horizontal or vertical. Both disposal methods were treated in the reference projects of SÚRAO – the reference project of 1999 dealt with the vertical method of disposal while the updated version of the reference project of 2011 dealt with the horizontal method of disposal, namely the form of disposal into supercontainers. Studies comparing the vertical and horizontal methods of disposal were prepared in the time between the reference projects but without reaching an unambiguous result or agreement that any of the methods is the most optimal (Grunwald et al. 2018).

In KBS-3H case, the assembly of the supercontainer is performed in the reloading station (Figure 5-1) without employing a radiation shielded handling cell; for more details, see Posiva (2018c). The reloading station will be equipped with necessary lift arrangements for handling of the various components. The assembly is performed with the supercontainer in a vertical position. To enable lifting and tilting from vertical to horizontal position and transport of the supercontainer after assembly, the supercontainer is placed in a so-called transport tube (See Figures 5-1 and 5-2) (Posiva 2018b).

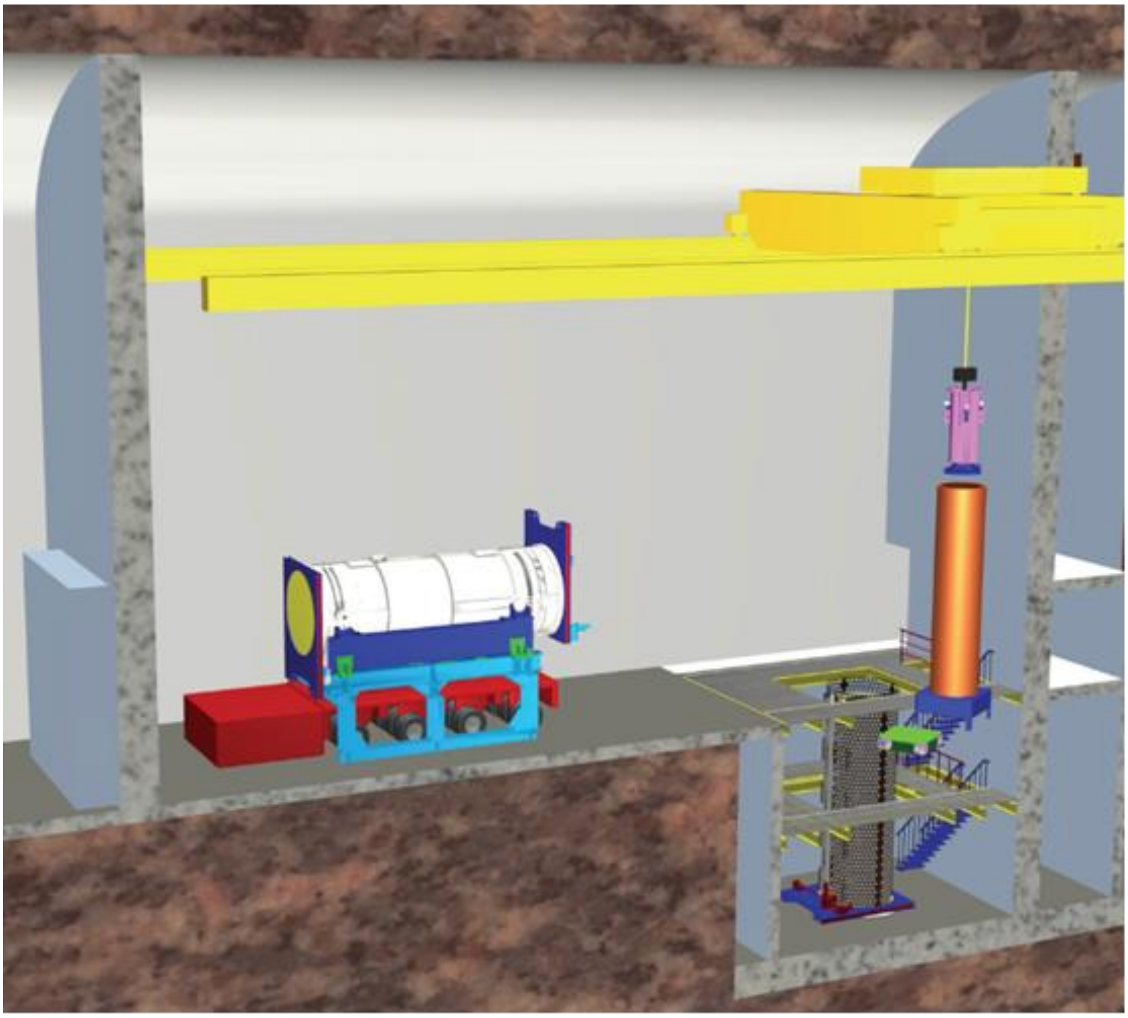

Figure 5-1. Conceptual presentation of the KBS-3H reloading station. Transfer vehicle (red) based on Self Propelled Modular Transporter. The transfer shielding tube (white) with the supercontainer inside turned to the horizontal position on the transfer support (light blue), (Posiva 2012a).

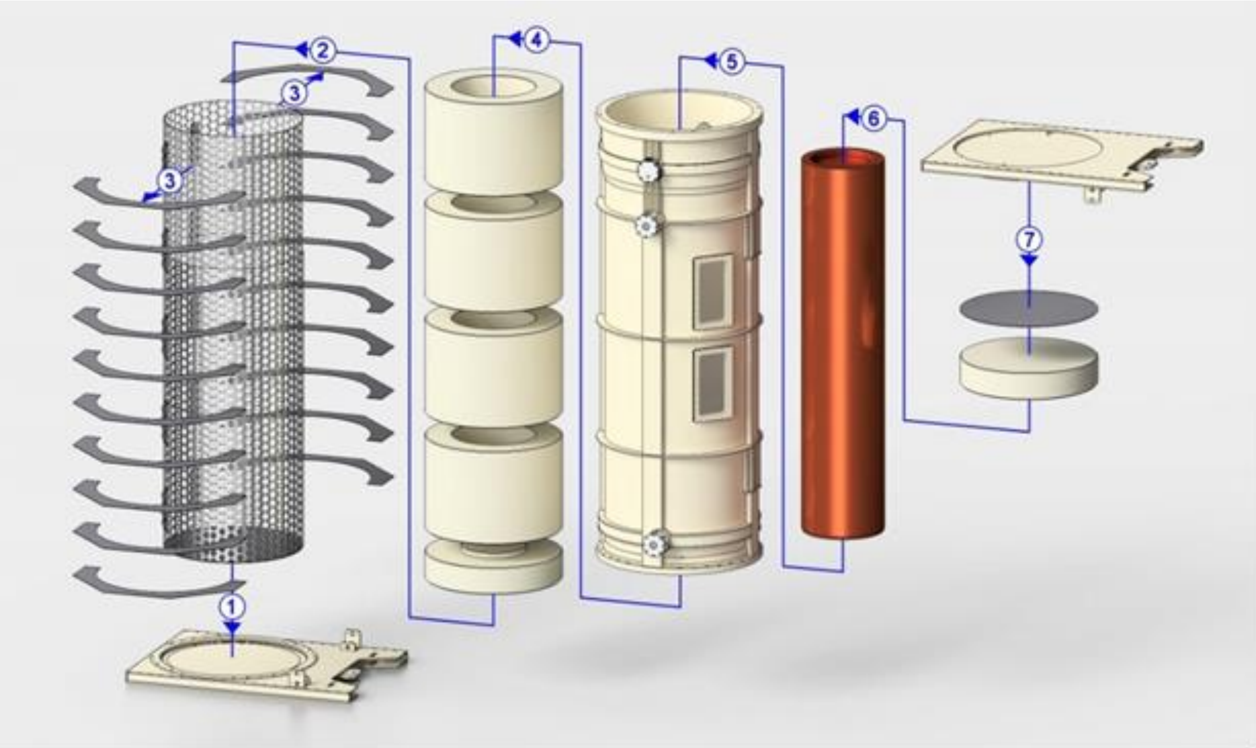

Figure 5-2. Illustration of the KBS-3H supercontainer assembly and placing the supercontainer in the transport tube (Posiva 2018b).

Fully loaded with canister and buffer the mass of the reference supercontainer is approximately 46 tonnes. The total mass of the reference supercontainer and the transport shielding tube is about 60 tonnes. In Posiva's horizontal concept plan, the supercontainers are transferred from the underground reloading station (Figure 5-1) to the front of the deposition drift/hole with a wheeled transfer vehicle based on Self Propelled Modular Transporter and inside a shielding tube (Posiva 2012a), see Figure 5-1.

In SÚRAO's horizontal concept plan, the railway transport-based robotic technologies a track radius of at least 200 m is preferred. Other intersections will be solved by railway turn-tables. In the transfer area/ reloading station at the disposal level canisters/ WDPs are transferred from the wheeled transport vehicle to the railway by a fully automated transfer system (Grunwald et al. 2018). The WDP with supercontainer components shall be transported further on the rails with the set of robotic vehicles (Figure 5-3).

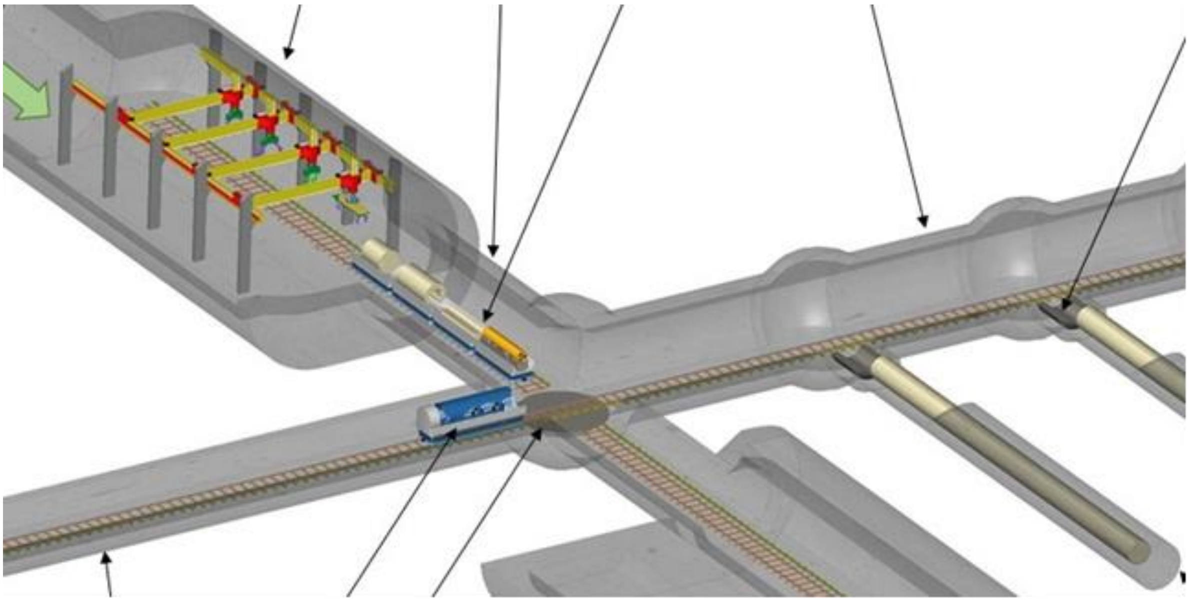

Figure 5-3. SÚRAO DGR horizontal concept model (Skařupa et al. 2017).

SÚRAO has not described any supercontainer assembly arrangement or deposition machine in more detailed in the initial data for this partial contract 22 ID3. KBS-3H deposition machine is illustrated in Figure 5-4. The supercontainer and the interlaced bentonite distance blocks, as well as filling blocks and transition blocks, are installed from the deposition niche using a deposition machine employing application of water cushion technology (Halvarsson 2008, Kronberg 2015).

KBS-3H includes more prefabricated industrial components and a reduced amount of human involvement in the disposal process, which is preferable and should result in theory in very high quality. The assembly of the supercontainer in the reloading station is done in an industrial process in a controlled environment, which is likely to be more consistent than the emplacement of the canister, buffer and backfill separately to a deposition hole.

