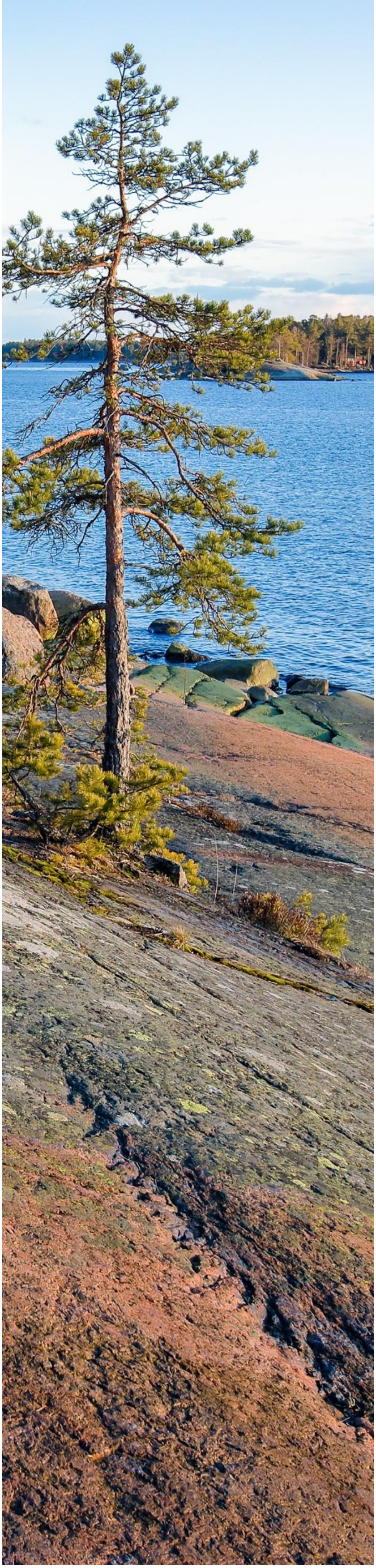

Technical Report

Deep Borehole Disposal Concept

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ABSTRACT

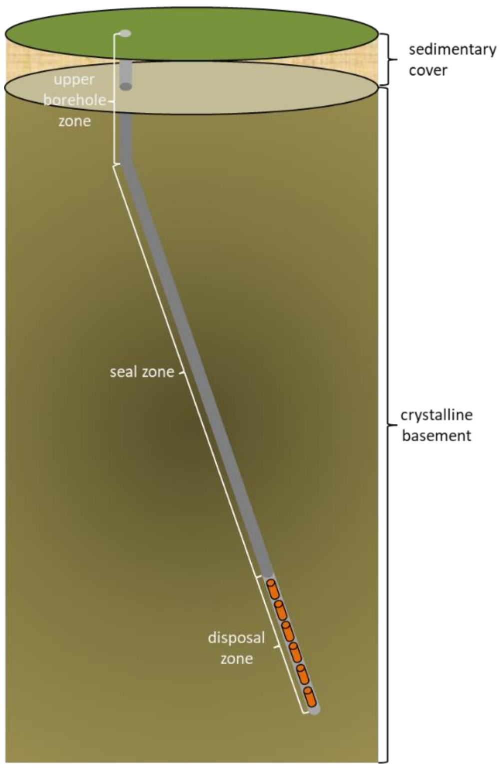
Norway's inventory of high-level radioactive waste originates from the research reactors in Halden and Kjeller, taken out of operation. NND is developing a comprehensive strategy for management of radioactive waste. For high-level waste this includes two options:

Deep Geological Repository, OR Deep Borehole Repository.

This report explored the deep borehole repository concept for Norway. The borehole disposal concept consists of drilling a borehole to a depth of several kilometres, emplacing waste containers containing spent nuclear fuel or high-level waste in the lower part of the borehole and then sealing the upper part of the borehole.

The report provides basic information about deep borehole disposal. The main part of this is a literature study to summarize the information available. In combination with some information about the radioactive waste in Norway (inventory of the existing waste), some parts of the concept have been adapted to the Norwegian project. For the disposal operation and mainly the borehole construction a simple feasibility analysis has been carried out. This is mainly focused on the borehole diameter and depth, since these have been constituted to be the main challenges and limiting factors of the project. At the end some recommendations for further studies are provided. These can set the basis for a more detailed concept, either for Norway, but also for other countries.

Several decisions are required during the development of a borehole disposal concept. Since most variables are related and dependent on each other, at some point decisions or assumptions need to be made in order to develop a concept. Some central decision points are the container design, which then strongly affects the borehole design. The borehole design on the other hand influences the container design as well. This is one of the mutual dependencies during the concept development of deep borehole disposal. In addition, the geology affects the borehole and container design significantly. There are three major aspects which influence all the other aspects discussed throughout this report:



Borehole design, Container design, and Geology.

While the borehole and container design are variables and can be changed and adapted relatively easily, the geology is set. This factor can only be influenced by the selection of the location. A potential design layout of the borehole is show on left. The borehole is adapted to the geological circumstances in Norway. The borehole diameter and the depths of the different parts of the borehole are not set yet.

TABLE OF CONTENTS

1 INTRODUCTION

1.1 Background

Norwegian Nuclear Decommissioning NND is working with Finnish AINS Group together with subconsultants VTT Technical Research Centre of Finland and BGE Technology GmbH of Germany. The group assists NND with the concept development and technical design for their disposal solution for radioactive waste in Norway.

Norway’s inventory of radioactive waste is characterized by high-level waste (HLW) from the research reactors in Halden and Kjeller, taken out of operation. In addition, there will be low and intermediate level waste from the planned decommissioning of the research reactors and other nuclear facilities. Norway has also other low-level waste generated by e.g. medical sector. NND is developing a comprehensive strategy for management of all classes of radioactive waste. Such a strategy could include the following facilities:

- Intermediate depth repository for low- and intermediate level waste,
- Deep geological repository OR Deep Borehole repository for high-level waste,
- Landfill-type repository for non-radioactive decommissioning waste.

Repository types are presented in the report “Concept Description for Norwegian National Disposal Facility for Radioactive waste“ (Ikonen et al. 2020). The report includes concise concept descriptions of the possible disposal options.

This report expands the deep borehole repository concept for Norway further than was presented in Ikonen et al. (2020).

1.2 Borehole disposal concept

Deep geological repositories use a combination of engineered and natural barriers to safely contain and isolate radioactive waste from people and the environment. Among the different geological formations considered suitable for hosting geological repositories, crystalline rocks are characterised by their high strength, thereby providing cavity stability, low heat sensitivity, low permeability and beneficial dissolution properties.

The borehole disposal concept consists of drilling a borehole to a depth of several kilometres, emplacing waste containers containing spent nuclear fuel (SNF) or HLW in the lower part of the borehole and then sealing the upper part of the borehole. Still, also other types of waste can be disposed of in boreholes, but the limited volume of the boreholes need to be kept in mind. Most of the concepts are based on the disposal of the waste packages in crystalline basement rock (typically granitic rock).

Borehole disposal facilities consist of surface facilities, such as disposal hall structure and emplacement rig, and the drilled deep borehole directly under the rig.

Disposal of nuclear and radioactive waste in deep boreholes has been examined as an alternative (or complementary) to the mined geological repositories. Primarily for small countries with limited radioactive waste deep borehole disposal is particularly interesting.

For larger waste volumes, numerous boreholes are required. In these cases, mined repositories could have advantages over borehole disposal. Also, the financial aspect comes to play if more boreholes are required for greater waste volumes. This is one of the main reasons why deep borehole disposal was not pursued further in Germany. Unlike excavated repositories, a deep borehole repository is inherently inaccessible to humans. While the primary benefits of borehole disposal are potential increased safety, reduced cost, and greater flexibility (Brady & Driscoll, 2010; Bates, Driscol, Lester, & Arnold, 2014), the method could also impact the implementation of international safeguards. One of the great advantages when it comes to the safety aspects is the fact that all work in deep borehole disposal is carried out on the surface. Compared to a mined repository, a great depth and thus a powerful geological barrier can be achieved relatively easily.

1.3 Borehole concept for Norway

Due to the small amount of high-level waste in Norway (e.g. Andreasson 2019), deep borehole disposal is a possible alternative to a mined repository (cf. IAEA 2017). With this concept, deep boreholes are drilled into crystalline rocks from the surface of the earth. After completion of waste disposal in the lower section, the upper section of the borehole is sealed with a long-term barrier system. The safety case for such a concept would place great emphasis on the great depth of burial, which shall ensure that the waste remain isolated from the accessible environment.

Crystalline rocks are widespread and offer advantageous conditions for deep borehole disposal in Norway. The geology of Norway is crystalline rocks sparsely covered with marine clay and other quaternary deposits. A borehole would reach the geological barrier at a shallow depth. The low heat flow and thus the low thermal depth gradients in the rock sequences of Norway are also considered to be advantageous. In wide areas of Norway, the seismicity is low. Also noteworthy is Norway's extraordinarily extensive expertise in deep drilling technology. There are numerous specialist companies and research and test centres that could contribute in the development of the borehole disposal techniques. Norway is recognized worldwide as a leader in the advances of offshore petroleum. For example, the department of Petroleum Engineering at the University of Stavanger has close ties with the local and international industry. Since 2002 Norway has been a member of the International Continental Scientific Drilling Program (ICDP). In addition, experience in drilling geothermal wells is constantly being gained in Norway.

Aspects regarding the disposal of high-level waste in Norway have already been discussed in Metcalfe et al. (2014) and in Mikkelsen & Kristiansen (2019). In addition, the report of Paulley et al. (2014) briefly discusses radioactive waste borehole disposal. The aim of this study was to describe a first concept of borehole disposal taking into account the waste quantities and general conditions in Norway and to investigate the possibility of deep borehole disposal in more detail. Metcalfe et al. (2014) distinguish two variants of borehole disposal:

1) The heat-generating waste is emplaced after little cooling, so that within the borehole sufficiently high temperatures are attained to melt the rock, thereby providing, after the melted rock subsequently cools and solidified, a low-permeability seal.

2) The waste is not melted by decay heat and sealing is provided by artificial barriers.

As already stated in Metcalfe et al. (2014), the first variant will not be feasible. The study only takes the second variant into account. Advantages and disadvantages of borehole disposal are also described in Metcalfe et al. (2014). According their study disadvantages are for example the immaturity of deep borehole disposal concepts as well as the use of non-shielded containers. In this regard, however, it must be taken into account that borehole disposal is also part of several concepts for radioactive waste disposal in mined repositories (cf. DBETEC 2016). An additional disadvantage could be the possibility of containers jamming in the borehole. The study looked into these issues.

1.4 Scope of work and structure of the report

The scope of this report is to provide basic information about deep borehole disposal. The main part of this is a literature study to summarize the information available. In combination with some information about the radioactive waste in Norway (inventory of the existing waste), some parts of the concept have been adapted to the Norwegian project. For the disposal operation and mainly the borehole construction a simple feasibility analysis has been carried out. This is mainly focussed on the borehole diameter and depth, since these have been constituted to be the main challenges and limiting factors of the project. Here again, existing reports have been the basis of the work. In the final chapter of this report, some recommendations for further studies are provided. These can set the basis for a more detailed concept, either for Norway, but also for other countries.

Figure 1-1 presents typical planning stages and their relationships for a deep borehole disposal repository. Each of the points are explained in more detail in the different chapters of this report. The different aspects described in the figure are mainly focussing on the construction and do not include external factors like the geology and governmental restrictions. Throughout the report, the dependency on the geology is pointed out several times, since it is one of the main influencing factors for the construction. Since this report focusses on the disposal of radioactive waste in Norway, the Norwegian geology is discussed in the beginning of the report in **Chapter 2**. Available waste packages as well as different materials are discussed in detail in **Chapter 3.** The aspects in Figure 1-1 are discussed in more detail in **Chapter 4**. The waste packages can be seen as a starting point for the construction planning process. The dimensions of the packages are influencing the borehole size and are therefore having a major impact on the whole project. For deep borehole disposal projects, the operation itself can be kept relatively simple and is focussed on in **Chapter 5**. In this chapter the general schedule of the project is discussed and factors influencing the duration of the different phases are explained. Also, different waste emplacement techniques (**Section 4.2.12**) are discussed. The final part of the disposal operation – closure – is discussed in **Chapter 6**. Closure also covers Institutional Control Period (also called “post closure”).

The structure of the report follows the general schedule of the disposal operation. Starting with the planning process, mainly based on the waste packages and the geology, followed by the construction. Next comes the operation and waste emplacement, before the operation is finalized and ended with closure actions. A general schedule for disposal operations following this schedule is shown in Figure 5-1.

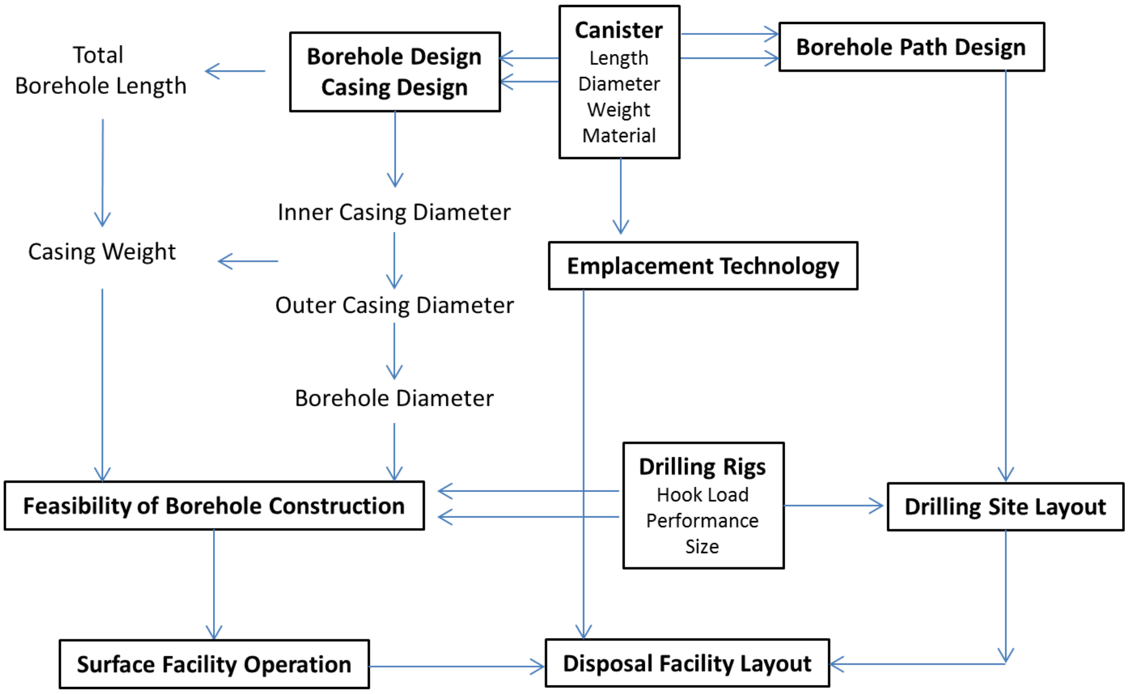


Figure 1-1 - Planning stages for a first design of a deep borehole disposal facility in Norway.

2 GEOLOGY OF NORWAY

2.1 Introduction

For borehole disposal, the geological and hydrogeological framework conditions are of the utmost importance, because the host rock contributes significantly to the isolation of the radionuclides. Thus, the geology is already decisive for the selection of the facility location (cf. Metcalfe et al. 2014: 6). The geological conditions, especially the occurrence of shear zones and faults, also have an impact on the borehole trajectory and depth as well as the casing and seal design. For this reason, the general geology of Norway is described in the following.

Topography is of minor relevance compared to a near-surface repository due to the small area required for borehole disposal. This can be an advantage of this disposal option, because Norway with a total area of 385,207 km² is dominated by mountain masses, with only one-fifth of its total area less than 150 m above sea level. The Glittertinden (2,472 m) and Galdhøpiggen (2,469 m) are the highest points in Europe north of the Alpine-Carpathian mountain range.

2.2 Main geological areas

Norway is formed of some of the oldest rocks in the world. The land is mostly made of crystalline rocks, but slate, sandstone, and limestone are also common, and the lowest elevations contain marine deposits (e.g. Ramberg et al. 2008). Above all, three large areas can be separated: the Precambrian basement, the Oslo rift zone and the Caledonides. This structure is important for the disposal of radioactive waste in boreholes.

Precambrian basement

The crystalline basement belongs to the Sveconorwegian province of the Baltic Shield. These rocks have an age of 1700 to 900 million years, so that after the periods of the earth's history the term Precambrian basement is also used. Most of these rocks were created during the Sveconorwegian orogeny. The orogenic belt is composed of five segments that were disrupted by both extension and compression in the timespan between 1140 and 980 million years ago. From west to east, the segments are the terrances of Telemarkia, Bamble, Kongsberg and Idefjorden plus the Eastern Segment. The segments are separated from each other by shear zones (Fig. A, cf. Gabrielsen et al. 2018).

As part of the Precambrian basement, the Western Gneiss Region should be considered separately. The region extends across western Norway from Bergen to Trondheim as a window in younger rocks. Outliers of the Western Gneiss Region crop out as far north as the Lofoten archipelago. The rocks are made up of variously deformed Precambrian basement.

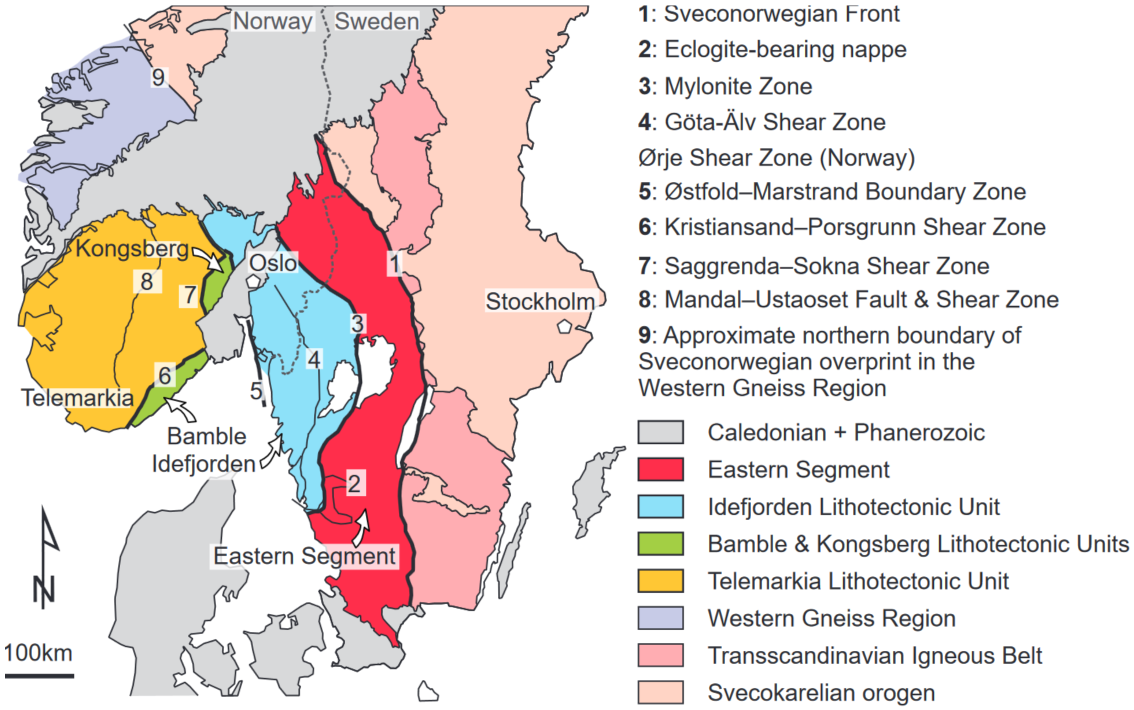


Figure 2-1 - The Precambrian basement of the southern part of Scandinavia (after Bingen & Viola 2018, cf. Bjørlykke & Olesen 2018 and Metcalfe et al. 2014, Fig. 2-1: Locations proposed in the Stranden Committee 2011).

2.2.1 Oslo rift zone

In southern Norway the crystalline basement is divided into two areas by the Oslo Rift (Oslo Graben). This rift has its earliest origins in the Precambrian; however, the rift as we know it today is largely Carboniferous-Permian. The rift was formed by lithospheric stretching, associated with igneous activity, so it is a high-volcanicity continental rift system.

It should be emphasized that light to minor Earthquakes occur along the rift, which can have magnitudes between 2.0 to 3.8 (“minor”) on the Richter Scale, and sometimes greater. Most recently there was a 5.4 (“moderate”) magnitude earthquake in Oslo on October 23, 1904. The continued movement of the Oslo Rift cause damage to roadways and bridges, and fracture foundations. There were at least 18 reported aftershocks that followed the main earthquake.

2.2.2 Scandinavian Caledonides

The largest area of Norway covers the mountains of the Scandinavian Caledonides that runs along the Atlantic coast. The assembly of the 1800 km long mountain belt was caused by a continental collision starting in the Ordovician and culminating in the mid Silurian to early Devonian. The Caledonian rocks form nappes that have been thrust over the older rocks. The rocks have normally suffered strong movements and alterations. In addition to the folding, the rocks were displaced along faults. Numerous shear zones are described (e.g. Fossen & Hurich 2005). Figure 2-2 is intended to illustrate the development of the mountain belt.

Much of the Caledonian rocks have been eroded since they were put in place meaning that they were once thicker and more contiguous. Now the roots of the mountain chain are exposed. It is also implied from the erosion that the nappes of Caledonian rock originally reached further east than they do today. The erosion has left remaining massifs of Caledonian rocks and windows of Precambrian aged rock. Quaternary glacial activities have carved out steep-sided valleys and deep fjords. Figure 2-3 shows a profile through Norway and illustrates the current geological situation and morphology. Figure 2-3 is intended to show the distribution of the essential geological elements of Norway on the earth's surface.

In order to better understand the orogenic processes, the project COSC (Collisional Orogeny in the Scandinavian Caledonides) was started. The project investigates the Seve Nape Complex that were emplaced onto the Baltoscandian platform and there influenced the underlying allochthons and the basement. COSC-1 is the first of two ca. 2.5 km deep, fully cored drill holes located in the vicinity of the abandoned Fröå mine, close to the town of Åre in Jämtland, central Sweden. It sampled a thick section of the lower part of the Seve Complex and was planned to penetrate its basal thrust zone into the underlying lower-grade metamorphosed allochthon. The hole reached a depth of 2495.8 meters.

Down to about 1800 meters, the COSC-1 drill hole penetrated a succession that is dominated by highly stressed rocks. Fractures are sparse. One obviously fluid-conducting set of steep fractures results in dissolution of calcite-rich bands in gneisses to form “micro-karst” (at about 175 meters and several levels between 1200 and 1320 meters). Increasing strain appear below 1700 meters in the form of deformation bands. Moreover, with increasing depth, rocks that were ground by tectonic pressure (mylonites) were found.

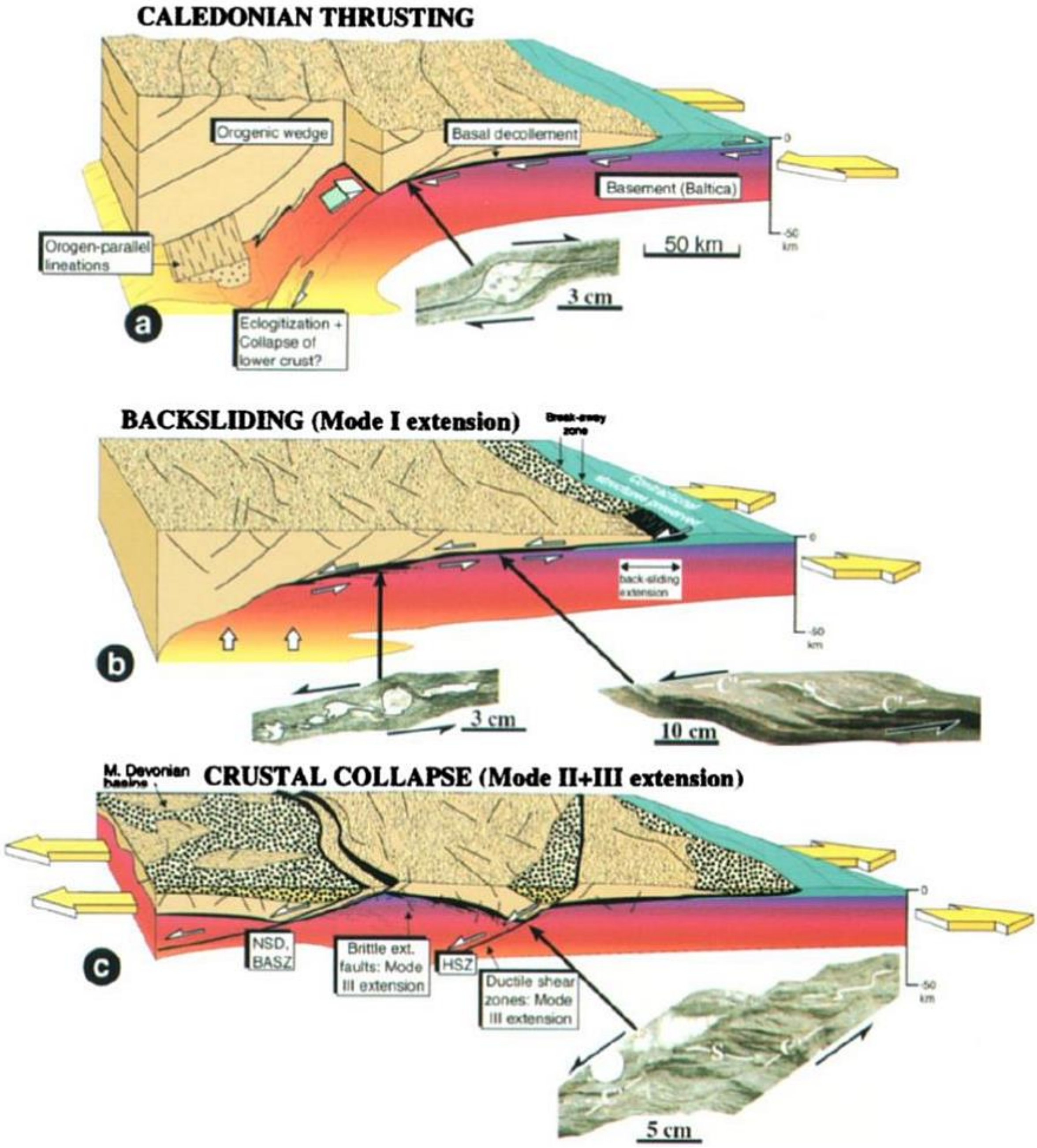


Figure 2-2 - Conceptual model for the structural and kinematic situation in western Norway from the Caledonian thrusting in (a), to the backsliding of the orogenic wedge (b) and crustal collapse (c). Additional images show structures formed during each mode. From Fossen (2000).

