Discussion on Deep Borehole Disposal of Spent Nuclear Fuel

Galla Uroić
Fund for financing the decommissioning of the Krško Nuclear Power Plant and the disposal of Krško NPP radioactive waste and spent nuclear fuel
Ulica Vjekoslava Heinzela 70A, 10000 Zagreb, Croatia
galla.uroic@fond-nek.hr

Želimir Veinović
University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering
Pierottieva ulica 6, 10000 Zagreb, Croatia
zveino@rgn.hr

Borivoje Pašić
University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering
Pierottieva ulica 6, 10000 Zagreb, Croatia
borivoje.pasic@rgn.hr

Andrea Rapić
Fund for financing the decommissioning of the Krško Nuclear Power Plant and the disposal of Krško NPP radioactive waste and spent nuclear fuel
Ulica Vjekoslava Heinzela 70A, 10000 Zagreb, Croatia
andrea.rapic@fond-nek.hr

ABSTRACT

Deep borehole disposal (DBD) of spent nuclear fuel (SNF) and/or high-level radioactive waste (HLW) is, at the moment, a much-debated topic. Some experts think that DBD is a potentially workable solution for the disposal of SNF and/or HLW, especially for small programs, and some think that it is insufficiently researched and technologically unfeasible concept for which disposal containers have yet to be designed and technology tested in life-size. Although the research process for this concept lasts for more than 50 years and has intensified recently, confirmation that the concept is feasible has not yet been achieved.

The original DBD concept is not new, however, it is still one of the least developed and researched concepts. Although, the petroleum industry has an abundance of experience in theoretically similar technology, disposal of SNF and HLW is a much different problem than drilling and production of oil and gas. Thus, it is inappropriate to draw a direct parallel between the technology of drilling the wells for oil and gas production with the technology of making boreholes for SNF and HLW disposal.

The main reason for favoring this concept is the idea of disposal at depths of more than three kilometers, with minimal rock destruction and without creating underground facilities resembling mines. Several problems are still not solved: achieving the appropriate borehole diameter at the required depth; preventing cannister jams, cannister design, cannister installation and borehole-closing technology.

Keywords: *deep borehole disposal concept, spent nuclear fuel, high level waste, concept, repository.*

1 INTRODUCTION

Although DBD is lately being more and more considered as a potentially applicable concept [1], [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14] and though it seems to be a simple solution for the disposal of SNF and/or HLW in countries with small programs [2], this technology and concept is actually not researched enough and still quite unapplicable. There are numerous worldwide ongoing projects with one main goal, disposal of different kinds of waste such as CO_2 or industrial waste, in suitable underground formations through the deep borehole [15], [16], [17].

Research into the concept of deep boreholes disposal involves the construction of a borehole up to 5,000 m deep, in which cannisters with SNF (or HLW) would be disposed of in the last couple of kilometers, leaving the rest of the borehole (2 km - 4 km) to be plugged.

The concept is shown in Figure 1.

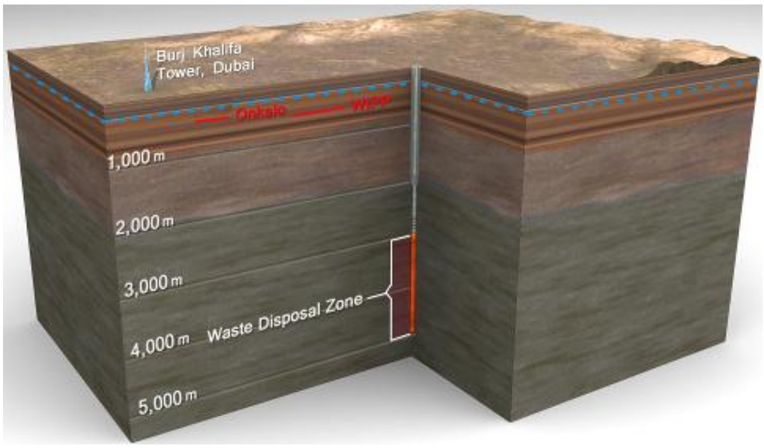


Figure 1: Schematic of the deep borehole disposal concept [18].

Although the concept is favored lately (see: [2], [10]) it still raises numerous questions and too many potential problems are readily taken as solvable. One of the main obstacles is the construction of boreholes of sufficient diameter to receive standard-sized containers intended for disposal SNF and HLW. Special containers, which could be installed in deep boreholes, have not been developed or are just conceptual and insufficiently examined. Note that containers intended for DBD should not be equated with containers for disposal of disused sealed radioactive sources (DSRS) in medium depth boreholes developed by IAEA. Since the borehole passing through several different layers (geological formation), wellbore diameter will inevitably be narrowed due to casing string installation. Using standard technology in Oil & Gas industry, at a depth of 5 km borehole it will be less than 15 cm in diameter. On the other hand, even with the widening of the borehole, utilizing existing technology from petroleum engineering, diameter of the borehole will finally be sufficient only for modified cannister that can hold only single SNF assembly.

The construction of deep boreholes is carried out primarily for the purpose of finding and extracting oil, gas, and geothermal water, while the deepest boreholes were drilled as exploration in terms of geological research of the earth's crust. For disposal in deep boreholes, options with a diameter of about 0.8 m and a depth of up to 5 km (4.5 km) are primarily considered [19].

In its simplest form [18], deep borehole disposal consists of making a large diameter borehole (up to 43 cm), or a series of boreholes, in crystalline rock to a depth of about 5 000 m, with the disposal of waste material in the lower ~ 2 000 m part of the borehole and sealing the upper part of the borehole with a combination of bentonite, cement and loose stone/crushed rock material. The reason for mentioning CRYSTALLINE rocks is because if the crystalline rock has a protrusion on or near the surface and if it is as compact as possible, it is possible to perform long borehole with minimal protection with casing, and therefore minimal narrowing of the borehole. However, some authors [2] think that "*The geological environment often assumed for the disposal zone of the borehole is crystalline basement rock, but there is no reason that DBD could not be deployed in other, stable, deep geological environments.*" Nevertheless, any other geological material, apart from crystalline rock, can easily undergo fracking or borehole collapsing if drilling mud pressures are too high and protective casing is not emplaced [20]. Site selection for the DBD is truly a challenge [21] especially in case of complex geology. Small programs usually go hand in hand with small countries which is likely to mean less choice in terms of favorable and simple geological environment sometimes equally for DBD as for the disposal of low and intermediate level waste [22], [23].