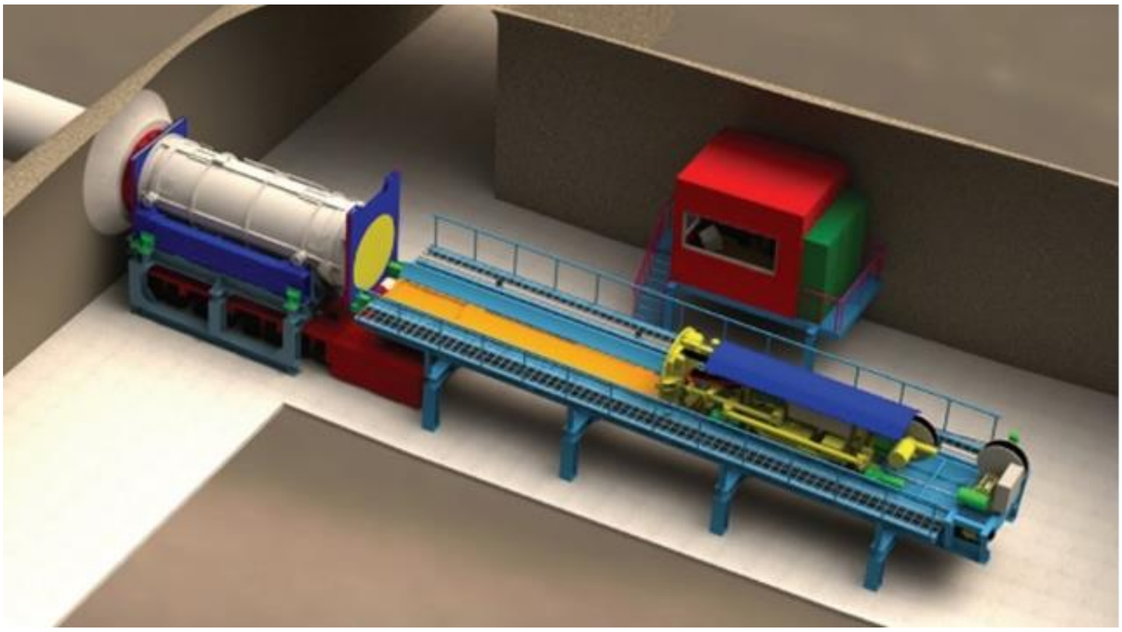

Figure 5-4. Central (/main) tunnel connection (deposition niche) at Olkiluoto (Kirkkomäki & Rönnqvist 2011) is part of the central tunnel system. Transfer vehicle (red, with wheels) under the supercontainer in the transfer shielding tube (white) is on the left and deposition machine (yellow) in the middle (Posiva 2018a).

The deposition works in KBS-3H comprises a deposition sequence that includes positioning of supercontainers in the deposition drift, installation of distance blocks and strategic positioning of filling components and plugs, i.e. the compartment plug and the drift plug (Posiva 2018b) - all these components are installed with the aid of the same, fixed deposition machine. After the supercontainers are emplaced into the deposition drifts, the drifts will be closed with a drift plug as soon as possible (Posiva 2018a), see Figure 3-3. In SÚRAO's horizontal concept plan drift plugs are assumed to be made of concrete and in KBS-3H concept drift plugs are made of titanium.

Deposition tunnel/ drift plugs both in vertical and in horizontal concept does not have long term safety function - they only need to work during operating period. The 3H plugs are grouted between the plug and rock surface. The 3V deposition tunnel plug is designed so that the concrete structure does not have the water tightness requirement and the sealing layer behind the plug (now a part of the backfill) will take care of the sealing, therefore there is no need to grout the boundary between rock wall and the concrete.

In vertical disposal concept the buffer blocks and canister are assembled to deposition hole with buffer installation machine (Figure 5-5) and canister transfer and installation machine (See Figures 5-6 and 5-7). The deposition works in vertical KBS-3V comprises a deposition sequence that includes positioning of canisters and buffer blocks in the vertical deposition holes, backfilling the deposition tunnel with bentonite (Figure 5-8) and building the tunnel plug. Posiva has been recently changed the design of deposition tunnel backfill (Posiva 2021c). The total mass of Posiva's reference canister for fuel from the Olkiluoto power plant units 1-2 is 24.5 tonnes.

Figure 5-5. Posiva prototype buffer installation machine above a deposition hole (Figure Posiva). The assembly of the final version for operating is underway.

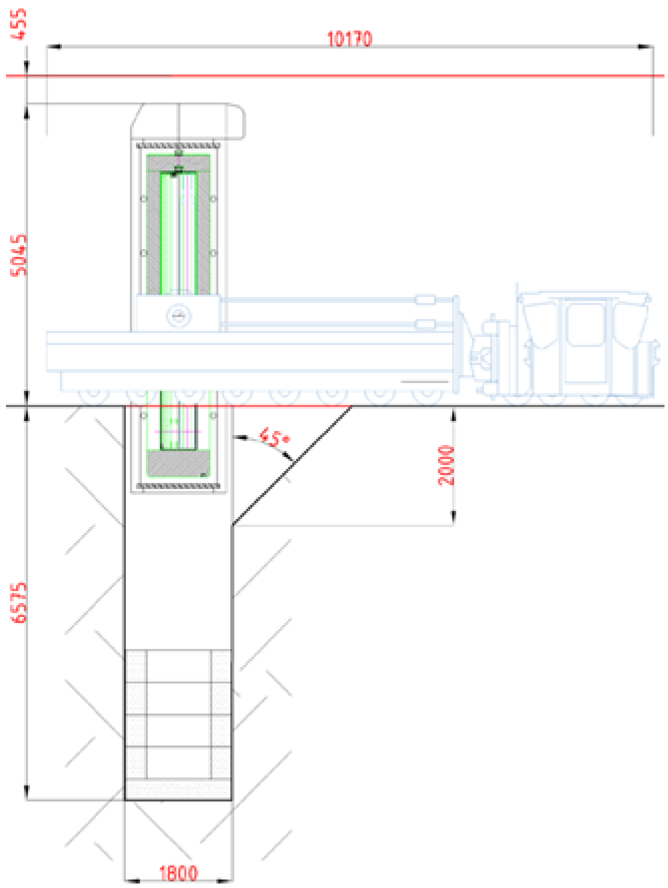

Figure 5-6. SÚRAO canister/ WDP transfer and installation equipment on tracks in the transfer corridor/ deposition tunnel (Grunwald et al. 2018).

Figure 5-7. Posiva prototype canister transfer and installation vehicle (Figure Posiva). The assembly of the final version for operating is underway.

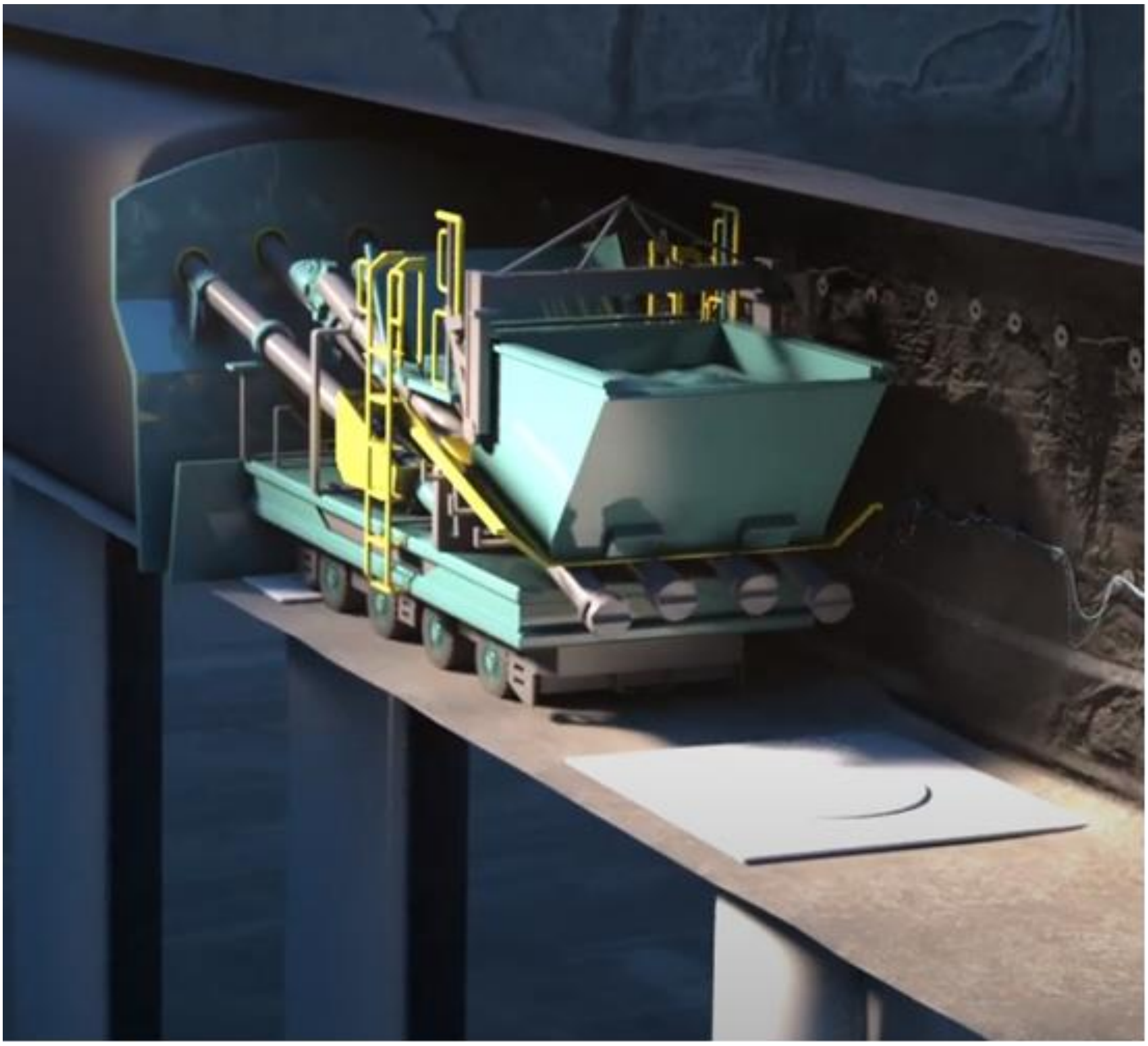

Figure 5-8. Posiva's final disposal tunnels are backfilled with granular bentonite clay (Figure Posiva). The assembly of the final version for operating is underway according to this design.

The layout of the underground openings is also related to safety and flexibility of the disposal operating. The most flexibility regarding the potential escape routes are the vertical variants D1 - VD, M and D2 - VD, C (Grunwald et al. 2018).

The differences between KBS-3H and 3V related to operational and occupational safety risks are discussed in Posiva (2012a). The occupational safety risks are related, for example, to fire and evacuation, welding in confined space, traditional occupational safety and radiological risks. According to the operational safety study, KBS-3H mainly differs from KBS-3V concerning the preparation of the drift, the reloading station and activities in the deposition area. Although separate risks were identified for the reloading station, the controlled assembly of the supercontainer in the controlled environment (compared with the mounting of bentonite into the deposition hole in the KBS-3V method) is considered an advantage. The lower lifting heights of the deposition machine inside the drift are also favourable from a safety analysis point of view compared with the higher lifting heights of KBS-3V. The main disadvantage is that, if a failure occurs in a deposition drift, there is a higher probability that several copper canisters will be affected or removed (Posiva 2012a). It also needs to be noted that the total lifting weight of the reference supercontainer (46 tonnes) is about double to the 3V reference canister lifting weight (24.5 tonnes). Overall, the accident risk is in some extent smaller in KBS-3H because fewer people will be working underground, and fewer machines and vehicles are needed in the repository.

The main potential positive effects of horizontal KBS-3H (as compared with vertical KBS-3V) are:

- a more industrialised process (full-face boring, supercontainers, distance blocks and plugs)
- prefabricated disposal container (supercontainer), which enables an easier quality assurance of the canister and adjacent buffer material
- less environmental impact - less excavated rock volumes and hence less filling material and related transports (in Posiva's case with waste amount of 5500 tU and optimized tunnel profiles KBS-3H disposal facility would be approximately 15–20% smaller than a corresponding KBS-3V facility at Olkiluoto in terms of excavated volume)
- reduced cost for construction and backfilling (Posiva 2012a).

The main potential negative effects of horizontal KBS-3H (as compared with vertical KBS-3V) are:

- More complex components and technology: e.g., Supercontainer shell, distance blocks, filling blocks, transition blocks, spray and drip shields, DAWE components (watering and air evacuation pipes), filling of the pilot hole stump, feet of drift components
- the total lifting weight of the supercontainer is high and about double to the 3V canister weight; the main disadvantage is that, if a failure occurs in a deposition drift, there is a higher probability that several canisters will be affected or removed
- Chemical erosion potentially a more critical long term safety issue than in 3V (domino effect) and sedimentation erosion due to gravity
- KBS-3H concept is far less mature than KBS-3V. More funds for further testing and demonstration are needed (supercontainer materials, detailed design of the underground reloading station, detailed design of the plugs, the intended grouting solution Mega-Packer, the design of the deposition machine, the transportation and installation of bentonite components, the automation in titanium welding, the feet of the drift components add complexity)

The layout arrangement of the underground spaces influences the lengths of transfer routes for SNF disposal. These impact the duration of canister/ WDP transfer and consequently of the whole process of disposal. In this respect, vertical variant D2 - VD, C is the most economical while horizontal variant D3 - HD, M is the least economical one (Grunwald et al. 2018).