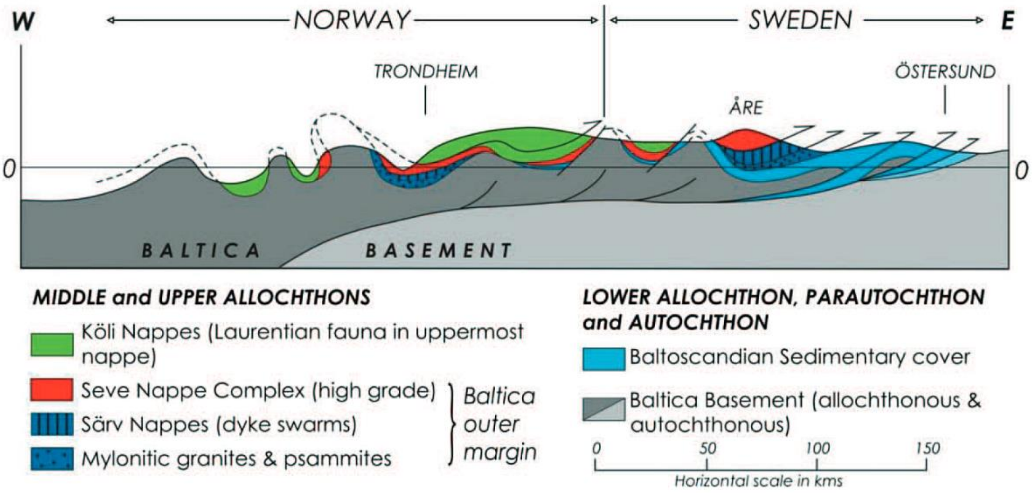


Figure 2-3 - Schematic profile through the Central Scandinavian Caledonides (Gee et al. 2010, cf. Bjørlykke & Olesen 2018).

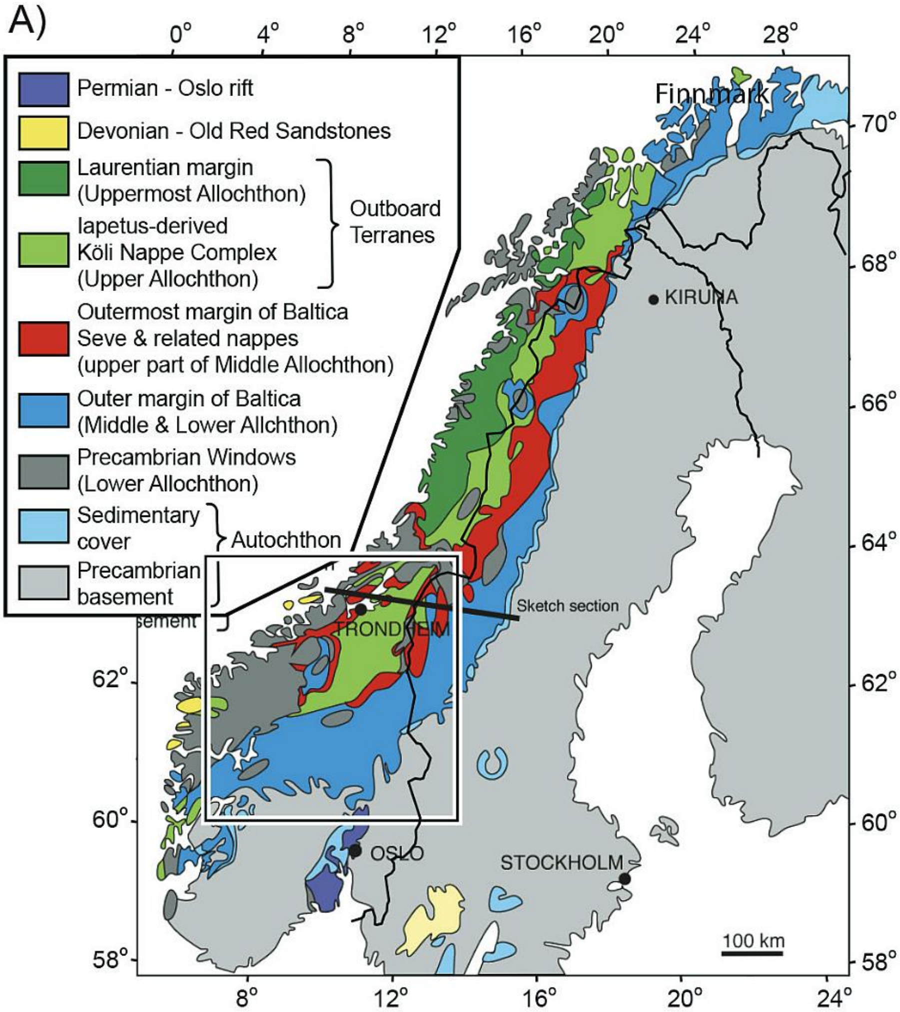


Figure 2-4 - Geological map of the Scandinavia showing the outcrops of the basement, the Caledonides, and the Oslo Rift.

2.3 Stress state, temperature and salinity

Information on stress and pressure (stress) as a function of depth is summarized in Figure 2-5. According to Simonsen (2018) collection of in-situ stress data shows that in most parts of Norway the major horizontal stress is greater than the vertical stress. Ridge push from the mid-Atlantic plate spreading is the primary source for tectonic stress in Norway. It is also likely the main reason for the high horizontal stresses in Norway. On regional scale, research has shown that the stresses to some degree are affected by the unloading due to deglaciation, and by the post-glacial uplift of the land.

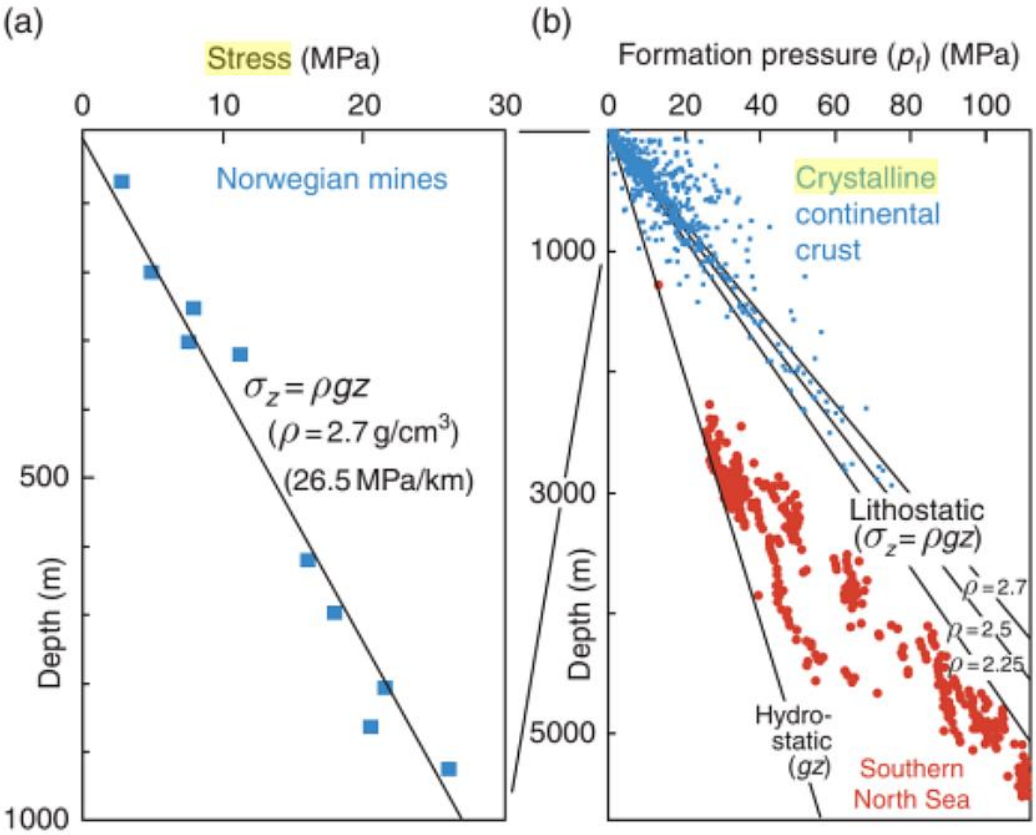


Figure 2-5 - (a) Vertical stress measurements compared to the theoretical curve for lithostatic stress (ρgz) in Norwegian mines down to 1 km depth (crystalline rocks). (b) Pressure data from crystalline rocks worldwide and North Sea sedimentary rocks. Note that these pressure data are for formation pressures, meaning fluid pressures. (From Fossen 2016)

Grønlie et al. (1980) describe for the Iddefjord granite in Østfold thermal gradients 1.4 to 21.5 °/km, and Midttømme et al. (2012) indicate that thermal gradients between 14 and 27 °/km are observed in Norway. Information is also given on the regional distribution of the heat flow, taking into account measurements from boreholes down to a depth of 1 km. On this basis, temperatures were derived for a depth of 5 km, which should be between 75°C and 140°C. Figure 2-6 shows rock temperatures versus depth from a COSC-1 borehole in the Caledonides. Results of another deep drilling are described in Rosberg & Erlström (2019).

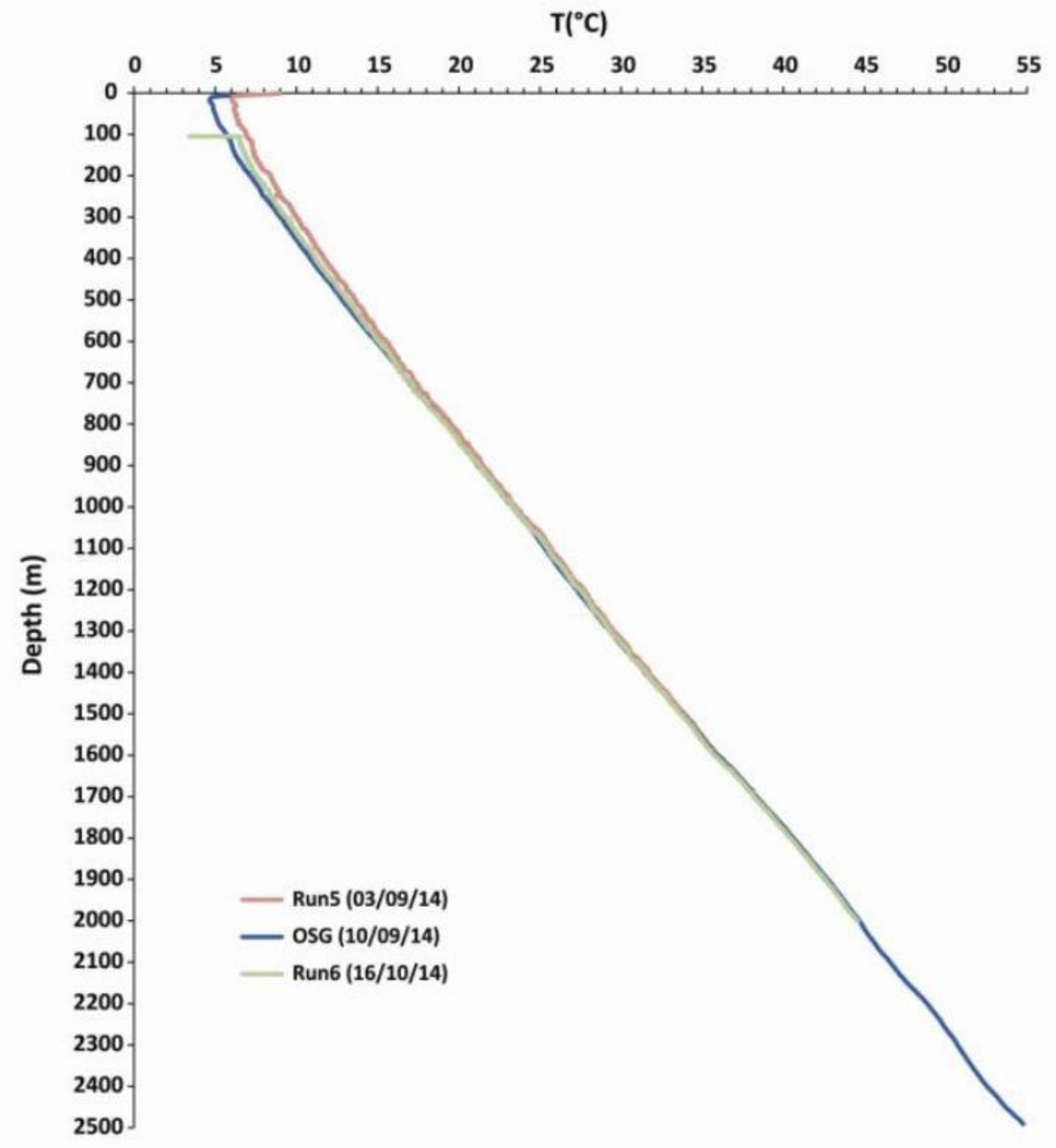


Figure 2-6 – Post-drilling temperature logs of the COSC-1 borehole according to Lorenz et al. (2015).

Crystalline rocks have characteristics of a decrease of their thermal conductivity with increasing temperature. Figure 2-7 illustrates this fact. Accordingly, the thermal conductivity of the rock formations decreases with increasing depth. This will impact the behaviour of the casing in the borehole, which is explained in more detail in chapter 4.2.5. Also, the thermal influence needs to be considered during the waste package design (chapter 3).

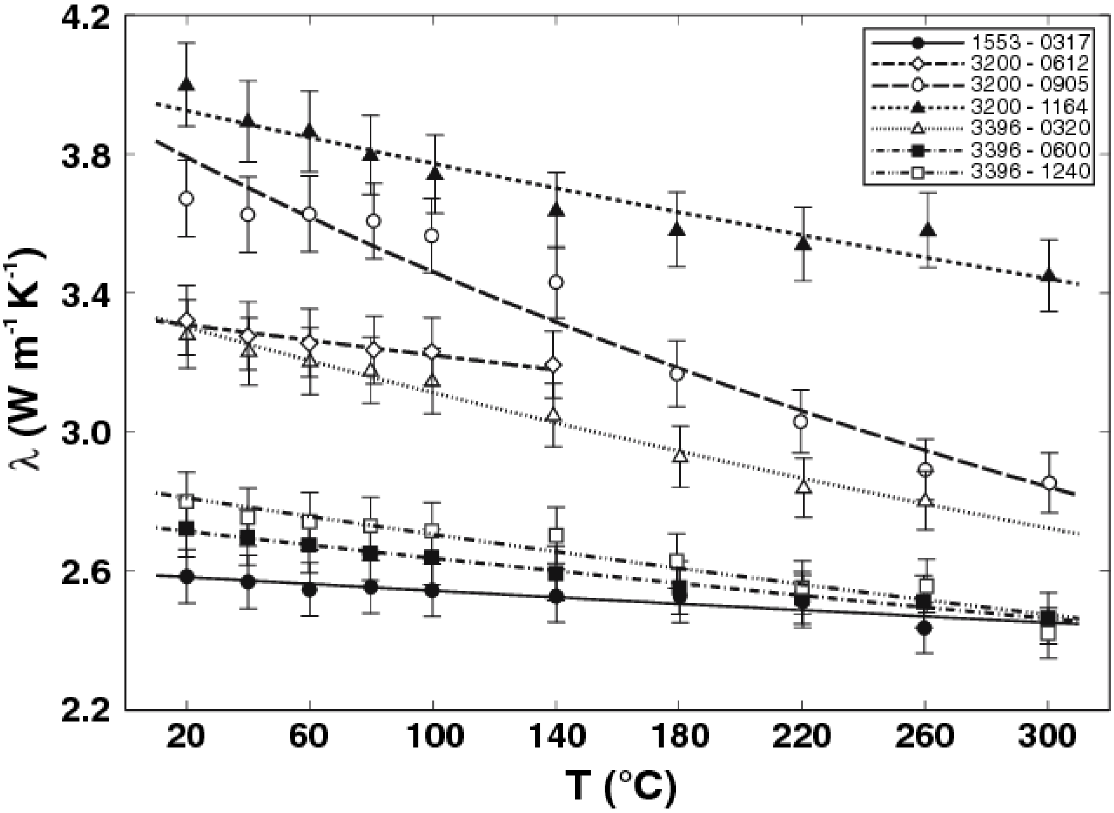


Figure 2-7 - Variation of thermal conductivity with temperature T for crystalline (metamorphic and magmatic) rock samples from the Kola Peninsula (after Mottaghy et al. 2008).

The salinity and density of groundwater and formation water generally increases with increasing depth. The waters are therefore less mobile and can only be exchanged to a limited extent. Their residence time in the deep rock strata is very long. In contrast to other disposal concepts, this fact can contribute to the long-term isolation of radionuclides in boreholes. On the basis of an initial, short-term literature search, however, no statements can be made about salinity or age of waters in deep Norway's crystalline rocks. Some basics of hydrochemistry can be found in Shand & Frengstad (2001).

2.4 Specifics in siting of borehole disposal facility

Siting a borehole disposal facility differs slight from the siting of a mined repository. The differences arise from example in the following areas:

- Less land area required for construction (no difference for operation),
- Greater depth of characterisation,
- Limited rock volume to be characterised,
- Less environmental disturbance (no drill/blast excavation, nor land areas for rock piles required)

The specifics of the site selection of a borehole facility are not further discussed in this document. The topic is covered for example in the work by Freeze et al. (2015).

2.5 Conclusion

In conclusion, the geology of Norway varies geographically. This affects in particular the area of the Oslo rift zone and the mountain range of the Caledonides. According to the known selection criteria (cf. Metcalfe et al. 2014), it can be assumed that borehole disposal in the Oslo rift zone is not feasible. In comparison to the Precambrian basement, a greater lithological heterogeneity and frequency of fractures can be expected in the area of the Caledonides. This is shown by the topography of Norway, which is supposed to be fault-controlled (Osmundsen et al. 2010). The Caledonian rocks are also strongly folded. However, borehole disposal provides the opportunity to react flexibly to these different framework conditions and to optimize the technical implementation accordingly. The Precambrian basement appears ideal for borehole disposal. Construction of the borehole in the Caledonides appears more challenging, but feasible.

3 WASTE PACKAGES

The IAEA terminology differentiates between waste packages and containers as follows; a waste package is the product of conditioning that includes the waste form and any container prepared in accordance with requirements for handling, transport, storage and disposal. (IAEA Radioactive Waste Management Glossary, 2003) Therefore, the container is basically a part of the waste package. The radioactive waste is placed into the container, which is then combined into packages, which are finally disposed of.

A container for the disposal of radioactive waste in deep boreholes needs to fulfil certain criteria. Bracke et al. (2016) list the following factors to be considered:

- Type and volume of the waste,
- Geometry of the waste,
- Mass of waste,
- Usable cross-section in the borehole,
- Design and choice of material for the waste package,
- Temperature field in the disposal area, and
- Medium (geological and geochemical environment) in which the disposal is to take place.

Aspects like the weight of the upper containers on the underlying containers also need to be taken into account. This means, the container does not only need to withstand the pressures and forces from the surrounding formations, but also gravitational forces in some way. Another important aspect, not listed above, is a suitable pick-up device for the coupling of the transport device (wireline, string etc. see Chapter 4.2.12).

All these factors, as well as the chemical environment in the disposal zone of the borehole, have an impact on the total lifetime of the container.

For the purpose of this report selected terms are clarified. In many papers and reports they are not used uniformly and sometimes they contradict each other (package, canister, container, capsule, transport container, etc.). The terms for this report only are defined as follows:

- Transport container (**transfer cask**): as the containers are not self-shielding, waste is placed in specially designed transport containers, which are shielding, for any transportation process (see Figure 3-1),
- **Container**: object that is lowered into the borehole; typically not self-shielding (see Figure 3-2),
- **Capsule/canister**: object that contains the actual waste package; typically not self-shielding; placed inside the container for the disposal into the borehole (see Figure 3-2),
- **Package**: a package describes a number of fuel rods or canisters of waste that is packed together; placed inside the capsule/canister (radioactive waste collection) or directly into the container (fuel rods).

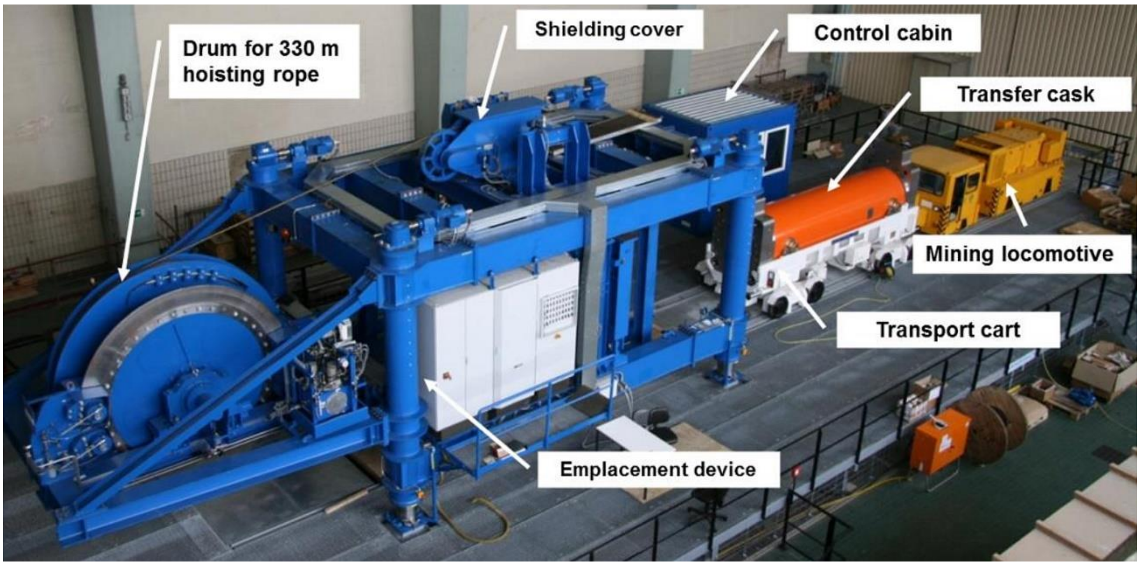


Figure 3-1 – Demonstration test stand of the storage device for deep vertical boreholes up to 300 m (Filbert et al., 2010)

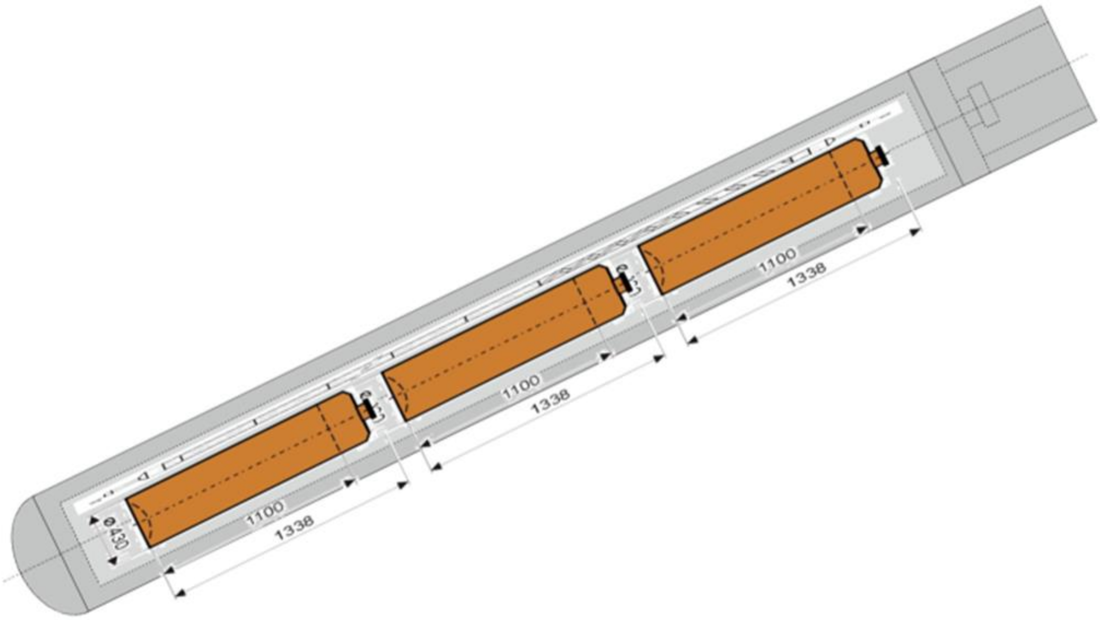


Figure 3-2 - Deep Borehole Container with three canisters and one rod for illustration according to Bracke et al. (2017).

There are also concepts studied in which the packages are not designed to withstand corrosion for long periods of time. In these cases, the waste containers have a relatively simple design, which will withstand mechanical stresses during handling and emplacement, as well as the hydrostatic pressures and temperatures. The containers are designed to retain their integrity until the borehole is loaded with waste, sealed and abandoned. (Brady et al., 2012) Even though this can be an option, in this project this approach was not followed.

3.1 IAEA Guidelines

According to IAEA (IAEA Nuclear Energy Series No. NW-T-1.19, 2009) the physical features of waste packages vary according to different waste package configurations. This means, the waste package design is strongly depending on the type of waste and disposal. The major parameters in which the packages differentiate are the physical properties like the size and mass, the container material, the type of radiological protection and the thermal output of the container. In addition, differences between long-term disposal containers and short-term durable containers have to be taken into account during the selection and design process.

Other than the design, which can be described as the dimension and mass of the container, IAEA provides a list of characteristics that should be considered during the selection. It needs to be differentiated between the different types of disposal. There are general requirements on the waste packages and separated to this, requirements on the waste containers itself. The general requirements on waste packages consist of the surface dose rate, the contamination and the waste package mass for example. The requirements on waste containers include basic requirements like the shape, the thermal resistance and mechanical stability and specifications of the inner containers. (IAEA-TECDOC-1515)

During the selection of a suitable waste container, the selection of the container material plays an important role. The materials can be subdivided into two main categories; concrete and metals, reinforcing and post-tensioning steel. For the long-term safety, different material aspects need to be considered (regarding IAEA-TECDOC-1515):

Concrete:

- Chemical – including leaching, corrosion, e.g. sulphate attack, acid attack (groundwater/acid rain), alkali aggregate reaction, and carbonation.
- Physical – including crystallization of salts, freeze-thaw action, abrasion/erosion, temperature cycling, vibration (fatigue), building movement and excessive loading (pressure).

Metals, reinforcing and post-tensioning steel:

- Chemical – corrosion, with rates enhanced by physical degradation, acidification, and chloride attack or migration (in concrete).
- Physicochemical – relaxation of tendons affecting the induced stresses (creep of concrete or steel).

The most important part during the selection or design process is the quality assurance and quality control program (see IAEA Safety Series No. 50-C/SG-Q).

