Rudarsko-geološko-naftni zbornik	Vol. 24	str. 49-59	Zagreb, 2012.

UDC 622.245.4
UDK 622.245.4

Review
Pregledni rad

Language/*Jezik*: English/*Engleski*

STATE OF THE ART OF DRILLING LARGE DIAMETER BOREHOLES FOR DEPOSITION OF HIGH LEVEL WASTE AND SPENT NUCLEAR FUEL

SADAŠNJE SPOZNAJE O BUŠENJU BUŠOTINA VELIKOG PROMJERA ZA ODLAGANJE OTPADA VISOKOG STUPNJA RADIOAKTIVNOSTI I ISTROŠENOG NUKLEARNOG GORIVA

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Key words title: high level waste, spent nuclear fuel, deposition, large diameter boreholes, drilling

Abstract

Deep geological disposal is internationally recognized as the safest and most sustainable option for the long-term management of high-level radioactive waste. Mainly, clay rock, salt rock and crystalline rock are being considered as possible host rocks. Different geological environment in different countries led to the various repository concepts. Main feature of the most matured repository concept is that canisters with spent nuclear fuel are emplaced in vertical or horizontal large diameter deposition holes. Drilling technology of the deposition holes depends on repository concept and geological and geomechanical characteristics of the rock. The deposition holes are mechanically excavated since drill & blast is not a possible method due to requirements on final geometry like surface roughness etc. Different methods of drilling large diameter boreholes for deposition of high-level waste and spent nuclear fuel are described. Comparison of methods is made considering performance and particularities in technology.

Ključne riječi: otpad visokog stupnja radioaktivnosti, istrošeno nuklearno gorivo, odlaganje, bušotine velikog promjera, bušenje

Sažetak

Duboko geološko odlaganje je međunarodno prepoznato kao najsigurnija i najodrživija opcija dugoročnog zbrinjavanja visoko radioaktivnog otpada. Kao moguće stijene za zbrinjavanje uglavnom su razmatrane glinovite, slane i kristalinične stijene. Različite geološke sredine u različitim zemljama su dovele do različitih koncepata odlaganja. Glavna karakteristika najrazvijenijih koncepata odlaganja je da se spremnici sa istrošenim nuklearnim gorivom odlažu u vertikalne ili horizontalne bušotine velikog promjera. Tehnologija bušenja bušotina za odlaganje ovisi o konceptu odlaganja i geološkim i geomehaničkim karakteristikama stijene. Bušotine se iskopavaju mehanički jer se metoda iskopa bušenjem i miniranjem ne može primijeniti zbog zahtjeva obzirom na hrapavost stijenki itd. Opisane su različite metode bušenja bušotina velikog promjera za odlaganje visoko radioaktivnog otpada i istrošenog nuklearnog goriva. Metode su uspoređene obzirom na učinkovitost i posebnosti tehnologije.

1. Introduction

Different principles and strategies for disposal of spent nuclear fuel (SF) and high-level waste (HLW) have been studied in many countries ever since nuclear power began to be used for large-scale electricity production in the 1960s and 1970s.

In principle, there are two main approaches for managing the spent nuclear fuel. One entails regarding the fuel as a resource, the other as waste.

Since 2000, a number of major overviews of methods for final disposal of spent nuclear fuel and/or high-level nuclear waste have been published:

- *Implementing Geological Disposal of Radioactive Waste. Technology Platform. Vision document/IGD-TP 2009/.*

Representatives of SKB (Svensk Kärnbränslehantering AB, the Swedish Nuclear Fuel and Waste Management Co), Posiva (Finland expert organization responsible for the final disposal of spent nuclear fuel), Andra (France, The National Radioactive Waste Management Agency) and the Federal Ministry of Economics and Technology (Germany) prepared the document. The report provides an up-to-date (2008) overview of the programmes for waste management in the EU's 16 nuclear power countries. The work with the report was initiated because of the discussion that followed from the EU-funded study:

- *A Co-ordination Action on Research, Development and Demonstration Priorities and Strategies for Geological Disposal /CARD 2008/.*

- Sixth situation report on: "Radioactive waste and spent fuel management in the European Union" /European Commission 2008/.

In this sixth situation report, the European Commission concludes that after 30 years of research, it is sufficiently demonstrated that geological disposal now represents the safest and most sustainable option for the long-term management of high-level waste and spent fuel subject to direct disposal.