The needed cooling period for the individual radiation sources from new nuclear sources is roughly five years longer if horizontal disposal method is used. The total disposal duration is also roughly five years longer for the horizontal disposal method than for the vertical method (Spinka et al. 2018).

The clear advantage of horizontal disposal method is the lower volume of excavation, mucking and backfilling. The total volume of excavation and the related volumes of suitable backfills are the highest in the case of vertical variant (D1 - VD, M), the most economical from this point of view is horizontal variant (D4 - HD, C) (Grunwald et al. 2018). In Posiva's case with waste amount of 5500 tU, it has been estimated that a KBS-3H disposal facility would be approximately 15–20% smaller than a corresponding KBS-3V facility at Olkiluoto in terms of excavated volume.

6 Long-term safety

Long-term safety related issues concern the impact of the construction work for the disposal facility on favorable properties of the host rock and the long-term performance of the barrier system of the geological repository. A systematic evaluation of these issues must eventually be based on a well-developed chain of requirements -- from stakeholder requirements to safety functions to performance targets, and further to design requirements -- that encapsulate an essential basis to develop a coherent long-term safety assessment. Examples of such requirements bases are (Posiva 2017a) for the KBS-3H (pertinent to design alternatives D2 - VD, C and D4 - HD, C), and (Posiva 2021b) (pertinent to D1 - VD, M and D2 - VD, C design alternatives) as the most recent document published by Posiva.

6.1 Impact of underground construction

The site investigations preceding the final decision on the repository site characterize a volume of bedrock in its natural state exhibiting characteristics that are considered favourable for the long-term safety. Typically, such characteristics are described as:

- the stability and water tightness of the rock; low rock stresses with regard to the strength of the rock, importantly this provides the depth envelope of the repository with respect to mechanical stability of the underground excavations. Near the Alps, on the other hand, one would expect abnormally high compression state of Earth’s crust (Ziegler & Dèzes 2007; Ziegler et al. 2016).
- low groundwater flow;
- favourable groundwater chemistry; reducing capacity and low concentrations of substances, including natural colloids, that may impair the long-term safety functions
- the retardation of radioactive materials in the rock; and
- protection against natural phenomena and human action (it is noted that part of the protection against human action is the paucity of natural resources at the prospective repository site, reducing the likelihood of inadvertent human intrusion).

These characteristics are then targets to be preserved. However, both the impact of underground construction and long-term performance are affected by the volume of the natural rock that is removed – and the method of removing. The critical impacts on the long-term safety of the construction work are defined:

- Drilling of investigation boreholes both from the ground surface (typically, for site characterization) and underground outside the excavated volumes (pilot and probe holes are planned to remain inside the excavated volumes are not of concern in this sense).
- Excavation induced effects: ED/dZ, Excavation Damage/disturbance Zones. EDZ is deemed to weaken the tightness of the host rock. It is noted that in the case of open tunnels EDZ and EdZ rather hinder inflows than enhance them. This effect is mainly attributed to stress redistribution by Mas Ivars (2006) while it has been suggested that even in such situations groundwater inflows may exhibit enhanced discreteness, or *hyperconvergence* (Black et al 2006). In the context of the long-term safety, EDZ conventionally denotes permanent, impaired tightness of the original host rock.
- Foreign materials (pre-grouting cement, cement additives, concrete structures, blasting residues etc.). It is desired to limit such materials entering the deposition tunnels and deposition drifts as much as is possible. We note that Posiva's policy posits that use of

organic, oxidizing or other harmful materials is limited as low as is possible in practice. Further, the Finnish radiation safety authority (STUK) stipulates that Posiva must have procedures to manage and approve materials used in construction and operating underground facilities. Posiva has established an expert group to assess, evaluate and approve any material that is intended to be used underground. This group then obtains all relevant documents that detail the composition of the material in question together with intended purpose, planned amounts, and estimations of unreturnable residues remaining. Nevertheless, practical tunnelling would need to use such materials. Furthermore, while not strictly defined as foreign materials (as they are included in imported barrier materials) buffer and backfill materials include both organic matter and sulfur even if limits are imposed on their amounts. This means they must be thoroughly addressed in long-safety considerations in order to properly evaluate the residual risk they present. While quantitative studies on the impact of foreign materials are exceedingly challenging, we note that (Höglund et al. 2018) is an example of reactive transport modelling of cement leachates at Olkiluoto and (Keith-Roach et al. 2019) an evaluation of the long-term safety risk of polyurethanes. As a further example, possible adverse impacts of titanium casing in the KBS-3H supercontainer have been studied by Wersin et al. (2012, 2018).

- Groundwater impact, due to groundwater inflow to open tunnels, in terms of groundwater pressure/water table drawdown, and hydrogeochemical impacts. Direct groundwater impacts as pressure or water table drawdown – while being "temporary" in the sense that they are expected to attenuate and vanish quickly when the underground repository system is closed (backfilled) – are effectively managed with sealing methods that reduce the inflows to a fraction of that what they could be without sealing. Sealing against inflow is also a key means to control the impact of underground construction on hydrogeochemistry. As an example, we note that intrusion of dilute and sulfate-rich waters from above and upwelling of very saline groundwater from below the repository are effectively controlled with sealing against inflows in Posiva's ONKALO facility. Dilute water at the repository depth increases the risk of bentonite erosion, sulfate in groundwater increases the risk of copper corrosion (through microbially induced transformation of sulfate into sulfide) whereas very high groundwater salinities may impair bentonite's swelling capacity that is needed to achieve low hydraulic conductivities.

The basic principle is that aforementioned impacts have to be limited or minimized to the extent that is possible in practice. As this is a qualitative requirement, imposing quantitative limits to disturbances is far from trivial and, in practice, calls for expert judgement with in-depth consciousness of uncertainty in the knowledge of the long-term performance of the repository together with what should be regarded as "unavoidable" in order to have a feasible and viable repository solution in the first place. For example, drilling of investigation boreholes and various multi-year investigations with them is an essential means of obtaining crucial site data. Managing their long-term safety impacts has, therefore, to be carefully planned in order to limit their undesired effects as much as is possible. A particular risk is due to inadvertent penetration of the disposal tunnels and drifts with investigation holes. While geolocating the drillhole tracks in the host rock is the critical information needed to prevent such mishaps. Another example of the "trade-off" is limiting the groundwater impact of the underground excavation. Limiting it with pre-grouting is a conventional technique but this comes at the expense of introducing cement-based materials of which the degradation products, in turn, are seen to affect the performance of bentonite barrier components in the long term.

Because open drillholes are likely to form high conductance channels connecting natural (gently dipping) bedrock structures, it is important to minimize the associated risk of hydrogeochemical disturbance with drillhole packers. While investigation holes are planned to be filled with durable, low conductivity materials after their utilization, their number and location with respect to underground excavation should be weighed against the risk of new transport routes they might form in the long term.

Design alternatives D1-D4 are different in their perceived impacts even if the construction work consistently adhered to limiting them. The most apparent differences are due to the excavated volumes that vary significantly between the design alternatives:

Design alternative	Total bored/excavated volumes of natural (intact) rock [m^3]
D1 - VD, M	5,045,945
D2 - VD, C	3,275,581
D3 - HD, M	2,003,596
D4 - HD, C	1,853,420

The excavated volume clearly produces the area of exposed rock surfaces. Amounts of shotcrete, rock reinforcing, rock bolts and steel mesh to ensure occupational safety increase with the area of the exposed surfaces. Even if such structures were to be removed (as much as is practical) by the time of closure, they would affect the quality of the rock surfaces enclosing engineered barriers. On the other hand, rock bolts, which reach a few meters from the tunnel wall, cannot be removed in practice. They would eventually corrode, and (porous) corrosion products would fill their holes in the host rock. The smaller total excavated volume in horizontal disposal option suggests smaller disturbance to the hydrogeological and hydrogeochemical conditions around the disposal facility. We note that Posiva has set constrains on the usage of cement-based materials in its ONKALO facility. For example, no cement-based pre-grouting materials are allowed in deposition tunnels; thereby silica-based pre-grouting is only applied to seal against inflows. Moreover, deposition tunnel plugs are only allowed to be made of low pH cement.

Besides the excavated volumes and tunnel face areas, there are apparent inherent differences in the long-term safety related factors in the design alternatives for the repository construction:

- EDZ is seen to be a lesser issue for the TBM construction method (e.g., Siren et al 2015). Its smaller and weaker excavation damaged zone is less likely to impair the favorable properties of the host rock whereas in D&B tunneling blasting exerts its dynamic force surpassing the strength of the rock beyond the planned excavation profile. Furthermore, the more circular tunnel profile of the TMB tunnel than the horseshoe shape of the D&B tunnel makes it more stable against stress induced damages. However, EDZ can also be controlled in drill & blasting excavation with careful planning in which the properties are the rock to be removed are considered in the drilling pattern, blasting design, and detonation sequence. In any case, as EDZ cannot be avoided altogether, it should be "accepted" as a permanent and undesired change in the host rock properties embracing the engineered barriers. We note that Posiva has carried out extensive studies on the EDZ in Posiva's ONKALO facility to quantify its occurrence and long-term safety significance (Follin et al (2021) and references therein). This said, the mechanical tunneling option and deposition drifts in design alternative D3 - HD, M should be regarded as optimal from the point of view of minimizing EDZ. One should, however, observe the risk of occurrence of weaker quality of rock bringing about instabilities on the drift wall.

- Groundwater impact is most effectively limited by pre-grouting measures, which can be carefully planned based on pilot hole and systematic probe hole data.[1] Drilling such probe holes is readily included in the staged D&B construction. In the case of Posiva's nuclear waste repository, the inflows exceeding a criterion in deposition tunnels will be pre-grouted with injecting silica-based material (which is assessed to be chemically inert). It is seen that post-grouting or, generally, post-excavation sealing means are less efficient and costlier. However, as deposition drifts are possible to seal against inflows – see section 4.1 and references therein for the "Mega-Packer" – this difference between mechanical and D&B tunneling is not regarded significant in itself from the point of view the long-term safety.
- Mechanical excavation in design alternatives D1 - VD, M and D3 - HD, M can be regarded as a more favorable in terms of lesser amounts foreign materials introduced in the form of blasting residues. Thereby this inflicts lesser risk of metal corrosion due to reactive nitrogen compounds. Further, deposition drifts in design alternatives D3 - HD, M and D4 - HD, C avoid the impact of measures for occupational safety (shotcrete, steel mesh, rock reinforcement). It also is consistent to assume that mechanical tunneling, and, in particular, boring deposition drifts are clearly less likely to cause oil spills (fuel, hydraulics, lubrication) or exhaust fumes that may add to the risk of microbial activity in the vicinity of waste packages. In any case, given the complex thermo-hydro-chemical system and its evolution into the far future, quantitative predictions of undesired impacts of diverse foreign materials are a tall order. Thereby, rather than having a firm foundation to impose quantitative limits on a certain compound, the focus is put on controlling its use and means to ensure that detrimental discharges are minimized. In this spirit, we note that the gravel in the TBM tunnels in design alternative D3 - HD, M (Figure 6-1) raises questions about possible foreign materials in the composition (and whether the gravel leveling represents a hydraulically conductive flow and transport route along the tunnel). This notwithstanding, the benefits related to long-term safety include the lack of deposition tunnel plugs in design alternatives D3 - HD, M and D4 - HD, C. The deposition tunnel plugs are large concrete structures planned at the mouths of the deposition tunnels in vertical concept KBS-3V (pertinent to design alternatives D1 - VD, M and D2 - VD, C). Cement structures are expected to degrade over time and ensuing leachates are considered to be detrimental to the long-term performance of the backfill and buffer (e.g., Sun et al. 2022). It is noted, however, that in the Finnish repository design the concrete plug in the deposition tunnel is to be made of "low pH" cement which is predicted to have a significantly weaker impact of the groundwater alkalinity than the "traditional" Portland cement. Otherwise, all the cement structures – including shotcrete in central and technical tunnels – that have no role as barriers are planned to be removed from Posiva's ONKALO facility by the time of closure.

[1] In Posiva's tunnelling, pilot holes mostly aim to confirm the suitable rock conditions for the tunnel construction, and to indicate needs for any modification of the plans. Probe holes, in turn, are drilled to determine the need for pre-grouting or to assess any rock properties that should be considered before the excavation of the next rounds.