Still, IAEA states, the national authorities or repository operators need to define the waste acceptance requirements. Based on this, an individual waste package can be designed according to the needs.

3.2 Waste package materials

Four different materials can be considered as the basis material for the containers: copper, steel, iron and silicon carbide. Each of these materials has positive and negative aspects, which need to be considered. A major concern when it comes to the material selection is the resistance to corrosion. King et al. (2002) differentiate the corrosion into different areas, first the corrosion prior to water saturation, next during the water saturation and last after water saturation. In addition, the impact of thermodynamics needs to be considered when investigating the corrosion of any material.

Copper has been tested and investigated for more than 20 years in Swedish and Finish nuclear waste programs. The research work has tested the behaviour of copper in conditions which are most likely to exist in an underground nuclear disposal repository. (King et al., 2002) This vast experience about the behaviour of copper has made it the most common material in container and container design for deep geological disposal of radioactive waste. All around the world, disposal programs have been dealing with copper. Disposal programs in the UK (NDA, 2010), Canada (Maak, 1999), as well as Switzerland (Johnson & King, 2003) and Japan (JNC, 2000) have adopted copper as one or the main material of choice. Numerous other publications have investigated this topic, which shows the great knowledge about the behaviour of copper. As all of these publications show, copper seems to be one of the most suitable materials for disposal containers. According to the state of knowledge, the corrosion of the copper will not limit the container lifetime. The reason for this is simply, that in closed repositories, as the borehole will be after a short time, the lack of oxidants. The same study brings up the topics of stress corrosion cracking (SCC) and corrosion induced by radiation effects. As in most types of corrosion, the probability of SCC will be greatest in the beginning, shortly after the disposal and will reduce over time. Also, other stresses on the waste containers will have an impact when it comes to the SCC. For example, pressures from the formation might deform the container shape, which will impact the stability of the waste package. The corrosion of copper waste packages is strongly related to the geochemical environment in the surrounding formation. Still, research in different locations, Sweden/Finland and Canada, come to the result that corrosion will not be the limiting factor when it comes to containers made mainly out of copper. However, it needs to be kept in mind, that copper is a relative weak material, when it comes to stability against outer forces and stresses. Therefore, an inner stabilization cage of some other stronger material should always be considered. (King et al., 2002)

Other containers, which are mainly used for transport purposes, are made out of steel or cast iron. In addition, aluminium containers have been designed. Previously SKB proposed to use containers made out of high purity alumina for the disposal. The production and the quality control of this material are relatively complex. Still, tests and calculations have shown that these containers are suitable for the disposal of radioactive waste in deep boreholes. As with all the other materials, certain criteria need to be followed to assure a safe and long-term disposal. (Mattsson, 1981)

Even though cast iron seems to be a suitable material option, concerns regarding the corrosion stability exist. The conditions in the deep geological formations will corrode the material fast and not uniformly. This makes it impossible to have reliable information about the long-term stability of containers made from cast iron itself. According to

Mattson (Mattsson, 1981), who refers to PNL (Westerman, 1980) and Shreir (Shreir, 1976), cast iron is not ensuring performance.

Whereas carbon steel containers have a relatively low mechanical strength and poor corrosion behaviour at higher temperatures, which can be expected in the deep disposal scenarios, silicon carbide has been investigated as a container material. Silicon carbide is a ceramic material, which is used in abrasive and cutting tools. Lee et al. have discussed a container with a combination of a Silicon carbide ceramic with an outer stainless steel coating. Even a feasibility test of the production has been carried out for this container design in a 1/3 scale. (Lee et al. 2018.)

3.3 Possible Waste Containers for borehole disposal

For the disposal of radioactive waste, different containers are available on the market. In general, containers can be differentiated in two different categories. First the transport and storage container and second the disposal container. Transport and storage containers are commonly used for the handling of fuel rods. These containers are also tested for the final disposal of the rods in horizontal disposal options in underground mines for example. An example of these types of containers is the CASTOR container, which is tested and built in different variations for disposal operations. The different variations differentiate in material, size, and design and have different shielding abilities. Another container designed for the disposal in the horizontal parts of mines is the POLLUX container. Different publications and research projects, like the LABRADOR research project (Dörr, Bollingerfehr, Filbert, & Tholen, 2011), have dealt with these containers and described the different characteristics in more detail. Containers designed for mined geological repositories, such as the KBS-3 canisters, are not suitable for deep borehole disposal due to the outer diameter of more than one meter. The general design can be used as a basis for a future canister, but with a reduced diameter to fit into the boreholes. Therefore, other options have been designed.

Although several different containers have been designed, not all will be considered in more detail in the following since either the containers are not suitable for the disposal of radioactive waste in deep boreholes or the current development status is not sufficient. Special containers designed for deep borehole disposal are described in different publications such as (Hoag, 2006) and (Rigali & Price, 2016). The containers can be differentiated in material, size, and weight for example.

For the deep borehole disposal concept in Norway, only containers with a diameter up to 50 cm can be considered. Larger-sized containers would be beneficial for the disposal operation, since fewer containers would need to be disposed; on the other hand, these large containers would push the capability of the drilling operation over the limit and would therefore not be possible.

All the containers for the disposal in deep boreholes are cylindrical in shape or are slightly conical. This shape fits perfectly to the round inner shape of the casing. Another feature, which is required for all containers, is something to grip onto. This is needed for a controlled disposal operation and also in case the container needs to be retrieved.

The most common and most advanced alternative is the so-called Brennstabkokille (BSK). This container is specially designed for the disposal of fuel rods in boreholes. The BSK containers have first been created as an alternative for the commonly used POLLUX containers, since the POLLUX was not designed to be disposed in vertical boreholes. The standard BSK container has a wall thickness of 40 mm. The container is made out of stainless steel. And if required this material choice can be adapted to other ones. (GNB, 1998) As many other containers, the BSK consists of a primary and secondary top, which represent a first and second safety barrier. Both tops are screwed onto the body of the container with a disk for neutron shielding in between. For special operations, there are modified BSK containers designed as well. These have a larger diameter to fit more or larger waste inside. Typically, any modifications are specially designed to fit assemblies with the radioactive waste. Similar to the BSK container design is the HAW container. This container is smaller and combined to packs of three, which are to be placed into an overpack. The overpack is a cylindrical body with a small wall thickness of 5 mm.

For disposal in shallow vertical boreholes, which is not considered for the Norwegian concept, two different options have been designed. The HLW and the CSD-C containers are designed for boreholes up to 300 meters in depth, as a part of mined repository in Germany. In the operation, only a sealing zone of about 10 meters is considered, which leaves up to 290 meters as the disposal zone. The actual disposal length depends on the heat development and type of waste to be disposed of. (Filbert, et al., 2010) Another option is the BSK 3 container. This container design is based on the BSK design but is slightly adapted. Due to these adaptations, the container is able to withstand lithostatic pressure at greater depth. Another difference to the classic BSK and HLW container is the closure. In this case the entire container is welded closed. Since the dimensions are similar to the most advanced and common alternative, the same handling and transportation equipment can be used for this container as well. The inside of the BSK 3 is designed to hold spent fuel rods or PWR fuel assemblies. Figure 3-3 shows a fabricated container dummy based on which is the design specifications of the BSK 3. (Filbert, et al., 2010)

Figure 3-3 - Fabricated container dummy (from Filbert, et al., 2010)

Other publications and companies have come up with their own container designs. These are mostly based and oriented on the already existing designs. One example is given in the publication by (Bracke, et al., 2016). The so called DBC-R has almost the same dimension as the BSK-R container. Both options are featuring a part on the top to secure the retrievability of the container, this the “R” in the container designation. The company Deep Isolation designed a small container for their concept. The container can be handled easily, but also cannot hold large volumes of radioactive waste. Deep Isolation has shown in a field test that it is possible to retrieve a container that has already been disposed of, from a horizontal borehole. (Deep Isolation. 2019) Another idea was brought up by Hoag (2006), who proposed to place PWR assemblies directly in the casing strings. This has the benefit that no additional containers need to be produced and handled. The long-time safety of this disposal method has not been studied or shown yet though.

A summary of the above-mentioned container designs is presented in

Table a.

Table a – Dimensions of different disposal containers.

	Outer length [mm]	Outer diameter [mm]	Inner length [mm]	Inner diameter [mm]	Mass [kg]	Additional information
BSK	4980	430 - 440 (at the lid)	4550	350		BSK-R has similar dimensions, only slightly longer
BSK-R	5060	520	4845	431		Container has slightly conical shape, (lower end has smaller diameter than the upper end)
Modified BSK (BSK THTR/AVR)	4980	705 - 715 (at the lid)	4550	625	3000 to 5000 (when filled)	
HLW canister	1338	430			500	
CSD-C canister	≤ 1345	≤ 440			850	
BSK 3	4980	≤ 440			5226	
DBC-R	5600	640 to 740		435	Up to 15000 (when filled with fuel rods)	To be designed

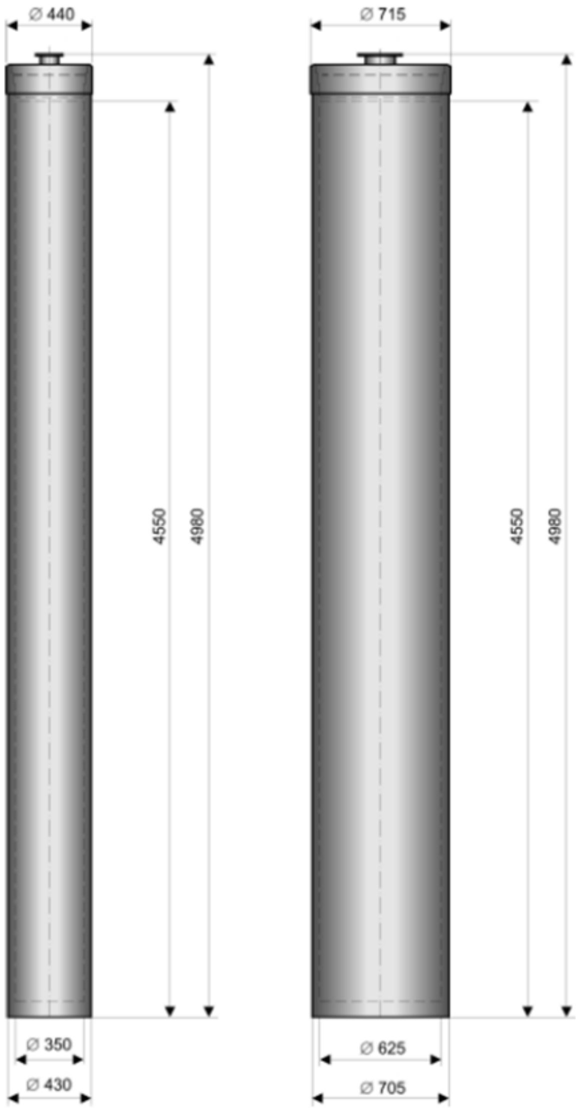


Figure 3-4 – schematic display of the standard BSK (left) and the modified BSK (BSK THTR/AVR) (right).

The available information indicates that general container designs already exist. The size and material are not defined and can be adapted to each project. For the Norway concept, the experience and knowledge from the Finnish and Swedish disposal programs was considered. Therefore, copper is the preferred material for the disposal container. The container will have similar dimensions as the BSK, DBC and KBS. These containers are similar in length and diameter. Also, the container size allows it to be fairly easily handled while providing adequate volume for the radioactive waste.

The PASS study (Nirex Report N/108, 2004) presented another option. This VDH (very deep borehole) concept considered two containers. The outside dimensions of the containers are the same in both cases, only the construction material and inner design is different. A titanium container with a concrete fill or a copper canister were considered. The titanium version contains, other than the concrete filling, either intact BWR (Boiling

Water Reactor) assemblies or consolidated assemblies, while the copper version is fabricated by using HIP (Hot Isostatic Pressing). Another important fact of this concept is that the containers are stacked on top of each other and are separated by bentonite buffers in the borehole. (SKB, 1992). This is similar to the concept proposed for Norway. The container design can be seen in Figure 3-5.

Another different container was developed for the so-called BOSS concept (IAEA, 2011). This container is for disposal of radioactive sources and not applicable for deep borehole disposal of fuel assemblies. This container type is therefore not considered further in this report.

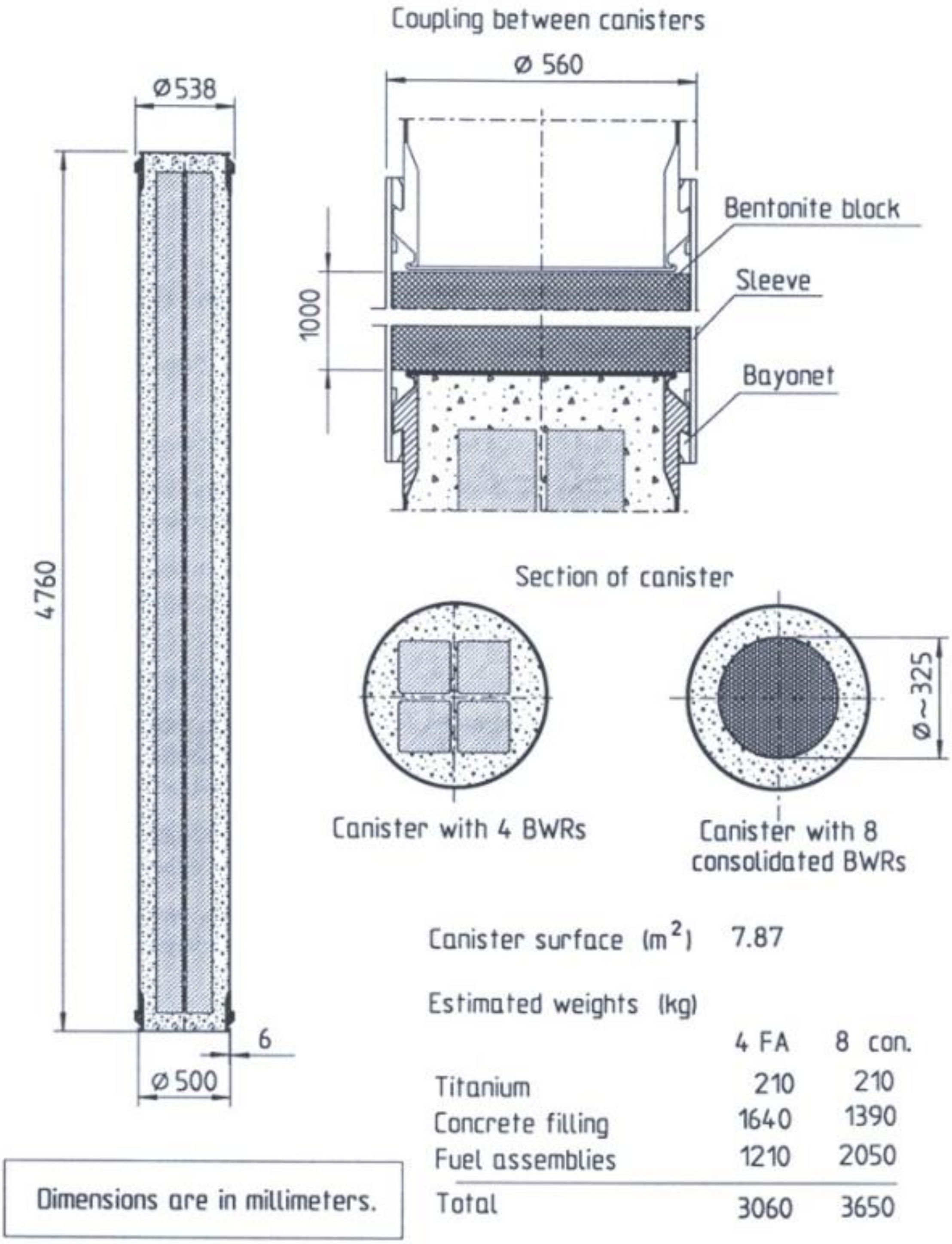


Figure 3-5 – Borehole container design for the use in VDH concept as presented in PASS study (Nirex Report N/108, 2004).

3.4 Number of canisters required for Norway

Considering the design of the BSK-R canister for this disposal concept in combination with the provided inventory as seen in Figure 3-6, first simple calculations have been carried out. These calculations are based only on geometric principles, basically the principle of how many small circles fit into a larger circle. Also, no safety measurements are considered at this stage of the concept development.

Reactor	JEEP I	HBWR 1st charge	JEEP II	HBWR 2nd to 4th charge	HBWR 5th charge	HBWR Booster	HBWR experimental
Fuel	U metal	U metal	UO_2	UO_2	UO_2	UO_2	UO_2, MOX, ThO_2
^{235}U enrichment (%)	0.72	0.72	3.5	≤ 10	≤ 10 (mostly 6)	≤ 20	≤ 20, >90 (HEU-Th)
Cladding material	Al	Al	Al	Zircaloy	Zircaloy	Zircaloy	Various
Uranium mass per rod (kg)	19	22	1	0.6 – 0.9	0.4 – 0.9	0.2 – 0.9	0.1 – 0.9
Burn-up (MWd/kg_U)	≤ 1	≤ 0.021	≤ 15	≤ 79.4	≤ 79.4	≤ 79.4	≤ 102.1
Rod length (m)	2.4	2.8	1.5	~ 1.8	1.1	≤ 1.1	≤ 1.1
Rod diameter (mm)	25	40	15	12.25 – 14.3	12.25	6.25 – 9.5	6.25 – 14.3
Number of rods (ca.)	170	300	1500	700	4500	2000	
Assemblies or single rods*	Assemblies	Rods	Assemblies	Assemblies	Mostly rods	Rods and assemblies	Mostly rods
Assembly length (m)	2.8	2.8	1.5	2nd charge: 2.83, 3rd & 4th charge: 3.66	1.1	1.2	Max. 1.2
Assembly diameter (mm)	70	40	90	≤ 70	≤ 70	≤ 70	≤ 70
Number of rods per assembly	2*	1*	11*	7*			
Number of assemblies (ca.)	85**	300**	136**	100**			
Mass (kg)	3000	7000.0	1500	3600		1400	
Mass per assembly (kg)	35.29	23.3	11.03	4.2 - 6.3	0.4 – 0.9	0.2 – 0.9	0.1 – 0.9
Current storage condition	Dry	Dry	Dry	Dry / wet	Dry / wet	Dry / wet	Dry / wet

Figure 3-6 – Waste inventory for Norway. Data is from WP1 report[1], table 2-1.

The waste from the different reactors are handled and the number of BSK-Rs are calculated individually. The diameter of the assemblies and the inner diameter of the BSK-R are providing a diameter ratio. This is then used to see how many assemblies fit into one BSK-R. Next the length of the assemblies and the inner length of the BSK-R are used to see how many assemblies can be stacked above each other in the canister. These two numbers provide a value for the number of BSK-Rs required for each reactor. Carrying out this calculation for each canister results in the total number of canisters.

The total number of canisters is 69. Considering an additional meter per canister as buffer zone, this results in a total disposal length of just over 450 meter.

3.5 Summary

For borehole operations there are two ways to choose the waste container. Either the borehole diameter is based on the dimensions of the container or the containers are selected and designed to fit the borehole. The slightly conical shape of the BSK-R seems to be the perfect option for the waste disposal in boreholes. Since the bottom part has a

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[1] Loukusa & Nordman. 2020. Feasibility of KBS-3 spent fuel disposal concept for Norwegian spend fuel. NND WP1 Technical Report. VTT. Espoo, Finland. May 2020.

smaller diameter than the top, lowering the packages into the borehole will run smoothly. Other than the diameter of the packages, the length is not fixed. The outer diameter is limited due to the limited borehole diameter. The length can be adapted to the length of the fuel rods or vitrified waste containers. An individual length according to the type of waste should be considered. This might influence the cost, since several different container types are needed, but the borehole depth can be optimized.

With all the different available options, no additional, totally new container needs to be designed for the disposal concept in Norway. Having an inner diameter of the disposal casing of roughly 600 mm in mind and consideration of the required clearance, the maximum outer diameter of the container is about 520 mm. This makes the BSK-R container suitable for the operation. Due to the extensive knowledge about copper and its good corrosion behaviour, the main material of the container is copper. The favourable option for this disposal concept is the BSK-RCu. This container has the same dimensions are the BSK-R and is made out of copper.

4 CONSTRUCTION

4.1 Disposal facility layout

The design and layout of the site varies depending on the type, characteristics, and quantities of waste and on the site characteristics. In the case of this study, it is assumed that vehicles (for example trucks) deliver non-self-shielding containers in shielded transport or transfer cask. Initially, an acceptance control (quality control) takes place. The emplacement container is then separated from the transport cask. The emplacement device is the most important part of the site with regard to the objective of the work and the aspects of radiation protection; however, numerous activities for monitoring and ensuring radiation protection are required. The shape and size of the disposal facility must be selected so that all work can be carried out without problems and the required safety distances can be maintained. Due to the fact that no site has been selected so far, it is assumed that the site area is almost flat. In addition, it is assumed that no special measures due to unfavourable climatic conditions are required, such as flood barriers / embankments in case of flooding. Restrictions or requirements for the project can also result from nature conservation laws or emission control laws.

The aim of this chapter is to identify the essential functional elements that are required for the operation of the facility. Then criteria for their arrangement are listed. Their application will resulted in a first draft of the facility layout (Ikonen et al. 2020). For the purpose of this generic description, the facility is assumed as a deep borehole disposal repository, which is located on the same site as repositories for LLW and ILW. Still, an additional security zone for the borehole disposal facility has been considered. The description can be used more widely in the borehole disposal concept, not just to the specific concept case that was described in WP2 report (Ikonen et al. 2020). Scheme of a disposal facility layout is shown in Figure 4-1.

Basically, the facility area can be divided according to its use:

- security zone around the facility, which can be secured by fences or walls (outer and inner perimeter). A site is here defined as an area where the facility owner has an authority, surrounded by physical barriers and where only controlled access takes place,
- open spaces (grassed or green areas),
- traffic areas (sidewalks, roadways, parking lots, garages, or covered areas), and
- buildings.

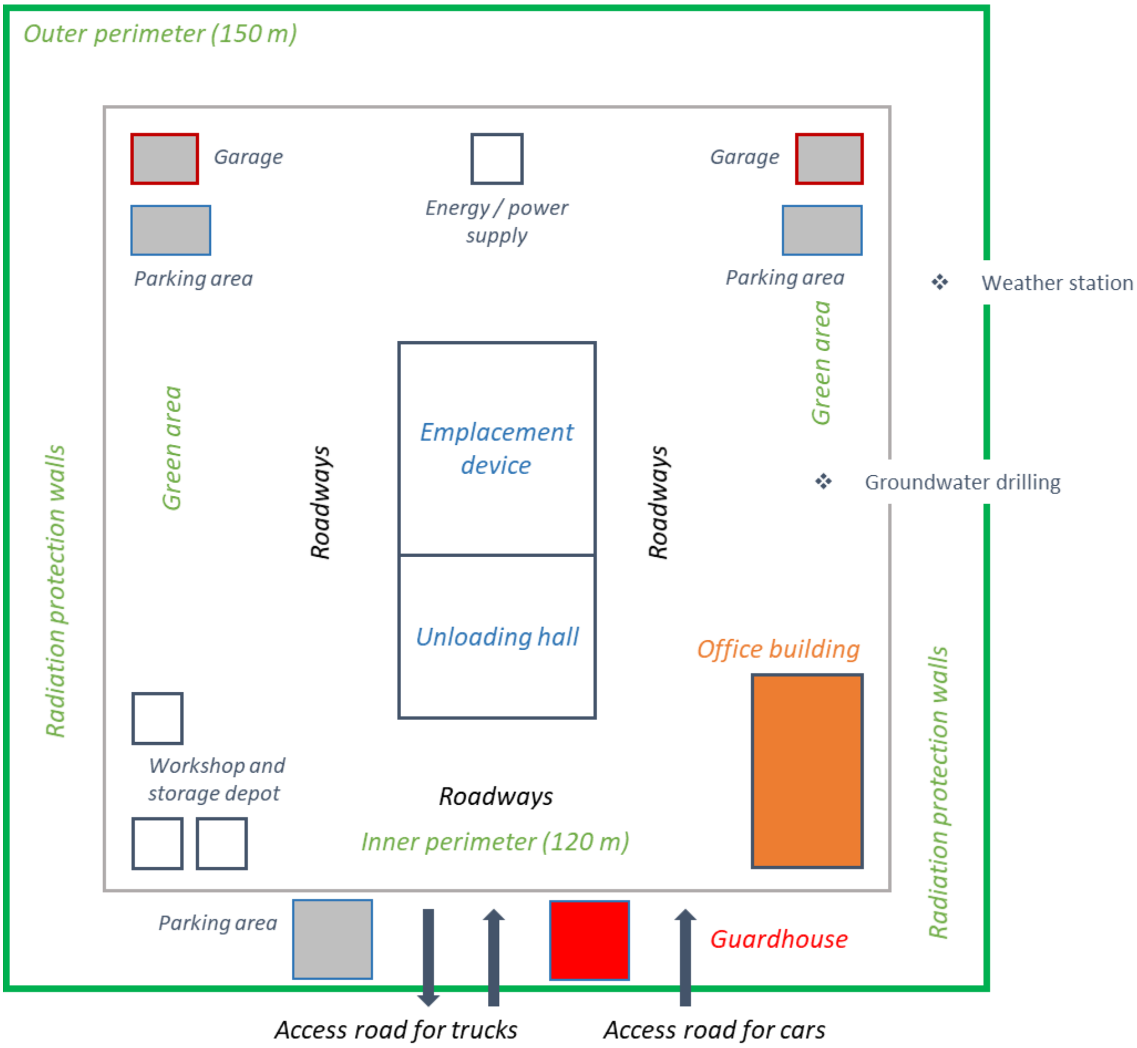

Figure 4-1 - Scheme of the disposal facility layout. The edge length of the square base is 150 m. Unloading and emplacement takes place in a closed hall called emplacement building. The unloading hall also contains rooms for performing activities to ensure radiation protection.

4.1.1 Security zone

Between the fenced inner and outer perimeters, the guardhouse is located. The distance between the fences must be large enough that trucks can stop there. In the security zone there can also be parking spaces, lighting equipment, earth walls and radiation protection walls. Measuring devices of the monitoring and surveillance program can also be positioned here.

4.1.2 Open spaces

Within the inner perimeter open areas are required, for example, to maintain minimum distances between buildings. All areas of a security zone should be accessible without being forced to cross another security zone. Open spaces can also be used as parking and driving areas in the event of an accident or as a helipad.

4.1.3 Areas of passenger and vehicle traffic

Before determining traffic areas, the traffic has to be structured according its type and frequency. Groups that can be specified include:

1 Transportation (delivery) of the waste packages by vehicle (for example a truck). Sometimes, the transports is escorted by extra security.