There certainly are some benefits of DBD concept if ever utilized. Using DBD concept, disposal of SNF would be at several times greater depth than in the case of conventional geological disposal facilities (GDFs). Among other things, at these depths, groundwater density stratification inhibits vertical advection for a long time (upward seepage), and reductive rock conditions reduce the possibility of corrosion and solubility of radionuclides and increase sorption, which in turn significantly inhibits transport and makes it particularly long-lasting. The rise in temperature caused by radioactive decay and the associated induced groundwater flow along the borehole should last only a few hundred years, after which slow diffusion is the predominant long-term mechanism for radionuclide transport.

An additional reason in favor of this method of disposal is the cost of disposal per ton of SNF. Brady et al., [24] estimate the cost of disposing of boreholes at about $ 40 million US, which includes drilling, borehole isolation and completion, as well as waste installation, which would take less than 2 years for an individual borehole. Recent research [25] suggests a more realistic estimate of 45 - 191 US$/kg HM (Heavy Metal), with the first project likely to be more expensive, but would not exceed 400 US$/kg HM.

Another reason for the eventual selection of this technology is, that it is relatively easy to move to another location, if the first one proves unfavorable. Disposal in deep boreholes is modular, and construction and operation costs are reduced linearly to the waste inventory. This "pay as you go" approach avoids large pre-investments for a classic deep geological repository. If, for example, drilling shows that the location where the deep borehole was started is not suitable, the equipment is simply moved to another potential location and the process is repeated until an acceptable disposal site is found. Relatively simple finding of crystalline basement at a depth of < 2 km means that disposal could be decentralized to achieve a greater geographical and political degree of equality, which, too, can reduce transportation costs and risks. And, as mentioned before, the DBD should also be attractive to countries that have smaller reserves of SNF and/or HLW – the entire inventory could fit in several boreholes.

Finally, geological conditions are far more favorable in this than in concepts that involve disposal in conventional GDFs. The presence of "old" salty and chemically reducing groundwater at these depths is crucial for disposal in deep boreholes. The presence of old water, at the stated depth, which lost active contact with the surface and hydrosphere hundreds of thousands of years ago is proof that there is little driving force to move water upwards. The presence of dense, saline solutions at depths over 4 km poses a serious obstacle to the upward movement of groundwater. Oxygen-poor reducing conditions at these depths reduce the possibility of cannister corrosion with SNF and/or HLW [24]. Also, the large depth of disposal in deep boreholes reduces the number of surface factors that must be considered to assess the long-term behavior of such a repository. These factors include infiltration of shallow groundwater, human intrusion, and the effects of climate change, including glaciation. Hydrological conditions at depth should also limit the advective transport of radionuclides upwards. In addition, crystalline rocks in the underlying bedrock generally have very low permeability.

However, following issues are clear from this concept:

1. Is a borehole that will have a diameter of 500 mm - 800 mm at the depth of 5 km feasible?
2. What should be the starting diameter of such a borehole?
3. In what host rock could such a borehole be constructed?

4. How many fuel elements (assemblies) fit in a cannisters that would fit in such a borehole?
5. What is the thickness of the wall of such a cannister?
6. Which doses of ionizing radiation are to be expected in the vicinity of such a cannister?
7. What will be the heat transfer from such a cannister?
8. What is the durability of the cannister?
9. What material should be used for sealing the borehole?
10. Which technology should be used for cannister emplacement and prevention of cannisters trapping?

In view of the above, the question arises "why try to develop such a concept at all, since there are already far more feasible and explored concepts for disposal of SNF and/or HLW?" The answer is as follows: technology is potentially cheaper, more adaptable, and simpler, especially for the small programs. Waste material would, as many authors agree [26], [27], be more isolated in deep boreholes, as the depth of disposal is greater, as are water density gradients and severe reductive conditions, which would go hand in hand with the movement of radionuclides toward the surface.

2 BOREHOLE DIAMETER AND SELECTION OF THE HOST ROCK

An uncritical comparison of the construction of deep boreholes for oil and gas exploration and production with SNF and/or HLW disposal boreholes is utterly wrong and merely a few authors do emphasize that the “large borehole diameters cannot currently be drilled using state-of-the-art deep drilling technology at 5 000 m” [13].

For the exploitation of oil, gas, or geothermal water, the location of the boreholes depends primarily on the location of the reservoir to be exploited, but also on other specific conditions such as the composition and properties of the rocks through which the borehole will be constructed, the type and properties of the fluid intended to be extracted, pore and fracturing pressure values, expected well drainage radius, expected flows, etc. The process of designing a borehole begins with determining the installation depth of each column of protective casing (large diameter protective pipes) that will cover (line) individual parts of the borehole. The depth of installation of an individual column of casing string primarily depends on the change of pore pressure and fracture pressure (of the rock through which it is drilled) with depth. However, the properties of the rock in which the shoe of the casing string will stay should also be considered, as these layers will be exposed to high pressure values during the cementation process of the casing string which may cause them to fracture. Figure 2 shows the development of the pore pressure gradient curves (blue solid line) and the fracture pressure gradient (fracking) gradient with depth (left side of the image) for the hypothetical borehole construction shown on the right side of the image. The values of the pore and fracture pressure gradient at particular depth were expressed through the equivalent density of the drilling mud which would result in one or another pressure at a certain considered depth. The picture itself shows additional (auxiliary) dashed curves which try to cover the fluctuations of the mud pressure that will inevitably occur during the process of wellbore drilling. In other words, the selected drilling mud must have a density that at the considered depth will provide a hydrostatic pressure higher than the formation (pore) pressure to prevent the inflow of stratified fluid into the borehole, and at the same time lower pressure than the fracturing pressure to avoid fracturing (cracking) rocks in the open borehole section.