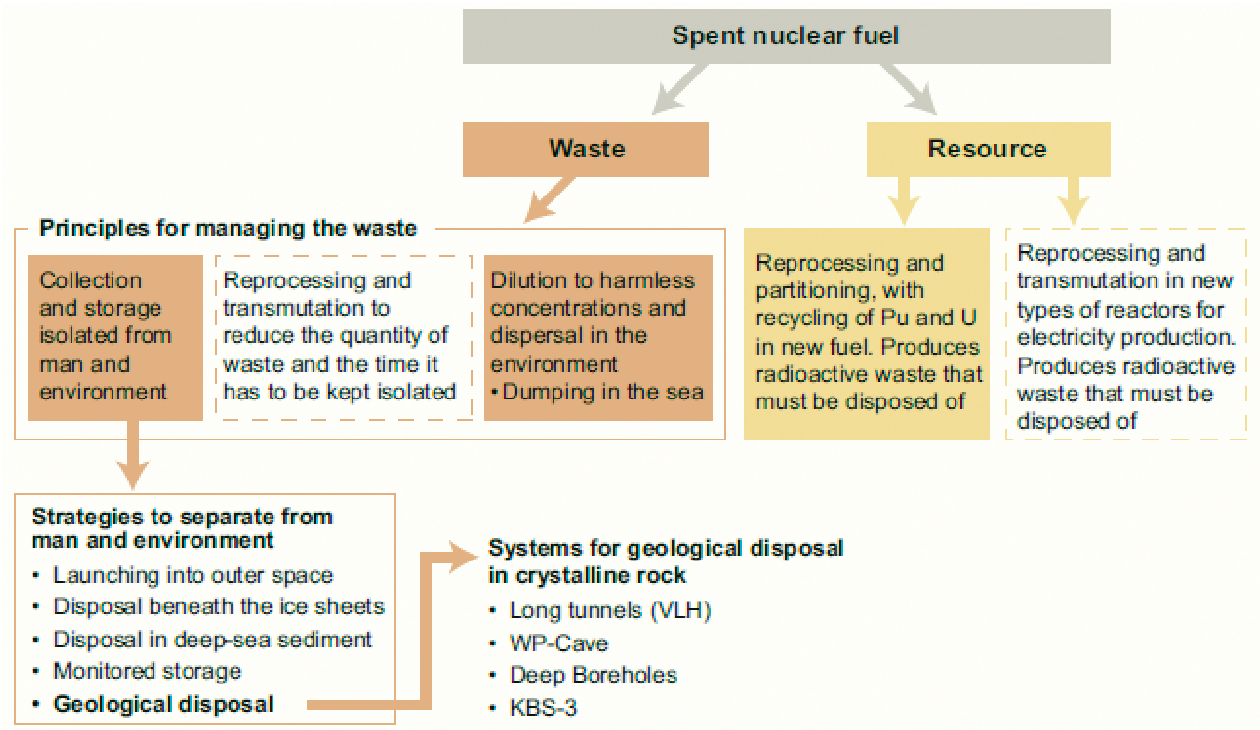


Figure 1. Principles, strategies and systems for disposal of spent nuclear fuel (The principles in the dashed boxes are based on technology that is not available today). (SKB, 2010. Report P-10-47)

***Slika 1**. Principi, strategije i sustavi odlaganja istrošenog nuklearnog goriva (principi u crtkanim poljima su temeljeni na tehnologiji koja danas još nije moguća). (SKB, 2010. Report P-10-47)*

Geological disposal entails utilizing an environment that has been and will be stable over a very long time. The safety of the repository is based on a combination of the natural barrier comprised by the rock, the great depth and the environment at repository depth, plus fabricated engineered barriers. The engineered barriers are designed so that they do not require any maintenance after deposition is concluded and the repository has been closed.

Different geological settings have been studied according to the natural conditions existing in different countries. The bedrock being considered in Sweden and Finland is crystalline rock that is between one and two billion years old. Clay and salt formations are among the geological media being investigated in other countries. Those different geological environment in different countries resulted in various repository concepts.

2. Comparison of repository concepts

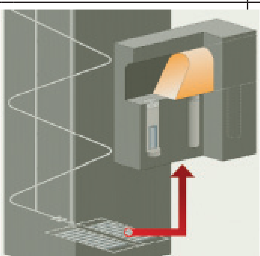
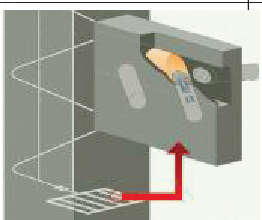
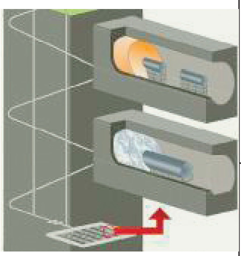
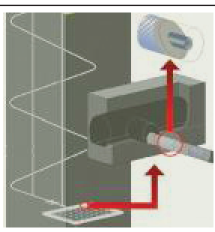
In table 1, there are compared twelve concepts for geological deposition of HLW and SF at different countries. Distribution and nomenclature of deposition concepts are adopted from Geological Disposal Options for High-Level Waste and Spent Fuel. Report for the UK Nuclear Decommissioning Authority (Baldwin et al. 2008). Twelve different concepts for geological disposal are described in the report. The description includes design, origin, maturity, constructional, operational and environmental aspects, and which countries have the concept in their programmes. In table 1 methods, i.e. concepts are compared considering dimensional characteristics of deposition space.

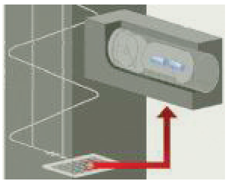
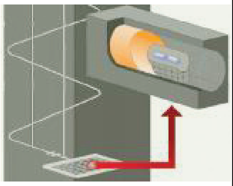
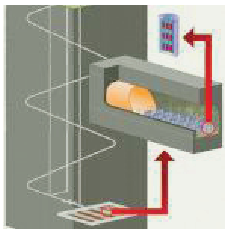
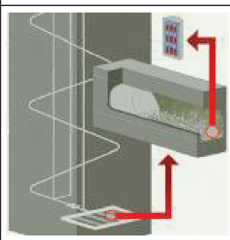
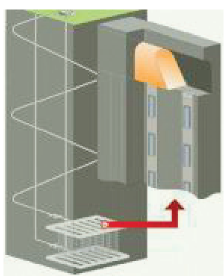
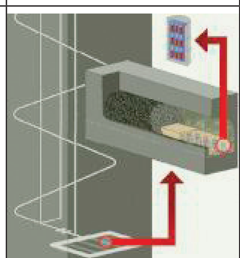
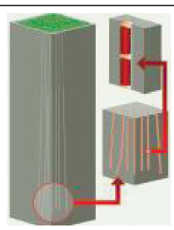
Analyzing table 1, someone can conclude that concepts under numbers 7, 8, 9, 11 and 12 are at early stage of development (desk stage) or there is no detailed design of them up to date. Concepts 3, 4 and 6 imply tunnels with relatively large circular crossection for deposition of containers with HLW and SF but among them, only concept three is well matured for implementation based on 30 years of research. Large diameter borehole for deposition of containers is significant for concepts 1, 2, 5 and 10. Like concept three, concept one is also based on long lasting development (Sweden, Finland). Concepts 2 and 5 are not very mature but in great part use extensive knowledge base from concept 1. Long-term safety performance and development of weight-bearing interim seals that prevent the weight of upper waste packages crushing the lower ones are major research directives for concept 10.