2 Departure of the vehicle with the transport cask.

3 Delivery of conventional goods by vehicles.

4 Movement of employees in vehicles

5 Traffic as a result of visits from craftsmen, qualified visitors or external company employees, and

6 Traffic of fire brigades, police, ambulances, and security guards.

The trips of the group 1 go into the control near the emplacement device. Traffic of the group 2 leaves the control area. Otherwise, no cars or trucks are moved in this area during normal operation of the facility; however, the use of forklifts is possible. Vehicles of the traffic groups 3 and 4 should definite not get into the control area and traffic of the group 5 should be avoided unless absolutely necessary. Traffic of the last group is special because this traffic does not follow planned routes and the amount of traffic is difficult to deduce. The traffic routes of the first five groups has to be planned in such a way that the traffic of this last group can flow smoothly. Traffic will follow national traffic regulations. Oncoming traffic and return trips should be avoided as far as possible by minimizing the traffic to a minimum.

The number of car parking spaces is based on the number of employees and the foreseeable visitor traffic. Parking spaces for trucks of the first and second group are not required outside the unloading hall (part of emplacement building). A longer stay on public roads (travel and parking time) should be excluded by appropriate logistics of the delivery.

Garages or covered places are connected to the transport network and are therefore described here and not in context with the buildings. They serve to protect vehicles and equipment and can be used as storage areas. For example, winter service vehicles can be parked.

4.1.4 Buildings

The operation of the facility requires buildings according their function. A distinction be made between the following buildings.

1 Emplacement device and the unloading hall form the emplacement building (waste activities buildings according to Gaynor 1989, chapter 4.2.3),

2 Buildings to carry out radiation protection activities, including the access control building with the personnel entrance/exit for the controlled area (Gaynor 1989, chapter 4.2.2),

3 Buildings with showers, changing facilities and offices for the storage and serving of personal protective equipment,

4 Office buildings (administration buildings according to Gaynor 1989, chapter 4.2.1), which should also contain meeting rooms, first-aid rooms, break rooms and a canteen,

5 Guardhouses,

6 Buildings with energy supply systems, emergency generators, heating technology, etc., and

7 Warehouses, workshops, and an area for the washing of vehicles (maintenance buildings according to Gaynor 1989, chapter 4.2.4).

A petrol station has not been considered. Vehicles that do not leave the facility should be electric. An operation of diesel or gasoline engines is avoided. Residential buildings are not built and the administrative offices are to be reduced to a minimum. In practice several of the listed buildings can be organised as a single physical building.

4.1.5 Criteria for the arrangement of the buildings

In contrast to the drilling site (chapter 4.2.4), there are no detailed guidelines for planning sites of deep borehole disposal facilities. However, the experience and knowledge of building surface and near-surface facilities can be considered.

In order to ensure optimal use, the buildings should be combined into multifunctional buildings as far as this makes sense. This includes, for example, the combination of type 1 to type 3 buildings (see the list above). The total usable space required results from the kind of activities and the number of employees. The total usable area does not have to correspond to the space requirement, because multi-story buildings can be erected. With a longer operational period of the facility, buildings with a basement could also be useful. However, based on current planning and short duration of the operations, it is assumed that container type buildings can be used at least in part and/or buildings that will be built in a modular design.

For the arrangement of the buildings, their use, i.e. their assignment to the individual security zones is relevant. In addition, an assignment to the traffic routes must be made. It is important to make the transport, walking and driving routes as short as possible. This applies in particular to the length of the escape routes. Frequently or permanently used buildings, such as the guardhouse, should be as far away as possible from the location of the emplacement device and ventilation devices of the buildings in the control area.

With the aim to save costs and time, the work for the construction of the drilling site and the disposal facility should be coordinated. For example, it is possible to continue driveways of the drilling site, storage areas and building foundations. These recommendations and requirements result in a concentric layout of the facility. The unloading hall, the emplacement device and the radiation protection and monitoring facilities are located in the central control area forming so called emplacement building in Ikonen et al. (2020). Type 4, 6 and 7 buildings are located at the edge of the inner perimeter. The guard building (type 5) must be in the area between the fences of the inner and outer perimeter (see Figure 4-1). A short and direct route from the guardhouse should lead directly to the unloading hall.

The layouts of a deep borehole facility and of a deep geological repository are comparable. The differences in size and shape result from the differences of the delivery frequency and the size of the waste packages as well as the type of delivery. Compared to other types of final disposal, the low space requirement during construction of a deep borehole facility should be emphasized, even with comparable waste quantities. Figure 4-2 shows a sketch of the area around the Konrad 2 shaft in Germany. In accordance with nuclear law, the Konrad was licensed in 2007 as the first repository in Germany. The former iron ore mine is currently being converted into a LILW repository and will store over 303,000 m^3 of radioactive waste.

Blasted rock and crushing plant, backfill manufacturing plant and encapsulation plant are assumed to be located outside the National Facility (Ikonen et al. 2020), so repositories, it is not necessary to store large amounts of excavated rock at the site. The volume of a borehole is small and it is assumed that the rock material will be removed from the premises. Consequently, the reference borehole facility layout considered no areas for storing rock material.

Figure 4-2 - Planned construction of the surface facilities around the Konrad 2 shaft.1: transfer hall; 2: shaft tower; 3: guardhouse; 4: engine shed, 5: warehouse and workshop, 6: winding system; 7: forklift, garage 8: petrol station; 9: supply area, 10: helicopter pad; 11: truck parking spaces; 12: buffer hall; 13: mine water transfer station; 14: shielding wall.

4.2 Implementation and construction

Drilling a well can be described as a repetitive process of digging and construction. Every time a part of the hole is dug, or rather drilled, a process of construction, to stabilize the hole, follows.

4.2.1 General drilling process

Figure 4-3 is intended to show the dependence of the drilling depth on the time when drilling deep boreholes. The ascending sections apply to the drilling process. During the time phases, which are marked by horizontal sections, casing or liner is installed, repair or maintenance work is carried out or borehole measurements are done. These horizontal sections represent the construction parts. It can be seen that the depth of the boreholes does not depend linearly on the duration of the work. For example, the sections of the drilling work flatten out with increasing depth.

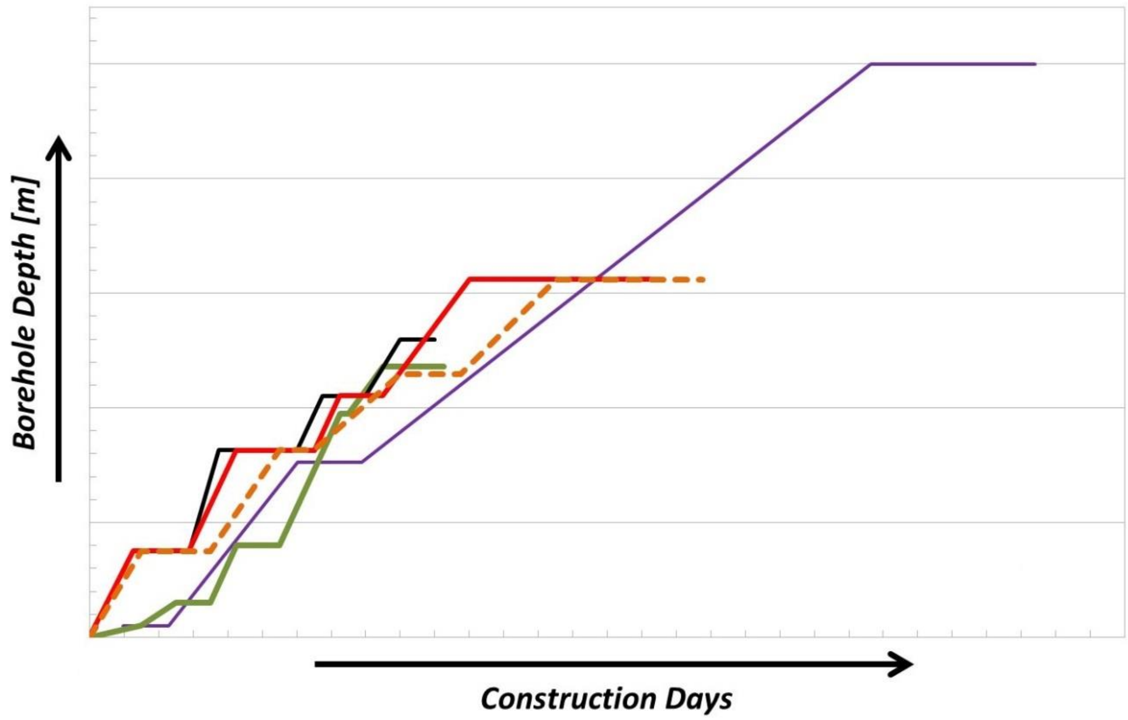

Figure 4-3 – Time versus depth graph

As in any subsurface construction the drilling process has its complexities in both digging and constructing phases. These are related to the construction medium, the geological environment. Factors affecting the drilling process are for example:

- Geology: formation tops, formation dips, faults
- Pore pressures: high pressure lenses, pressure margins
- Fracture gradients: wellbore integrity, loss/weak zones
- Formation fluids: oil/gas/brines, H_2S, CO_2

The related uncertainties are minimized by site investigations. The investigations can include offset wells, seismic studies, geological modelling and so on. In addition, during the drilling work the borehole/well is characterised so that the construction process can be adapted, if needed, to take account the actual hole conditions.

In addition to the above-mentioned geological factors there are construction related uncertainties, such as

- Hole condition: cumulative dogleg, hole tortuosity, calliper/ledges
- Logging: wireline/TLC
- Running casing: squeezing salts, swelling shales, sloughing coals
- Cementing: hole volume, flow regimes, centralization/standoff[2]

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[2] Terms widely used in oil/gas borehole industry are explained here www.glossary.oilfield.slb.com

Condition of the hole has the greatest impact on the construction. An unfavourable hole condition will complicate all the activities and may lead to an overall non-optimal operation.

All wells are pretty much established the same way. This process is described by the well delivery workflow. The workflow provides a basis for the well design and helps to establish the best way to complete the operation in the best and safest way. Wintershall Dea GmbH for example uses a five-step workflow (Wintershall Well Engineering Management Systems – WEMS).

1. Step: initiate well concepts
2. Step: verify well concepts (consider alternatives and select a concept in the end)
3. Step: finalize well design (detailed work based on the decision made before)
4. Step: execute well (starts with the spud of the well and ends with the release of the rig)
5. Step: evaluate well results (followed by a share and learn process, which can directly be used for the next wells drilled → lesson learned)

This shows how much effort needs to be put into the operation and how small the actual execution of the drilling itself is.

Drilling a borehole cannot easily be summarized shortly, since it is a complicated activity and many factors are playing a role in the operation. The simple description of digging and constructing breaks drilling down to show the basics of this technology. Still, it has to be kept in mind that there are numerous factors which are playing a role throughout the whole operation.

4.2.2 Borehole design and construction

Within the past decades, wells have been drilled for several purposes. In most cases, the deep boreholes were for the production of oil and gas. With improving technology and a greater focus on costs, the industry started to look for options other than the traditional vertical well. In more and more cases, it was just not possible to reach a reservoir with a vertical well. Typical examples for this are an oil or gas reservoir under a town, a lake or a difficult to drill formation. Therefore, technologies were introduced to reach the reservoir from other surface locations. With time new equipment, more and more different options came up.

Today, the wellbore trajectory can be broken down into three different types additional to the classical vertical well. A basic overview of these three types can be seen in Figure 4-4.

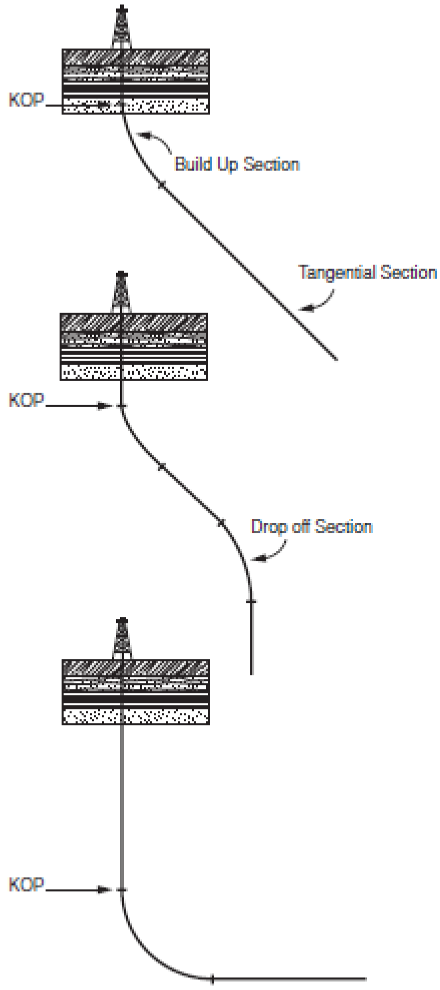


Figure 4-4 – Different well trajectories according to the Department of Petroleum Engineering of the Heriot Watt University. KOP: Kick-Off-Point

The upmost part shows the so-called build and hold well type. This means the first part of the borehole is drilled and a certain depth, for example after exiting the groundwater aquifer, the well is kicked off. This point is defined as the kick-off-point (KOP). From this point onwards, the well is built up. The length and the angle are different from well to well, depending on the required horizontal displacement and the prewritten well design. Once the required angle is achieved, the well will be drilled straight again to the wanted target.

Below the build and hold well type, the s-shaped borehole can be seen. This borehole design is similar to the build and hold design, it only has a drop off section prior to meeting the predefined target. This means the borehole has a vertical part at the beginning and the end with a tangential section in between. Both of these borehole types can be seen as inclined boreholes. The s-shaped boreholes are usually drilled if the subsurface target cannot be reached with a vertical well. Reasons are already mentioned before, but also an already existing drill site, which can be used, might be the reason to drill this well trajectory. Since the s-shaped drill path does not feature many benefits for the disposal of radioactive waste, it is not included in the upcoming discussion.

The last part of the figure displays a horizontal borehole. Here, the borehole is typically drilled vertical for a long distance until the KOP is reached. Again, a build-up section follows. Once a horizontal tangent can be drawn from the borehole, the path is straightened, and the horizontal section of the borehole is drilled.

In the past, combinations of the different borehole trajectories have been implemented. In addition, operations with the so-called multilateral drilling are widely used in the drilling industry today. Multilateral drilling means that one well is drilled, but several laterals are side-tracked from this main borehole. Therefore, the upmost part of the borehole is used for several laterals, which minimizes the drilled length, as well as the surface footprint.

Directional drilling summarizes all wells that are drilled while controlling direction and deviation of the borehole path. Drilling directional wells, either s-shaped or horizontal, is done for several reasons other than the reason already mentioned. In the oil and gas industry, this provides the advantage to maximize the length through the hydrocarbon reservoir. This can be done either by drilling at an angle or by drilling horizontally. Since money plays an important role in the oil and gas industry, companies try to minimize the surface footprint, as this is always linked to costs. Directional drilling provides the possibility to drill several wells from only one surface location. Therefore, only one drilling location is needed, as well as only one production facility.

It needs to be mentioned, that all three well types can be drilled with today's technology, but they are different in terms of complexity of the operation. Vertical wells are the easiest wells to drill. Deviated wells are already more complex, but still do not require a lot of special tools and are relatively easy to handle. The most complex operations are linked to horizontal wells. Linked to the complexity of the well types is the rate of penetration. Usually vertical wells can be drilled and completed faster than other trajectories. With the improving technologies and the focus on deviated and horizontal drilling, the rate of penetration has improved significantly. Today, downhole motors used for any type of deviated wells are almost as efficient as the equipment used for vertical wells.

Even though the horizontal wells seem to be most promising, since many positive arguments can be found for this option, there are also several counter arguments to its use. Once the well is at its horizontal stage, there is almost no limit to the length of the disposal zone. Of all the options, horizontal wells provide the longest disposal zone, no matter how the well is drilled. With a rather small surface footprint, a relatively large amount of radioactive waste can be disposed of in the subsurface. This long horizontal section brings, compared to the other options, a first negative aspect. The longer the horizontal section, the more challenging is the drilling operation. Horizontal drilling is a complex operation, which is carried out regularly in the drilling industry, but constantly challenges the drillers. Problems with the torque and drag and a relatively high wear on the equipment are commonly faced. The minimum curve radius for the change from vertical to horizontal is limited by three basic conditions:

- The control options of the drilling process (change of direction of the drill bit during the drilling process

- The technical possibilities when setting the casing

- The length and diameter of the waste packages and the distance from the borehole wall required to prevent the waste packages from wedging

This limits the possibilities to select the well trajectory for horizontal wells greatly. During the completion of horizontal wells, the cementing operation can be complicated. To have competent and even cement job all around the casing in the horizontal section is complicated to achieve and brings problems to many drillers. The longer the horizontal section is drilled, the more challenging is this operation, without considering slightly upwardly inclined sections. Most of the negative aspects are closely linked to the drilling and completion operation. Once the containers are disposed of, some positive aspects come up. First, the disposed containers are not experiencing pressure from containers disposed of above, since they are placed next to each other in the horizontal section. Even if the disposal zone is drilled slightly upward, only small stresses are put on the containers. The idea of a slightly upward disposal zone comes from the thought of a potential flow path to the surface. The worst-case scenario is that radioactive waste gets out of the containers and contaminates fluids through which the radioactivity can be transported. In common wells, the well itself is a direct connection between the disposal zone and the surface. Even if the wellbore is sealed, plugged and backfilled, a potential flow path will remain. Therefore, contaminated fluids might migrate through the sealed borehole. If the disposal section is slightly upward, these fluids would need to migrate through the undisturbed formation, which is a natural, geological barrier. Another challenge comes up during the disposal and potential retrieval phase. Placing containers with radioactive waste in horizontal sections of a borehole requires special equipment. Here are still some technical limits. Table b summarises the positive and negative aspects of borehole trajectories.

Table b - Positive and negative aspects of the wellbore trajectories for radioactive waste disposal.

	Vertical wells	**Deviated wells**	**Horizontal wells**
Positive aspects	Easiest to drill and complete Possibility to minimize casing program Disposal and retrieval relatively easy Relatively easy sealing and backfilling operations	Several wells from one surface location to different subsurface targets possible Reduced pressure on containers	Longest disposal zone Less potential flow path through the borehole (if the horizontal section is slightly upward) No pressure put on disposal containers by other containers
Negative aspects	Short disposal zone Potential flow path to the surface through the borehole Great pressure on the lowest container by overlying containers Only one borehole from one surface location	Potential flow path to the surface through the borehole Increased torque and drag during the drilling operation	Complicated drilling operation (torque and drag etc.) Cementation of horizontal part challenging Disposal and retrieval difficult Diameter might be limited Uniform cement job in the horizontal section challenging

Even though Deep Isolation has successfully and briefly tested equipment for the disposal and retrieval of waste containers in a borehole with a depth of over 2000 feet (The Deep Isolation Texas Demonstration, 2019), there is no final solution yet. On the other hand, Deep Isolation has developed a concept for the borehole disposal in horizontal wells. Figure 4-5 shows the schematic display of this concept. This concept consists of a rather shallow borehole down to 1000 meters. Here the horizontal section starts. The final length of the borehole is dependent on the waste amount. Because of the small-diameter borehole, no exact number is given, only small containers can be placed into the hole. (Muller et al., 2019) The negative aspects and the horizontal concept is discussed several times in this report.

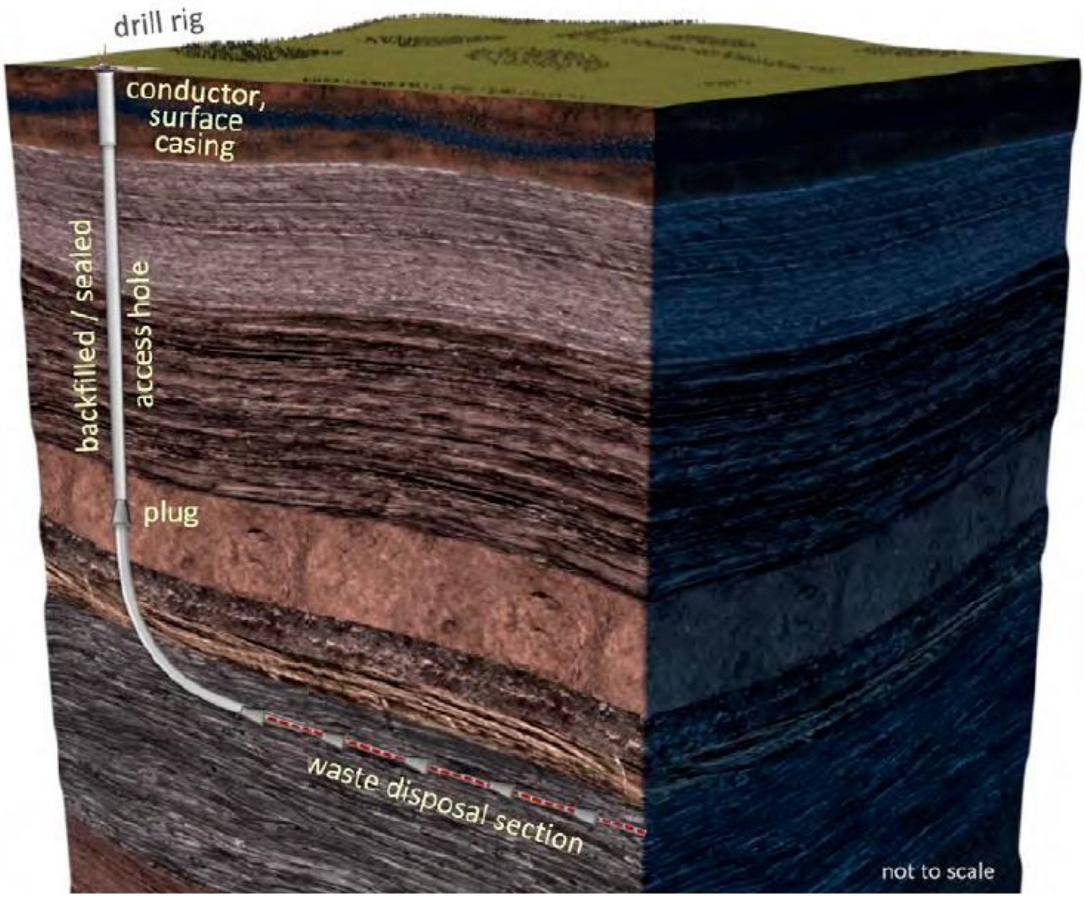


Figure 4-5 – Schematic of a deep horizontal drill hole repository (not to scale).

Vertical wells have the positive aspect that they are relatively easy and fast to drill and complete. Also, this type of well has simplest well design program. Many vertical wells only required the surface casing plus one additional casing. This always depends on the formation pressures and the depth of the wells, but to a depth of 3000 meters this is definitely feasible. Also in vertical wells stress is put in the drilling equipment, in this case this stress is mainly caused by the drill string itself, which also causes the required weight on bit (WOB) needed for the penetration through the formation. Of the three different well types, the vertical well has the shortest disposal zone, since only the bottom part of the well can be used and no extension is possible. On the other hand, this wellbore type is beneficial for the disposal and possible retrieval of waste containers. The containers can relatively easily be lowered into the borehole by a winch, without special tools to push the containers to the final location, since gravity does this work. Gravity also brings a negative aspect, the first container to be disposed, need to carry the weight of the all the containers put on top. Therefore, special attention needs to be given to the container design so it can withstand these forces. Another positive aspect is the fact that sealing and backfilling operations are strongly supported by gravitational forces once the disposal of the containers is completed. Also, vertical wells do not necessary require modern downhole motors, which provide the possibility to steer the drill bit and therefore control the direction of the well. Still, steerable BHAs (bottom hole assemblies) are widely used, no matter what type of wells are drilled.

A mix of both already described options is the deviated well. Here the part of the positive and negative aspects of the vertical and horizontal well comes together. The greater the deviation angle of the well, the more come into play the aspects of the horizontal well. Since the deviation angle is variable, the length of the disposal zone can be varied to the requirements. In case one borehole is not sufficient, there is the possibility to drill other wells right next to the first one without establishing a totally new drill site.

As already mentioned before, there are stresses put on the drilling equipment. These might either be the weight of the drill string, bending moment in the curved section or even gravitational forces if the drill string hang loose in the hole during the operation. Some of these stresses are necessary for the drilling process, such as the weight on bit. Others are just not possible to be eliminated. Due to the great complexity of this topic, it will not be discussed in detail. Nonetheless, it needs to be mentioned that horizontal drilling operations bear the most room for failure due any type of mechanical loads. The rigs that are used today provide detailed measuring while drilling equipment. This helps the driller to notice any unusual occurrences and react to it immediately.

Another option, that is not discussed in more detail due to limits and uncertainties in the technical feasibility, is the option of drilling a multilateral well. Multilateral wells consist of one main borehole, from which several laterals are coming off. This bears the positive aspects that the surface footprint is limited even more. In the oil and gas industry this technique is already widely used. For the large diameters that are required for the disposal of radioactive waste, this technique has not been applied yet. For the Norway case it is currently assumed that only one deep borehole is required for the disposal operations. Therefore, the option of a multilateral well is not further considered and investigated in more detail. Still, there is an option to use any well and drill a lateral in case it is required. Even the vertical section of backfilled wells can be re-drilled and side-tracked to extend the disposal zone.

Two aspects control the selection of the wellbore trajectory for borehole disposal of radioactive waste. First the required disposal length and second the required borehole diameter. The diameter is more of a limiting factor for the general feasibility. For small waste volumes, a relatively short disposal zone is required. In this case, the vertical well is probably most suitable. The greater the waste volume, the longer the disposal zone needs to be. Therefore, either deviated wells or even horizontal sections are options. Even though the horizontal well provides a long disposal zone, it bears many challenges and risks. Therefore, the option with the current state of technology is the deviated well. If the disposal zone of one borehole is not enough, drilling a second borehole from the same location can easily be done.

For the disposal operation in Norway, one borehole should be sufficient. Different disposal concepts brought up different solutions for the required disposal length. Based on the concepts presented in (Bracke, et al., 2016) simple calculations have been carried out. Table c presents the inventory of radioactive waste in Norway.

Table c – Waste inventory Norway.

Reactor	**JEEP I**	**HBWR 1st charge**	**JEEP II**	**HBWR 2nd to 4th charge**	**HBWR 5th charge**	**HBWR Booster**	**HBWR experimental**
Rod length (m)	2,4	2,8	1,5	1,8	1,1	1,1	1,1
Rod diameter (mm)	25	40	15	14,3	12,25	9,5	14,3
Number of rods (ca)	170	300	1500	700	4500	2000	
Assembly length (m)	2,8	2,8	1,5	3,66	1,1	1,2	
Assembly diameter (mm)	70	40	90	70	70	70	70
Number of rods per assembly	2	1	11	7	1	1	1
Number of assemblies (ca)	85	300	136	100	4500	2000	

The disposal concepts differ in the borehole diameter and container design. For the calculation of the required disposal length, the inner diameters of the containers are important. An overview of the different options is presented in Table d.