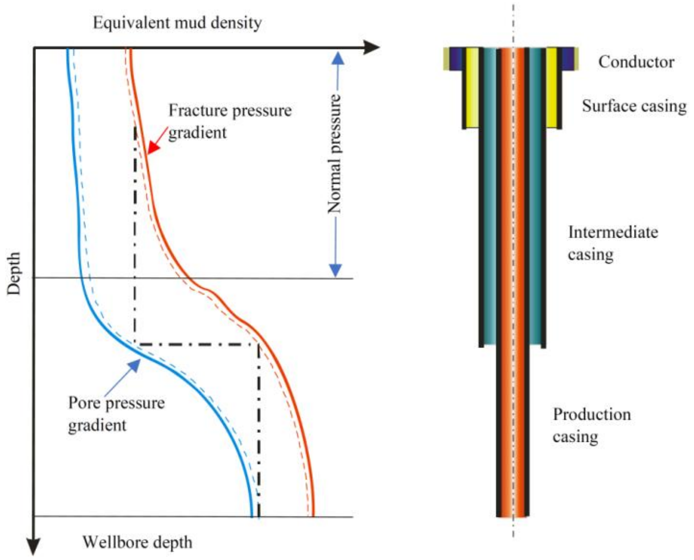
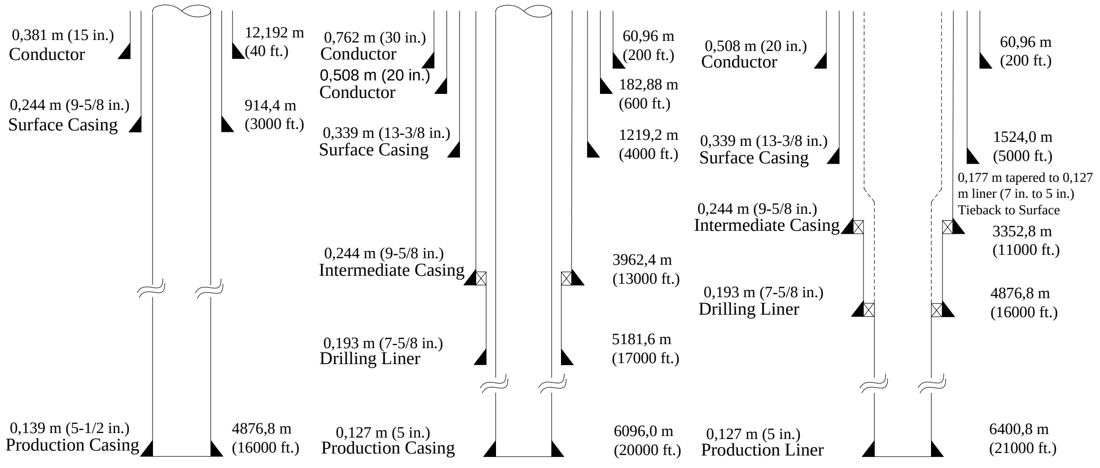


Figure 2: Schematic representation of the construction of the borehole channel and the method of choosing the installation depth of each column of casing [28].

Attention should be paid to the formation of a mud cake which, in the lower part of the borehole, might serve as a buffer material in DBD, since it consists mostly of bentonite clay, but it also creates problems in the upper part of the borehole. Before the cementation process it is necessarily to remove all mud cake from the face of the wellbore wall to obtain good zonal isolation between cement and rock on one side and between casing and cement on the other side.

Under normal circumstances, a layer pressure acting at a certain depth corresponds to the pressure of the bed water column at the depth considered. Although this situation would be ideal from the point of view of designing the construction of the borehole, in the underground one can find layers with abnormally high and abnormally low layer pressure. In case of abnormally high layer pressure at a certain depth, it is necessary to increase the mud density to prevent the inflow of formation fluid into the borehole and avoid possible well control problems, while too low layer pressure values can lead to fluid losses (mud or cement slurry) in the range of relatively small (0.16 m^3/h) to complete [29].

The number of required columns of casing, their diameter and depth of installation will depend on the earlier mentioned parameters and expected problems during drilling in a particular area. Figure 3 shows some of the common borehole designs for different areas in the United States.



(a) MISSISSIPI (b) OFFSHORE LOUISIANA (c) TEXAS DELAWARE BASIN

Figure 3: Examples of well channel construction for different areas in the USA (acc. to [30]).

Figure 3a shows the construction of a borehole approximately 5 000 meters deep in the Mississippi area that includes a 0.381 m diameter conductor pipe installed to a depth of 12.19 m, a 0.2445 m diameter surface casing installed to a depth of 914.4 m and a production casing with a diameter of 0.1397 m installed up to a depth of 4 877 m. Given the relatively large depth of the borehole, this simplified construction can be made in the mentioned area because there is no danger of zones of increased (abnormal) layer pressure, loss of mud or cement slurry or other problems that could jeopardize the construction of the borehole in accordance with technical characteristics defined by the project. This can be expected in targeted sites for disposal of SNF and/or HLW, in the case where after a few hundred meters of fractured rock or change of geologically unfavorable materials follows a thick layer of desirable host rock - crystalline rock where no major structural changes are expected and only minimal cracking. Only this case will allow disposal in deep boreholes with currently available technologies, but even then, only with cannisters that will hold one SNF assembly each.

It is possible to widen the disposal borehole. The technology of expendable liner has been implemented in practice for many years, and it is possible to expand casing with a diameter up to 0.4064 m (16 ") for about 20%. Although this technology was patented as far back as 1963, it did not experience its first practical application until 1993 by Royal Dutch Shell. To date, different companies have developed different systems for expanding casing string after its installation into wellbore, and in practice the bottom-up system is most used, which involves creating a pressure chamber and applying a spindle [31] (Figure 4).

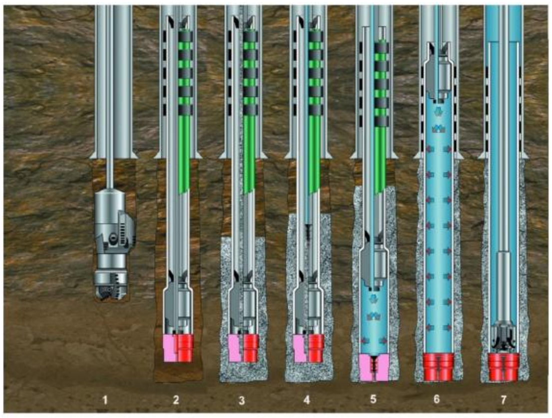


Figure 4: Expanding the liner in the open channel of the well by the bottom-up procedure [30].

In addition to the values of pore pressure and rock fracture pressure in the considered area, a great role in the construction of boreholes is played by the stability of the borehole (the stability of the borehole walls). The stability of borehole depends primarily on the stress within the rock before and after the borehole is made, as well as the physicochemical interaction of the mud used, and the rock being drilled. Namely, immediately before the construction of the borehole, in-situ stresses act on the rock, which make the vertical stress and the maximum and minimum horizontal stress. Depending on the values of in-situ stress in the rock, the new stresses on the walls of the borehole and the strength of the rock being drilled, various forms of shear or tensile fracture, or instability of the borehole channel, may occur [32].