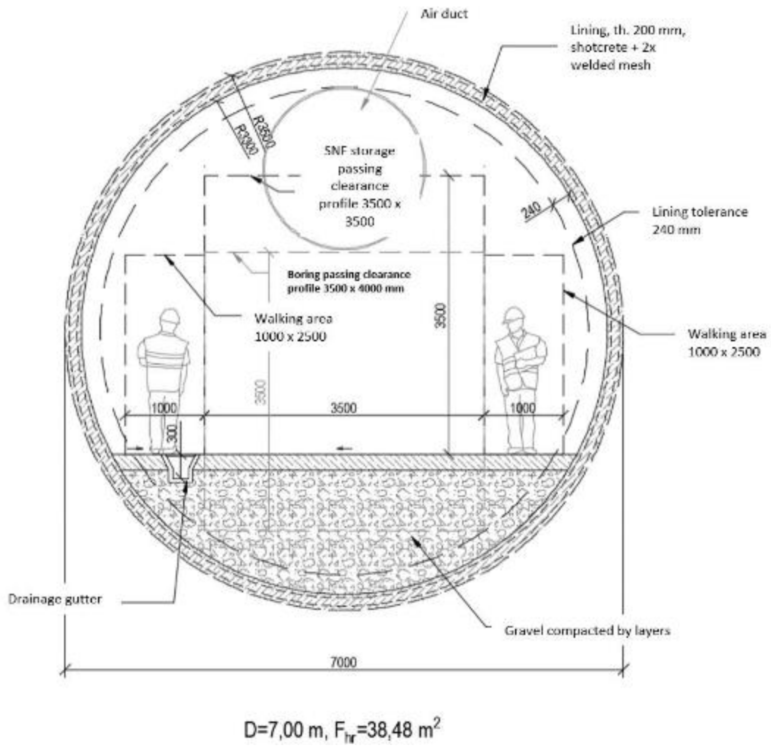

Figure 6-1. Cross-section of the transfer and extraction tunnels, TBM boring method, design alternative D3 - HD, M for horizontal disposal. Note that a significant part of the cross-section area is occupied by gravel. Authors of this review are not aware if the gravel levelling is planned to be removed before closure. If it is intended to be left in the repository, its impact on the groundwater flow and chemistry is an issue to be assessed.

6.2 Suitable rock environment for the waste packages

Local rock conditions, that is, fracturing and groundwater conditions; inflow and groundwater chemistry are considered in locating the deposition holes (in design alternatives D1 - VD, M and D2 - VD, C) or the supercontainers (waste package) in the deposition drifts (in design alternatives D3 - HD, M and D4 - HD, C). While Posiva has defined a criterion for the deposition hole inflow it is stressed that no measures to limit inflows to deposition holes are planned. Rather, a too high inflow rate that is observed in the pilot hole for the deposition hole will lead to a decision to abandon that particular deposition hole location as unacceptable (it would not meet the so-called *rock suitability criteria,* RSC, which have been developed over many years by Posiva, and also jointly with SKB).

Furthermore, as the correlation between the inflow in the deposition hole pilot hole and subsequent deposition hole is not “perfect” but stochastic (depending on the spatial frequency of varying rock qualities) it even may happen – but with a low likelihood -- that the deposition hole itself fails to meet its criteria after passing the pilot hole criteria. This is would not be unlike what could also happen in the deposition drift. In practice, the consequence would be a lower tunnel (design alternatives D1 - VD, M and D2 - VD, C) or deposition drift utilization (design alternatives in D3 - HD, M and D4 - HD, C).

Another and a clearly more critical criterion affecting the suitability of the candidate deposition hole site is the size of the fracture intersecting the deposition hole. Namely, an intersecting fracture that is larger than a *critical size* has a significant potential to shear, leading to failure of the canister or waste package in the event of strong earthquake. Even if the number and frequency of such fractures decrease very effectively as the critical size increases, a single large fracture has also potential to intersect several deposition holes – or waste package positions in the case of horizontal drifts. Geometrically, deposition holes are more likely to be intersected by subhorizontal large fractures than vertical ones. Regardless of the design alternative it is of paramount importance to develop the criteria for suitable waste package locations and obtain reliable estimation of the sizes and orientations of intersecting fractures for an effective tunnel or deposition drift utilization. Such criteria effectively mitigate the risk of canister failure due to rock shear regardless of the design alternative and site characteristics, but this might be achievable at the expense of utilization (see (Pekkarinen 2014) for a case study).

Developing effective suitability criteria for deposition drifts in design alternatives D3 - HD, M and D4 - HD, C is regarded as a significant challenge. Based on the "groundwork" with the RSC for the deposition holes already available, it should, however, be possible to base them on well-defined pilot hole data concerning the quality of the host rock; orientations, sizes, and transmissivities or inflows of intersecting fractures.

6.3 Long-term performance of the barrier system

Eventually the tunnels will have been backfilled with imported materials. From the point of view of the long-term performance of the repository, the fundamental premise is the definition of the criteria or requirements, in other words, *performance targets* that each release barrier is designed to meet (Posiva 2017a, 2021b). A low hydraulic conductivity (to be attained by the saturated bentonite with a high swelling pressure) and chemical stability are the fundamental requirements that Posiva has defined for the buffer and backfill in the deposition holes and tunnels, respectively. Generally, the performance targets of the buffer and other clay-based components will be fulfilled during the assessment time frame as long as the materials are saturated and the dry density of the buffer is maintained and expected swelling pressure is achieved, and, consequently, microbial activity that could lead to sulfide production is suppressed (Posiva 2018d, 2021e).

It is understood that the performance targets for bentonite barriers will be attained as their saturation with water progresses. During the early stage of evolution prior to the saturation, however, the waste packages are exposed to some limited corrosion due to the residual oxygen. Since the deposition drifts in design alternatives D3 - HD, M and D4 - HD, C are, by volume, much smaller than deposition tunnels in design alternatives D1 - VD, M and D2 - VD, C, this form of corrosion is judged to be a lesser issue for the former.

As the bentonite in the buffer and backfill is known to include small concentrations of sulfur, thus introducing a risk of sulfide corrosion of copper canisters, the deposition drifts (in design alternatives D3 - HD, M and D4 - HD, C) are judged to minimize this risk due their smaller volumes, thus smaller total amount of sulfur, in comparison with deposition tunnels (in design alternatives D1 - VD, M and D2 - VD, C). However, it is noted that a significant part of the total sulfur may take place in the form of pyrite, which is a very stable compound in anoxic conditions. On the other hand, gypsum, that is also found in bentonites, exhibits a readily available source of sulfate. This contributes to the risk of sulfide corrosion through microbially induced sulfate reduction. Regardless, if the bentonite buffer maintains its dry density (that is, no significant mass loss has taken place) the fluxes of corroding substances through the buffer stay limited so that the canister's lifetime surpasses 1 Ma (Posiva 2021e). It is noted that SÚRAO's disposal plans of spent nuclear fuel depict waste packages made of stainless steel. As a material stainless steel shares the same corrosion mode of microbially induced (localized) corrosion with copper (e.g., Rajala et al. 2022). In any case, the risk of corrosion of the primary barrier in the actual rock environment – regardless its material – calls for expert assessments. Further, as was mentioned earlier, the deposition tunnel plugs, even if made of "low pH" cement, represent a residual risk of on the performance of the backfill and buffer in the design alternatives D1 - VD, M and D2 - VD, C.

Mass loss of bentonite due to interaction with relatively dilute groundwater is referred to as "chemical erosion" (Figure 6-2). Experimental studies on clay erosion in horizontal fractures have consistently demonstrated that emplaced montmorillonites or bentonites extrude uniformly to extents which depend on fracture aperture, bentonite content, and ionic strength (Kanno & Wakamatsu 1991, Baik et al. 2007, Tanai & Matsumoto 2008, Vilks & Miller 2010, Schatz et al. 2013, Reid et al. 2015, Hedström et al. 2016, Schatz et al. 2016, Alonso et al. 2019). The swelling of bentonite into fractures will be resisted by frictional forces acting within the bentonite and at the rock surfaces and the density of the bentonite material correspondingly decreases as it swells further into these spaces. Such swelling/extrusion will continue until the density of the bentonite material at the front is decreased (from that of the installed buffer at the deposition hole/fracture interface) to such low levels that its swelling ability is balanced by the friction with the rock, and it becomes a gel. With decreasing salinity, the gel will eventually weaken to the point that it breaks down and particles are released.

With respect to sodium montmorillonite (from Wyoming bentonite) against sodium chloride, erosion threshold concentrations of 8.6 mmol/L (Schatz et al. 2013) and 20 mmol/L (Hedström et al. 2016) have been inferred. On the other hand, it is well-known that bentonites rich in divalent cations (Ca and Mg) are less susceptible to erosion than sodium bentonites. While they can, as Na bentonites do, reach very low hydraulic conductivities at saturation, they provide smaller swelling pressures. They also possess greater shear strength making them less favorable in the event of earthquake. It is important to note, however, that depending on the site specific hydrogeochemical environment, bentonites are expected to transform due to cation exchange: Na bentonites transforming toward Ca bentonites and vice versa. While this process is inevitable in itself, it is expected take a long time in the buffer (Posiva 2021f).

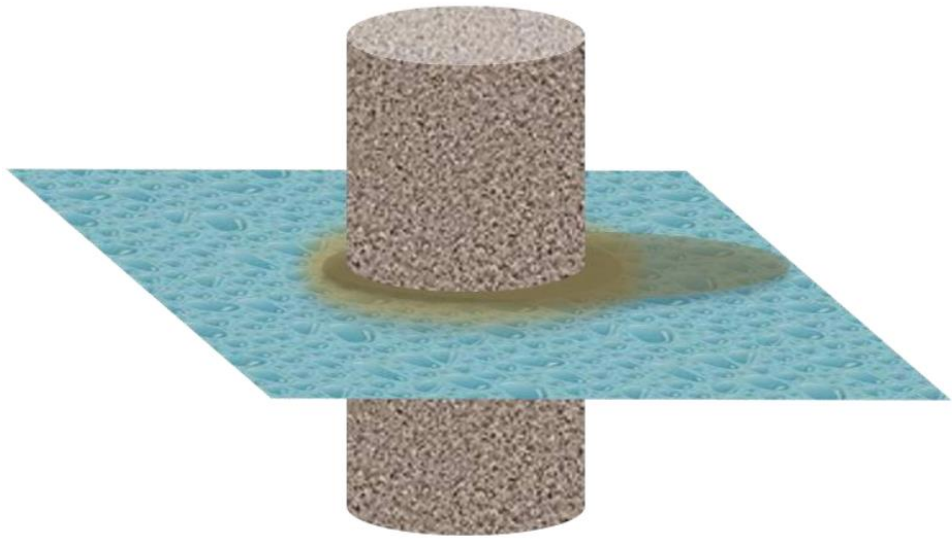

Figure 6-2. Conceptual illustration of chemical erosion of buffer material in an intersecting fracture in the deposition hole. Groundwater flows from the left to the right. Figure adopted from (Schatz & Akhanoba 2018).

An additional aspect of chemical erosion concerns the effect of gravity, which can act to destabilize the extruding phase and thus drive mass release by sedimentation (Figure 6-3). Geometrically, this should be seen more likely for the horizontal design alternatives (D3 - HD, M and D4 - HD, C). Experimental studies on clay erosion in sloped fractures have demonstrated that increased mass loss is always observed with increasing fracture slope angle from 0 (horizontal) to 90° (vertical). Raw bentonites and purified montmorillonites with ≤50% calcium content of exchangeable cations, placed in fractures at 45° slope angles, have been found to be stable to erosive mass loss down to a contact solution charge concentration of 8.6 meq/L or less (depending on cation valency), similar to that observed in horizontal fractures (Schatz & Akhanoba 2018).

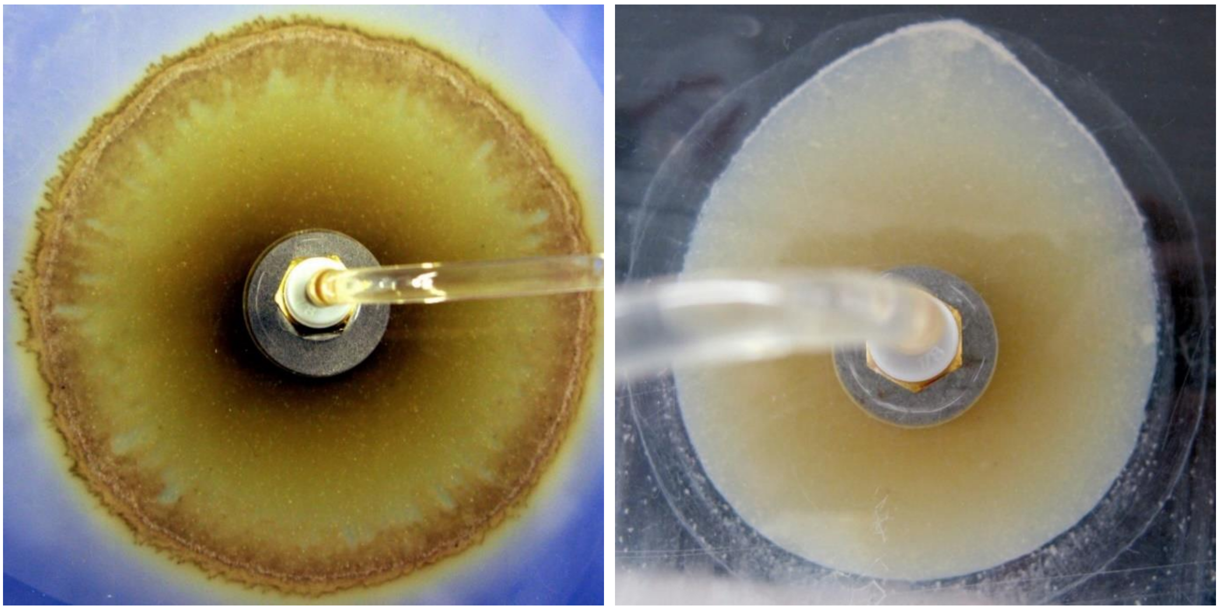

Figure 6-3. Images of artificial fracture tests performed on mixtures of sodium montmorillonite and quartz sand in a horizontal (left) and 45° sloped (right) fracture at 288 and 716 h, respectively (Schatz & Akhanoba 2018). The tests were conducted in 1 mm aperture fractures with the Grimsel groundwater simulant[2] solution flowing through the fractures at 0.09 ml/min (~6×10^{-6} m/s). The samples were initially emplaced at montmorillonite dry densities of ~1.6 g/cm^3.