After comparison of most relevant repository systems developed by different countries, it is evident use of large diameter boreholes (~0.6 – 2 m) for deposition of canisters with HLW and spent fuel in great majority of concepts matured for implementation. Orientation of boreholes is in some concepts vertical and in others is horizontal or slightly inclined. Length of boreholes is variable, from eight to 9 meters to more than 200 meters. Subject to specific geological conditions at different countries, boreholes are anticipated to be drilled in rock mass with various mechanical characteristics, from very hard crystalline rocks to evaporates (salt) and clays. Besides different mechanical characteristics, little or none at all flow of groundwater is common to all geological environment at different countries.

Table 1 Comparison of concepts for deep geological disposal of HLW and SF.

Tablica 1. *Usporedba koncepata za duboko geološko odlaganje visokoradioaktivnog otpada i istrošenog nuklearnog goriva.*

Name of the Concept and Illustration (Baldwin et al. 2008).		**Dimensional Characteristics of Deposition Space**	**Development of Concept**
1. In-tunnel (vertical borehole) with long-lived or short-lived canister		System of horizontal tunnels at a depth of 400–700 meters. The tunnels will be approximately 250 meters long and spaced at a distance of 40 meters. On the floor of the tunnels, vertical deposition holes will be spaced at intervals of about 6 meters, each approximately 8 meters deep. Each deposition hole is 1.75 m in diameter (SKB, 2006).	Sweden, Finland (crystalline rock)
2. In-tunnel (horizontal borehole) with long-lived or short-lived canister		Waste packages are emplaced in steel-lined horizontal or near-horizontal boreholes 0.7 m in diameter for HLW and 3.3 m for SF, drilled in the walls on both sides of the disposal tunnels. The boreholes will be approximately 40 meters long for deposition of HLW and 45 meters for disposal of SF. (Andra, 2005.).	Belgium, France, Netherlands (clay)
3. In-tunnel (axial) with short-lived canister and buffer		The disposal tunnel diameter is 2.5 m (in clay) and, based on the preliminary layout (Nagra, 2002), is expected to have a length of ~800 m. The spacing between disposal tunnels is 40 m. Relatively large tunnel diameter-3.7 m in Swiss crystalline rocks; 2.5 m in clay; 2.0 m in clay-Belgium.	Switzerland (crystalline rock, clay) Japan, Spain Belgium(clay) Germany(salt)
4. In-tunnel (axial) with long-lived canister and buffer		The Concept similar in essentials to Concept 3, but uses a long-lived copper or titanium canister, with an iron insert for mechanical strength, in place of the short-lived steel overpack.	Canada (crystalline rock)
5. In-tunnel (axial) with super container (small annulus)		The canisters are deposited in horizontal deposition boreholes (Ø 1.75 m, 7.83 m long) bored in both walls of the deposition tunnels. The spacing between the deposition tunnels is 60 m.	Sweden, Finland (crystalline rock)

Name of the Concept and Illustration (Baldwin et al. 2008).		**Dimensional Characteristics of Deposition Space**	**Development of Concept**
6. In-tunnel (axial) with super container (concrete buffer)		Waste is emplaced axially in circular tunnels (Ø 3.6 m), lined for support Each tunnel will be ~1000 m long and there will be approximately 50 m between disposal tunnels, except for spent fuel, where there will be 120 m inter-distance (Bel *et al.* 2005).	Belgium (clay)
7. In-tunnel (axial) with super container (large annulus)		The Concept is nominally similar to Concept 5 with the addition of backfill. The tunnels are larger than the super container diameter by ~1 m or more and may be some hundreds of meters long. The Concept is only at the desk study stage.	Switzerland
8. Caverns with steel MPC (bentonite backfill)		The caverns are of the order of 10-20 m wide and high. The Concept has only been the subject of limited desk studies to date.	Japan
9. Caverns with steel MPC or concrete/ DUCRETE CDC (cement backfill)		The caverns are of the order of 10-20 m wide and high. The Concept has only been the subject of limited desk studies to date.	Japan
10. Mined deep borehole matrix		Waste packages are emplaced in stacks in long (~200 m or 300 m in salt-Germany) vertical boreholes, which are bored from deep underground either directly from a disposal tunnel or between an upper operational cavern and a lower cavern. In the latter case, raised boring allows excavation of large diameter holes (1.5-2 m). In salt formation in Germany, boreholes are foreseen to be 0.6 m in diameter (Bollingefehr, W. et. all, 2010.).	Canada, Japan (crystalline rock) Germany (salt)
11. Hydraulic cage (around a cavern repository)		The concept of a hydraulic cage around a disposal cavern (or whole repository) commonly refers to the use of a zone of material that has a high permeability compared to the average host rock and to the repository volume. Cavern is 15 m wide. Currently, no programmes are actively pursuing this option for HLW or SF.	Sweden Japan
12. Very Deep Boreholes		Simple metallic waste packages with no overpack are emplaced in the lower region (the bottom 1000 – 2000 m) of a borehole drilled from the surface to a depth of about 3 to 5 km. The key issue with this Concept is the lack to date of any detailed design or performance assessment study.	Sweden United Kingdom

3. Excavation of vertical deposition holes

Technology for excavation of the deposition holes depends on repository concept. Canisters with spent nuclear waste can be stored in vertical or horizontal deposition holes. Design of the canisters and backfill will influence on the size of the deposition boreholes. The deposition holes must be excavated with a very high level of accuracy with respect to straightness, tolerances of the diameter and wall surface smoothness (Bäckblom et al., 2004). The Swedish Nuclear Fuel and Waste Management Company (SKB) have performed investigation on rock excavation methods for a deep-rock repository for Sweden's spent nuclear fuel. The raise boring method was proposed to excavate large diameter holes.