The outer diameters of the commercially available or theoretically developed disposal cannisters range from 0.43 m for the BSK-3 cannister [33] up to 1.05 m for the KBS-3 concept disposal cannister [34]. For cannisters of these diameters to be safely emplaced in the borehole, the diameter of the borehole in the range of 3500 m to 5000 m (interval in which disposal is planned) should certainly be a certain percentage larger than the specified outer diameters of the cannister. If the technical solution for the well construction includes casing the interval in which the cannister would be emplaced, the diameter of the borehole should be even larger so that it can accommodate protective casing of sufficient internal diameter to accommodate SNF cannisters. In both cases, it should be considered that the construction of a borehole for the disposal of SNF or HLW will not consist of only one installed column of protective casing string, given the relatively large depth of the borehole and potentially complex geological structure the disposal site. Therefore, the problem of borehole construction can be viewed in two ways. The first approach would include the application of existing, commercially available technology for the construction of boreholes for the needs of the oil and gas industry, which is certainly more cost-effective because the existing technical solutions are available and proven in practice. The second approach would include a kind of improvement of the existing drilling technology, which primarily refers to the development of larger and more powerful drilling rigs with which it will be possible to make a borehole with the diameter larger than usual and install and cementing larger and heavier strings of casings. Only the first approach, which includes the maximum utilization of available drilling technology in the Oil & Gas industry with minimal modifications, will be considered in this paper. The main disadvantage of this approach is the small capacity for waste disposal per borehole, which imposes the need to build more boreholes (or multi-lateral boreholes) for disposal of a predefined volume of waste.

The traditional (conventional) well construction includes installation of a conductor and a series of casing and liner string (casing that do not reach the surface) of the different nominal outer diameter (Figure 5. left side). If it is necessary to install protective casing at a greater depth, it is also possible to design a borehole with one diameter (monobore well plan) from the wellhead (surface) to the desired depth, using expandable liner technology (Figure 5. right side).

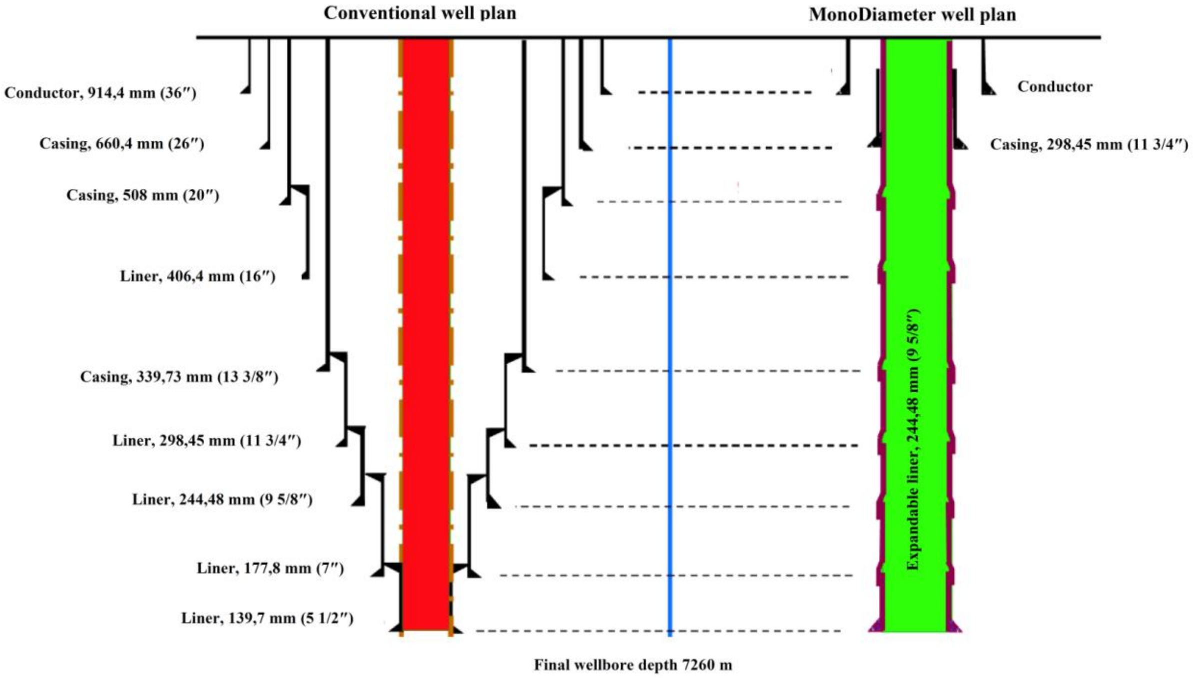


Figure 5: Comparison of conventional well channel construction (left) and single diameter well channel construction involving the use of expandable liners (right) [35].

It is considered that the last section (disposal/cannister emplacement section) of the borehole is not protected with casing (open borehole section). The primary reason is to avoid contamination of the cannister/sealing material/host rock environment with the additional foreign material, which may affect the durability and functionality of the borehole and the disposal concept. For the same reason, the upper part of the borehole, the one where the sealing material is located, is also supposed to be covered by casing string. The idea is to avoid installing a column of protective casing under a depth of 1,500 m! The concept is shown in detail in Figure 6. It should be emphasized that the implementation of such a concept is possible only in the case of high quality (crystalline) rock. As mentioned earlier: the installation depth of a single column of protective casing will primarily depend on the pore and fracture pressure at a certain depth, but also on other parameters such as the existence of low compressive strength layers prone to fracture, clay layers prone to swelling or unstable formations prone to collapse, etc. Therefore, the requirement to install casing into only the first 1,500 m may be too demanding or impractical, and selection of a location with a suitable host rock will be crucial.

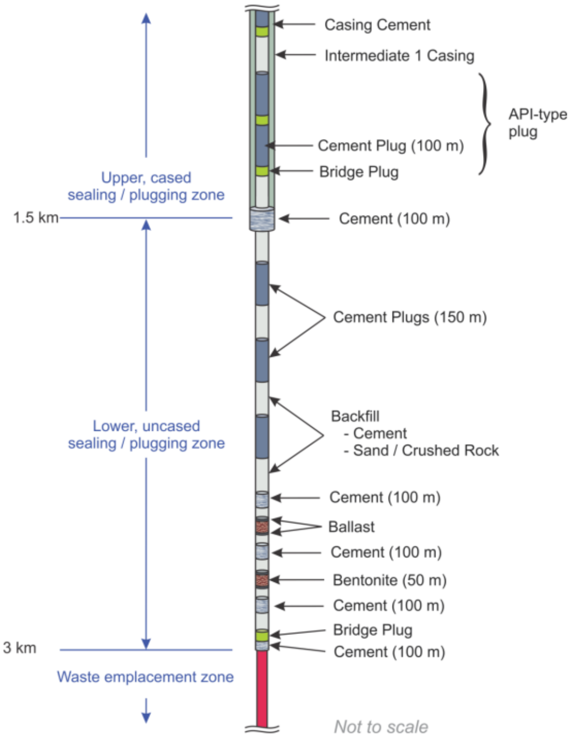


Figure 6: Borehole sealing, plugging, and backfilling reference design schematic [18].