With the different container dimensions and the inventory, simple calculations can be carried out. For this, basic geometrical assumptions have been made to fit the maximum amount of waste into the containers. Based on how many circles of a diameter x fit in a larger circle with the diameter y, the number of assemblies per container according to the diameters have been calculated. The diameter x refers to the assembly diameter and the diameter y represents the inner diameter of the container. The next step was to fit as many assemblies as possible in the container based on the assumed inner length of the container. With these two values, a result for the required number of containers has been calculated, which again could be added up to a required disposal length. In addition to the container length, an additional meter per container was added as a buffer zone. In case the containers cannot be packed as assumed, there is enough room left to extend the disposal zone without drilling a new hole. The disposal zone calculations are presented in Table e.

Table d – Technical data of disposal concepts (Bracke, et al., 2016)

Concept	**#1**	**#2**	**#3**
Diameter of borehole [mm]	445	900	750
Outer diameter container [mm]	265	635	525
Inner diameter container [mm]	175	435	435
Assumed inner length container [mm]	4800	4800	4800

Table e - Disposal length calculation.

			Required disposal length [m]
concept #1	Assemblies per container (based on the container length)	14	
	Assemblies per container (based on the container diameter)	31	
	Required containers	522	
	Required disposal length		**<u>3445,2</u>**
concept #2	Assemblies per container (based on the container length)	14	
	Assemblies per container (based on the container diameter)	232	
	Required containers	69	
	Required disposal length		**<u>455,4</u>**
concept #3	Assemblies per container (based on the container length)	14	
	Assemblies per container (based on the container diameter)	232	
	Required containers	69	
	Required disposal length		**<u>455,4</u>**

As the required disposal lengths show, concept #1 requires a long disposal zone. For this option the diameter of the disposal borehole would be rather small. In the small hole, only smaller containers can fit, this means a longer disposal zone. As the numbers show, a borehole with a maximum disposal zone of 1500 meters would not be enough. At least three boreholes would be required.

Concepts #2 and #3 are only showing marginal differences. The two concepts only differentiate in the container dimensions. Here only the outer diameter of the containers is different, while the inner diameter remains the same. The number of containers does not differentiate and the same number of containers is required for the disposal operation. For these cases, the disposal length, based on the simple calculation, is less than 500 meters. Even with a more conservative and refined calculation, the required disposal zone is not likely to overcome the maximum disposal length of 1500 meters per borehole. This means that for concept #2 and #3 only one borehole will be sufficient.

In other concepts, smaller diameter boreholes are investigated and discussed in more detail. As discussed by Bracke et al. (2016) one option would be deeper boreholes with a smaller diameter. Also the horizontal disposal zone is investigated in more detail. Chapter 4.2.15 gives a more detailed overview of alternative options.

4.2.3 Drilling Rigs

The main equipment for a drilling operation is the drilling rig. With the now existing technology, rigs are able to produce more than 12 km long holes. Of course, the rigs are not the only part which makes this possible, but the rig can be seen as the centre of every drilling operation. In this chapter, only drilling rigs for deep drilling technologies are considered. Rigs for the groundwater drilling activities are not included in the following, since these rigs are not able to carry out operations similar to the planned deep borehole disposal. Excluding these rigs, according to Baker Hughes rig count; today there are more than 1500 rotary rigs worldwide (Baker Hughes, 2020). Additional to the rotary rigs, which are generally onshore rigs, there are offshore rigs, which are not included into this count. Other rig types like the smaller workover rigs are not included as well. Because there are so many different types and sizes of rigs it is difficult, if not impossible, to get an overall picture of the total number of rigs in the world.

While in the offshore sector there is a detailed classification and distinction for the rigs available, this is not the case for onshore drilling units. In the offshore sector there are four different categories:

- Submersible rigs,
- Jack-up rigs,
- Semisubmersible rigs, and
- Drillships.

This classification is mainly linked to the water depth the rig is working in and the substructure of the rig. While the semisubmersible rigs and drill ships are floating on the surface, the submersible and jack-up rigs are set on the seafloor. This makes it impossible to operate submersible and jack-up rigs in great water depth. Drill ships and semisubmersible rigs are hold in place either by cable and lines or with a GPS based system which controls propellers on the bottom of the structure.

While the offshore sector has a clear classification for rigs, onshore drilling and workover units are not having these clear groups. Mainly, the rigs are differentiated by their technical capabilities. Different literature sources provide various classifications or descriptions for different onshore drilling rigs. Many rigs are classified by their function or mobility. Generally, onshore rigs can be used either for drilling operations or for workover operations. Workover rigs are normally smaller and mobile. This means that they are not suitable for activities involving heavy weights. In these cases, rigs need to be set up for workover activities like tubing changes and cannot be used for casing setting operations, since the casing presents the heaviest load put on the hoisting system during the lifetime of a well. For the classification of drilling rigs, the mobility plays a special role. Smaller rigs, as the mentioned workover rigs, can be considered as mobile rigs. But also drilling units for shallow wells are often mobile. Even some of the bigger rigs are not limited to operations at one place. The small rigs usually fit onto one truck. Packed up they are looking like mobile cranes and have about the same size. Still, these small mobile rigs are not of interest for deep drilling operations. Most rigs are categorised under stationary rigs. In this case, stationary does not mean that they cannot be transported to another place, but this requires several trucks and a long time to dismantle the whole equipment and rebuild the rig at the new location. The stationary rig basically covers rigs that are not easily transportable from one site to another. Still, even this differentiation is spongy. So called walking rigs can be moved without dismantling everything. These rigs are self-moving at a rather slow speed. Therefore, these rigs are usually drilling several wells from one drill site, as an example cluster drilling for cavern storage. They move only a few meters to drill a new well.

To summarize the challenge when it comes to the classification of onshore drilling rigs, no general classification can be made. It needs to be mentioned, that there are different types for onshore operations, like walking rigs, workover rigs, stationary rigs and mobile rigs. Today, many drilling activities require rigs which are specially designed for the particular operation. These are called fit for purpose rigs. The International Association of Drilling Contractors (IADC) gives an overview over the different onshore and offshore drilling rigs with more detailed information in their drilling manual (IADC, 2015). An onshore drilling rig should therefore be only evaluated by its technical characteristics. The capabilities of the rig regarding possible drilled depth, maximum hole diameter, maximum hook load are the main parameters when comparing rigs.

More important than the classification are the different parts of the drilling rig. The general setup is similar in almost every case and the rig consists of the same basic parts. Every drilling rig consists of five different systems:

- The hoisting system,
- The power system,
- The circulation system,
- The rotating system, and
- Blowout prevention /well control system.

These systems are necessary to carry out a drilling operation. Each of these systems consists of different equipment parts. At this point, the rig starts to differentiate. Some rigs require certain technical tools, since they are designed for a special type of operation. The equipment of other rigs in minimized as much as possible to carry out a simple drilling operation. A general outline of an onshore rotary drilling unit is displayed in Figure 4-6. Rotary drilling units are most common types of rigs. These rigs are named after the drilling process.

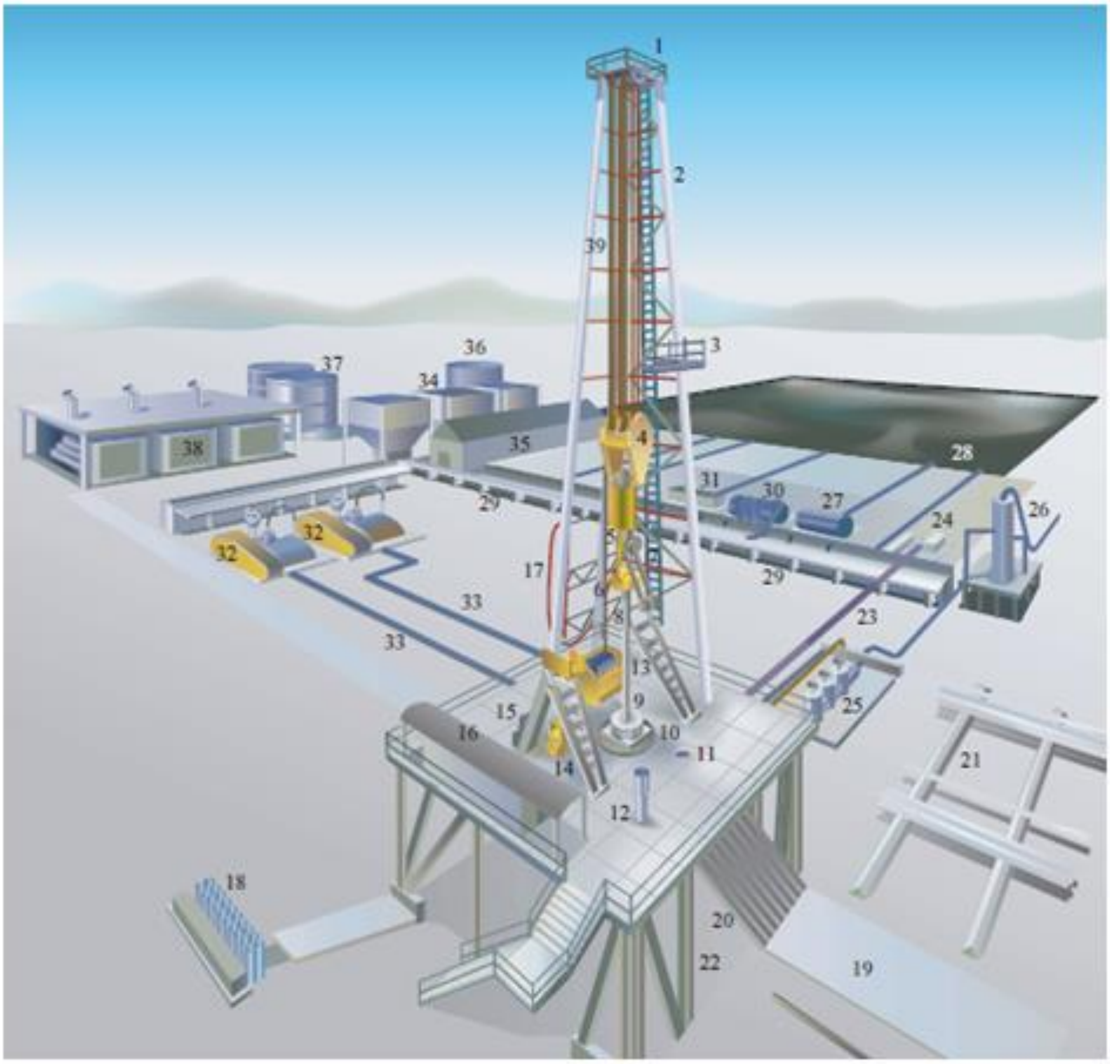


Figure 4-6 – Setup of a rotary drilling rig. See also Table f (from Oil & Gas Portal 2020). Index explanations are presented in Table f.

To distinguish the different systems of the rig, table f provides a list of the detailed equipment. Some parts cannot be linked to one system, since they are relevant for several systems; these either are mentioned in several systems or are summarized under the row “other” in the table.

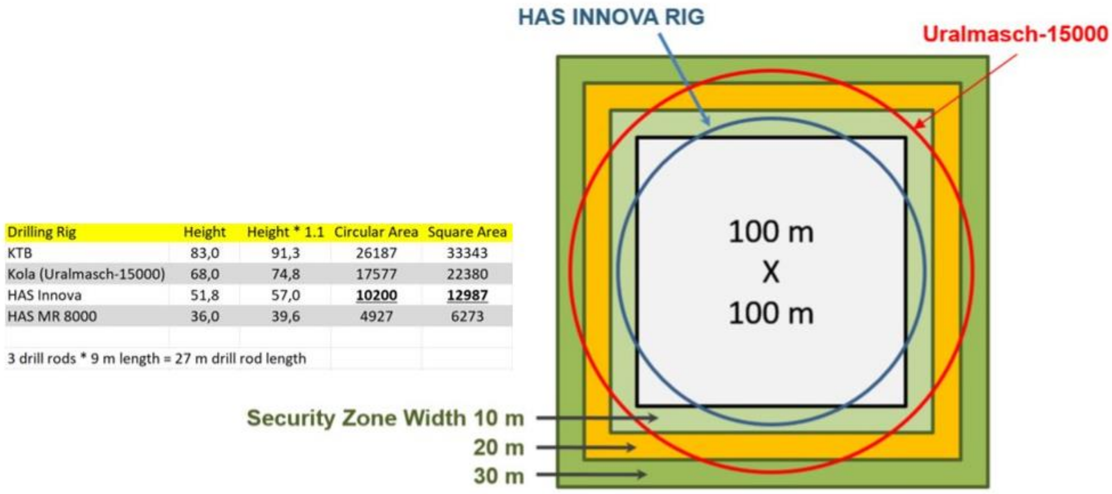
Table f – Listing of the main drilling rig systems and equipment, please also refer to Figure 4-7.

Drilling rig system	Equipment of a rotary drilling rig
Hoisting system	• Crown block (1) • Mast (2) • Monkey board (3) • Travelling block (4) • Hook (5) • Swivel (6) • Draw works (13)
Power system	• Fuel storage (37) • Engines and generators (38)
Circulating system	• Swivel (6) • Mud return line (23) • Shale shaker (24) • Choke manifold (25) • Mud gas separator (26) • Mud pits (29) • Mud pumps (32) • Water tank (36)
Rotating system	• Kelly (8) • Kelly bushing (9) • Rotary table (not shown) • Drill string (not shown) • Bottom hole assembly (not shown) • Drill bit (not shown)
Blowout prevention / well control system	• Accumulator unit (18) • Blowout preventer (not shown)
Other	• Driller's console (15) • Pipe ramp (20) • Pipe rack (21) • Substructure (22)

Each of these parts has a defined function, but some parts are not required in every operation. This setup displays only one possibility. Especially build for function rigs might differentiate significantly from this. In cold regions or urban areas, the derrick is not freestanding as it is displayed. To protect the workers against the cold, the derrick is then covered to have at least a small protection. Urban areas bring up the problem of noise and space. Often, all noise-creating parts, like the hoisting and power system are covered with noise-cancelling materials to minimize the impact on the surrounding area. In some operations space might be limited, therefore larger parts, especially parts of the circulating system, like the mud pits, are adapted to the operation. For example, mud pits are often replaced by large, upright standing tanks, which are emptied on a regular basis. These are just examples of modifications on the setup of the drilling rig and drilling location.

The most notable part of the rig is the mast, which is the highest part of the rig. The mast is the main part of the hoisting system, which is mainly responsible for the maximum hook load and therefore affects the capability of the rig. Different rigs have different mast heights. They range from only 20 meters for mobile workover rigs (DRILLMEC - Drilling Technologies) to heights of over 50 meters for heavy drilling rigs (benTEC, 2020). For challenging operations, such as the world record well, the Kola Superdeep Well, exceptional drilling units are required. For the operation on the Kola Peninsula, a specially designed rig was built, the Uralmasch 15000. This rig had a mast height of almost 70 meters (Kozlovsky). An even taller rig is that used for the drilling and completion of the KTB well. Several sources provide a maximum height of the mast of more than 80 meters (Bracke, et al., 2016). Both of these drilling units are fixed at the location and are just built for this operation. Since these examples are considered as ultra-deep operations, the engineers expected to have enormous hook loads due to the long drill strings and drilling equipment. An even greater load is put on the hook by the long casing strings. A correlation between the height of the drilling rig and the maximum hook load can be extracted from these examples. Of course, not only the mast height is playing an important role when it comes to the load, but also the draw works are important since they, in combination with the power system, provide the drive to move and hold the loads.

The height of the derrick also provides a rough estimated for the required surface area for the drilling operation. German law for example takes the height of the mast as the basis for the surface area. According to the German Deep Drilling Ordinance (BVOT) §18, the centre of the well needs to have a minimum distance to the nearest building, public traffic facility and similar protected objects of at least the mast height times 1.1 (Bergverordnung für Tiefbohrungen, Untergrundspeicher und für die Gewinnung von Bodenschätzen durch Bohrungen im Land Niedersachen (Tiefbohrverordnung - BVOT-), 2006). What this means in detail for different rigs can be seen in Figure 4-7.



Drilling Rig	Height	Height * 1.1	Circular Area	Square Area
KTB	83,0	91,3	26187	33343
Kola (Uralmasch-15000)	68,0	74,8	17577	22380
HAS Innova	51,8	57,0	<u>**10200**</u>	<u>**12987**</u>
HAS MR 8000	36,0	39,6	4927	6273
3 drill rods * 9 m length = 27 m drill rod length				

Figure 4-7 – drilling site size according to the rig height

Not only is the hoisting system the most significant part of the rig, it also sets limits to the capability of the possible operations which can be carried out with this rig. In general, the smaller workover rigs are mobile, but as the name already suggests, these rigs are specially designed for workover operations. For these types of activities, the required maximum hook load and power of the engines are relatively small. Many of these mobile rigs are limited to operations which do not exceed a hook load of 90 tons. As the name also implies, these rigs are not designed for drilling operations. Rigs actually designed for drilling are more complex and bigger. They and require a greater surface area for the whole setup and equipment. Their maximum hook load and the horsepower of the engines often classify drilling rigs. For shallow operations, drilling units with a maximum hook load of 200 tons and 1000 horsepower engines are available on the market. Standard and common rigs can be found up to 450 tons hook load, combined with a 2000 horsepower engine. Still, there are rigs with even greater capabilities. BenTEC has a so-called stationary desert rig with a maximum hook load of 680 tons and a 3000 horsepower engine in their drilling rig brochure (benTEC, 2020). For even heavier operations, special rigs need to be designed. These can then be summarized under the topic of fit for purpose rigs.

Other specifications of the rigs are provided in characteristic sheets provided by the companies. Included in these sheets are values for the mast height and required area for the substructure as well as information about the power system of the hoisting. This includes the installed draw works and the drilling line specifications. Most rigs already have mud pumps and systems with them. An example of an information sheet of the biggest drilling rig from the company benTEC can be seen in Figure 4-8. Other companies also provide references of previous operations carried out with their rigs. This gives an idea of the capabilities of the drilling units.

National laws differentiate significantly in different countries. This has an impact on required parts of the drilling rig. Some countries require open drilling mud pools, where the used mud is pumped in, whereas other legislations demand closed containers. This in the end will influence the required surface location and the extent of the drilling equipment.

An important factor is safe and secure work. Therefore, the drilling units have been equipped with more new technologies, which aid the drilling process for the operator and reduces the actual human work on the rig, which is always linked to a certain risk. Today many rigs are equipped with automated pipe handling systems. These systems reduce the contact of the workers with the heavy pipes. In addition, with the new pipe handling systems, the number of workers for pipe tripping operations can be reduced from five people to only one. Since the operation in Norway will consider large diameter pipes with great weights, the risk when handling the pipes will be even greater. Therefore, one of the probable requirements of the rig is that it needs to be equipped with an automated pipe handling system.

As already mentioned earlier, there are some large rigs in operation around the world. Still, there is only a limited number of manufacturers for special heavy drilling rigs. In Germany the most challenging operations other than the KTB well have been drilled with rigs of the HAS series. Here the rigs HAS MR 8000 and the HAS Innova Rig capabilities of drilling challenging wells are presented. Both rigs have drilled geothermal wells, which typically have large diameters. In addition, these two drilling units are mobile. Considering the great loads due to the large and long casing strings, which are required in Norway, the smaller HAS MR 8000 might not be suitable. Even the larger HAS Innova Rig might not be capable of carrying these loads.

For the selection or design process of a possible rig, a final casing design with the maximum weight of the casing string is required. Based on this information, a rig can be selected, equipped or designed especially for the needs. Certain criteria can be set nonetheless even without knowing and details yet. Special technologies like the automated pipe handling system already reduce the number of potential rigs. Other aspects like the drilling method or even the availability of rigs for onshore operations in Norway will reduce the possible rigs further. Most important for the rig selection for the disposal project in Norway are two aspects, first the maximum hook load capacity of the rig. The second important factor is that the rig needs to be capable to work with large diameter bits and casings, which is limiting factor in many drilling units.

STATIONARY DESERT RIG **680 t / 3,000 hp**

Parallel Lift Substructure

Software Solutions

- Power Management System
- Z-Torque System
- Bentec Rig Care System
- Remote Drilling Process Control
- Bentec ROP Optimization

Optional Equipment

- Bentec Rig Walking System/Skidding System
- Bentec Iron Roughneck
- Bentec Hydraulic Catwalk System
- BOP Closing Unit
- Casing Stabbing Board
- Gas Detection
- Grid Supply Container
- Moving equipment

Sub-supplied equipment

- BOP Stack
- Drill String
- Handling Tools

Well Type

Shale, Conventional, Geothermal, Horizontal

Bentec Open Face Self-Elevating, Free Standing (Cantilever) Mast

System:	Rig up by drawworks
Mast height:	152.00 ft (46.32 m)
Mast base:	35.00 ft x 8.00 ft (10.67 m x 2.45 m)
Maximum rated static hook load:	1,500,000 lbs (680 t @ 14 lines)

Bentec Parallel Lift (Sling Shot) Substructure

System:	Rig up by hydraulic winch
Height of drill floor:	35.00 ft (10.67 m)
Free height underneath rotary table:	30.00 ft (9.14 m)
Rotary capacity max.:	1,500,000 lbs (680 t)
Setback load max.:	800,000 lbs (363 t)

Bentec Drawworks E-3000-AC (Double Gear)

Power Rating:	3,000 hp (2,200 kW)
Drill line diameter:	1 ⅝" (42 mm)
Max.line pull:	123,000 lbs (547 kN)

Bentec Top Drive TD-750-HT

Load capacity:	750 ton (680 t)
Electric motors:	1,600 hp (1,200 kW)
Continuous torque:	73,760 ft-lb (100,000 Nm)

Three (3) Bentec Mud Pumps: T-1600-AC (R)-7½"x12"

Electric motors:	1 x 1,600 hp (1,200 kW) each
Max. pressure:	5,000 psi

Bentec Mud Tank System-Rectangular tanks

Active mud volume:	1,383 bbl (220 m³) in basic configuration

Bentec Rotary Table RDE-375 – Emergency Drive

Diameter of opening:	37 ½" (952 mm)

Power Generation

Five (5) Engine Caterpillar 3512B with Generator Leroy Somer
Emergency generator Caterpillar C 15 ACERT

Bentec Power Control Room - AC-Variable Frequency Drive

OEM Solids Removal Systems

Shale Shaker, Mud Cleaner with Desander and Desilter

Bentec Instrumentation System

Bentec "InfoDrill" Drilling Information System
Ex-proof Stainless Steel Drillers Cabin

Figure 4-8 – stationary desert rig (from benTEC 2020).

4.2.4 Drilling Site Layout

Section 4.1 discussed the requirements for a typical disposal facility layout of borehole operations. This section discussed the specifics related directly to the drilling process.

In addition to the drilling rig, numerous other facilities are required for drilling the disposal borehole. They are needed to operate the rig (drilling related equipment), as accommodations and workplaces for site workers or as storage areas. These categories include:

- Power supply, control units and the elements of the flushing system. Compressors for air flushing or flushing pumps and the devices for separating the cuttings from the flushing medium (Figure 4-9).
- Shower and locker rooms, break rooms, first aid room, offices, laboratories, workshops.
- The storage area of the drill pipes, warehouse for measuring devices and tools, including logging tools. A warehouse for the storage of cuttings and drill cores. Storage rooms for fire protection devices and operating materials, and a storage location for waste.

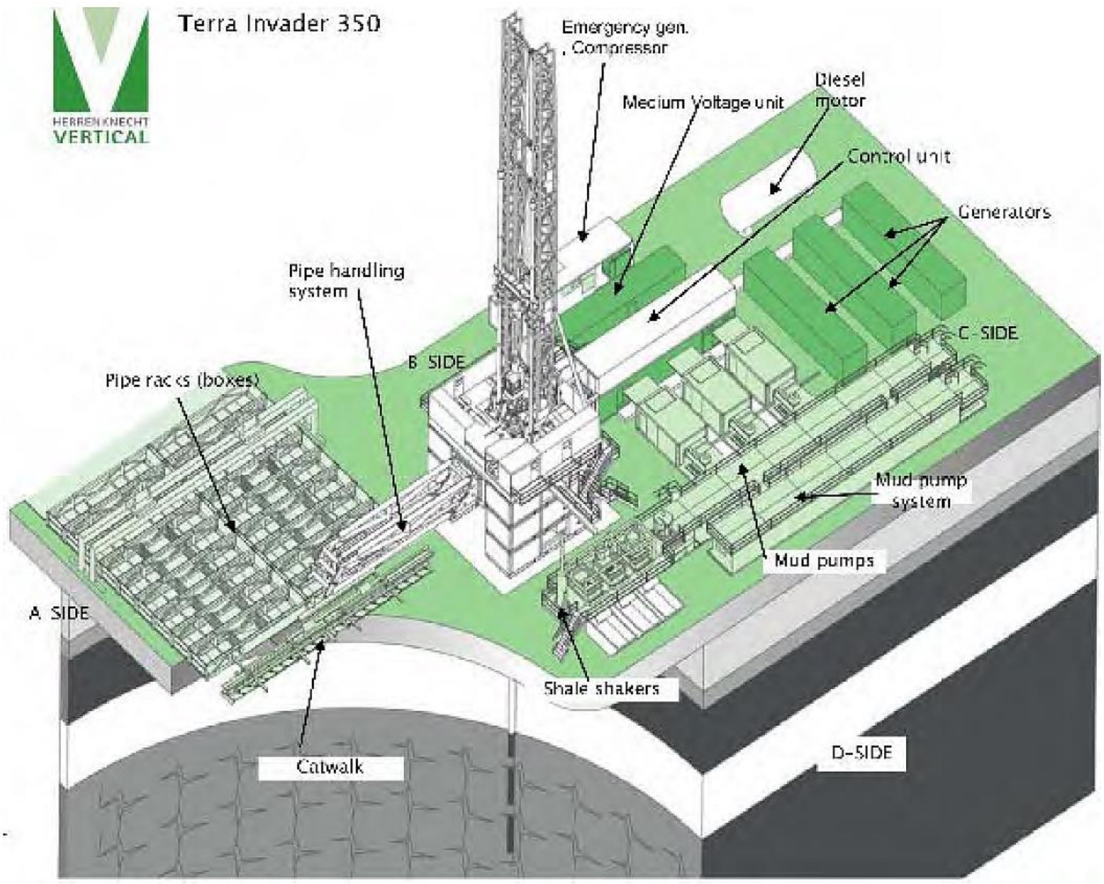


Figure 4-9 - Sketch of the complete InnovaRig installation with derrick (center), pipe racks (left) and pumps and mud system (right). Sketch by Herrenknecht Vertical (from Wohlgemuth et al. 2007)

Due to the relatively short operating time, it can be assumed that ISO containers are primarily used as temporarily building facilities at the site. This is customary in the drilling industry. The use of such containers is also common for construction work in the context of mined repositories, such as the Konrad mine and the Asse II repository. Alternatives can, however, be considered if the building can also be used during the operational period of the disposal facility. The most common ISO containers are 8 feet (2.44 m) wide, either 20 feet (6.10 m) or 40 feet (12.19 m) long and can be stacked. They are therefore delivered by truck, so that dimensioned routes and parking spaces must be available for truck traffic. This is also necessary because numerous materials are delivered by truck. Roadways and parking areas must also be available because many borehole investigations and cementation work are carried out by external companies that require the appropriate areas to carry out the work. In this regard, the planning guidelines of the public traffic system must be taken into account. Further planning requirements result from fire protection.