Raise boring is a continuous, mechanical method of boring vertical, or nearly vertical, openings used for ventilation, man ways, and ore and waste transportation for operating mines. A raise borer is a machine used to create bores, or holes, between two existing levels of a mine.

Raise boring, which originates from North American mining, is the most common shaft excavation process. The boring equipment developed from borehole technology and called a Christmas tree, is scarcely suitable in middle to hard rock. Wirth was already building large hole enlargement boring equipment in the 1960s, later categorized under the term raise boring (Maidl et al., 2008).

Raise boring machines have been used in both mining and civil projects for holes in the range 0.6-6.0 m-diameter and up to 1,000 m-long. Standard raise boring machines are capable of boring raises at angles from vertical to 45 degrees from horizontal. Horizontal and low-angled raise boring was achieved with a few accessories and minor adjustment of the standard machine (ATLAS COPCO, 2007).

Three methods of raise boring are typically used for drilling: conventional raise boring, blind boring; blind and down reaming.

Conventional raise boring is most common raise method. First the pilot hole (Figure 2-a) is bored between upper and lower level. Once the pilot hole is bored, the drill bit is removed, a reamer or raise head is attached, and the reamer is rotated and pulled upwards. The cuttings fall to the lower level by gravity (Figure 2-b).

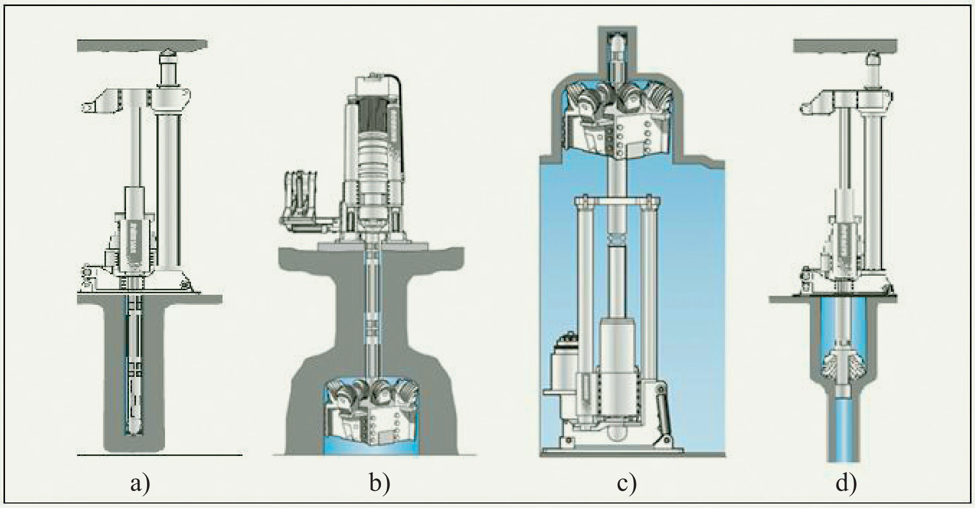


Figure 2 Methods of raise boring - a) pilot hole b) conventional raise boring c) blind boring d) down-reaming (ATLAS COPCO, 2007)

Slika 2. *Metode uzlaznog bušenja (raise boring) – a) vodeća bušotina b) konvencionalno uzlazno bušenje (raise boring) c) "slijepo" bušenje d) bušenje proširivanjem prema dolje (ATLAS COPCO, 2007)*

Blind or boxhole boring is most difficult raise method. This method is used to excavate raises where there is limited or no access to the upper level. When the machine is set up a full diameter raise is bored upward. The cuttings are carried by gravity down the hole, and are deflected from the machine and removed at the lower level. The newer machines are now able to first pilot a hole then ream the hole (Figure 2-c).

The longest known blind borehole drilled to date, has been with a Robbins 53R over a distance of some 192m at a near vertical angle in 1989 at Anglogold Ashanti in Tautona Mine (*Ferreira, 2005).*

In down-reaming method, pilot hole is drilled downwards until it connects to a lower access level. The final raise diameter is enlarged by reaming from the upper level to the lower level. The cuttings are carried by gravity down the pilot hole. The geometrical requirements of borehole are achieved by upper and lower stabilizers (Figure 2-d).

For the excavation of vertical deposition holes, blind shaft boring or modified blind boring method can be applied. Three full-scale deposition holes were bored in Olkiluoto Research Tunnel in Finland (Autio & Kirkkomäki, 1996). The holes had a diameter of 1.527 m and approximate depth of 7.5m. Blind boring method with few modifications was used for excavating these holes. Normally blind boring is used for upward boring and the cuttings are carried by gravity down the hole. Since vertical deposit holes must be drilled downwards, the main problem is removal of cuttings. According to authors, boring was based on the rotary crushing and removal of crushed rock by vacuum flushing and suction through the drill string. A separate pilot hole was bored before boring the large hole began. The bit used for boring of the pilot hole was then used in front of the large diameter cutter head as a guide and stabilizer,

Figure 3. Photo of the reamer and pilot bit above the excavated hole (Autio and Kirkkomäki, 1996).

Slika 3. *Fotografija proširivača i vodeće bušače krune iznad izbušene bušotine (Autio and Kirkkomäki, 1996).*

Figure 3. For the excavation of the deposition holes Subterranean-005L-137 raise boring machine was used. The weight of machine was 8890 kg and the maximum height was about 3.6 m. The total installed electrical power of the boring machine was 151 kW (380V and 50 Hz). For the excavation of pilot holes a Sandvik Coromant Roller Bit**,** a standard three-cone bit with a diameter of 311 mm intended for use in very hard rock was used. Vacuum suction was achieved through nozzles installed on three openings in the bit.