While substantial insight has been gained in recent years through laboratory and modelling studies chemical erosion is still a research topic. The current state of knowledge is exhibited by Hedström et al. (2023) and Pont (2023).

Erosion of bentonite under the influence of dilute groundwater might be more problematic for KBS-3H (pertinent to design alternatives D3 - HD, M and D4 - HD, C) than for KBS-3V (pertinent to design alternatives D1 - VD, M and D2 - VD, C) – and could lead to a case of multiple canister failure (Posiva 2018d). Namely, a particular issue of chemical erosion with the deposition drift, "domino effect", was depicted by Smith et al. (2017); see Figure 6-4. If bentonite erosion at one location along the drift is sufficiently severe, it could potentially affect conditions not only around the nearest canister, but also around other canisters along the drift. This effect could, in principle, lead to erosion to one fracture causing successive canisters along the drift to become exposed to advective conditions and potentially fail due to corrosion. This is regarded as the main downside of the KBS-3H design (pertinent to design alternatives D3 - HD, M and D4 - HD, C). Moreover,

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[2] Composed of an aqueous solution of 0.04 g/L NaCl and 0.016 g/L CaCl2, which corresponds to relative Na+ and Ca2+ concentrations of 0.68 and 0.14 mM, respectively, a solution ionic strength of 1.1 mM and a total cation charge concentration of 0.96 meq/L. The weakly mineralized, high pH groundwater sampled from the migration shear zone at the Grimsel Test Site in Switzerland is often used as a reference composition for groundwater diluted by glacial meltwater.

the erosion resistance of alternative filling materials should be studied further. Some other uncertainties are related to the early evolution in the drift and buffer performance: desiccation and formation of cracks, the final density of buffer in the gap between the supercontainer and the rock.

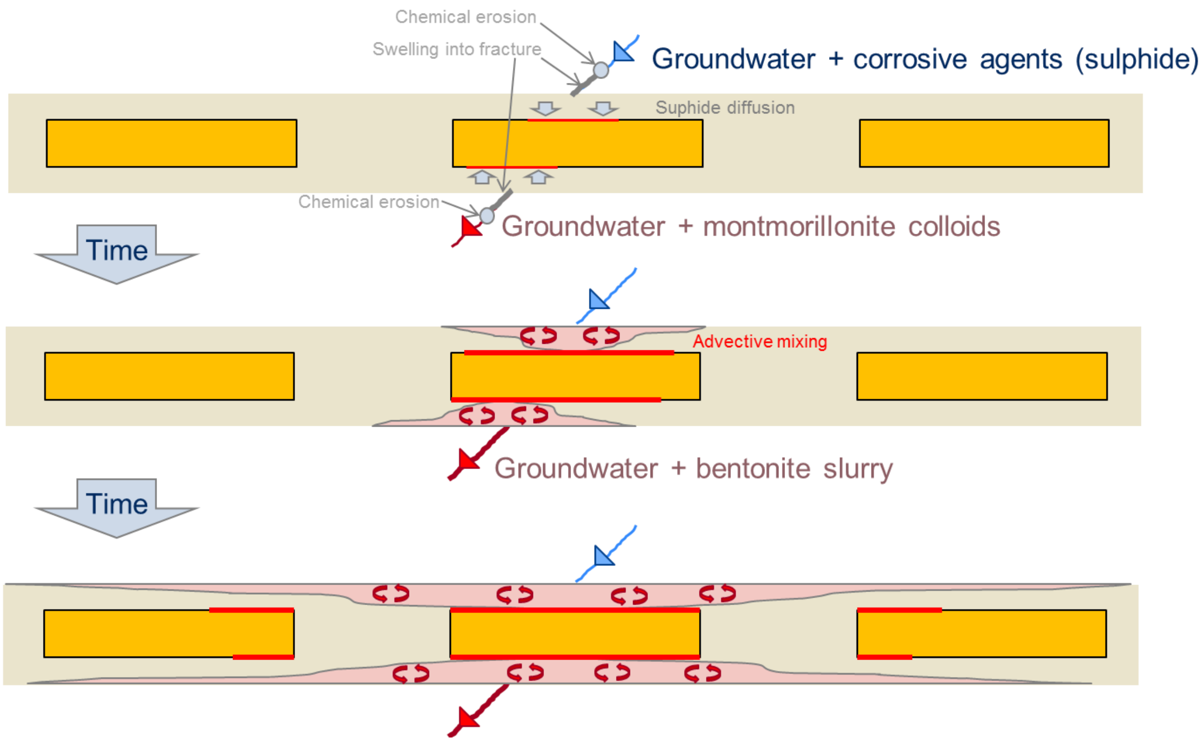

Figure 6-4. Hypothetical sequence of states leading to the "domino effect" in the deposition drift for the horizontal was package design alternatives (D3 - HD, M and D4 - HD, C). Upper figure: bentonite is extruded into a fracture and eroded gradually at times when low-ionic strength conditions prevail. Middle figure: severely eroded conditions occur locally in the buffer. Lower figure: severely eroded conditions propagate further along the drift, affecting multiple canisters. Figure adopted from (Smith et al. 2017).

It is noted that whether chemical erosion is to occur at a chosen repository in the far future, it results from many factors – future hydrological and hydrogeochemical environment under influence of the surface evolution, host rock characteristics, bentonite characteristics, suitability criteria imposed to minimize the risk of erosion – subject to dedicated studies.

In addition to the possible chemical erosion of buffer, mechanical erosion – which is linked to a highly nonlinear behavior of the unsaturated swelling clay under wetting -- is also possible. While, in principle, this risk can be mitigated by limiting the inflows saturating the buffer, the effectiveness of such a strategy cannot be confirmed. Instead, the risk of mechanical erosion was one of the main reasons that the DAWE design alternative in KBS-3H was proposed (Posiva 2012a). Using artificial water filling will also ensure that the buffer and other clay components in the drift will relatively quickly achieve the desired hydraulic conductivity and swelling pressure thus corroborating the long-term integrity of the clay barriers.

Vertical and horizontal orientations of the waste packages in the different design alternative may have different exposures to mechanical failure in rock shear. The case of compression shear at a skew angle was modelled by Börgesson & Hernelind (2016), along with other rock shear cases. According to the results, a rock shear in KBS-3H does not yield higher stresses and plastic strains in the copper canister than a rock shear in KBS-3V, although the stresses are higher in the welds in KBS-3H (pertinent to design alternatives D3 - HD, M and D4 - HD, C) than in KBS-3V (Posiva 2018d).

A more nuanced difference between the horizontal and vertical design alternatives are to do with earth currents induced by high voltage direct current (HVDC) power transmission lines.[3] Such currents would give rise to corrosion in correlation of the strength of the gradient of the electric potential filed. The presence of such an HVDC line in the close vicinity of the repository will induce stronger currents in vertically aligned canisters, whereas the electric potential emanating farther away from the source would align horizontally. However, estimations (Posiva 2018d, Taxén et al. 2014) – while always yielding corrosion rates ≪ 1 µm/a – of the corrosion depth will depend on number of details. For example, the perforated titanium "cage" enclosing the 3H canisters would attenuate the electric field inside it. However, galvanic corrosion needs to be considered before finalizing the decision to use titanium as the supercontainer shell material for the horizontal disposal design.

6.4 Summary

The KBS-3H horizontal design – pertinent to design alternatives D3 - HD, M and D4 - HD, C -- is less mature in terms of its technology and it would require several years of extensive studies before reaching the current maturity level of KBS-3V. It is therefore not possible to single out the "best" design alternative, but distinct *differences* between them from the point of view of the long-term safety are identifiable, in particular, based on Posiva's work on vertical (KBS-3V; pertinent to design alternative D1 - VD, M and D2 - VD, C) and horizontal design (KBS-3H; pertinent to design alternatives D3 - HD, M and D4 - HD, C) options. It is conduced that the main differences between the design alternatives are as follows:

- The volume of the excavated rock and area of exposed rock surfaces are minimized in the horizontal alternatives (KBS-3H) D3 - HD, M and D4 - HD, C. It is consistent to assume that introduction of foreign materials in the repository is also minimized with the smaller excavated volume and area of the exposed tunnel surface. Deposition tunnels have to be equipped for occupational safety utilizing foreign materials, and blasting damages contributing to EDZ and residues and organic emissions from working machinery is an issue in D&B tunnelling. Deposition drifts would also have a minimal EDZ around waste packages. On the other hand, managing high water inflows in the deposition drifts is an outstanding challenge at least until the performance of a post-grouting method (see the discussion on Mega-Packer in Section 4.1) shown to be viable whereas pre-grouting with silica is adopted by Posiva in the deposition tunnels -- pertinent to design alternatives D1 - VD, M and D2 - VD, C.
- While Posiva has developed effective rock suitability classification for the deposition holes, similar ones are yet to be devised for the waste package sites in the deposition drifts. It should, however, be possible to base them on well-defined pilot hole data concerning the quality of the host rock, the transmissivity or inflows of intersecting fractures. Based on Posiva's rock suitability classification, it is argued that occurrence of large fractures (i.e., larger than the critical size in the event of a strong earthquake), including their orientation should be seen as critical knowledge also in connection with the deposition drifts in design alternatives D3 - HD, M and D4 - HD, C.

[3] The authors, however, are not informed of potential (current or future) locations of the HVDC lines in the vicinity of the prospective repository sites in Czech Republic.

- Chemical erosion of bentonite exposed to dilute water has been consistently observed in laboratory studies. Even after advances over the recent years, there are still details yet to be captured by erosion modelling. In this regard chemical erosion should still be seen as an issue yet to be fully resolved. Even if this process concerns both the deposition holes (design alternatives D1 - VD, M and D2 - VD, C) and deposition drifts (design alternatives D3 - HD, M and D4 - HD, C), it is assessed to be a more significant issue in the case of the latter. The foremost reason is the possible “domino” effect: continued erosion due to a distinct fracture intersection in the deposition drift propagating to affect the performance of the buffer around several waste packages over a longer time.
- The deposition tunnel backfill in design alternatives D1 - VD, M and D2 - VD, C, depending on its sulfur content and composition, is a potential source of sulfate for microbially driven sulfide production, which may contribute to corrosion of the waste package. Deposition tunnel plugs also are a source of cement leachates that affect the properties of bentonite.

7 Economics

In 2020 costs were calculated for two alternatives (Saanio et al. 2020). Alternatives were D1 - VD, M using Tunnel Boring Machinery for the excavations and D2 - VD, C using conventional drill & blast technique for the excavations. Also, very rough cost comparison has been done to compare the costs for above mentioned vertical disposal alternatives (D1 - VD, M and D2 - VD, C) to the costs of horizontal alternatives (D3 - HD, M and D4 - HD, C).

The total costs were calculated as costs for research and development costs following preparation, construction, operational and closure costs without specifying a specific site. A generic site with granitic rock was considered as a reference case. This chapter describes the costs according cost estimation (Saanio et al. 2020).

All costs are presented in Euros. The prices do not include the value-added tax (VAT). The cost level is 1/2020. The interest rate of the money has not been taken into account. Finnish working methods and Finnish prices of materials and labour costs are applied.

Operation period of the deep geological repository is supposed to be 100 years. The repository will be excavated in phases and backfilled continuously during the long operation period.

Different costs are calculated with different methods considering that items are designed at different detail level. For example, backfilling technique and materials are not defined in detail yet and hence the costs cannot be calculated in detail.

Contingencies for unspecified costs are included in the summary tables. Contingency includes different kind of uncertainties. Reasons for uncertainties are:

- Very early design phase, conceptual design. There may be systems that are not yet well designed, defined or known. Designs may change in later design phases. Usually also costs will change.
- Technology and working methods may change and this may change the costs as well.
- The price of some materials may change differently than normal inflation rate. For example, the price of bentonite could change, and this would have a strong impact on the total costs.
- Geology, fracturing, fracture zones, groundwater conditions, groundwater geochemistry, rock mechanical conditions and meteorological conditions may be different than what was assumed.