However, many authors assume that intensive installment of casing shall not be needed [1], [36], [37], [38], [39] and that the borehole can be constructed with the minimal number of the casing strings, and consequently decreasing in the wellbore diameter. Experience from the petroleum industry and the production of oil and gas begs the differ, except when the (host) rock – geology at the site, is simple and constant, which is really rare.

3 DISPOSAL CANNISTER

The cannister, as in other SNF or HLW disposal concepts, should ensure a high level of safety in terms of radionuclide retention during all phases of surface work, emplacement and during the closure period. Also, the design of the cannister and the mode of transport/handling must be such as to meet safety standards in terms of ionizing radiation protection.

Cannister requirements are:

- The cannister must ensure a high level of safety in terms of radionuclide release during handling and installation. Cannister welds and seals must prevent the release of either solid, liquid, or gaseous radionuclides.
- Cannisters must maintain structural integrity during filling, transport, and handling before installation.
- Cannisters must maintain structural integrity during installation, borehole filling, and the closure of the repository. The design of the cannister must ensure a high level of safety in terms of how cannisters will withstand fluid pressures (drilling mud and ground water)

mechanical loads (mass superposition) and temperatures during installation and the rest of the operating period.

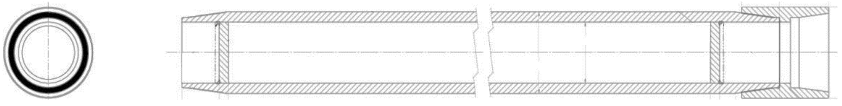
- If cannisters are to be emplaced as a series of connected cannisters, they must have an integrated connection system with one another and with the drill pipe (technology readily used in oil industry) to descend to the disposal zone. The connection between the cannisters must be strong enough to withstand mechanical stresses during and after installation and for potential retrieval during the operational phase.
- The internal length of the cannister must be sufficient to accept an intact (mechanically undissembled) fuel element, according to which their minimum length is determined. Disassembling of fuel elements (assemblies) will assume the existence of a special dismantling plant and trained people.
- Cannisters must maintain integrity for as long as necessary (practical). However, the concept of DBD does not rely mainly on containers as a significant (primary) barrier to the release of radionuclides after the operational period (after closure and abandonment of the facility).
- The design, handling, and installation of the cannister must prevent any possibility of criticality.

The hydrostatic pressure of the fluid (mud and groundwater) on cannisters will be a function of the depth and density of the fluid within the borehole. Fluid density is a function of salinity and temperature, which also depends on depth. Highly saline groundwater is expected in the parent rock at depths to which boreholes will be drilled, but the fluid composition in the borehole can be controlled to some extent during drilling and tank installation. Fluid pressure within the borehole is conservatively based on the assumed salinity and density, which can vary from the density of fresh water on the surface (up to a depth of 500 m) to 1,3 times the density of water (at depths of 5 000 m). With an assumed temperature gradient of 25 ºC/km, the fluid pressure at the bottom of the five-kilometer borehole is about 57 MPa, according to which the tanks are designed.

The nominal mechanical load requirement for cannisters assumes that the cannisters will be lowered into the borehole in rows of about 40, at approximately 200-meter intervals (depending on the drill rig, applied technology etc.). The maximum compressive force at the lowest cannister after installation will be equal to the maximum tensile stress force at the highest cannister in the series, when the tank is lowered.

In case that the cannister will not contain only one spent fuel assembly, but with the assumption [18] that fuel elements from Pressurized Water Reactor (PWR) will be disassembled into bars and 421 bars (weighing 2,39 kg/rod) from which the total mass of cannisters and waste for 40 cannisters is about 69 400 kg. Buoyancy due to fluid in the borehole is neglected in this case (conservative approach).

A sketch of the probable container design for 421 disassembled fuel rods is shown at Figure 6 Although the containers are in the development phase, the design of this one seems interesting from the principle of connecting with a drill pipe, or other cannisters, since it is connected with a robust thread. On the other hand, there is a possibility that several cannisters connected in this way in series would be too rigid or too susceptible to deformation in the case of descent into a borehole with the certain deviation in inclination and azimuth. An alternative to this solution is to use a cannister that would receive one intact fuel element.



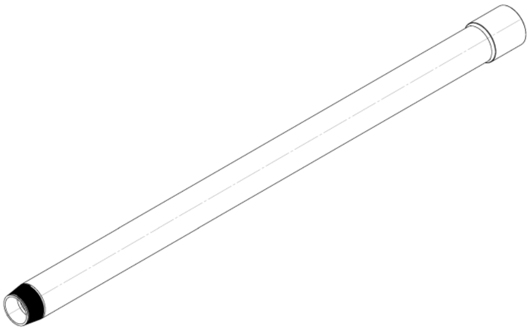


Figure 6: Schematics of the cannister [18].

Muller et al. [10] have suggestion for such cannister design, however, with one huge fault. The method of connecting the cannister to the working string (drillpipe or tubing) is clearly underdeveloped, as it appears to be insufficiently robust (Figures 7a & 7b). There is a real possibility of connector’s thread damage, as well as breaking of connectors in case of the trapping, pulling and other reasons for overload.

Figure 7: Schematics of the cannister (a) and connector for installation of cannister (b) [10].

The model developed and presented in Arnold et al. [18] makes more sense than the simplified version presented in Muller et al. [10]. Couplings used in the oil industry are designed and tested to withstand significant masses and loads, so that robust and fast conical couplings are used, i.e. "premium" couplings of high load capacity (Figure 8), which are, in the opinion of the authors of this paper, recommended for use on disposal cannisters as well.

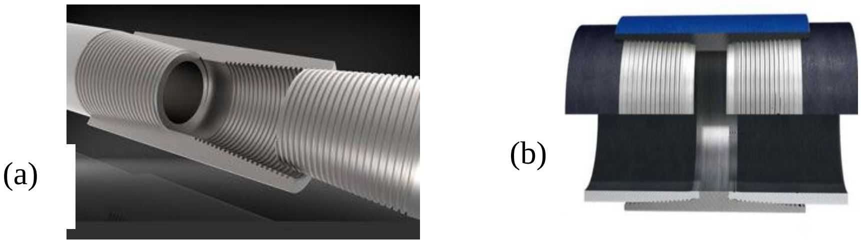


Figure 8: Example of a coupling (transition) with a stronger (a) and less pronounced (b) conical thread in the Oil & Gas Industry [40].