For excavating large diameter cutter head Sandvik Coromant CBH-4 was used. This large cutter is designed for blind boring with the hole diameter of 1524 mm. The full weight of cutter was 3800 kg. Maximum penetration achieved was 1.2 m/h with an average of 0.9 m/h while the machine actually performed. The penetration is limited by the efficiency of vacuum cleaning in keeping the bottom of the hole free from excavated rock. Total time used for work in tunnel was 64 workday. According to authors, only 13% of total time was used for the actual boring of pilot and large holes. The rest of time was used for repair and maintenance of equipment, emptying of tank for crushed stone, transferring equipment and setting up equipment and preparation of boring. Total time of boring activities is shown in figure 4.

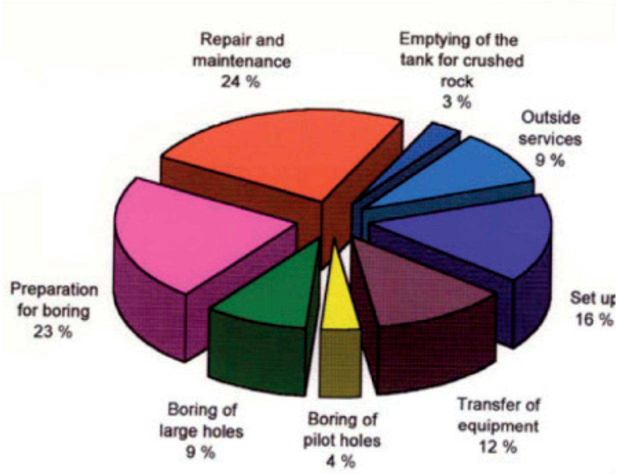


Figure 4. Total time of boring activities (Autio and Kirkkomäki, 1996).

Slika 4. *Ukupno vrijeme bušačkih radnji (Autio and Kirkkomäki, 1996).*

Another concept for boring full-scale vertical deposition holes was presented in Äspö Hard Rock Laboratory (Andersson & Johansson, 2002). The dominant rocks on Äspö belong to the 1700–1800 million-year-old SmÍland granite. Four main rock types: Äspö diorite, SmÍland granite, greenstone and fine-grained granite make up most of the rock mass in Äspö HRL.

Thirteen experimental deposition holes have been bored at the Äspö Hard Rock Laboratory, Oskarshamn, Sweden. The holes were bored in full scale with diameter of 1.75 m and a depth of 8.5 m. For the excavation of deposition holes, a novel type Shaft Boring Machine (SBM) was used. The shaft-boring machine is similar to the design of TBM with some modifications suitable for boring 1.75 m diameter holes from a relatively small tunnel.

Machine was billed by the Robbins Company in the USA and designed to fit into the transport tunnels made by a TBM with a diameter of 5 meters. Design of the shaft-boring machine is shown on figure 5.

Boring cycle starts when the starter casing is placed and second casing is placed on trailer (Figure 6). At this time, thrust cylinders are fully retracted. When the first starter casing has been dragged into position, the casing is then bolted to the SBM and the head frame of the trailer. The lower stabilizers are ungripped and the machine is retracted to steering position. The boring begins when one casing is bored and the cylinders are fully extended. At this time the lower stabilizers are gripped to the shaft wall and the bored chasing is then unbolted from the head frame. The thrust cylinders are fully retracted and a new casing can be dragged into position.

Trailer was used for transporting shaft-boring machine. Machine was equipped with 20 cutters, carbide button cutters and steel disc cutters. The total maximum thrust of the thrust cylinders was 3,500 kN and the cutter head rotation varied from zero to 23 rpm. According to authors, a practical maximum rate of rotation notified when boring was 10 rpm and maximum thrust of the thrust cylinders was 2,000 kN.

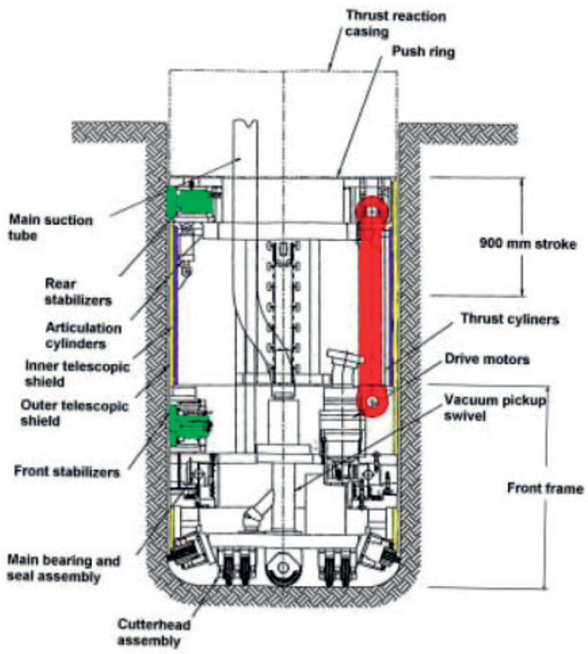


Figure 5. Design of the shaft-boring machine (Andersson & Johansson, 2002).

Slika 5. *Izvedba stroja za bušenje okna (Andersson & Johansson, 2002).*

The effective average rate of penetration was 0.45 m/machine hour with a maximum penetration of 1.1 m/h. The average total time for boring one deposition hole was 105 hours.

According to Steinberg, S. (1993.) comprehensive field testings were performed on large diameter vertical borehole drilling at former salt mine Asse in Germany. There was developed and patented (patent No. DE4127472C1) the EHV 1202 dry drilling equipment connected with the modified lock drill head SBK 602 for underground use by means of which large diameter directional holes of 600 mm up to a depth of 600 m can be drilled in salt rocks for different purposes.