At the location of deep drilling rigs, their own weight and loads from drilling operations act. Accordingly, foundations, pile foundations or floor replacement must be provided and dimensioned. However, the foundations must only be taken into account in the immediate area of the drilling rig. In addition, other paved areas must be taken into account, e.g. for tank systems, magazines, workshops, rod storage, and sanitary facilities, sewage and sewage treatment plants, residential camps, access roads for supply and disposal vehicles, parking lots. Due to the fact that the rig must be easily accessible at all times a wide driveway is built around this foundation, from which smaller roadways and walkways branch off. According to the German Deep Drilling Ordinance (BVOT, drilling operation § 18) drilling must be carried out in such a way that the distance from buildings, public, traffic, infrastructure and similar objects that have to be protected is at least 1.1 times the height of the drilling rig. Due to this requirement and the desire to realize short distances and thus escape routes, a concentric drilling site layout results, with the containers being positioned on the edge of the site. The entire site is usually square or rectangular and is surrounded by a fence or noise barriers. This is followed by a grass strip, which is interrupted by the access roads. Lighting devices are often installed along the fence. In the fence are doors that can be used to escape.

Access roads are usually 5.50 meters wide. In the immediate area of the drilling site, the road will be widened to around 8 meters to allow the parking of heavy vehicles. Moreover, the planning of the driveways, parking areas, and the facilities has to take into account access for cranes and fire brigade.

The requirements result in sizes for the drilling site, which are usually between 7,000 and 10,000 m², when using high-power drilling rigs. When building a deep disposal borehole, more space is expected because there is a greater need for laboratories and storage space. In the simplest case, this would result in a square with an edge length of 100 meters. The area required for the green strip (security zone) must be added to this area. This was illustrated in Figure 4-8 with circles referring to the BVOT and the drilling rigs HAS INNOVA and Uralmasch-15000. The rig Uralmasch-15000 was used to drill the Kola Superdeep Borehole that penetrated about a third of the way through the Baltic Shield continental crust and reached Archean rocks at the bottom at a depth of approximately 12 km.

Taking into account the borehole construction and operation of the disposal facility and the desire to reduce conversion work, a total surface area of 150 x 150 meters (22500 m³) should be used as the basis for the planning.

A helpful document for planning a drilling site is the “Well Site Spacing Recommendations” of the Wellsite Spacing Committee (WSC 2003). There are also numerous plans for existing systems in the literature (eg. Cherutich 2009). Figure 4-10 shows, as an example, the drill site COSC-1 (Lorenz et al. 2015). The working area of this site is nearly quadratic with an area of about 10050 m². The drill rig, the combined mud tanks and manual pipe handling system and some peripherals such as workshop and mud mixer formed the central part of the drill site. In immediate proximity to the northwest, the laboratory container was located. The south-eastern part of the drill site was occupied by common facilities and office space. In the northern quarter of the drill site, the on-site laboratory was located. The remaining space was used as storage space for drill rods, logging equipment, and drill core and for parking. Figure 4-11 shows the drilling site of the Continental Deep Drilling Program in Germany (Kontinentales Tiefbohrprogramm, KTB) with the routes for the connection to the public transport network. The main super-deep borehole of the scientific KTB project reached a depth of 9,101 meters in the Earth’s continental crust.

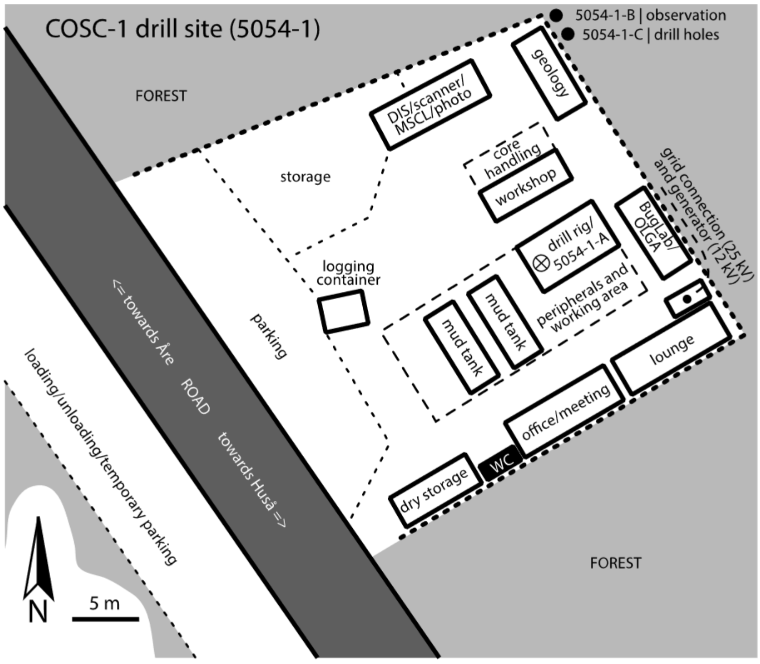


Figure 4-10 - Sketch of the COSC-1 drill site according to Lorenz et al. (2015)

Figure 4-11 - Drilling site of the Continental Deep Drilling Program. (photo: Google Maps 2020).

4.2.5 Borehole Casing Design

The installation of the casing string is one of the major parts of completing a borehole. The casing can be seen as an assembled length of steel pipes configured to suit a specific wellbore. After the drilling of a hole section, the casing pipes are connected and lowered into the wellbore, before they are cemented in place. The casing can be subdivided into different parts, of which each has a specific task. All casing strings have one major task in common, maintenance of the well integrity throughout the life of the well. This includes prevention of the hole from caving in during the drilling operation and afterwards, prevention of the contamination of fresh sands and control of pressures during the drilling operation. The casing provides a barrier between the penetrated formation and the open hole to minimize the exchange of fluid and gases.

The casing scheme is different from wellbore to wellbore. The reasons for this are different conditions in every case. There are different casing types, which have different functions and are therefore installed if required. Every installed casing string will reduce the final wellbore diameter; therefore, a drilling engineer will try to reduce the number of casing strings as far as possible. Every well consists of at least two, in most cases three casing strings. Deeper wells through more complicated formations require more casing strings. Figure 4-12 shows a typical casing scheme of a borehole with four different casing types.

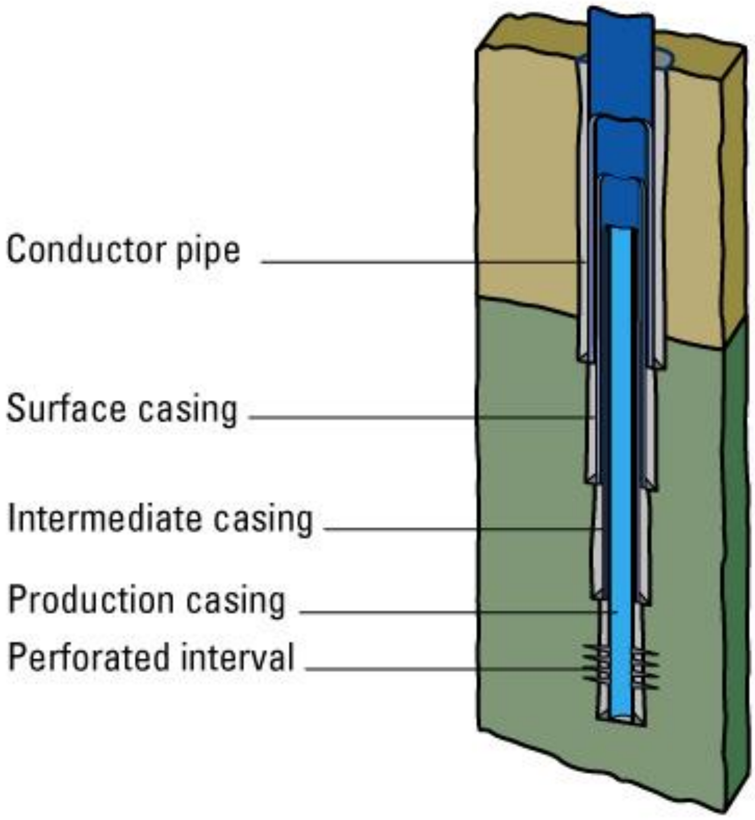


Figure 4-12 – Casing strings (from Schlumberger Oilfield Glossary, 2020).

The upmost part of the well is completed with the conductor pipe; this is the largest diameter casing. The conductor pipe prevents the weak formations at the surface from caving in. In addition, the conductor pipe sets the basis for the wellbore, because of this, the conductor pipe is also known as the drive pipe. Typically, the conductor pipe is not drilled, but hammered into the ground. The depth of this part typically is not deeper than 10 meters. The casing type below is the surface casing. This is already more complex and needs to fulfil more functions than the conductor pipe. Still, the surface casing has to isolate the weak formation and keep the upper part of the borehole stable until down to the depth of the more competent formation. In shallow regions, shallow gas can potentially be met; this is isolated by the surface casing. Other functions of the surface casing are:

- Support the wellhead and BOP (blowout preventer),
- Support subsequent casing strings,
- Provide a casing seat strong enough to safely close in a well after a kick,
- Provide wellbore stabilization, and
- Protect surface freshwater formations.

The third casing, which is installed in every well, at least if it is planned to produce gas, oil or water, is the production casing. As the name already describes, this casing string penetrates into the production zone of the well. It provides zonal isolation of this special zone of interest, confines production to the wellbore and provides the environment to install subsurface completion equipment. In some cases, a production liner is installed instead of a production casing. This is usually the case if the borehole diameter is already too small to install the required production equipment in the final casing. Then this equipment can be placed slightly above in the casing string, which will still allow the well to produce. The liner is basically a casing string, which does not extend to the top of the wellbore, but is anchored, in the previous casing string. Therefore, the weight of the whole casing installation can be reduced. The last casing type is the intermediate casing. Not every well requires the intermediate casing. If no troublesome formations are penetrated during the drilling operation, this casing type can be left out to reduce the total number of casings. In addition, it only has two functions, the isolation of potentially troublesome formations and providing the integrity to withstand the high mud weights necessary to reach total depth or the next casing seat.

Other than the names of the different casing strings, casings can be classified more specifically. In the industry, there are certain characteristics, which describe the casing by its parameters and make the selection of the right casing for the operation easier. The common parameters are:

- Outside diameter of the pipe,
- Wall thickness,
- Grade of the material,
- Type of threads and couplings,
- Length of each joint and
- Nominal weight.

During the lifetime of a well, the casing can barely be replaced. Replacements are often linked to costly operations, which are often more expensive than drilling a new well. Therefore, the design engineer needs to understand the loads on the casing, and secure that the casing does not collapse under any circumstances. During the drilling and production phase, the casing needs to withstand several different loads, which can be classified into mechanical and thermal loads. The mechanical loads can again be sub classified into static and dynamic loads. Static loads include collapsing loads, due to external pressure, axial loads, due to tension, compression and bending, bursting loads, due to internal pressure and torsion, due to torque. Dynamic loads are subdivided into inertial and shock loads. In deeper regions, the casing is facing great temperatures, which lead to thermal loads. Mainly these are tension and compression due to material behaviour in different conditions.

There is no general rule for at which depth a casing needs to be set. The reason is that every location and formation is different and therefore bears its own difficulties and challenges. For the determination of right casing depth, geological criteria are playing a major role. The fracture gradient curve and pore pressure curve provide the basis for the casing design. Between these two curves, a margin can be found. With the help of this, a casing scheme can be created as displayed in Figure 4-13.

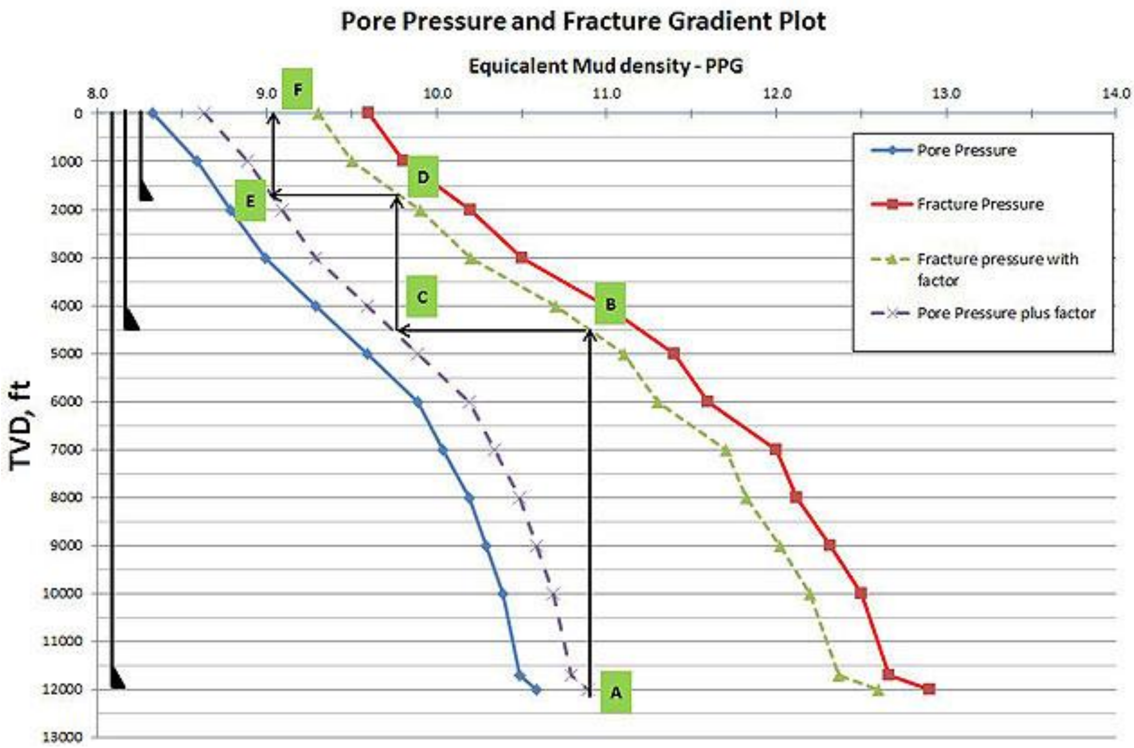


Figure 4-13 – Casing seat selection based on the pore pressure and fracture pressure gradient (from DrillingFormulas.com 2014). TVD is true vertical depth.

If these two curves are more fluctuating, the casing scheme will be more complicated and more intermediate casing strings might be required. Usually the design engineer will design the casing scheme by the bottom up principle. This means, the whole casing setup will depend on the required bottom hole diameter. In any type of production wells, this depends on the size of the subsurface equipment and the required flow rate. In the case of deep borehole disposal, the diameter of the disposal containers will be the driving factor for the casing sizes. Once the final required inner diameter is defined, the chart displayed in Figure 4-14 will ease the casing design process.

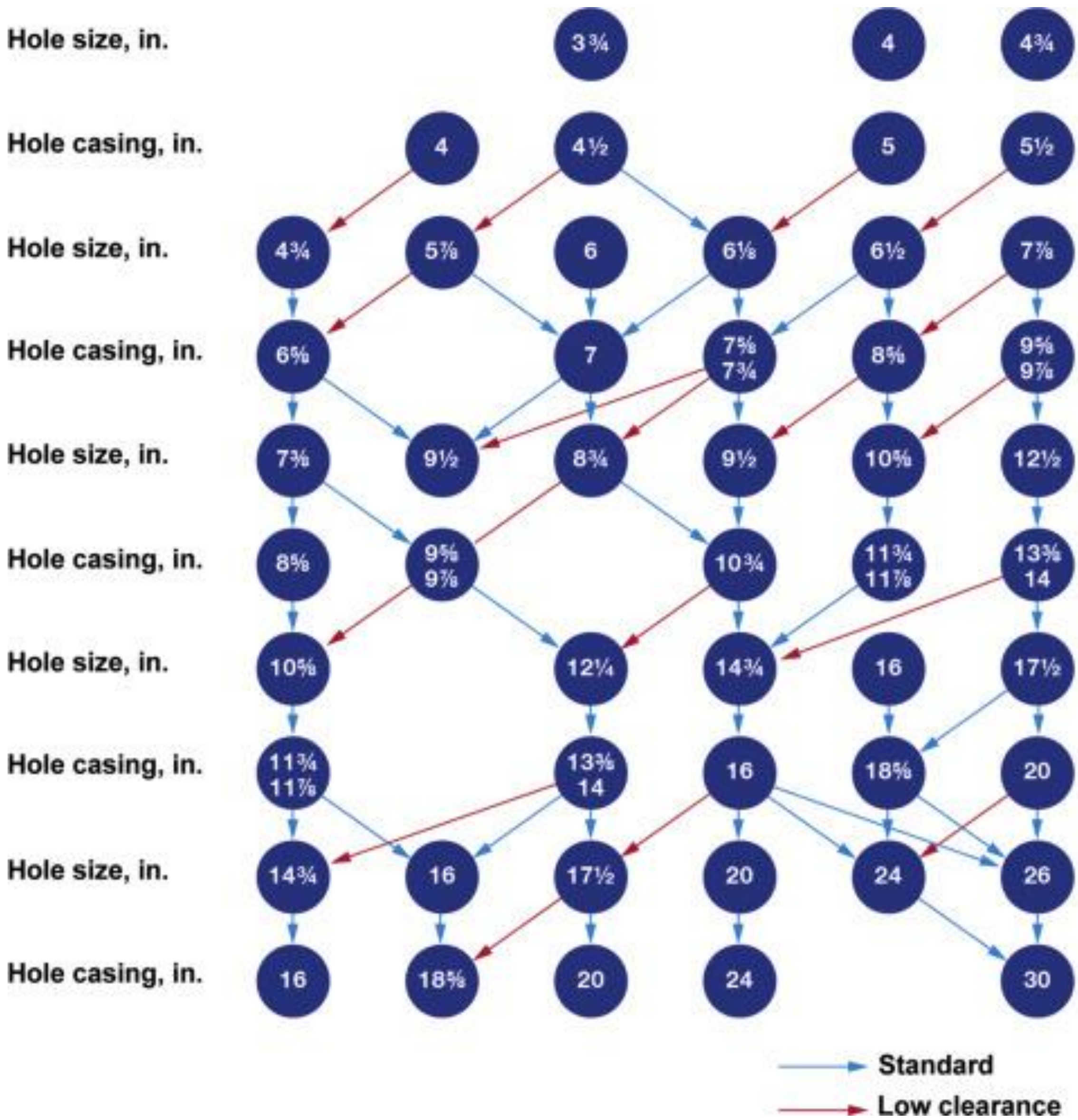


Figure 4-14 - casing and hole size chart (from Deepwater Drilling 2019).

Similar charts display the inner diameter of the casing. Once the right casing diameter is chosen, on the next level, the required hole size can easily be found in the chart by following the arrows. From this point, the next casing size can be selected. In case three casing strings are required, these steps will be repeated three times. As mentioned before, every additional casing string is linked to a reduced finale casing string or a larger surface casing. Therefore, engineers also tried to minimize the clearance between the casings to a minimum clearance. For a proper cementing job after the casing is set a certain clearance is required to fit enough cement between casing and borehole wall. This also has an impact on the possibilities regarding the casing design. Drilling larger diameters is typically more challenging since cutting removal and maintaining the weight on bit becomes more complicated. This is the reason why often the casing diameter is seen as one of the limiting factors for the total depth of the well. In addition, drill bits and casings are only available up to a limited size; this therefore sets a limit for the casing diameter on the surface. This chart for the casing and hole size selection already considers these aspects.

Another factor influencing the casing program is the casing itself. This includes the wall thickness, as well as the material of the casing. The selection of the right material and casing type needs to be done carefully for every program. Since the casing is in most cases not just one long string that is lowered into the wellbore, but rather short parts attached to each other, the connection points are the most critical parts of the system. The American Petroleum Institute (API) has set standards for different coupling types. There are also standards for the casings. For the connections, API has set three standard coupling systems. The thread casing connections as displayed in Figure 4-15 and Figure 4-16 consist of one male part and two female parts. The male part acts as a connection part, which holds the pipes together. These two connection types differentiate in the type of thread. While the round thread casing has rounded chest and flanks, the buttress thread casing rather jagged. The terms male and female parts of a thread refer to the fitting. Male threads are on the outside as marked in blue in the figure, while female parts have the threads on the inside (marked in red).

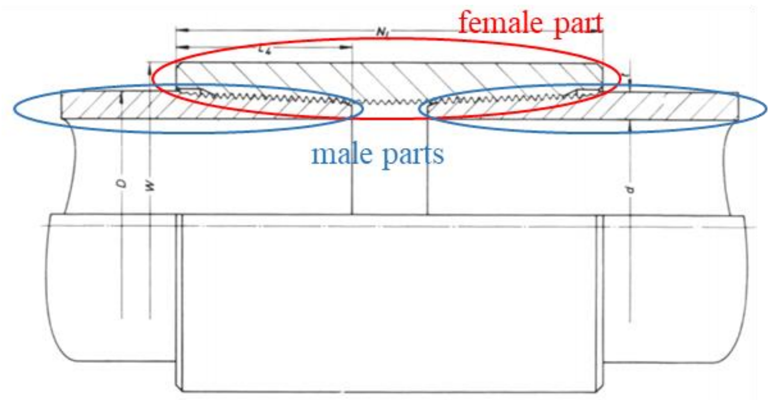


Figure 4-15 - API Short / Long Round Thread Casing (from Well Planning 2017/2018).

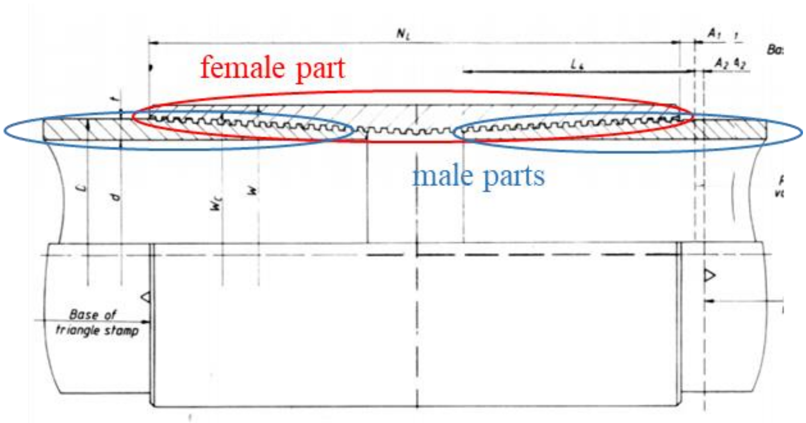


Figure 4-16 - API Buttress Thread Casing (from Well Planning 2017/2018).

The API Extreme Line Casing is the last casing connection classified by API. This connection consists of only one male and one female part. These two parts are screwed into each other.

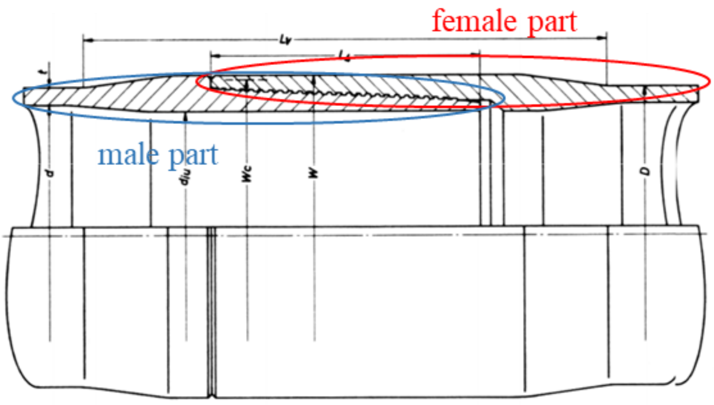


Figure 4-17 - API Extreme Line Casing (from Well Planning 2017/2018).

The displayed casing types do not have an impact on the inside diameter of the casing. For the disposal operation this is an important factor, since the disposal containers need to fit through the inside of the casing. Any type of unevenness or narrowing within the casing bears the risk of a stuck container. A smooth and even inside surface is beneficial for the actual displacement operation of the containers.

Another important aspect of the casing scheme design is the selection of the material. For most operations, the casings are staying in the borehole for the whole lifetime of the well. The actual time the well is production is depending on the reservoir volume and the production rate, next to some other aspects. In literature the production lifespan of an oil well is given as at least ten years. In some cases the production can last for more than fifty years. Typically, this number is only valid for the largest reservoir around the world. (Total Foundation, 2015) (Hood, 2015) For this time frame, the casing needs to withstand great pressures from the formations, but also from the produced fluids or gases. In many cases the casings face severe thermodynamic conditions, which result in additional stresses. Another important factor affecting the casing design is corrosion. The high pressures and temperatures in combination with fluids and gases are often causing significant corrosion processes, which then will have negative impact on the condition of the material. The worst scenario would be an opening in the casing string caused by corrosion. (Boskovic, Cebašek, & Nuhanovic, 2014) Therefore, a special interest needs to be put on the casing material selection. Most casing pipes are produced by the standards provided by API. These casings fulfil the general requirements for standard oil and gas production. Still, even these qualified materials are not completely corrosion resistant. One option to reduce the probability of corrosion-caused leakage of the casing string is a greater wall thickness. This might lead to another problem, which is faced especially in deep wells or any wells with long, single casing strings. With longer casing strings, the weight of the string obviously increases. Every drilling or workover rig has a maximum hook load, which limits the weight it can securely hold. The operation and casing design is therefore often also limited by the weight of the casing string. Reaching the limit can either be caused by a long casing string, a high wall thickness of the casing or a combination of both. The perfect material for casing operations is therefore a light, corrosion and stress resistant material, which does not change its behaviour with changing temperatures.

Especially in operations where high temperatures are expected, the casing selection is of special interest. Radioactive waste will radiate heat which will impact the material behaviour. Figure 4-18 shows the general behaviour of casing materials during heating and cooling of the material. Since the temperature in the formation will rise, when the radioactive waste is emplaced, the casing material will be impacted as well. With increasing temperature the casing material will expand. Since it is cemented in place, there is no possibility for the casing to move and axial compression is the result. During the heating phase a common risk is the collapse of the pipe (bulge), if the temperature increases further, material yielding might be the result. (Thorbjornsson, 2016) In oil and gas wells, this material behaviour can impact the operation to the loss of a well. In a deep borehole disposal operation, the temperatures are not likely to reach the critical values until the waste is emplaced. Once the radioactive material is emplaced, the borehole will be closed and sealed, therefore an intact casing is not important anymore.