Contingency for uncertainty does not include changes in the amount of waste or changes in the actual repository concept, for example some new disposal concept.

7.1 Total costs, vertical alternatives D1 - VD, M and D2 - VD, C

Research and development costs are based on Posiva's realized costs and experience in disposal concept design, disposal site selection and confirmation investigations and preparation of the safety case. Due to the extensive timespan of the research and development (R&D) work the estimate cannot be based on exactly defined work packages and unit costs. The cost estimate is presented in Table 7-1.

Table 7-1. Estimate of SÚRAO's R&D costs for DGR.

	Site selection phase (Million EUR)	Site confirmation phase (Million EUR)	Construction phase (Million EUR)	Total (Million EUR)
Site investigations	60	95		155
Concept development	25	50	40	115
Safety case	10	15	35	60
Monitoring			20	20
Total	**95**	**160**	**95**	**350**

Preparation costs include exploratory and geodetic works, designing, site preparation, site equipment and engineering activities for the deep geological repository (Grunwald et al. 2018).

In this report site preparation is assumed to start 15 years before operation of the deep geological repository begin.

After the site is selected for the deep geological repository, more detailed site investigations are still needed on the site to locate the repository exactly on the site and to decide exactly the depth of the repository. These detailed site investigations include drilling, borehole investigations, hydrogeological investigations, rock mechanics and other investigations. Investigation results will be used for the construction and for the long-term safety assessments. Rough estimate of the site investigations cost that is needed for the construction is 50 Million EUR. Total costs for the site investigation in this phase is 95 Million EUR (Table 7-1) including 50 Million EUR for the construction.

In this report most of the other preparation costs are introduced in Chapter 5 Construction costs. Site preparation and site equipment are included in the costs for above ground rooms and infrastructure. Designing and engineering activities are part of the owners costs.

Preparation costs for 15 years period is collected in Table 7-2. *All these costs are included also in the research and development costs (Chapter 3) or in the construction costs (Chapter 5).*

Table 7-2. Preparation costs (EUR).

Activity	D2 - VD, C Costs (EUR)	D1 - VD, M Costs (EUR)
Detailed site investigations for the construction on the site	50 000 000	50 000 000
Site preparation and site equipment	24 290 000	24 290 000
Designing and engineering activities	82 709 000	152 938 000
Investigations during construction	27 580 000	27 580 000
Total	**184 579 000**	**254 808 000**

Investment costs for alternatives D2 - VD, C and D1 - VD, M are summarized in Table 7-3

Table 7-3. Investment costs (EUR).

Activity	D2 - VD, C Costs (EUR)	D1 - VD, M Costs (EUR)
Above ground rooms and infrastructure	176 317 000	176 317 000
Excavation	694 693 000	1 818 651 000
Construction	191 048 000	255 823 000
Backfilling above capsulation plant	14 493 000	14 493 000

Vertical disposal boreholes	217 344 000	199 104 000
HVAC systems	20 000 000	20 000 000
Electrical systems	15 000 000	15 000 000
Equipment	22 000 000	22 000 000
Investigations during construction	27 580 000	27 580 000
Owners costs, 15 %	206 771 000	382 345 000
Sub-total	**1 585 246 000**	**2 931 313 000**
Contingency for uncertainty, 20%	317 049 000	586 263 000
Total	**1 902 295 000**	**3 517 576 000**

Dominating operating costs are backfilling of the transfer corridors, personnel costs and disposal canisters. Some of the costs are calculated based on the costs per year and some are calculated based on the amounts and volumes of the repository and waste. Operation period will last 100 years. Operating costs are presented in Table 7-4.

Table 7-4. Operating costs (EUR).

Activity	D2 - VD, C Costs (EUR)	D1 - VD, M Costs (EUR)
Canisters	682 500 000	682 500 000
Concrete boxes	6 000 000	6 000 000
Bentonite blocks of vertical boreholes	92 035 000	78 342 000
Dismantling of structures	19 313 000	31 111 000
Transfer corridors, backfilling	1 562 718 000	2 661 194 000
RAW area, backfilling	6 805 000	6 805 000
Concrete plugs for transfer corridors	13 425 000	22 660 000
Personnel costs	1 488 000 000	1 488 000 000
Energy costs	180 000 000	180 000 000
Water and water treatment	10 000 000	10 000 000
Maintenance and reparation	625 829 000	651 280 000
Insurance	137 100 000	227 600 000
Owners' costs, 15 %	254 144 000	420 017 000
Sub-total	**5 077 828 000**	**6 465 484 000**
Contingency for unspecified costs, 20 %	1 015 566 000	1 293 097 000
Total	**6 093 394 000**	**7 758 580 000**

Closure costs include costs for the closure phase and are presented in Table 7-5.

Table 7-5. Closure costs (EUR).

Activity	D2 - VD, C Costs (EUR)	D1 - VD, M Costs (EUR
Dismantling of the structures	19 891 000	27 526 000
Backfilling of capsulation plant	14 199 000	14 199 000
Other backfilling	74 527 000	114 786 000
Plugs of the shafts and tunnels	492 000	606 000
Owners' costs	16 366 000	23 567 000
Sub-total	**125 475 000**	**180 684 000**
Contingency for uncertainty	25 095 000	36 137 000
Total costs	**150 570 000**	**216 821 000**

Total costs are presented in Table 7-6. It should be noted that following changes have been made compared to the costs shown in Table 7-1 … Table 7-5.

- Table 7-1 Research and development costs. 50 Million EUR has been deleted from “Site investigations in site confirmation phase” since these costs are allocated for the construction and therefore included in the preparation costs, Table 7-2.
- Table 7-3 Investment costs. 24,290 Million EUR has been deleted from “Above ground rooms and infrastructure” since these costs are allocated for site preparation and site equipment and therefore included in the preparation costs, Table 7-2.
- Table 7-3 Investment costs. Designing and engineering activities costs are deleted from “Owners costs” since these costs are included in the preparation costs, Table 7-2. Costs for designing and engineering activities are 82,709 Million EUR for alternative D2 - VD, C and 152,938 Million EUR for alternative D1 - VD, M. *Calculation is presented in Chapter 4*.
- Table 7-3 Investment costs. 27,580 Million EUR has been deleted from “Excavation” since these costs are allocated for investigation during construction and therefore included in the preparation costs, Table 7-2.

Table 7-6. Total costs for the deep geological repository, EUR (ALV 0%), cost level 1/2020.

Activity	D2 - VD, C Costs (EUR)	D1 - VD, M Costs (EUR)
Research and development costs	300 000 000	300 000 000
Preparations	184 579 000	254 808 000
Investment costs	1 767 718 000	3 382 998 000
Operation costs	6 093 394 000	7 758 580 000
Closure costs	150 570 000	216 821 000
Total costs	**8 496 260 000**	**11 913 208 000**

7.2 Total costs, horizontal alternatives D3 - HD, M and D4 - HD, C

This chapter introduces very roughly identified differences in the costs between horizontal alternatives (D3 - HD, M and D4 - HD, C) and vertical alternatives (D1 - VD, M and D2 - VD, C). Comparison covers construction costs, operational costs and closure costs.

Alternatives D1 - VD, M and D3 - HD, M are based on TBM excavation. Costs for alternative D3 - HD, M are compared to alternative D1 - VD, M. Alternatives D2 - VD, C and D4 - HD, C are based on drill & blast excavation. Correspondingly, costs for alternative D4 - HD, C are compared to alternative D2 - VD, C. Main differences in the volumes between the alternatives can be recognised in Table 7-7.

Table 7-7. Volumes of the main components in different alternatives.

	D1 - VD, M (m^3)	**D2 - VD, C (m^3)**	**D3 - HD, M (m^3)**	**D4 - HD, C (m^3)**
Transfer corridors	3 800 000	2 100 000	440 000	440 000
Vertical disposal boreholes	126 000	126 000		
Horizontal disposal boreholes			445 000	445 000
Main tunnels	400 000	132 000	390 000	287 000
Total	**4 800 000**	**2 753 000**	**1 710 000**	**1 550 000**

7.2.1 Construction costs

Alternative D3 - HD, M

Alternatives D1 - VD, M and D3 - HD, M are based on TBM excavation. Difference in the total volume is more than 3 000 000 m^3. Main reasons for the differences are transfer corridors and disposal boreholes. In alternative D3 - HD, M only the first part of transfer corridor is excavated and on the other hand vertical disposal holes are not needed. Instead, horizontal disposal holes are drilled. Equipment and systems in the horizontal alternative D3 - HD, M are more expensive. In the other cost components, no major differences have been identified.

Estimated differences; alternative D3 - HD, M compared to alternative D1 - VD, M:

Excavation and disposal boreholes	- 1 000 Million EUR
Equipment and systems	+ 200 Million EUR
Total	- 800 Million EUR

Alternative D4 - HD, C

Alternatives D2 - VD, C and D4 - HD, C are based on drill & blast excavation. Difference in the total volume is about 1 200 000 m^3. Main reasons for the differences are the same as in previous paragraph. Additionally, main tunnels are longer in the alternative D4 - HD, C. In the other cost components, no major differences have been identified.

Estimated differences; alternative D4 - HD, C compared to alternative D2 - VD, C:

Excavation and disposal boreholes	- 500 Million EUR
Equipment and systems	+ 200 Million EUR
Total	- 300 Million EUR

7.2.2 Operational costs

Dominating operating costs in vertical alternatives D1 - VD, M and D2 - VD, C are backfilling of the transfer corridors, personnel costs and disposal canisters. In horizontal alternatives D3 - HD, M and D4 - HD, C backfilling of horizontal disposal boreholes is one of the dominating cost components as well.

Alternative D3 - HD, M

Transfer corridors and disposal boreholes are backfilled and closed during operation period. Total volume to be backfilled is roughly 3 000 000 m^3 lower in the alternative D3 - HD, M than D1 - VD, M. Length of the operation period is estimated to be slightly (5 %) longer for horizontal alternative D3 - HD, M than for D1 - VD, M. Time depending on operation costs for the alternative D1 - VD, M are about 30 MEUR per year including for example personnel, maintenance and reparation, energy and insurance. No major differences in the other cost components have been identified.

Estimated differences; alternative D3 - HD, M compared to alternative D1 - VD, M:

Backfilling of transfer corridors and disposal boreholes	- 2 100 Million EUR
Yearly costs, personnel etc.	+ 100 Million EUR
Total	- 2 000 Million EUR

Alternative D4 - HD, C

Total volume to be backfilled is in alternative D4 - HD, C is roughly 1 200 000 m^3 lower in the alternative D4 - HD, C than D2 - VD, C. Length of the operation period is estimated to be slightly (5 %) longer for horizontal alternative D4 - HD, C than for D2 - VD, C. Time depending on operation costs for the alternative D2 - VD, C are about 30 MEUR per year including for example personnel, maintenance and reparation, energy and insurance. No major differences in the other cost components have been identified.

Estimated differences; alternative D3 - HD, M compared to alternative D1 - VD, M:

Backfilling of transfer corridors and disposal boreholes	- 800 Million EUR
Yearly costs, personnel etc.	+ 100 Million EUR
Total	- 700 Million EUR

7.2.3 Closure costs

Closure costs covers dismantling of structures and backfilling of the tunnels that are not closed yet during operation period, see Table 7-5. Rooms in question are technical rooms, capsulation plant and tunnels and shafts to above ground. There does not exist major differences in these facilities between alternatives D3 - HD, M and D1 - VD, M or either between alternatives D4 - HD, C and D2 - VD, C. Therefore, closure costs of alternative D3 - HD, M are roughly the same than closure costs of alternative D1 - VD, M. Correspondingly closure costs of alternative D4 - HD, C are roughly the same than of alternative D2 - VD, C.

7.2.4 Total costs

Totally costs of alternative D3 - HD, M are estimated to be 2 800 Million EUR lower than the costs of alternative D1 - VD, M.

Costs of alternative D4 - HD, C are estimated to be 1 000 Million EUR lower than the costs of alternative D2 - VD, C.

7.3 Cost summary

The total costs for alternative D1 - VD, M are 11 900 Million EUR and 8 500 Million for alternative D2 - VD, C. The costs are:

Activity	D1 - VD, M (MEUR)	D2 - VD, C (MEUR)
Research and development costs	300	300
Preparations	255	185
Investment costs	3 383	1 768
Operation costs	7 759	6 093
Closure costs	217	151
Total costs	11 913	8 496

The total costs for horizontal alternatives D3 - HD, M and D4 - HD, C have estimated to be remarkable lower than the costs for vertical alternatives. Totally costs of alternative D3 - HD, M are estimated to be 2 800 Million EUR lower than the costs of alternative D1 - VD, M. Correspondingly, costs of alternative D4 - HD, C are estimated to be 1 000 Million EUR lower than the costs of alternative D2 - VD, C. Main reason for the differences is big difference in the volumes between horizontal and vertical alternatives. This has a strong impact on excavation and backfilling costs. Remarkable cost savings could be possible by developing the concepts. E.g., if the size of the transfer corridor in alternatives D1 - VD, M and D2 - VD, C could be shrunk, the volumes would be considerably smaller and the cost differences between horizontal and vertical alternatives would be smaller.