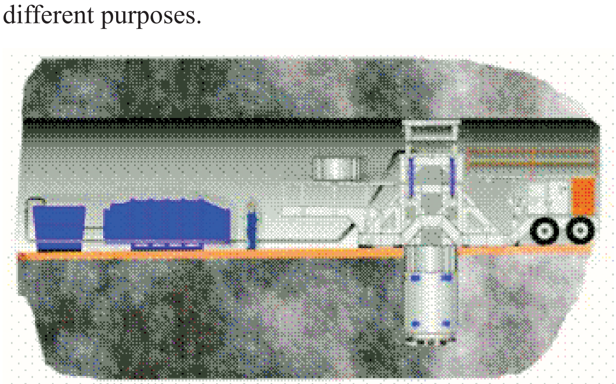


Figure 6. Trailer with the boring machine (Andersson & Johansson, 2002)

Slika 6*. Prikolica sa bušačkim strojem (Andersson & Johansson, 2002)*

The equipment is extensively automated that during the drilling only two persons (1 tool pusher and 1 assistant) are required to operate it, and drilling performance of between 15.0 m and 18.0 m per shift can be reached.

4. Excavation of horizontal deposition holes

Another repository concept is to make serial deposition of canisters in long horizontal boreholes instead of single canister deposition in the vertical deposition hole. For the excavation of horizontal deposition holes, horizontal pull-reaming method can be applied. For the application of this method, two horizontal tunnels are required. After the pilot hole is drilled, the reamer is attached and pulled backwards (Figure 7.). This method is similar to the conventional vertical raise boring. However, most types of raise boring machines can be modified to pull horizontal and low angle raises. These modifications generally include an altered gearbox lubrication routing, a modified base plate, and the addition of a rear support for the guide columns (ATLAS COPCO, 2007).

The main problem of this method is transporting of the rock cuttings from face of borehole, because gravity does not help in the same way as for vertical holes. The scrapers are used for the transporting of the rock cuttings. A large volume of water is also required to keep the rock face clean and free of cuttings.

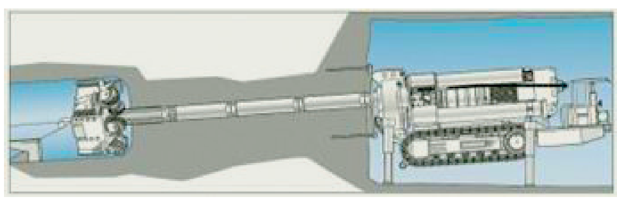


Figure 7. Horizontal pull reaming (ATLAS COPCO, 2007)

Slika *7. Horizontalno proširivanje povlačenjem*

The main disadvantage of this method is necessity of an extra service tunnel and significant amount of backfill that increases total cost. To reduce this disadvantage the more favorable method would be horizontal push reaming. Horizontal push reaming was tested in Äspö Hard Rock Laboratory (Bäckblom & Lindgren, 2005). Two deposition drifts were excavated. Both drifts were excavated with the diameter 1.85 m using horizontal push-reaming technology. One horizontal drift was 15 m in length and another one 95 m in length. The purpose of the first short drift was to test and if necessary improve the technology and equipment. This drift was also used for construction of the low-pH shotcrete plug.

Excavation started with the pilot hole and then reamed to full diameter using conventional raise-drilling equipment (Figure 8.). To avoid bending and buckling of the drill string the drill pipes are supported by stabilizers. Where the stabilizer spokes are attached, drill pipes are specially designed with an outer bearing.

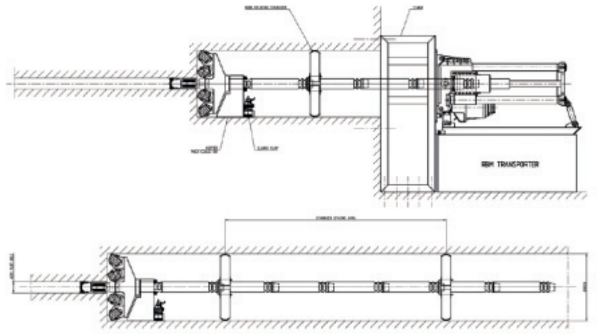


Figure 8. Principle for horizontal push-reaming drilling (Bäckblom et al., 2004).

Slika 8. *Princip bušenja uz proširivanje potiskivanjem (Bäckblom et al., 2004).*

For this project the Indau 120 H machine with some modification was used. Modification consisted of setting up one extra thrust cylinder, increasing max working force from 120 tons to 240 tones. While machine is operating, it generates significant volumes of muck and the rock cuttings need to be removed from the horizontal drift using flushing water. During pilot hole drilling, average penetration rate has been around 1.5 m/hour. For the blind hole reaming, the average penetration rate at Äspö has been around 0.5 m/hour.

The main conclusion is that horizontal push reaming can produce 95 m drifts in good rock that likely will meet the requirements for operational and long-term safety. The technology would also be applicable for 300 m long drifts if it is developed and tested to drill straight enough pilot holes.

The principle of water-percussion drilling is a down-the-hole hammer-drilling tool in which water at high pressure drives the hammer. Experience from the mining industry has proven the method considerably more cost effective. The drilling speed is higher compared with pressurized air-driven hammers, with 2/3 less energy consumption (Tuomas, 2004). Those experiences lead to that another method called cluster drilling, a variant of percussion drilling technique, was developed by Swedish Nuclear Fuel and Waste Management Company for drilling of the horizontal deposition drifts. Several water powered down the hole percussion hammers are put together in a frame that slowly rotates (Figure 9). Cluster technology is used as standard practice in several mines, but often for sub-vertical holes with diameters less than 1 m.