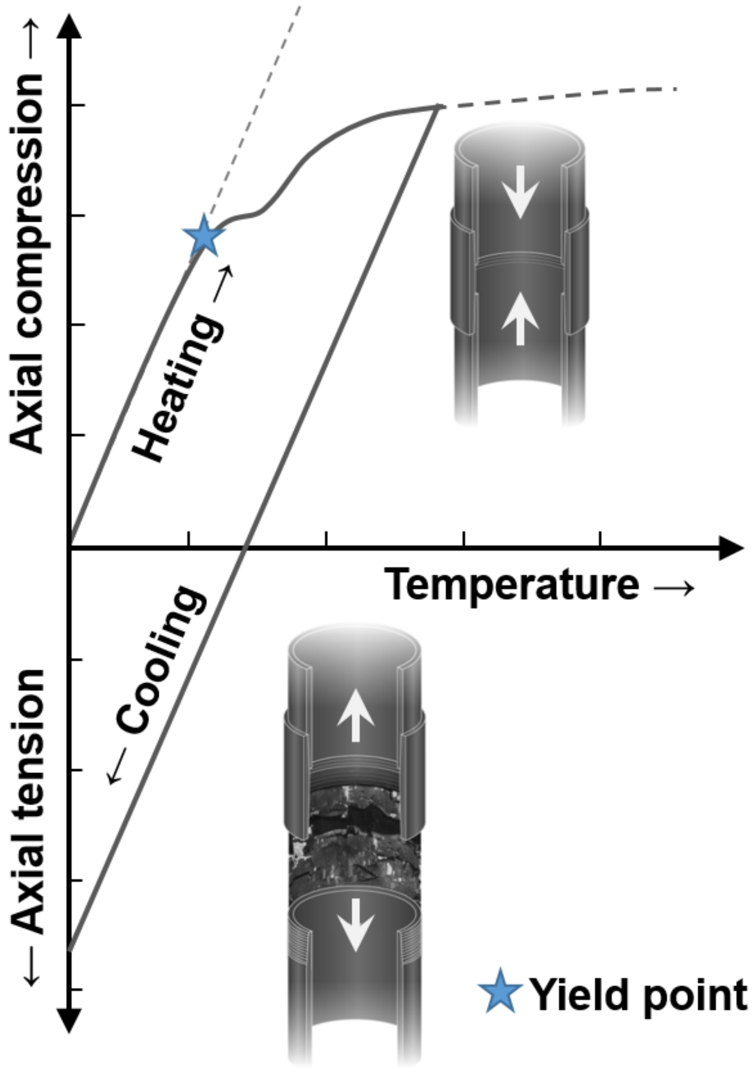


Figure 4-18 – Concept diagram for the failure mechanism where axial tension is generated subsequent to strain that formed in compression (from Thorbjornsson, 2016).

The quality of the couplings, the right material and the long lifetime of the whole casing system is important for the production of oil, gas and geothermal wells. In these wells, a leakage could lead to the loss of the well, since produced hydrocarbons would end up in the ground uncontrolled. Therefore, a special interest is put on this topic. For exploration, research or in this case wells for the disposal of radioactive waste, the casing quality does not need to fulfil these high standards, since the casing will not be needed and put under stresses for such a long time. For the disposal of radioactive waste, the borehole needs to be drilled and completed. Once the radioactive waste is disposed of in the disposal zone, the upper parts of the casing are most likely to be removed. Therefore, the casing will only stay in the hole for a short time and will not have a long-term function.

For a borehole drilled into a depth of 3500 to 4000 meters in strong geological formation a rather simple casing design is recommended. Since no oil/gas production is planned, but only the disposal of containers, no special production casing is required. This suggests that a borehole with two casing strings seems feasible. Depending on the pore pressure and fracture pressure, a three-casing string design might be required. To be on the safe side, the more complex design with three casing strings will be considered. As in every well, the conductor pipe is the first casing which needs to be set. For this project, the conductor pipe is not part of the three-string casing design. In the hard crystalline formations in Norway, a conductor pipe to a depth of 10 meters is sufficient to fulfil the functions in this part of the well. The conductor pipe mainly provides a start for the actual drilling operation. The upcoming three-string system can possibly be reduced to a two-string system, depending on the pressure regimes and the formation stability. Some regions and formations allow the driller to drill down to the final depth with a single diameter, which requires only one casing string. Still, drillers and well designers usually consider the design basis as in this case. In regions where many wells have been drilled before and a lot of information about the geology is available, the two-casing design will be favourable. Since in Norway only a limited number of wells have been drilled onshore, the more conservative option is more suitable. For the disposal of radioactive waste, the bottom hole diameter plays an important role, since the disposal containers are defining this variable. This can also have an impact on the number of casing strings. If the required inner diameter in the disposal zone is too large, this might limit the possible casings that can be set above. Any option requiring more than three casing strings are most likely to reduce the final diameter too much.

As mentioned above, the final casing design is depending on the dimensions of the disposal containers: the smaller the container diameter, the smaller the required borehole diameter need. As discussed in Chapter 3, the suggested disposal container is the BSK-R container. A display of this container with its dimensions can be seen in Figure 4-19.

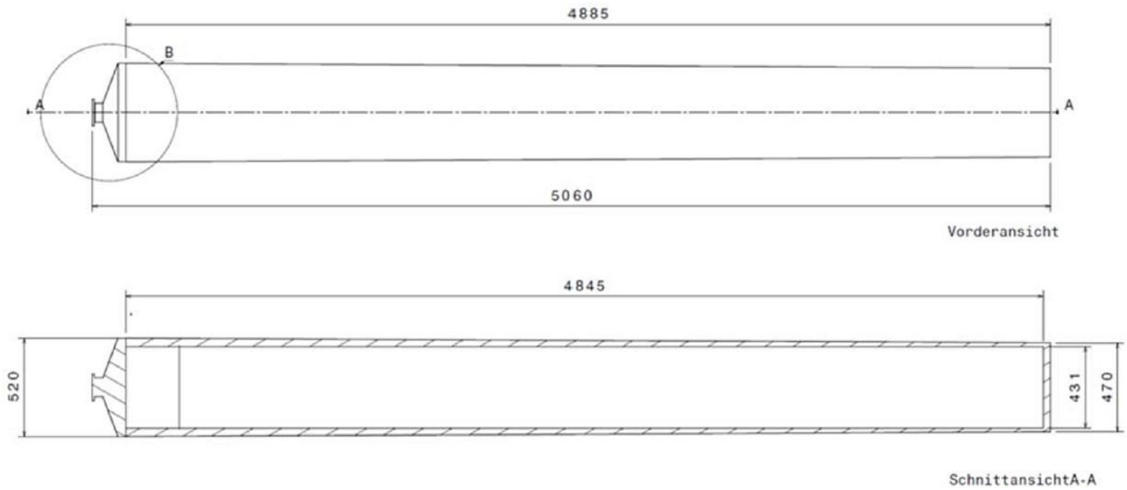


Figure 4-19 – Side view (top) and cut (bottom) of the retrievable container BSK-R (from GRS 2012).

To secure a safe disposal of these containers, (Bracke, et al., 2016) planned with a clearance of 25 mm around the container, whereas other literature sources assumed an inner casing diameter 100 mm greater than the maximum container diameter (Bollingerfehr, Herold, Dörr, & Filbert, 2014). This means a minimum final casing diameter of 670 mm or 720 mm is required. In both cases, the outer diameter of the casing is considered. This leads to two different scenarios for the casing sizes and design: (i) a conservative scenario based on the clearance assumed by Bollingerfehr et al. and (ii) the other option with the tighter clearance based on (Bracke, et al., 2016). The casing diameters for both scenarios are displayed in Table g. Assumed for this casing design is a casing wall thickness of 50 mm for the final disposal casing string. In combination with the outer casing diameters, the table g also provides hole diameters. Here a clearance between the last casing string and the upcoming hole section is considered. To keep the hole diameter as small as possible, this clearance is reduced as far as possible. Depending on pressures in the formation, the wall thickness of the casings needs to be adapted.

Table g – Casing design options.

		Bollingerfehr et al.	Bracke et al.
Conductor pipe	Hole diameter [mm] Outer casing diameter [mm]	1016 1016	1016 1016
Surface / intermediate casing	Hole diameter [mm] Outer casing diameter [mm]	940 880	914,40 830
Disposal casing	Hole diameter [mm] Outer casing diameter [mm]	790 720	740 670

Since these large diameter boreholes are not typically drilled and completed in the conventional drilling operations, there are no standard casing strings available. The correlation between the different casing sizes and hole diameter is based on drilling operations with smaller diameters. (Bollingerfehr, et al., 2012) proposed a borehole radius 40 mm larger than the outer casing diameter. Others have proposed even more conservative casing setups. While in this case a rather small clearance between the casing and borehole is assumed, other papers consider much larger numbers for their casing design. Rigali et al. (Rigali, Hardin, Stein, & Su, 2015) consider a borehole with a final depth of 3000 meters, with a final borehole diameter of more than 90 cm. This leaves enough room to fit a 32 inch casing and a large container. A well with these dimensions has not yet been drilled. Also Beswick et al. (Beswick, Gibb, & Travis, 2014) recommend a similar borehole design. The feasibility of both of these designs remains questionable. Beswick and Rigali consider larger disposal containers for their disposal program. By using smaller containers, the overall borehole diameter can be reduced significantly, which brings the operation closer to the realistic feasibility.

A combination between the different scenarios leads to the casing scheme for the disposal project in Norway as displayed below. The final inner diameter of the casing leaves enough room to fit the BSK-R container in the borehole with enough clearance. The concept considers a wall thickness of at least 50 mm for each of the casing strings. This number is rather conservative, since most standard casings have a wall thickness of not even a quarter of this. More engineering that is detailed will reduce the surface diameter. The considered rather high wall thickness has positive and negative aspects. On the one hand, the casing strings are stronger and are able to withstand more pressure from fluids or the formation; on the other hand, this means more loads on the drilling rig during the completion operation.

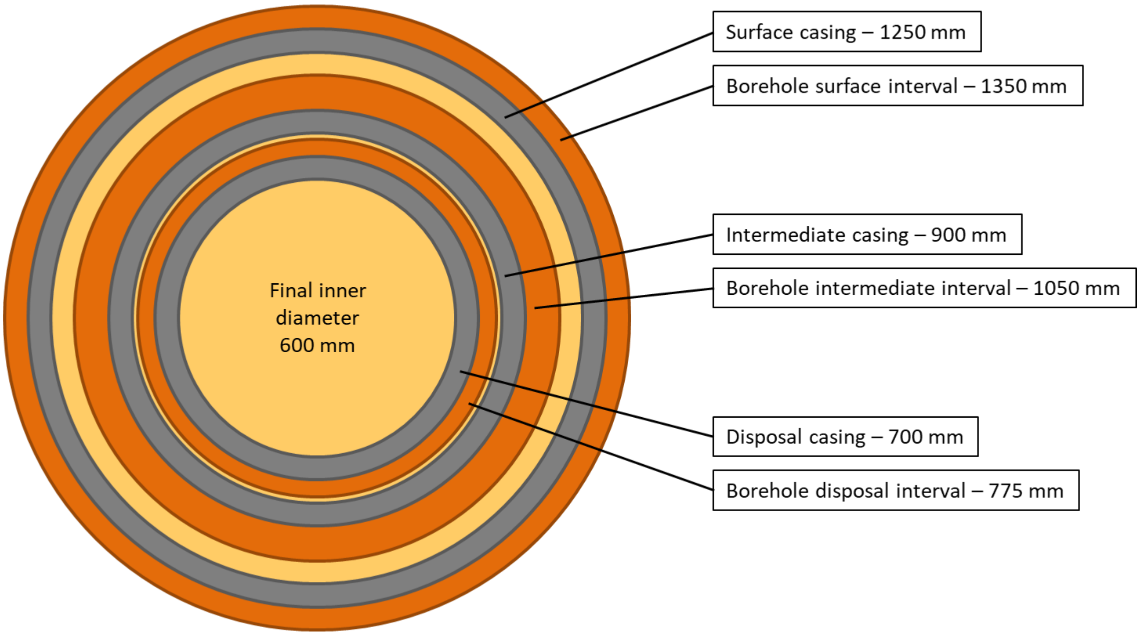


Figure 4-20 - casing scheme (top view); including clearance zones; conductor pipe not included. All casing diameter in this figure are outside diameters.

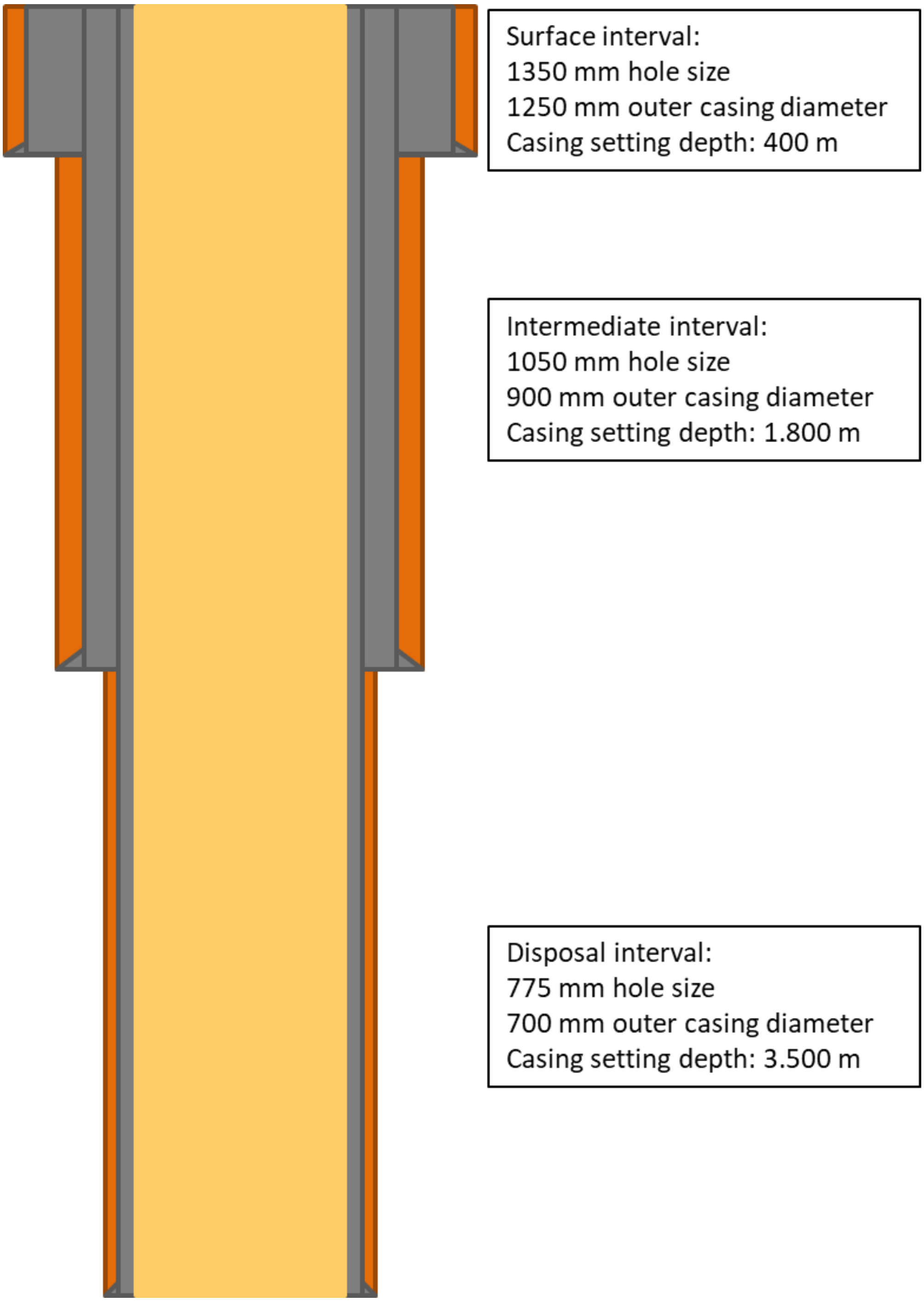


Figure 4-21 - Casing scheme (side view); conductor pipe not included.

For the casing setting depth Rigali provides an option for an operation in Norway. Due to the limited knowledge about the formation and the absence of a site, it is not possible to give a detailed depiction of the casing setup. As mentioned before, the conductor pipe is hammered in the subsurface only 10 or 15 meters. Depending on the groundwater level and potential near surface gases or aquifers, the surface pipe will be set between 250 and 500 meters. In the optimal scenario, the next casing can be set at final depth. In the more conservative option used in this case, the completion with the intermediate casing at a depth of 1500 to 2000 meter will be fulfilled. The final disposal casing will then be installed to final depth at a maximum of 3500 meter.

A complete summary of the proposed casing design is provided in Table h. These values are only rough estimates, which can be fixed once the final disposal site is selected and some more information about geology and pressure regimes are available. Once these variables are set, a final casing design can be proposed.

Table h – Proposed casing design.

	Casing (outer) diameter [mm]	Casing setting depth [m]
Conductor pipe	1500	15
Surface casing	1250	~ 400
Intermediate casing	900	~ 1800
Disposal casing	700	3500

Another aspect which needs to be considered is the casing weight. Every drilling rig has a maximum hook load. During operation, the maximum load is the casing hanging in hole before cementing. Casing weights vary widely. Factors influencing the weight are the material, the casing diameter, the wall thickness and possible fluids in the hole, which provide buoyancy and therefore reduce the load. Standard casing pipes used in the oil industry have smaller diameters and wall thicknesses than the ones considered for borehole disposal of radioactive waste. This means that the casings do not put that much load on the rig in the oil industry. An example of the weight of a 3500 meters long casing string is shown in Table i. The casing material is steel. The connections are not included in the calculation. Therefore, the actual weight of the string would be even greater.

Table i – Casing weight example calculation (from Octal Steel)

outside diameter [in]	20.00
wall thickness [in]	0.64
inside diameter [in]	18.73
nominal weight [lb/ft]	133.00
borehole depth [m]	3 500.00
borehole depth [ft]	11 482.94
casing weight [lb]	1 527 231.02
casing weight [kg]	692 739.77
casing weight [ton]	**692.74**

Comparing the casing design numbers, like the outside diameter and wall thickness, in the table with the proposed numbers for Norway show once again the great challenge in the drilling operation. Since the casings for Norway need to be much larger and greater wall thicknesses are required to withstand the great loads, the total weight of the casing string will be much greater than the one calculated. This in the end will have an impact on the rig selection as well as the overall feasibility of the drilling and completion operation. By using an alternative like a liner instead of the final casing string, the maximum hook load can be reduced significantly. Other aspects which impact the hook load significantly are buoyancy forces and potential frictions on the borehole wall. These two aspects are not discussed in this report, but reduce the actual hook load significantly compared to the casing weight hanging free in the air. There are several tools which are used commonly in the drilling industry and which include these two factors in the design process. With these two influencing factors in mind, designs which seem impossible at first sight can be feasible in the end. Without further knowledge about the required borehole trajectory, these estimates are not useful since fit to purpose calculations would be needed.

Finalizing a casing design is almost impossible without knowledge about the final location and geology of the formation. Therefore, this chapter can only provide a proposal for a potential solution for a general disposal project. Aspects like the availability of the required equipment have not yet been involved into the process. The drilling industry is barely drilling in these large scales; therefore, most of the equipment will have to be manufactured especially for this operation. This chapter also shows how many different aspects will have an impact on the casing design. Only small changes in the setup might require a completely new design process.

4.2.6 Casing Cementation

The borehole requires a solid bond between the casings or liners and the rock formations. With the aim of holding the casings in place, it may also be necessary to seal and stabilize loose or loosened rocks. With regard to their long-term stability a favourable chemical environment is to be guaranteed. In addition, movements of fluids along the borehole should be largely restricted, in particular to prevent or at least to limit corrosion processes. These tasks are performed with materials that are pumped into the voids, where they harden to low permeable solids.

The materials are suspensions that always contain a binder that reacts with the carrier liquid. The use of the following binders or cement types can be considered:

- Classic cements of civil engineering on the basis of Portland cement clinker according to EN 197-1, EN 14216 or DIN 1164-10.
- Well cements containing Portland cement clinker according to EN ISO 10426-1.
- Supersulfated cements according to EN 15743.
- Calcium aluminate cements according to EN 14647 (cf. Roy et al. 1980, Sugama et al. 2005).
- Calcium aluminate phosphate cements.
- Alkali-activated binders (“geopolymers”).

In order to modify the properties of the mixtures in the liquid or hardened state, the cements contain reactive (supplementary cementitious materials, SCM) or inert additives (fillers), which can also be added to the mixtures separately. The use of admixtures such as flow agents and retarders is common. It can be an advantage to use expansive agents to reduce tensile stresses during hardening, which could lead to cracking. Other potential components are pigments or aggregates. In the case of cementing the casings, however, the use of aggregates is limited due to the small width of the flow paths. Due to the extensive selection and optimization options, high-performance materials can be used for cementation. When selecting suitable recipes, numerous effects or influences must be taken into account, which results in a multitude of requirements.

With regard to cementation process, i.e. the placing of the flowable suspension, it must be taken into account that the time of workability (pot life, thickening time, set time) decreases with increasing temperature. Moreover, temperature influences the rheological properties (flowability, stability) of the suspension. Due to this fact, there are basically three different temperatures to consider:

- Bottom hole circulating temperature (BHCT),
- Bottom hole static temperature (BHST), and
- Temperature differential (temperature difference between the top and bottom of cement placement).

The BHCT is the temperature to which the cement will be exposed as it circulates past the bottom of the casing. The BHCT controls the time that it takes for the cement to setup (thickening time). BHCT can be measured using temperature probes that are circulated with the drilling fluid. If actual wellbore temperature cannot be determined, the BHCT can be estimated using the temperature schedules of the American Petroleum Institute. The BHST considers a motionless condition where no fluids are circulating and cooling the borehole. The temperature differential becomes a significant factor when the cement is placed over a large interval and there are significant temperature differences.

Figure 4-22 is intended to provide additional information about this topic and is intended to indicate the influencing factors that affect the hardened cementation.

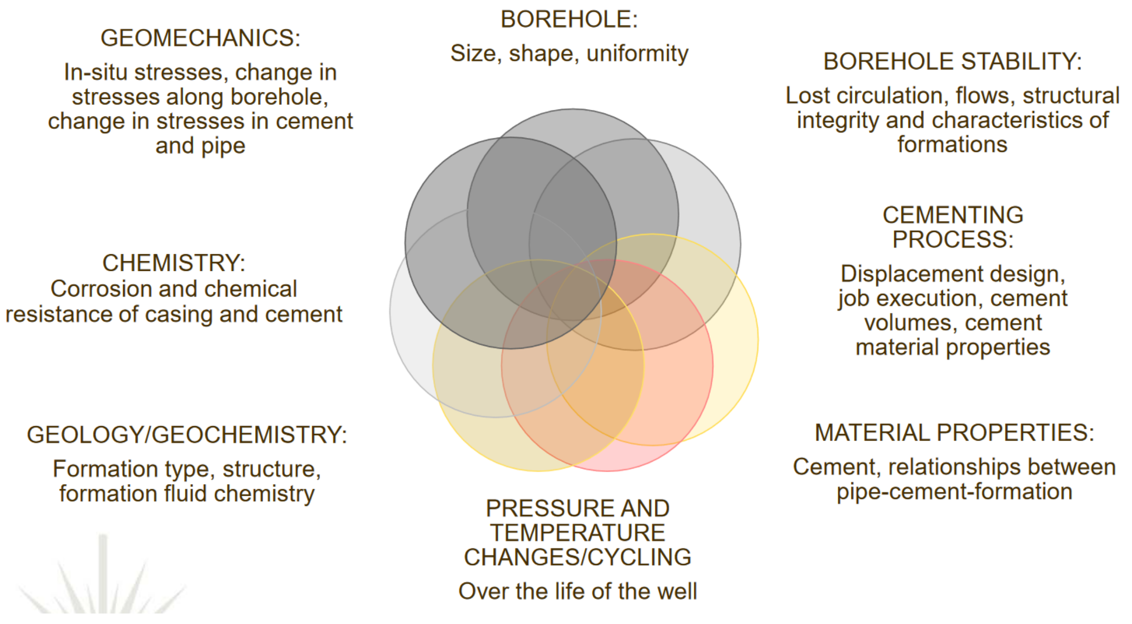


Figure 4-22 - Framework conditions that influence the quality of casing cementation.

The procedure for selection, material development or optimization is known for conventional drilling. From the extensive knowledge and wealth of experience, it can be deduced that two recipes are required for the casing cementation of the disposal borehole. For the upper part of the borehole there are no requirements resulting from the waste disposal. This part can be cemented with a known recipe and proven technology. Usually, recipes containing cement according to EN ISO 10426-1 are used. Depending on the chemical composition of the formation waters (cf. DIN 4030), it may be necessary to use a sulphate-resistant cement if there is contact with the rock formation. The solid components of these recipes are transported to the construction site as a premix.

Cementing very deep holes has long. Mixtures with cement according to EN according to class G are mostly used. There are also extensive developments for cementing of deep geothermal boreholes. With regard to borehole disposal, however, the additional temperature rise resulting from the disposal of heat-generating waste must be taken into account. The resulting temperatures can lead to high stresses or loads in the casing, the cementation and in the rock formations and in axial and radial borehole direction. It is extremely important that so-called fracture pressures are not exceeded.

With regard to the long-term stability of the materials, it should also be pointed out that the radioactive heat generation leads to a temperature rise above the temperature of the building material that was achieved during hardening (cf. Lorenz et al. 2015). This can lead to dehydration of mineral phases. However, it can be assumed that the tests of applicability result in suitable recipes, especially since there are extensive application rules for the development of temperature-resistant building materials and their use. For example, it is recommended to use raw materials with a low thermal expansion coefficient and recipes with a high proportion of reactive components so that the hardened material has a low pore space saturation. This can reduce pressure build-up by compaction or the evaporation of water. Today, the majority of geothermal wells are cemented with silica-stabilized Portland cement composites. Cement grouts are used in cementing operations up to 400°C. Above approximately 160°C tobermorite changes to xonotlite, the stability and durability of which is similar to that of tobermorite. In order to reduce the corrosion of the casing, mixtures should be used that guarantee a high pH in the long term (cf. IAEA 2009).