The proposed couplings between cannisters consist of "premium" threaded couplings (transitions) with an outer diameter corresponding to the size of the cannister and the tools used in the oil industry. Data on existing couplings have a parry minimum strength of 550 MPa. There are a few slightly different designs, depending on the manufacturer, but they all work in a similar way.

Couplings between individual cannisters would not significantly affect the construction, additional load, or safety of the cannister, and their length would not significantly reduce the usability of the part of the borehole intended for disposal. An individual coupling would be about 300 mm long, about 380 mm in outer diameter and weighing 10 kg -30 kg, depending on the thickness of the tank, design, etc. (Figure 9).

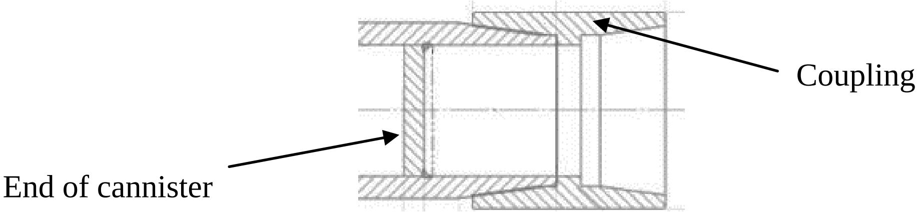


Figure 9: Proposed design of coupling [18].

For large programs, Fuel Consolidation Technology (FCT) is considered a viable solution. FCT involves disassembling the fuel elements and packing the fuel rods densely into the cannister. This technology involves significant technology investment, considered justified because it uses a narrower cannister, a smaller diameter borehole and a higher density of fuel packaging, which means fewer cannisters, fewer boreholes and thus lower operating, transport, and drilling costs [39]. The low temperature cannister (thinner walls) can accommodate approximately 367 fuel rods, while the high temperature cannister (thicker walls) can accommodate 349 rods. For comparison, the standard 17x17 PWR fuel cell contains 268 fuel rods, which means that dense packaging achieves 37% higher cannister filling, compared to the technology in which a single fuel cell would be packaged in a cannister. Thus, in the case of the disposal of SNF from the United States into boreholes, instead of 950 boreholes, 700 boreholes would have to be drilled [24].

For HLW, it would also be necessary to develop new cannisters and a new initial packaging method, as the existing one has too large dimensions for disposal in boreholes. The standard dimensions of the vitrified HLW cannister are about 400 mm diameter and about 1300 mm height. The mass of a full tank is about 550 kg [41].

Filling the cannister with a single SNF element is certainly the simplest way, regardless of space utilization. Since the development of technology, plant, and training of people to disassemble certain fuel elements and perform dense packaging certainly represents a significant investment, increased risk of problems and accidents, including the possibility of criticality, a simpler way - packaging of intact elements, is certainly desirable for small programs.

Testing of cannisters is necessary to confirm the possible dimensions of the cannister and the possible stresses and strains of the materials that would be used for their manufacture. Typical tests would include:

- cannister wall thickness (tolerance ± 6%);
- Integrity of joints (threads);
- Limit of elasticity of cannisters and joints under elevated temperatures;
- Welds and joints (x-rays);
- Contamination (ionizing radiation) of full cannisters;
- Testing by dropping from certain heights (cannister filled with water).

Cannisters must withstand hydrostatic stress at the depth of storage without internal support. Tests of (pressure) cannisters are thus carried out at pressures of about 57 MPa, with a safety factor of F = 1,2. Development and testing of cannisters must be performed along with the development of drilling and emplacement technology, and it might take several years just to produce working model. Therefore, assuming that DBD concept is “almost ready to be applied”, and that less than a decade will be enough to finish the development of the concept and necessary technology is entirely wrong.

4 SEALING OF THE BOREHOLE AND INSTALLATION OF THE BUFFER MATERIAL

To ensure the required safety of the SNF or HLW in the deep borehole disposal facility, it is necessary to decide which materials to use as buffer between cannisters and host rock and which materials for the final closure of boreholes, and how to install these materials.

Another material considered for plugging boreholes and as a buffer is bentonite clay. However, technologies for installation of bentonite as a buffer or a plug for DBD concept are not entirely developed nor properly tested. One of the proposed methods for plugging boreholes [42] involves the use of barite (barium heavy), $BaSO_4$, whose density (about 4.5 g/cm^3) and the property of insolubility in water or acids seems promising.

Unlike the permanent abandonment of oil and gas boreholes, where the borehole closure process is clearly defined and there is some experience and legislative framework, the process of filling and closing deep boreholes for the disposal of SNF or HLW have yet to be developed and provide a specific legislative framework. An additional problem is that currently there is no single realized project in life-size which can provide necessary experience and help technology development.

Filling the space between cannisters and the host rock in case of DBD, is an enormous technical and technological challenge. Despite the good practice of closing/abandoning oil and gas wells, the same technology and materials cannot be used for plugging and closing boreholes for the disposal of SNF or HLW. Installment of buffer material is a more critical part of the process of filling and closing boreholes due to the relatively small space between cannisters and the host rock. The oil industry offers several technical and technological solutions that can be used to inject bentonite suspension into the annular space that has to be filled, however, they cannot be applied directly. Certain modification of these procedures is required due to specific safety requirements and the fact that the containers are not tubular tools, and it is not possible to push fluids through them. In addition, some procedures, such as installation of buffer material in form of selected fluid from the surface, leave open the question of the quality of filling the space around the cannister. It is possible to expect forming of "pockets" of wellbore fluids within the buffer zone. Also, if bentonite suspension is to be used as a buffer there is an open question of its density, homogeneousness, effects of the water loss due to high pressure at the installment depth, etc.

The direction of further tests should go in the direction of accurately defining the suspension which is to be used as a buffer and plug, i.e., its composition, which would have satisfactory properties in terms of quality and long-term filling of the space around the cannister. It will have to be a suspension since there is no probable way to install bentonite or any other material in hard (compacted) form.

In literature it is common to find “complex/composite/multiplex borehole plug design” which readily consists of “any convenient fill” (drilling particles), asphalt, bentonite clay, concrete… Many references even provide lengths of such plugs, i.e. 300 m of bentonite swelling plug zone, however no one explains how they plan to install the bentonite plug [1], [43], [44]. Idea on the use of concrete as a material for closing boreholes [8], [1] have a major drawback in terms of the duration of concrete and its corrosion in conditions of low groundwater pH. Since that concrete has a pH of about 12, and leaching inevitably occurs at lower pH, not to mention effects of highly saline water, one idea is to install concrete "plugs" strictly on the parts of the borehole that are not exposed to groundwater, or groundwater which will not affect concrete.