SKB has developed and tested a drilling machine where first a pilot hole of 254 mm is drilled. After that, two sets of cluster with percussion drilling hammers are used to ream the hole to 1,440 mm then to full diameter 1,850 mm, Figures 10 and 11. Stabilizers are used to prevent the drill string to bend which can cause deviation of the borehole axis.

The weight of a cluster including hammers was around 6–7 tones. Water (~5,000 L/min) is used to drive the percussion hammers as well as for the flushing of rock cuttings from the borehole.

Figure 9. Frame with percussion hammers for cluster drilling (Thorsager & Lindgren, 2004).

Slika 9. *Okvir s udarnim bušačkim čekićima za "cluster" bušenje (Thorsager & Lindgren, 2004).*

A comprehensive test drilling was carried out during October/November 2003 at an underground water treatment plant located near Oslo, Norway. After drilling of 42 meter long pilot hole with a diameter of Ø254 mm and a theoretical inclination of 2° from the horizontal, it was reamed up to a total length of 33 meters with a diameter of Ø1440 mm. The drilling had to stop since the slope of the pilot hole had become too small and it was not possible to remove cuttings by water flushing from the borehole. At last, the borehole was reamed up to a total length of 14 meters with a diameter of Ø1850 mm. It was decided to stop the reaming after 14 meters because of temporal and finances constraints.

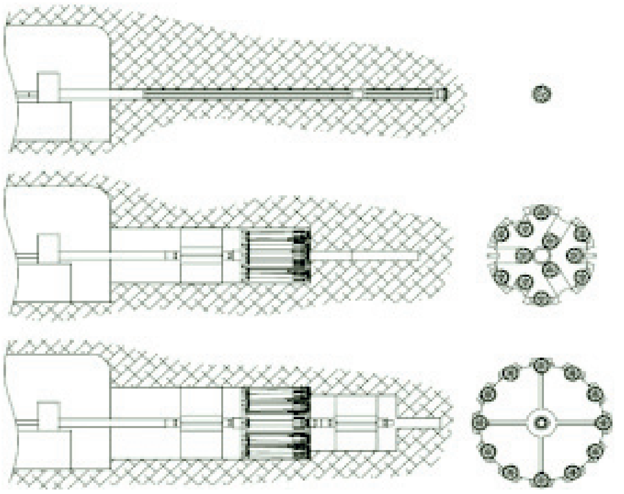


Figure 10. Three step excavation sequence of deposition drift with cluster drilling (Thorsager & Lindgren, 2004).

Slika 10. *Redoslijed otkopavanja hodnika za odlaganje u tri koraka "cluster" bušenjem (Thorsager & Lindgren, 2004).*

After the test drilling was completed, based on test results, it was concluded that expected time for drilling a 265 m pilot hole will be 7 days and that reaming to 1,440 and 1,850 mm takes each 10 days which makes in total around 27 days for excavating the drift assuming overall system availability of 70% (Bäckblom, G., et al. 2004).

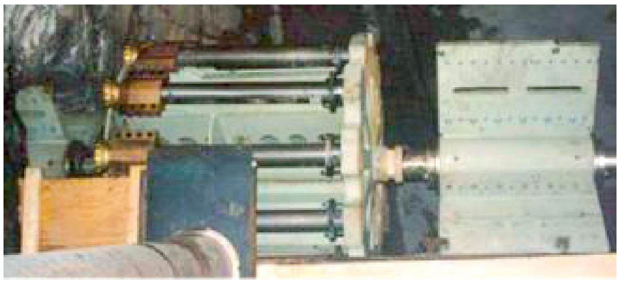


Figure 11. Typical layout of cluster drilling machine (Left part - The cluster for reaming to 1850 mm. Right part – Stabilizer) (Bäckblom et al., 2004).

Slika 11. *Tipični izgled "cluster" bušilice (Lijevi dio – skupina bušačkih čekića za proširenje do 1850 mm. Desni dio – Stabilizator) (Bäckblom et al., 2004).*

Andra employed a drilling company CSM-Bessac who was contracted for excavation trials in the Bure underground laboratory (Bosgiraud, et al., 2010). Trials were conducted in indurated clay to validate capacity to excavate and case the horizontal borehole (cell) for C type waste disposal concept. A TBM (Tunnel Boring Machine) was designed, fabricated, installed in situ and put in operations. A schematic of the TBM construction and borehole casing are illustrated in figure 12. Auger for evacuation of the boring cuttings can be seen behind the rotating head of machine. Three trial holes were drilled between April and May 2009:

- A depth of 20 m (half the planned length) was reached and the borehole lined,
- An open hole was kept as such to monitor the differed behavior of the clay formation,
- The drilling parameters (weight on bit, speed of rotation, penetration rate) were measured but to the knowledge of authors, they are not published

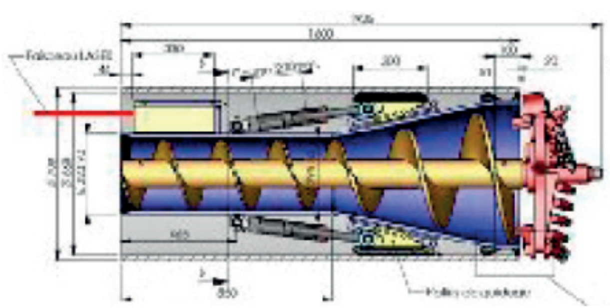


Figure 12. CSM Bessac's construction of the TBM machine (Bosgiraud, et al., 2010)

Slika 12. *CSM Bessac – ova konstrukcija TBM stroja (Bosgiraud, et al., 2010)*

According to Andra Dossier Argile (2005.), it was estimated that the total excavation time for disposal cell using TBM would be nine shifts where of three shifts would be only excavation (without lining tube connection). That was assumed based on premise that penetration rate for the 40 meters borehole, with diameter of 0.7 m, would be 2 m/h.