In Posiva’s case in Finland, the savings in construction, backfilling and component manufacture costs when using horizontal disposal was earlier estimated to be in some extent greater than what would have been the additional cost of switching from vertical to horizontal disposal in the mid 2010's. However, now that the decision was made to start with vertical and all equipment and infrastructure for that have been developed, switching to horizontal cannot be shown to be clearly economical. In any case, switching to KBS-3H would need KBS-3H method development of approximately five years in parallel with vertical repository operation.

8 Other aspects

Environmental aspects

Excavation of the tunnels and backfilling of the disposal facility cause large environmental impacts on the site. Also transfer of the excavated rock and backfilling material cause effects in the area. Amount of material to be transferred correlates to the effects. More transfers cause more environmental impacts.

Differences on the volumes of the alternatives are huge. Very roughly volume of alternative D3 - HD, M and D4 - HD, C is 2 million m^3, volume of alternative D2 - VD, C is 3 million m^3, and volume of alternative D1 - VD, M is 5 million m^3.

Environmental impacts of alternative D1 - VD, M will be largest while impacts of alternatives D3 - HD, M and D4 - HD, C will be smallest. Main reason for this is that transfer corridors are not needed in alternatives D3 - HD, M and D4 - HD, C. On the other hand, size of the transfer corridor in alternative D1 - VD, M is large, see Figure 2-1.

Size of the supporting area needed above ground will be largest for alternatives D1 - VD, M and D3 - HD, M because the use of the excavated rock in case of TBM may be difficult and larger storage area for the rock is needed.

Supporting area needed above ground is wide and should be designed and communicated with local residents. Wide supporting area is needed to assemble the tunnel boring machine and to store the excavated rock. Use of the excavated rock may be difficult and therefore larger storage area is needed. Assembly area is needed also in case of drill and blast method and difference in the size of the assembly area size may be minor but probably difference in the storage area size is larger. Blasted rock can be used for many purposes and is easier to sell and therefore smaller storage area for the rock is needed.

Parallel licensing

Instead of choosing only one of the alternatives (vertical or horizontal), parallel licensing might be possible also for SÚRAO. In the following an example of parallel licensing status in Posiva's current programme is presented.

The vertical disposal solution KBS-3V was presented in Posiva’s construction licence application (Posiva 2012c) as the reference solution. In the construction licence application documentation, the horizontal disposal concept KBS-3H was also presented as an alternative disposal solution. In the application, Posiva requested the Government’s opinion that a possible later transition to the KBS-3H option could be treated as a plant change and a new construction licence application would not need to be submitted.

In the construction licence granted to Posiva, permission was granted for both the reference solution KBS-3V and the horizontal solution KBS-3H, i.e., Posiva has a construction licence for both concept alternatives. If Posiva later decides to switch to the horizontal option, Posiva must submit an updated safety assessment, Final Safety Analysis Report (FSAR) documentation and a full post-closure safety case, which demonstrates the operational and long-term safety of horizontal disposal. A change from KBS-3V to KBS-3H would require a separate safety review of the KBS-3H alternative by the Finnish Radiation Safety Authority STUK.

In 2016, Posiva made a strategic decision that the KBS-3H development work was not to be continued immediately after the joint project with SKB ended. Instead, Posiva was to concentrate on closing open issues related to the KBS-3V concept. However, KBS-3H remains a strategic future alternative, while the focus is on developing and implementing KBS-3V (Posiva 2018g). In 2020, Posiva and SKB decided to put the continued development of KBS-3H on hold to focus on the licensing of KBS-3V (SKB 2021).

In Posiva's operating licence application (Posiva 2021d), KBS-3V is presented as the basic solution for disposal, and it is noted that its alternative, KBS-3H, is not being actively developed at the moment. Considering the long duration of the disposal activities, Posiva may reassess the KBS-3H option during the operation (Posiva 2021d). Should KBS-3H prove to be a better way for the disposal of spent nuclear fuel, the disposal method can be changed. However, this would require extensive safety analyses, feasibility assessments and several years of extensive studies before reaching the current maturity level of KBS-3V. Nevertheless, Posiva will also retain the possibility of transitioning to horizontal disposal, if necessary (Posiva 2021d).

Posiva has prepared for a possible later transition to a horizontal disposal solution in the design of the disposal facility and the dimensioning of the underground openings. The most significant plant change is related to the assembly of the supercontainers needed in the 3H option. For the assembly of these containers, a space reservation has been tentatively planned in connection with the underground canister storage. Also e.g., all the door openings and also central (/main) tunnels used for the 3H transfer vehicle would possibly need 30 cm higher free ride height than 3V transfers, but optimised KBS-3V transfer vehicle dimensions are not yet available.

The horizontal concept option could be switched to if it can be shown that the safety requirements are also met in this option and the change is economically justifiable, i.e., the additional cost of the investment resulting from the change and further development must be lower than the benefit from the change to the production costs. Based on the estimates made earlier, the potential for lower production costs can be seen in the 3H option, because the cost of excavating the necessary openings and the cost of backfilling are clearly lower than in the 3V option. In terms of the necessary investments, the earliest possible moment to switch to horizontal disposal could be when the first generation of the necessary 3V installation equipment (canister, buffer and backfilling installation systems) have reached the end of their life cycle.

If KBS-3H were to be selected as a disposal solution at Olkiluoto, attention would need to be paid to the necessary changes to the overall nuclear waste management plan and schedule, as noted by the Ministry of Economic Affairs and Employment in Finland (Posiva 2018g). Posiva estimates that at least 5 years must be reserved in parallel with KBS-3V repository operation for processing the change, preparing the necessary safety assessments and implementing the necessary plant changes. In addition, extra time would be needed for STUK's separate safety review.

9 Summary

SÚRAO will choose the site for the Deep Geological Repository (DGR) among four candidate sites. SÙRAO has four design alternatives for the DGR. One of the alternatives should be chosen for the discussions with local residents.

This report introduces a comparison of four design alternatives for deep geological repository. In two alternatives (D1 - VD, M and D2 - VD, C) canisters are deposited in vertical boreholes and in two alternatives (D3 - HD, M and D4 - HD, C) canisters are deposited in horizontal boreholes. On the other hand, alternatives D2 - VD, C and D4 - HD, C are supposed to be excavated conventionally using mostly drill & blast. Tunnel boring machine (TBM) is used for the excavation of most of the tunnels in alternatives D1 - VD, M and D3 - HD, M.

The comparison focuses on items affecting concepts suitability to all sites of the current site selection process. The report also contains a study of pros and cons of different excavation methods (Drill and blast vs TBM) and the most relevant arguments for vertical and horizontal deposition holes. Comparing solutions are done for technical properties, technical readiness, long term safety, major operational differences and economics.

Technically drill and blast method is more flexible for the changes regardless of the reason for possible change. Direction of the tunnel can be changed during the excavation quite easily. Cross-section, width and height of the tunnel can be changed. New pits and channels can be excavated along the tunnel. Also grouting is easier since the whole tunnel face and profile is open for the free choice of grouting hole drilling geometry. This partly improves the grouting result. Grouting (low seepage water volume) is important for the long-term safety.

Tunnel Boring Machines (TBMs) are highly automated and very fast during boring without interruptions. On the other hand, all interruptions are very expensive. Explosives, blasting and ventilation of explosive gases after blasting are not needed. Supporting area above ground is wide. Extent and focus of engineering geological survey is also wider compared to the drill and blast method. Use of the excavated rock may be challenging because of the shape and size of the rock chips.

Technical readiness for the excavation using both drill and blast method or tunnel boring machines worldwide is high. Differences rise when using of the methods especially for the nuclear waste repositories.

By definition, technical readiness is very high when technology or system is tested and proven in operational environment. Drill and blast method has been used for decades in several nuclear waste repositories including first deposition tunnels for the spent fuel disposal in ONKALO, Finland. Therefore, it can be deduced that the technical readiness of the drill and blast method for the DGR in Czech Republic is very high.

Since TBM method has been used a lot for conventional excavations worldwide, it can be deduced that the technical readiness of the method for the excavating transport/deposition tunnels and other tunnels of DGR in Czech Republic is very high. Anyway, technology is not tested and proven in operational environment meaning in the disposal rooms. Therefore, it can be deduced that the technical readiness of the method for the deposition tunnels of DGR in Czech Republic is high (instead of very high).

The horizontal disposal alternative (KBS-3H) is an alternative for vertical (KBS-3V). The horizontal disposal alternative introduces several benefits in comparison to the vertical concept, for example, the total excavated volume is smaller in some extent, the operational costs are smaller (for example, because no deposition tunnel backfill is needed) and the production process of supercontainers would be more industrial than the separate emplacement of buffer and canister in KBS-3V. On the other hand, the KBS-3H concept is far less mature than KBS-3V (and requires a larger underground footprint according to SÚRAO design). Also, KBS-3H is potentially much more sensitive to chemical erosion than KBS-3V, which makes the infiltration of dilute groundwater a risk for long-term safety, unless more erosion-resistant clay barriers are developed or new information on bentonite erosion behaviour becomes available. Reducing the uncertainties related to long-term safety and demonstrating a sufficient safety level is a key issue if KBS-3H development is continued in SÚRAO. Chemical erosion and the related potential domino effect are probably the most important topics to address. Solving them would allow the focus to be shifted from long-term safety uncertainties to other decision points, such as costs.

The lower lifting heights for the deposition machine inside the drift are favourable for the horizontal disposal but the total lifting weight of the supercontainer is about double to the vertical disposal canister lifting weight. One of the main disadvantages of the horizontal disposal operation is that, if a failure occurs in a deposition drift, there is a higher probability that several canisters will be affected or removed. The least flexibility regarding the potential escape routes are in horizontal alternatives D3 - HD, M and D4 - HD, C, but overall, the accident risk is in some extent smaller in horizontal disposal because fewer people will be working underground and fewer machines and vehicles are needed in the repository.

The needed cooling period and the total disposal duration for the individual radiation sources from new nuclear sources is roughly five years longer in the case of SÚRAO horizontal disposal.

At the moment, there is no active Posiva or SKB development work related to horizontal disposal. Vertical KBS-3V is presented as the basic solution for disposal for these two organisations. If SÚRAO would choose to proceed with horizontal disposal development, it would have to be economically worthwhile even considering the additional cost of further development of the concept and related risks.

The cost difference between the two concepts in Posiva case seems to be relatively small, because e.g. for Posiva now that the decision was made to start with vertical concept and all equipment and infrastructure for that have been developed, switching to horizontal cannot be shown to be clearly economical. It takes several years of extensive studies even before reaching the current maturity level of KBS-3V and the fulfilment of safety requirements would obviously have to be shown as well, using a similar approach as has been used for KBS-3V. Considering the situation of SÚRAO at an earlier phase of DGR development, the difference in R&D work needed may not be significant when comparing vertical and horizontal disposal, since neither of them has been developed very far. In SÚRAO's case, there might be some cost saving potential in choosing KBS-3H as the reference method if all development work is done independently by SÚRAO, or at least to carry out a thorough comparison between vertical and horizontal options before making significant investment decisions. However, if SÚRAO were to utilise Posiva's knowledge and existing operating 3V-equipment in full scale, it should be the most cost efficient and economical way in total costs for nuclear waste disposal.

In SÚRAO case the total costs for horizontal alternatives have been estimated to be remarkable lower than the costs for corresponding vertical alternatives. Main reason for the differences is big difference in the volumes between horizontal and vertical alternatives. This has a strong impact on excavation and backfilling costs. Remarkable cost savings for D1 - VD, M and D2 - VD, C are possible by developing these alternatives, e.g., the cross-section size of the transfer corridor which would shrink the cost difference.

Excavation of the tunnels and backfilling of the disposal facility cause some environmental impacts at the site. Also transfer of the excavated rock and backfilling materials cause effects in the area. Amount of material to be transferred correlates to the effects. More transfers cause more environmental impacts. Environmental impacts of alternative D1 - VD, M will be largest while impacts of alternatives D3 - HD, M and D4 - HD, C will be smallest. However, the storage area for the excavated rock above ground will be larger for alternative D3 - HD, M (TBM) than for D4 - HD, C (drill and blast) like described in Section 3.2.2.