5 CONCLUSION

In literature such as Fischer et al. [5], and Muller et al. [10] the idea of DBD of SNF and/or HLW is considered ideal for small programs. On the one hand it’s true, but the technology has not been really updated or developed since the original Sandia Laboratory research, although it seems not to be so. Therefore, main reasons why this concept will not be applied within next couple of decades are:

1. The existing technology does not allow the construction of a borehole that would be so wide at the surface that at a depth of about 5 000 m it would provide sufficient width to receive existing disposal cannisters, either for SNF or HLW, except in special cases of continuous homogenous geology of the host rock. Therefore, it is wrong to consider “some large diameter boreholes have been drilled, which show that the required diameters may be feasible” [4].
2. Modified cannisters which can be emplaced in a narrow borehole have yet to be designed, tested, and approved. The issue of proper cannisters is still not even fairly raised, and there are several problems:
   a. The size of the cannister is not decided upon (considering the number of assemblies it would contain, or the number of fuel rods in the case of disassembly of elements).
   b. There is no definitive design of cannister regarding connectivity of adjacent cannisters or equipment for run into borehole. In the case of connecting a series of cannisters (since most ideas refer to lowering a series, not individual cannisters), the question is whether they will eventually be connected to a cable with some type of hook (which is a serious challenge) or a tool (drill pipe/tubing)? In both cases, procedures in case of sticking and the moment of release should be considered, which requires robust mechanisms that are not susceptible to accidental release.
   c. Connecting individual cannisters with anything thinner than the coupling used in petroleum industry to connect tools (drill pipes) is ridiculous. The idea proposed by the authors of the article [10], shown in Figure 7, is out of the question, which can be confirmed by any petroleum engineer.
3. Site selection must start with the idea of crystalline rock which practically has outcrop at the surface in order to simplify the construction of the borehole, thus avoiding (in case of complicated geological environment):
   a. instalment of a large number of protective casing and significant narrowing of the borehole,
   b. widening of the borehole,
   c. installment of series of protective casing that do not reach the surface (liners)

   all potentially complicated technologies used in petroleum engineering which can additionally damage integrity of disposal borehole (host rock environment).
4. Idea of horizontal disposal boreholes [10], [11], [12] – although technology for drilling and equipping similarly designed boreholes exists in petroleum industry, the idea of applying it for SNF disposal is definitely not nearly enough explored nor confirmed as possible. With a change in borehole position there is a real chance of seating/sticking of cannisters, and the technology of installing buffer material in a horizontal position is practically unfeasible (buffer will lose its functionality).
5. Separating multiple boreholes from a single channel [1] is also a serious problem and although it is cited as a realistic possibility in theory, performance problems are numerous.
6. Sealing of deep boreholes although thoroughly analyzed by some authors [6] is still not properly tested. Most authors [3], [9], [18], [24] talk about properties of sealing and buffer materials but don’t reference to technology of emplacement or vaguely

describe it, which is a real issue. Sealing materials should be tested in reference to host rock and different geological and geochemical environments, as well as their emplacement with regard to available technologies (need to develop new emplacement technologies).

Although the concept of deep borehole disposal is considered to be a good idea, it should certainly be explored in situ, with a life-sized test borehole and cannister, which would either confirm its feasibility or abandon the idea until the necessary technology is developed.

REFERENCES

[1] M.J. Driscoll, R.K. Lester, K.G. Jensen, B.W. Arnold, P.N. Swift, P.V. Brady, Technology and Policy Aspects of Deep Borehole Nuclear Waste Disposal, Nuclear Technology vol. 180, no. 1, 2011

[2] N.A.Chapman, Who Might Be Interested In a Deep Borehole Disposal Facility for Their Radioactive Waste? Energies vol. 12, no. 8, 2019.

[3] E. A. Bates, A. Salazar, J. Driscoll, E. Baglietto, J. Buongiorno, Plug Design for Deep Borehole Dispoal of High-level Nuclear Waste, Nuclear Technology, Vol. 188, pp. 280-291, 2014.

[4] T. Fischer, H. Engelhardt, D. Mallants, Methodology for Designing Deep Boreholes for Disposal of Radioactive Waste, In Proceedings of the Waste Management Symposium, Phoenix, Arizona, 6-10 March 2022

[5] T. Fischer, H. Engelhardt, T. Wanne, Deep Borehole Disposal Concept, AINS GROUP BGE TEC, 2020.

[6] J. Engelhardt, T. Fischer, T. Wanne, Sealing of Deep Borehole in Crystalline Rock – Norwegian National Facility, AINS GROUP BGE TEC, 2021.

[7] D. Mallants, K. Travis, N. Chapman, P. V. Brady H. Griths, The State of the Science and Technology in Deep Borehole Disposal of NuclearWaste, Energies vol. 13, no 4, 2020.

[8] A.Freeze, E.Stein, P.V.Brady, Post-Closure Performance Assessment for Deep Borehole Disposal of Cs/Sr Capsules, Energies vol.12, no. 10, 2019.

[9] A. Freeze, E. Stein, P.V. Brady, C. Lopez, D. Sassani, K. Trevis, F. Gibb, J. Beswick, Deep Borehole Disposal Safety Case, SAND2019-1915, Sandia National Laboratories, United States, 2019.

[10] R.A. Muller, S. FInsterle, J. Grimsich, R. Baltzer, E.A. Muller, J.W. Rector, J.Payer, J. Apps, Disposal of High-Level Nuclear Waste in Deep Horizontal Drillholes, Energies vol. 12, no. 11, 2019.

[11] J.H.Payer, S.Finsterle, J.A.Apps, R.A. Muller, Corrosion Performance of Engineered Barrier System in Deep Horizontal Drillholes, Energies, vol. 12, no. 8, 2019.

[12] S.Finsterle, R.A.Muller, R.Baltzer, J.Payer, J.W.Rector, Thermal Evolution near Heat-Generating Nuclear Waste Cannisters Disposed in Horizontal Drillholes, Energies vol. 12, no. 4, 2019.

[13] G. Bracke, W. Kudla, T. Rosenzweig, Status of Deep Borehole Disposal of High-Level Radioactive Waste in Germany, Energies vol. 12, no. 13, 2019.

[14] N.C. Collier, N.B. Milestone, K.P.Trevis, A Review of Potential Cementing Systems for Sealing and Support Matrices in Deep Borehole Disposal of Radioactive Waste, Energies vol. 12, no. 13, 2019.