5. Discussion

For excavation of vertical deposition holes, drill & blast is not a possible method due to requirements on final geometry like surface roughness etc. Two different types of mechanical excavation (down reaming and shaft boring machine) are feasible as both can fulfill the geometrical requirements, but neither of the methods is satisfactorily efficient and further studies are required before selection of method. It is assumed that down reaming would be a more favorable method than using a shaft-boring machine, but additional testing is indispensable. Thorough field-testing on large diameter vertical borehole drilling at former salt mine Asse in Germany, resulted in development of automated dry drilling equipment. Equipment is capable to drill 600 mm diameter boreholes to the depth of 600 meters in salt formation. It is sufficiently developed for demands of German deposition concept.

Cluster drilling technology and horizontal reaming are deemed to be viable methods for excavation of horizontal deposition boreholes for the alternative KBS-3H deposition concept. Horizontal push reaming is preferred to pull reaming, as the latter requires an extra service tunnel and significant amount of backfill that increases total cost. The cluster drilling technology was tested and found technically feasible, however, the push-reaming was selected as the reference technique (Bäckblom and Lindgren, 2005). SKB had initiated practical field test with horizontal push reaming to provide a firm basis for later decisions in case the alternative of horizontal emplacement is pursued. In addition, TBM using button bits gear cutters may be feasible but full-scale test has not yet been conducted.

The Bessac's TBM capacity to adequately drill and case 40-80 m long horizontal disposal cells (boreholes) in indurated clay with a minimum clearance between the borehole wall and the lining is not yet entirely confirmed consequently additional tests are intended within the period 2010-2011 (Bosgiraud, et al., 2010).

It can be seen from table 2 performance comparison of deposition holes drilling methods. It is evident from table 2; because of greater specific average excavation rate, why is down reaming preferred method for drilling of vertical deposition holes in crystalline rock than drilling with shaft boring machine.

Table 2. Performance comparison of deposition holes drilling methods

Tablica 2. *Usporedba učinkovitosti metoda bušenja bušotina za odlaganje*

Method of drilling	Blind boring (down reaming)	Shaft boring machine	Dry drilling machine*	Push-reaming	Cluster drilling (presumed performance)	TBM (presumed performance)
Position of borehole axis	Vertical	Vertical	Vertical	Horizontal	Horizontal	Horizontal
Rock type	Crystalline rock	Crystalline rock	Salt	Crystalline rock	Crystalline rock	Indurated clay
Diameter of borehole [m]	1.527	1.75	0.6	1.85	1.85	0.7
Length of borehole [m]	7.5	8.5	600	15 and 95	265	40
Total time	64 workday/3 holes, 150 hours/hole	105 hours/ hole	291 hours/ hole	12 and 42 workdays	Assumed 27 workdays	72 hours (nine 8 hours shifts)/hole
Average penetration rate [m/h]	0.9	0.45	2.06	0.5	Data not available	2
Max. penetration rate [m/h]	1.2	1.1	2.25	1.0	Data not available	-
Specific average excavation rate [m^3/h]	1.65	1.08	0.58	1.34	-	0.77

*Performance calculated based on assumption that drilling performance of between 15.0 m and 18.0 m per eight hours shift can be reached (Steinberg, 1993.).

Regardless to fact shown that cluster drilling can produce horizontal boreholes that meet KBS-3H deposition concept requirements, SKB decided to select the push reaming technique for excavation of the boreholes as this technique is less costly and still meet the requirements of concept. Additionally, push reaming drilling method has relatively high specific excavation rate (table 2).

Performance of tunnel boring machine for excavation of horizontal boreholes in clay is surprisingly low (0.77 m^3/h). This is the consequence of demand of the disposal concept that boreholes have to be cased.

6. Conclusion

Based on current knowledge, geological disposal is the only method for isolating radioactive waste which fulfils the requirement for long term safety. Depending on the repository concept, canisters with spent nuclear fuel or high level waste can be emplaced in vertical or horizontal deposition holes. The geometrical requirements for straightness of the deposition holes are very strict. Drill & Blast method cannot fulfill such requirements on final geometry. For the excavation of vertical deposition holes in crystalline rock down-reaming and shaft boring machine can be used. Both methods can fulfill the geometrical requirements. The main issue is that neither of the methods is efficient due the technological limitations. Lot of time in boring cycle is used for repair and maintenance of equipment, emptying of tank for crushed stone, transferring equipment and setting up equipment and preparation of boring. A major limitation on the efficiency of the boring machine is the efficiency of the vacuum suction system. Even though technological development is needed, it is likely that down-reaming is simpler to advance in technology than the shaft boring machine.

According to Steinberg (1993), dry drilling equipment and technology is sufficiently developed for demands of German deposition concept.

In case of horizontal emplacement of canisters in crystalline rock a horizontal push-reaming and cluster drilling are feasible, but it is likely that horizontal push-reaming would show overall advantages. The horizontal pull-reaming main disadvantage is that it requires an extra service tunnel and significant amount of backfill which increases total cost. The excavation efficiency mainly depends on removal of the rock cuttings. Using present standard technology, both methods can fulfill stringent requirements for the horizontal drifts although to ensure that 100-300 m-long horizontal drifts are sufficiently straight, further development of technology is necessary.

Use of tunnel boring machine for excavation and casing of 40 to 80 meters long horizontal deposition borehole in clay is partly confirmed because during trial test a depth of only 20 meters was accomplished.

It can be concluded that basic technological principles for drilling either vertical or horizontal large diameter boreholes are known. Because of complex demands of deposition concepts majority of tested drilling technologies have shown some imperfections or undercapacity. For improvement of perceived deficiencies, more field studies are necessary.

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