Instead of choosing only one of the alternatives (vertical or horizontal), parallel development and licensing might be possible also for SÚRAO. This, however, depends on the regulator's stand on the inclusion of two different methods in a licence application. In Finland, it was possible to include KBS-3H as an alternative in Posiva's construction licence application, and the licence was granted acknowledging KBS-3H as a possible alternative. In some other countries, it is possible that the regulator will consider only one disposal method in a single application. If this is the case, then it is recommended to select a disposal method (whether vertical or horizontal) well before the licence application stage and, thereby, save in R&D costs.

Even if Posiva were never to resort to applying the KBS-3H alternative in the Olkiluoto disposal facility, the extensive studies carried out for years by Posiva and SKB would benefit SÚRAO for possible considerations of the horizontal disposal method.

It should be noted that when Posiva compared the vertical and horizontal methods, the underlying assumption was that the Olkiluoto site would be suitable for both. The bedrock fracturing is generally rather minor at the planned disposal depth (about 400–450 m) at Olkiluoto, and the locations of more pronounced fracture zones are quite well known, as shown by the experiences during the underground excavation. At sites where the occurrence of faults or other fracture zones is higher and their locations are more unsure, it may be more practical to employ the vertical method, as in a deposition tunnel it is easier to carry out more detailed investigations and use the acquired information to select locations for deposition holes, avoiding the lower-quality parts of the rock mass. In KBS-3H, supercontainer emplacement may be difficult if a major fracture zone has been unexpectedly intersected by a deposition drift, resulting, on the one hand, in potential irregularities in the rock surfaces and, on the other hand, large drift sections that may not fulfil the requirements for supercontainer locations.

In all there are no known exclusionary items that would prevent the implementation of the facility with either of the alternative concepts - they are all suitable for all different sites at this stage of SÚRAO development work.

A summarizing table of the main differences is included as an Annex 1.

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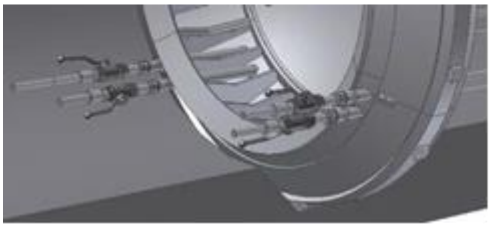
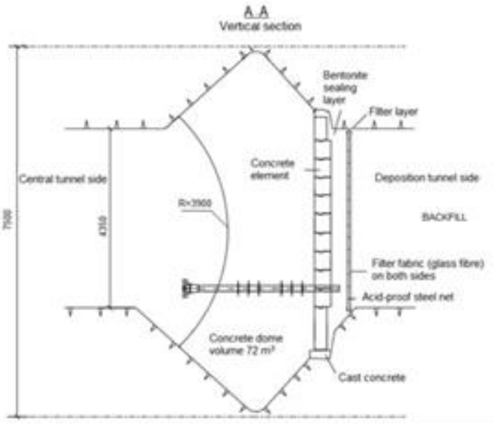
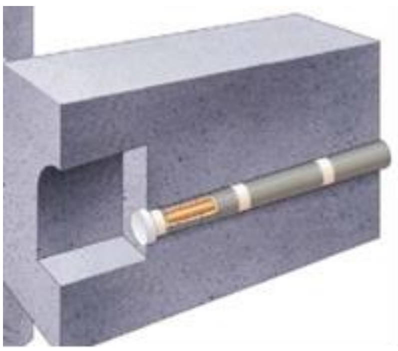
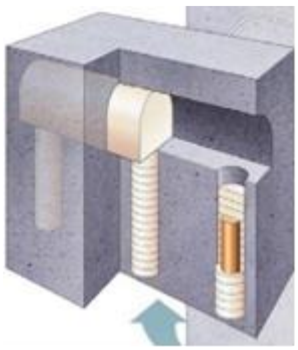
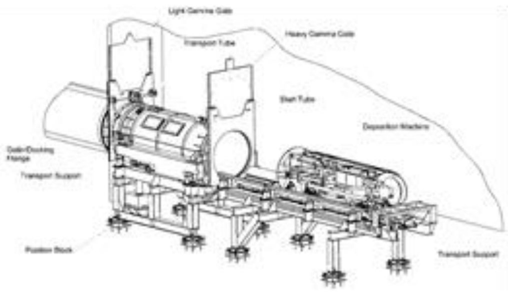
Annex 1. Summary of the main differences between KBS-3H and KBS-3V

In the table below, the main differences between the horizontal concept KBS-3H and the vertical concept KBS-3V are given. The similarities (e.g. components that are common to both concepts) are not listed in the table.

Topic	KBS-3H (D3 – HD, M and D4 – HD, C)	KBS-3V (D1 – VD, M and D2 – VD, C)
Barriers	No deposition tunnels to be *backfilled; Filling components*; *compartment plugs* and *drift plugs*; *buffer* is both inside the supercontainers and in distance blocks, *closure* includes the filling of the deposition niche and the filling of the drift entrance section; *host rock* is less disturbed due to mechanical excavation.	*Backfill* (in deposition tunnels); *buffer* is installed in deposition holes; some differences in *closure* (closure backfill is used in deposition tunnel entrance sections and deposition niches; *host rock* (a larger EDZ due to drill and blast method).
Non-barrier components in the repository	Supercontainer shell; spray and drip shields, DAWE components (watering and air evacuation pipes); filling at the drift end and filling of the pilot hole stump; feet of drift components.  *Watering and air evacuation pipes, which are located in the lower part of the plug (Posiva 2018e)*	Deposition tunnel plugs  *Deposition tunnel plug and the sealing and filter layers (Karvonen 2018)*
Materials	Titanium in supercontainer shells, compartment plugs and drift plugs (SÚRAO drift plug assumed to be concrete); possibly different clay material in erosion-resistant filling blocks than in buffer; less residuals from explosives.	Concrete in deposition tunnel plugs; bentonite in deposition tunnel backfill possibly different from buffer material; more residuals from explosives.
Repository openings	Deposition drifts (KBS-3H maximum length 300 m) 	Deposition tunnels (KBS-3V maximum length 350 m) and vertical deposition holes 

	Deposition drift. Courtesy of SKB, Illustrator: Jan Rojmar	*Deposition tunnel. Courtesy of SKB, Illustrator: Jan Rojmar*
Other openings in the disposal facility	Central/ main tunnels with a greater height than in 3V; total length of central tunnels may be greater.	Central/ main tunnels with a smaller height than in 3H; total length of central tunnels may be smaller.
Overall disposal facility	Smaller total volume; less excavated and filling material; thereby, smaller environmental impact.	Larger total volume; more excavated and filling material; thereby, larger environmental impact.
Underground footprint	A larger underground footprint is needed for the horizontal disposal D3 - HD, M and D4 - HD, C SÚRAO layouts. In Posiva's design there is no remarkable difference between 3H and 3V footprint in theory.	A smaller underground footprint is enough for the vertical disposal D1 - VD, M and D2 - VD, C SÚRAO layouts. In Posiva's design there is no remarkable difference between 3H and 3V footprint in theory.
Construction methods	Boring of the deposition drifts (maximum length 300 m) by full-face horizontal push-reaming; Mega-Packer to be developed for post-grouting of deposition drifts.	Boring of the deposition holes by full-face vertical push-reaming, but deposition holes are only about 7-8 m deep; drill and blast excavation and conventional grouting of the deposition tunnels (D2 - VD, C) or TBM method (D1 - VD, M).
Operation	Supercontainer assembly performed before KBS-3H disposal; easier quality assurance of the canister and adjacent buffer; installation of drift components using the fixed deposition machine; overall, more prefabricated industrial components and a reduced amount of human involvement in the disposal process; use of artificial water filling.  *KBS-3H deposition equipment (Posiva 2018b)*	Installation of canister, buffer and backfill separately; more difficult quality assurance of canister and buffer; mobile installation equipment.  *Prototype buffer block installation machine above a deposition hole (figure by Posiva Oy)*
Repository level transfers	From Posiva re-loading station with wheeled transfers; From SÚRAO transfer area with railway-based robotic technologies.	From Posiva re-loading station with wheeled transfers; From SÚRAO transfer area with railway-based robotic technologies.
Operational and occupational safety	The controlled assembly of the supercontainer in the controlled environment (reloading station) is an advantage; the lower lifting heights for the deposition machine inside the drift are also favourable but the total lifting weight of the supercontainer (46 tonnes) is about double to the 3V canister weight; the main disadvantage is	The mounting of bentonite into the deposition hole in the KBS-3V method entails operational safety risks not included in 3H; the higher lifting heights in deposition tunnels are less favourable but the total lifting weight of the canister (24.5 tonnes) is about half of the 3H supercontainer weight; it is an advantage that, if a failure occurs

	that, if a failure occurs in a deposition drift, there is a higher probability that several canisters will be affected or removed; the least flexibility regarding the potential escape routes (D3 - HD, M and D4 - HD, C); overall, the accident risk is in some extent smaller in KBS-3H because fewer people will be working underground and fewer machines and vehicles are needed in the repository.	in disposal operations, only one canister is likely to be affected or removed; the most flexibility regarding the potential escape routes (D1 - VD, M and D2 - VD, C); the overall accident risk is in some extent higher because more people will be working underground and more machines and vehicles are needed in the repository.
Long-term safety		
Volume of excavation, area of exposed rock surface	Smaller total excavated volume indicates smaller area of exposed rock surface and thus a smaller disturbance to the hydrogeological and hydrogeochemical conditions around the disposal facility.	Larger total excavated volume indicates larger area of exposed rock surface and thus a larger disturbance to the hydrogeological and hydrogeochemical conditions around the disposal facility.
Inflow control	Post-grouting methodology (Mega Packer) has been proposed but not in routine use.	Effective, proven pre-grouting method developed by Posiva to minimize undesired impact of groundwater inflows in D2 - VD, C.
Foreign materials	Use of foreign materials is seen to be minimized in deposition drifts due to smaller excavated volumes and exposed rock surfaces.	Deposition tunnel backfill is a source of sulfate for microbially driven sulfide production, which may increase canister corrosion. Deposition tunnel plugs also are a source of cement leachates that affect the properties of bentonite. Deposition tunnels must be equipped for occupational safety (rock support), blasting residues and organic emissions from working machinery is an extra issue in D&B tunnelling.
EDZ	Only a thin EDZ is foreseen around deposition drifts as mechanical excavation exerts a very limited dynamical pressure outside of the rock bit. Moreover, the circular cross section of the TBM tunnel is more stable against stress induced damage.	Blasting induced damage, while can be controlled with careful drilling and blasting planning, unavoidably extend outside the perimeter of the excavated tunnel. Furthermore, the “horseshoe” geometry of the D&B tunnel profile may be more vulnerable to stress induced damage (which does not depend on the method of rock extraction) than a mechanically produced tunnel profile.
Chemical erosion	Chemical erosion potentially a more critical issue (domino effect) than in deposition holes and sedimentation erosion due to gravity.	Chemical erosion a lesser issue due to less likely interaction between deposition holes in the deposition tunnel, and geometrically less likely exposure to sedimentation erosion.
Rock suitability classification	Yet to be developed for deposition drifts and waste package locations	Mature set of criteria has been developed for the deposition holes. A critical fracture size for singling out unsuitable deposition hole sites is a central concept.

Testing and demonstration	Multi Purpose Test has been carried out; further testing and demonstration is needed (supercontainer materials, detailed design of the underground reloading station, detailed design of the plugs, the intended grouting solution (Mega-Packer), the design of the deposition machine, the transportation and installation of bentonite components, the automation in titanium welding); the feet of the drift components add complexity to the testing; a full-scale heater test at actual repository depth is needed.	More extensive testing has been done; full-scale demonstrations are done with prototype machinery; far less technical and technological problems due to wider development work done by Posiva. Posiva has already built and the Finnish regulator controlled most of the final equipment that will be used in the real operating of the Posiva disposal facility and the rest are under construction and factory acceptance tests controlled by the regulator.
Technical readiness of the excavation method	D3 - HD, M: Technical readiness to use TBM for the deposition drifts is high and for other openings very high. D4 - HD, C: Technical readiness to use TBM for the deposition drifts is high and drill and blast for other openings very high.	D1 - VD, M: Technical readiness to use TBM for the deposition tunnels is high and for other openings very high. D2 - VD, C: Technical readiness to use drill and blast for the deposition tunnels is very high and for other openings very high as well.
Total costs	D3 - HD, M: 9 000 MEUR D4 - HD, C: 7 500 MEUR	D1 - VD, M: 12 000 MEUR D2 - VD, C: 8 500 MEUR
Environmental aspects	Environmental impacts are smaller because of smaller volumes of the DGR and excavated rock piles.	Environmental impacts are larger because of larger volumes of the DGR and excavated rock piles.
Size of the surface area	D3 - HD, M: Larger because of TBM requirements above ground D4 - HD, C: Larger because of TBM requirements above ground	D1 - VD, M: Larger because of TBM requirements above ground D2 - VD, C: Smaller because mainly drill and blast excavations

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