[15] N.Gaurina-Međimurec, K. Novak Mavar, M. Majić, CCS technology: overview of projects, technology and monitoring, Rudarsko-geološko-naftni zbornik, vol. 33, no.2, pp. 1-15, 2018

[16] N. Gaurina-Međimurec, K. Novak Mavar, Depleted hydrocarbon reservoirs and CO2 injection wells – CO2 leakage assessment, Rudarsko-geološko-naftni zbornik, vol. 32, no. 2, pp. 15-27, 2017

[17] J. Ivšinović, I. Dekanić, The basis of model for marginal testing of costs for disposal of extracted formation water, Rudarsko-geološko-naftni zbornik, vol. 30, no. 2, pp. 85-100, 2015

[18] B. W. Arnold, P. V. Brady, S. J. Bauer, C. Herrick., S. Pye., J. Finger, Reference Design and Operations for Deep Borehole Disposal of High-Level Radioactive Waste, SANDIA REPORT SAND2011-6749, 2011.

[19] C. Juhlin, H. Sandstedt, Storage of Nuclear Waste in Very Deep Boreholes, Technical Report TR-91-35 Svensk Karnbrnslehantering AB, 1991

[20] B. Pašić, N. Gaurina-Međimurec, D. Matanović, Wellbore instability: Causes and consequences, Rudarsko-geološko-naftni zbornik, vol. 19, no. 1, pp. 87-98, 2007

[21] T.Malvić, M.A.P.Dinis, J.Velić, J. Sremac, J. Ivšinović, M. Bošnjak, U. Barudžija, Ž. Veinović, H.F.P. e Sousa, Geological Risk Calculation through Probability of Success (PoS), Applied to Radioactive Waste Disposal in Deep Wells: A Conceptual Study in the Pre-Neogene Basement in the Northern Croatia, Processes, vol. 8, no. 7, 2020

[22] D. Perković, Ž. Veinović, R. Leopold, A. Rapić, Site Selection for Croatian Low and Intermediate Level Radioactive Waste Repository, Journal of Maps, vol. 16, p. 21-29, 2020

[23] Ž. Veinović, Z. Vrankić, A. Rapić, Site Characterization for LILW Long-Term Storage Facility and Repository, , In Proceedings of the 11th International Conference of the Croatian Nuclear Society, Zadar, Croatia, 5-8 June 2016, pp. 110-1

[24] P.V. Brady, B.W. Arnold, G.A. Freeze, P.N. Swift, S.J. Bauer, J.L. Kanney, R.P. Rechard, J.S. Stein, Deep Borehole Disposal of High-Level Radioactive Waste, SAND2009-4401, Sandia National Laboratories, 2009

[25] E. A. Bates, Optimization of deep boreholes for disposal of high-level nuclear waste. Nuclear Science and Engineering, Cambridge, MA, MIT. Ph.D., 2015

[26] W. Cornwall, Deep Sleep, Boreholes drilled into Earth's crust get a fresh look for nuclear waste disposal. Science 349: 132-135, 2015

[27] J. Tollefson, US seeks waste research revival, Nature 507: 15-16, 2014

[28] https://petrowiki.org/File:Devol2_1102final_Page_578_Image_0001.png (accessed on June 25, 2020)

[29] N. Gaurina-Međimurec, B. Pašić, Risk Due to Wellbore Instability. In Risk analysis for prevention of hazardous situations in petroleum and natural gas engineering, Matanović, D., Gaurina-Međimurec, N., Simon, K., Eds.; IGI Global., Hershey PA, USA, pp. 23-46, 2014

[30] A.T. Bourgoyne Jr., K.K. Millheim, , M.E. Chenevert, F.S. Young Jr., Applied Drilling Engineering, chapter 7. Casing Design, SPE textbook series, Vol. 2, Society of Petroleum Engineers, Richardson, TX, USA, 2005

[31] N. Gaurina-Međimurec, P. Mesarić, Application of Solid Expandable Tubulars in the Petroleum Industry, Rudarsko-geološko-naftni zbornik, vol. 37, no. 1, 2022

[32] B. Pašić, N. Gaurina Međimurec, D. Matanović, Wellbore instability: causes and consequences, Rudarsko-geološko-naftni zbornik, 19 (1), 87-98, 2007

[33] W. Bollingerfehr, W. Filbert, J.-M., Bosgiraud, B. Haverkate, Waste cannister transfer and emplacement technology – Module 2, Final Report, Contract Number: FI6W-CT-2004-508851, ESDRED, EC, 2009

[34] S. Pettersson, & L. Bengt, Final repository for spent nuclear fuel in granite - the KBS-3V concept in Sweden and Finland. Proceedings of the international technical conference on the practical aspects of deep geological disposal of radioactive waste, (p. 346). Czech Republic: Ceske vysoke uceni technicke, Fakulta stavebni, 2008

[35] https://petrowiki.org/File:Devol2_1102final_Page_578_Image_0001.png (accessed on June 25, 2020)

[36] NIREX, A Review of the Deep Borehole Disposal Concept for Radioactive Waste, United Kingdom Nirex Limited Nirex Report no. N/108, 2004

[37] C.I. Hoag, Cannister Design for Deep Borehole Disposal of Nuclear Waste, Massachussetts Institute of Technology, 2006

[38] G. Heiken, G. Woldegabriel, R. Morley, H. Plannerer, J. Rowley, Disposition of Excess Weapon Plutonium in Deep Boreholes – Site Selection Handbook, Los Alamos National Laboratory, 1996

[39] J.S. Gibbs, Feasibility of Lateral Emplacement in Very Deep Borehole Disposal of High Level Nuclear Waste, Dept. of Nuclear Engineering. Cambridge, MA, MIT, 2010

[40] https://pinetteemidecau.eu/en/oil-gas/structural-premium-connection-testing, Pinette Emidecau Industries, (accessed on June 25, 2020)

[41] NIREX, Nirex Report Specification for Waste Packages Containing Vitrified High Level Waste and Spent Nuclear Fuel, United Kingdom, 2005

[42] SKB, Sealing of investigation boreholes, Report P-17-10, 2017

[43] SKB Technical report: Project on Alternative Systems Study (PASS) Final Report, TR 93-04 Svensk Karnbranslegantering AB, 1992

[44] O.L. Kedrovsky, Method for Disposal of Spent Nuclear Fuel from RBMK, Proceedings from 5th International Conference „Radioactive Waste management and Environmental Remediation", Berlin September 3-9, 1995