Although the implementation of the cementation work is assessed as less problematic, the specification of a final recipe does not seem to make sense at the current time. For example, site-specific framework conditions must be taken into account. In addition, future material development should be considered when making this decision. In particular, the synergy effects that result from the processing of comparable tasks from international repository projects should be used (e.g. Crusset et al. 2017). With regard to the mechanical stability, it should be emphasized that the cementations of a disposal borehole are not subject to relatively short-term temperature changes, which often occur in the case of production drillings or boreholes of gas or oil storage facilities. Detailed guidelines have been developed for the implementation of cement jobs. There are also numerous test methods to prove the success of the cementation work that are performed as a part of a quality assurance program. A prerequisite for the successful completion of the work is sufficient knowledge of the quality of the borehole contour and its geometry. The geometry of the borehole is important in determining the amount of grout required for cementing, and to prove the complete backfilling of the voids. The borehole dimensions can be measured using a variety of methods, including acoustic callipers, electric-log callipers or fluid callipers.

BGE Technology GmbH has extensive experience regarding the cementation in deep boreholes. Some example pictures are presented in the following. Typically, several trucks with the components come to the site and line up around the borehole. With pumps, the different components are brought together and pumped into the hole.

Figure 4-23 – Drilling site during a sealing measure of a vertical borehole extending into the rock salt of a salt dome in Northern Germany. The photo show delivery vehicles as well as the mixing and pumping system. (BGE TECHNOLOGY GmbH.)

Figure 4-24 – Cementation line-up around a borehole (BGE TECHNOLOGY GmbH).

4.2.7 Feasibility of the borehole construction

The feasibility analysis of a borehole can be broken down into individual steps. In the first step, it is examined whether a borehole of the required length and the required diameter can be drilled. The second step concerns the investigation of the rock quality. Then, it is checked whether the casing can be handled with available drilling rigs. Finally, it is proofed whether the borehole quality is suitable for the disposal of waste containers.

4.2.8 Borehole dimension

The length and the achievable diameter of a borehole depend on numerous factors, in particular on the capacity of the rig, the drilling technology and the geological environment. In this study, the individual influencing factors are not assessed, but a simplified procedure is chosen. In analogy to preliminary studies, the diameter and the length of boreholes that have already been drilled are evaluated and compared with the requirements. In particular, boreholes in crystalline rocks are taken into account.

A list of boreholes and relevant information is included in Sassani & Hardin (2015) and in the Nirex (2004) report, which is from the Juhlin & Sandstedt (1989). This list considered boreholes drilled into crystalline rock to a depth of 1500 meters or greater. Moreover, Rowley & Schuh provide a comprehensive compilation of crystalline rock drilling data. Figure 4-25 shows a diagram with information of the diameter and depth of deep boreholes.

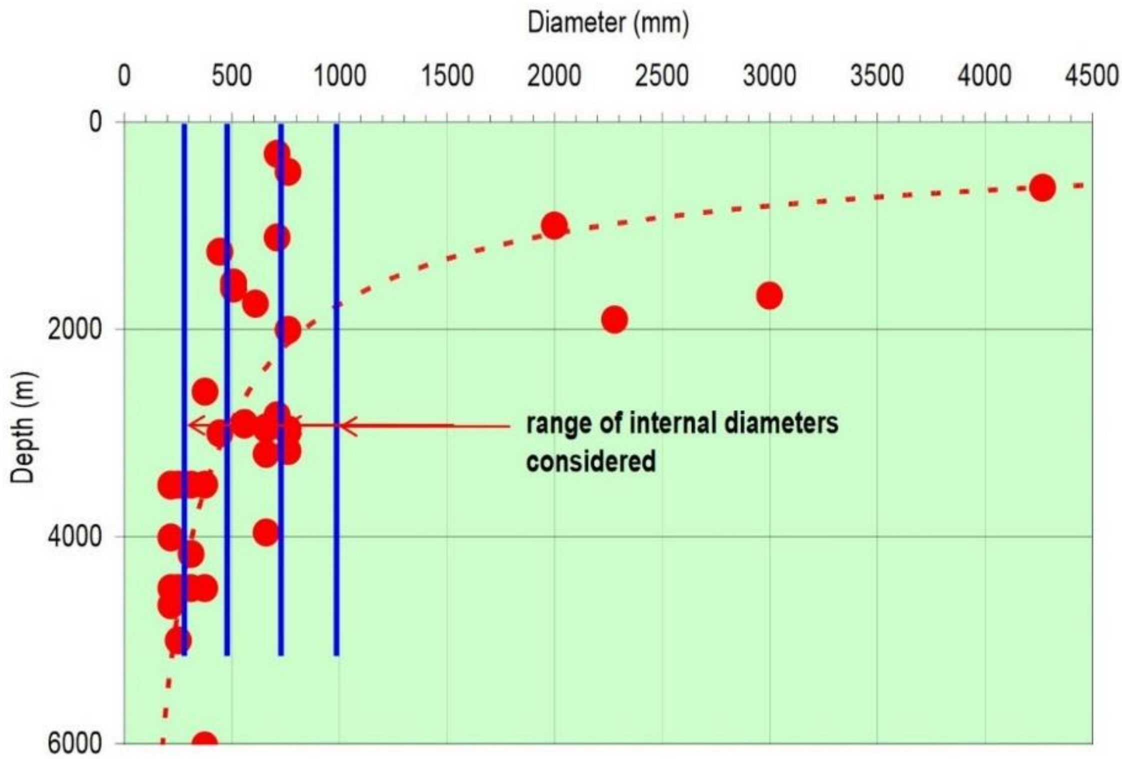


Figure 4-25 - Relationship between Depth and Diameter Generated by Actual Practice according to Arnold et al. (2012) (from Beswick 2008, cf. Beswick et al. 2014, Sassani & Hardin 2015).

Within the last decade, no significant changes regarding the borehole diameter have been made. Many wells are drilled deeper, but almost all of them are drilled with a small diameter. The hydrocarbon industry as well as the geothermal industry do not require large diameter boreholes, therefore there is no interest on enlarging the boreholes, since typically the costs are increasing with increasing diameters.

For the borehole in Norway, when using BSK containers, a required minimum borehole diameter of 75 cm was determined. The length of the disposal zone is estimated to a maximum of 1500 meters.

For the borehole in Norway, it is foreseen to drill an inclined disposal zone. However, the radii of curvature will be large due to the need to transport the containers (cf. Gibbs 2010.) Plotting the values of the actual borehole length or true vertical depth (TVD) into the diagrams will not lead to any deviating results. The proof clearly shows that a borehole of the required dimensions can be drilled in Norway.

4.2.9 Investigation of rock quality

As a result of the mechanical impact during the drilling process and stress redistributions a damaged zone forms around the borehole wall. In comparison to the undisturbed rock this zone has a higher porosity, lower strength, and increased permeability. The strength of the rock influences the bond with backfilling and sealing materials, such as the casing cementation. In this case, it is necessary to take into account that the heat of hydration results in additional thermally induced stresses. Moreover, the knowledge about permeability as well as the number and width of fractures are a prerequisite for the planning and the construction of seals (cf. Borm et al. (1997). Roughness of the borehole surface, its purity (Rautio et al. 2004) and mineralogical composition are significant parameters, which influence the quality of cementations and seals. Knowledge must be available to decide whether, for example, reaming the borehole is necessary or not.

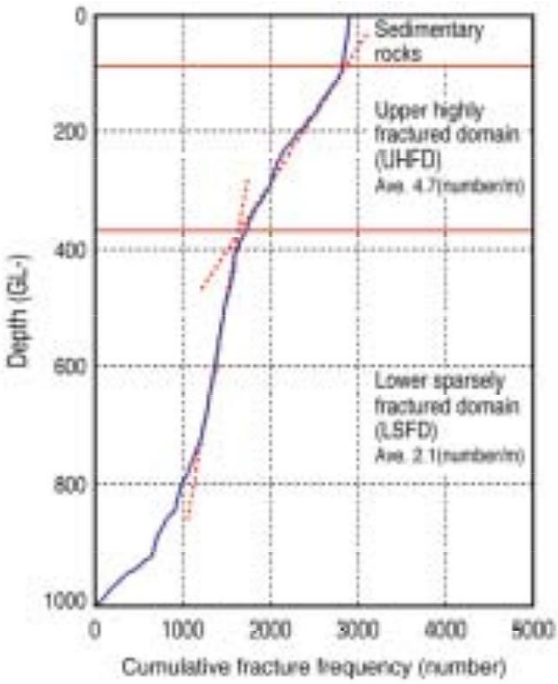


Figure 4-26 - Cumulative fracture frequency in the MIU-2 borehole after Nakano et al. (2003).

Some of this information can be obtained by extracting drill cores. However, it is always essential to carry out borehole measurements. These measurements are carried out during drilling (known as measurement while drilling [MWD]), and logging while drilling [LWD] or after drilling, before or after borehole casing has been fully installed.

The techniques were developed in oil and gas drilling, exploration drilling and for scientific investigation drilling. In this context, the work of the International Continental Scientific Drilling Program (ICDP) deserves special mention. For example, the continental deep drilling program (KTB) in Germany and the China Continental Scientific Drilling Project (Da Wang et al. 2015). The CCSD project resulted in a total drilling depth of 35000 meters. One drilling into an ultrahigh-pressure metamorphic terrain reached the target depth of 5118.2 meters after 1309 days (Xu et al. 2005, Xu et al. 2017). With regard to the drilling and investigation of deep drillings that are typical of Norway, reference is also made to the publication by Lorenz et al. (2015). For example, Harms (2015) describes techniques of coring, data and sample management, downhole logging, permanent downhole monitoring, and drill site instruments. The extensive measurements that have been and are being carried out in bores as part of repository bores must also be taken into account. An overview of inspection tools in the context of deep borehole disposal give Finch et al. (2018).

The borehole length is not a limitation in this case, because a large number of the boreholes in Norway are drilled to greater depth on a regular basis. In addition, there are no exceptional framework conditions such as extremely high temperatures to be expected in this disposal borehole (e.g. Lorenz et al. 2015). When planning the drilling activities in detail, however, it must be taken into account that the extraction of drill cores always leads to increased costs and time. Detailed knowledge of the borehole path (borehole deviation) is also essential for the planning and implementation of numerous works. However, such measurements are part of routine work in the deep drilling industry.

In summary, it can be said that all necessary work can be carried out without major problems.

4.2.10 Handling of the casing

This test examines whether the vertical forces actually occurring during the drilling process exceed the hook load capacity of the rig (cf. Stober & Bucher 2013). The vertical load or total force is a result of the weight of the drill string, the drill collars and any equipment reduced by any force that tends to reduce that weight. Some forces that might reduce the weight include friction along the borehole wall (especially in deviated wells) and buoyant forces by immersion in drilling fluid. If the blow out preventer is closed, any pressure in the wellbore acting on the cross-sectional area of the drill string in the blow out preventer will also exert an upward force.

In this simplified view, these influencing factors are neglected and the weight of the casing in the air is compared with the information on hook loads from rigs. For a length of 3500 meters a maximum weight of more than 2500 tons is calculated, considering a casing made of steel and not of aluminium or any other lighter material. Also, this scenario considers a wall thickness of the casing of 50 mm, which can most likely be reduced. The mentioned influencing factors will reduce the actual hook load, which makes it possible to drill to these depth.

In comparison, (see also 4.2.3), for example, oil-field rigs are available with lifting capacities up to 900 metric tons. So far, drilling units with hook loads of 150 to 500 tons have been used for drilling for deep geothermal wells in Germany. Including the effects of drilling fluids and deviated wells, there are surely rigs on the market which are capable of drilling the required borehole. Still, there is more detailed calculation with special programmes necessary.

According to Arnold et al. (2013) the borehole reference design presented in Arnold et al. (2011) requires a 2,000 horsepower drilling rig with a minimum hook load of 1,000,000 pounds (454 tons). The availability of such a rig was not classified as critical.

Other selection criteria such as the noise level are not considered to be decisive in this study. It can also be assumed that modern rigs do not lead to unacceptable noise emissions.

4.2.11 Borehole logging

Final tests must in particular check the quality of the casing when installed and the quality of the cementation.

Cement bond logs (CBL) have been available for many years. These pulse-echo sonic tools are conveyed downhole on wirelines and detect the bond of the cement to the casing and formation via resonance. Casing that is not bound has a higher resonant vibration than the formation. Variants of CBL, combined with neutron density measurements that can be run in a single pass, are also available. These provide more detailed information on cement quality and integrity.

Ultrasonic imaging tools that combine azimuthal measurements and signal attenuation with those of resonance are a more recent development and allow the identification of any channels in the cement. More advanced versions of this technology, employing also flexural waves, are able to detect low density solids behind casing from liquids. Moreover, their azimuthal coverage allows imaging around the entire circumference of the casing with a solids-liquid-gas map pinpointing any channels in the cement and confirming the effectiveness of zonal isolation. Third-interface echoes provide additional information on the position of the casing within the borehole, the borehole shape, and any casing corrosion that may have already occurred.

In general, casing damages can be caused by deformation, physical influences, wear, and corrosion and there are four commonly used techniques for the inspection of casing:

Cased-hole callipers,

Flux-leakage tools,

Electromagnetic phase-shift tolls, and

Ultrasonic tools.

There are several other aspects of borehole logging, which are not addressed in this report. In this regard, reference is made to the extensive literature, such as DBETEC (2016). Detailed information can also be obtained from the numerous companies that are specialized in borehole logging. However, it can be concluded that a quality assured borehole for radioactive waste disposal can be implemented according the requirements.

4.2.12 Waste emplacement techniques

Emplacement techniques are a central part of the borehole disposal operations. A suitable emplacement technique is an indispensable prerequisite for the implementation of deep borehole disposal. There are techniques available that are based on concepts for borehole disposal in mined repositories (e.g. Bollingerfehr et al. 2011) and the experiences which were gained by the deep drilling industry. However, differences from the oil and gas industry result from the requirement of a remotely operated, personnel-free transfer of containers into the borehole and the greater weights of the waste containers compared to drill probes. Knowledge of shaft conveyor systems is also valuable. The differentiation from other deep wellbore operations (oil/gas etc.) is the requirement that the containers of high mass have to be transported to great depths, as well as the required reliability of the emplacement technology due to the unshielded radioactive waste containers. Five principle emplacement techniques are described (cf. Arnold et al. 2013, Beswick et al.2014, NWTRB 2016):

- Free fall,
- Wireline,
- Use of drill pipes/drill strings,
- Use of coiled tubing systems, and
- Conveyance liner.

Figure 4-27 is intended to illustrate the emplacement into a fluid-filled borehole using a wireline, drill pipe or coiled tubing system. The housing of the emplacement device is required in order to ensure radiation protection.

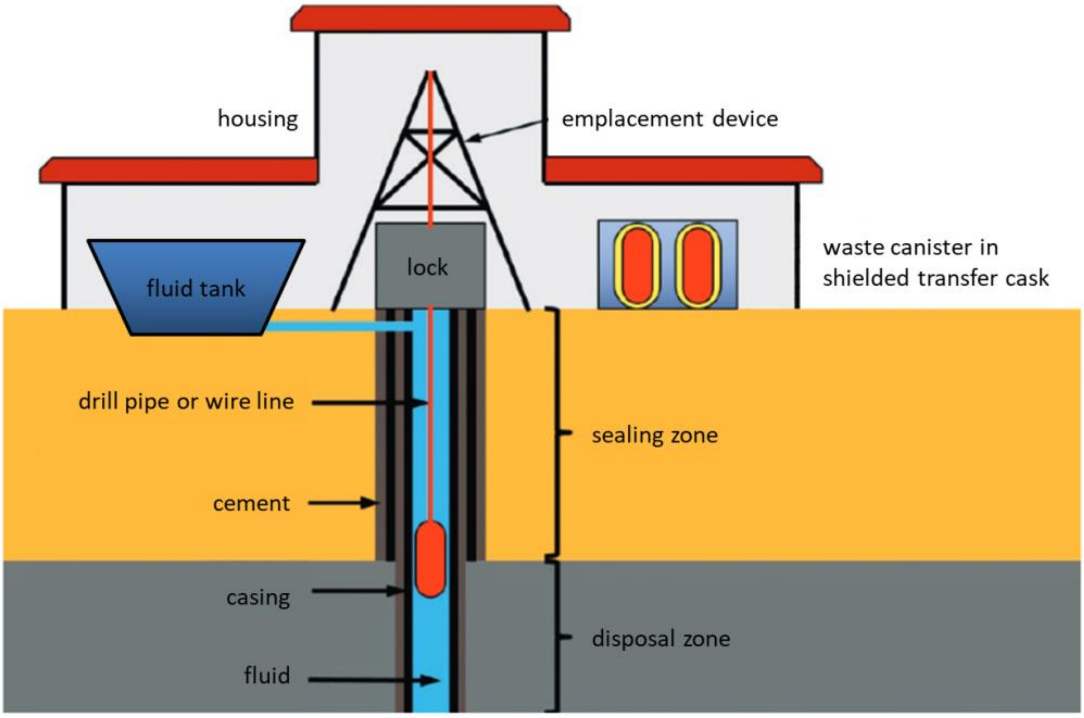


Figure 4-27 - Schematic of emplacement of the disposal container according to Rosenzweig et al. (2019).

Free Fall

This technique can only be used if the borehole is filled with aliquid. It is not an uncommon means of down-hole emplacement in drilling operations. However, for deep borehole disposal, free fall should not be employed as there is no control on the emplacement. The technology is excluded due to insufficient occupational safety. If a container is jammed in the borehole, releasing it could be difficult and time consuming. In addition, it does not seem possible to retrieve containers, since they are mostly likely damaged after the impact on the bottom of the hole. However, studies on the free fall could be carried out in order to describe the effects of a container loosening from an emplacement device.

Wireline

Wireline techniques are often used in mining and in boreholes, especially for vertical or almost vertical transports. Basic information on winch systems can be found in Liebherr (2019). Information on shaft hoisting systems is given for example in CTECH (2002). Mobile hoist winches (shaft winders) are used as an auxiliary drive system for inspecting shafts and as an emergency drive system for rescuing people. The company Siemag TecBerg GmbH (Germany) offers a self-driving and autonomous inspection and auxiliary winch that reaches a maximum depth of 1300 meters with a speed of up to 1.0 m/s. Its rope load is up to 50 tons and the suspended load (cage inclusive payload) is between 2.0 and 3.5 tons depending on depth.

Beswick (2008), Beswick et al. (2014), Freeze et al. (2016), SANDIA (2015), for example, deal with the use of the wireline technique in the field of deep borehole disposal and give general information.

An emplacement device for the use in mined repositories was developed by BGE Technology GmbH. It can emplace BSK3 containers with a length of approximately 5 meters and a mass of around 5.2 tons in vertical boreholes and has already been tested. Figure 4-28 shows the emplacement device. Bollingerfehr & Filbert (2007), Bollingerfehr et al. (2009), and Filbert et al. (2010) describe details. Although this device is only suitable for emplacing containers in boreholes a few hundred meters deep, much greater depths of emplacement could be achieved by appropriate modification. It should be emphasized that tests have been carried out with the device that prove the perfect functionality.

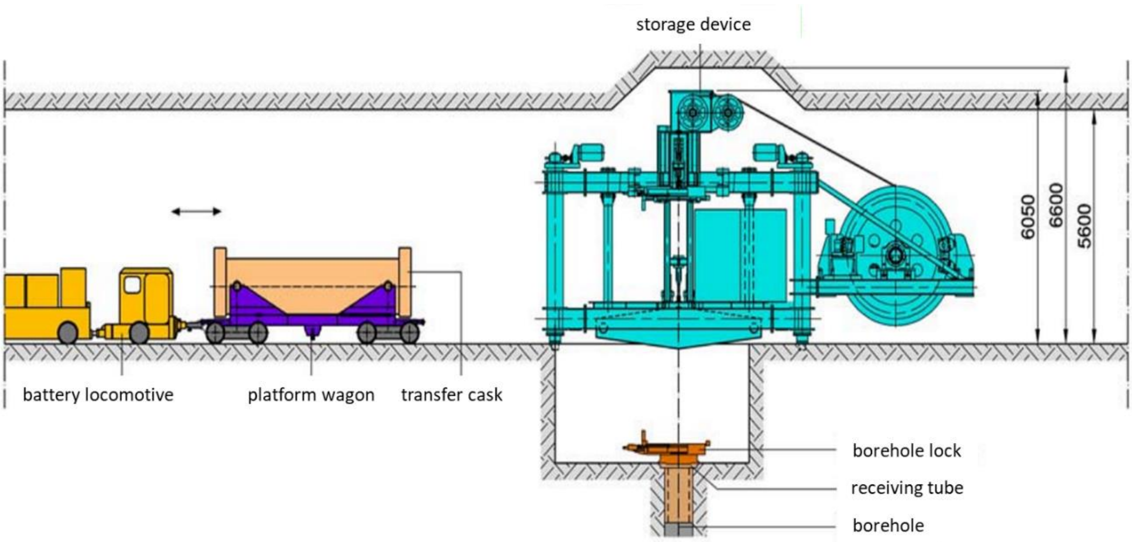


Figure 4-28 - Emplacement device for the emplacement of BSK 3 containers in boreholes. Schematic drawing according to Wehrmann (2006).

Moreover, experience with the emplacement of containers in boreholes was gained in the context of the Spent Fuel Test Climax (SFT-C), which was carried out between 1978 and 1983. This was an operational test in which containers were transferred to vertical holes in the Climax Mine at 416 meters depth and were retrieved after 3 years (Figure 4-29). The main goal was the demonstration of the feasibility of safe and reliable transport, storage, and retrieval of spent nuclear fuel. Operating procedures, administrative controls, and personnel training contributed to attaining this objective. Patrick (1986) gives a description of spent fuel handling, which is reproduced here. Accordingly, 11 encapsulated assemblies were stored at a rate of about two per week. The assemblies were shipped from the reactor to an engine maintenance, assembly, and disassembly facility (EMAD) by truck-mounted, licensed, commercial shipping casks. Once the casks were received and encapsulated, a three-component handling system was used for all operations. Each assembly was encapsulated in a 356-mm diameter stainless steel container that was sealed and backfilled with helium gas. An integral shield plug and grappling knob provided the interface with the handling system. The handling system had three major components:

- The surface transport vehicle (STV)—a special trailer with a rotatable shielding cask and a commercial tractor. It was designed to move the encapsulated spent fuel from EMAD to the test site.
- The underground transfer vehicle (UTV)—a rail-mounted, remotely controlled shielding cask with an on-board jib crane, received the spent-fuel containers underground and emplaced or retrieved them from the boreholes.
- The container-handling system was a wire-line hoist with control and braking subsystems. It lowered and raised the spent fuel between the STV and the UTV. An automatically actuated brake travelled with the container for protection in the event of a hoist or cable failure. Control systems and closed-circuit television permitted remote operations with no risk of excess radiation exposure to personnel.

Arnold et al. (2012) state that the containers had a diameter of 36 cm and length of about 4.5 meters and each contained a single PWR fuel assembly. The containers were lowered with the wireline hoist through a cased borehole with an inside diameter of 48 cm to a depth of about 420 meters. The operations showed that spent fuel can be safely handled with available technologies (cf. DOE 1980). Wilder & Patrick (1981) summarize further information.

Figure 4-29 - Climax Test with shipping cask turned vertically. Shielded lid on bottom of shipping cask (Cochran & Hardin 2015a).

Cochran (2016) and Hardin et al. (2015) describe an emplacement device that was specially developed for use in deep boreholes. In this case, a standard truck- or skid-mounted wireline with 6100 meters of 1.2 cm double-armoured 7-conductor electric wireline can be used for emplacing waste packages. The device was developed for transporting containers with a dry loaded maximum weight of 2100 kg and a buoyant loaded maximum weight of 1650 kg in drilling mud. The containers are radiologically and thermally hot, long and narrow (5.6 m by 0.27 m). Figure 4-30 shows a sketch of a wireline device (Hardin et al. 2015).

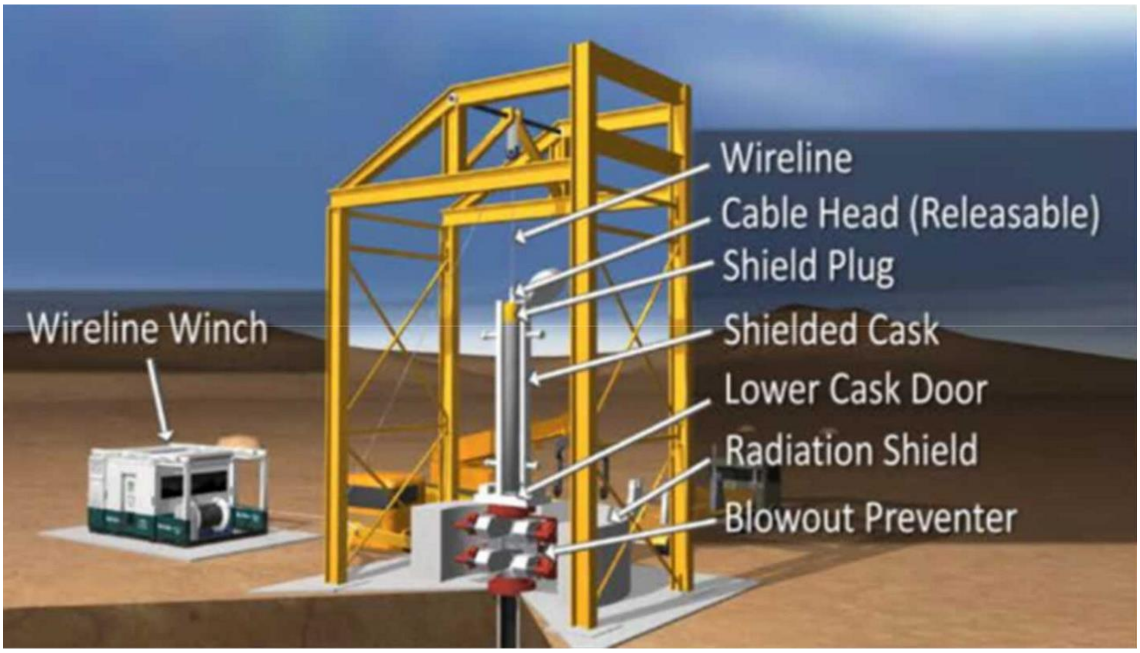


Figure 4-30 - Cutaway visualization of BOP (blowout preventer) shield, and transfer/shipping cask in position for waste emplacement (cf. Sassani & Hardin 2015).

As part of this study and the CREATIEF (2018) research project, BGE Technology GmbH carried out extensive studies on the usability of the wireline technology. The calculations showed that even taking into account the rope safety factors and the nuclear regulations, a container of type BSK3 could be lowered to a depth of significantly more than 3 km. The calculations were based on the requirements of DIN 15020, EN 12927 and the technical requirements for shaft and inclined conveyor systems. The calculations showed that a wire with a diameter of more than 50 mm diameter would be required. Such a wire has a high weight, so that a powerful winch is required. Wires of this diameter cannot be bent arbitrarily. Consequently, a large drum has to be used. The storage device described by Bollingerfehr & Filbert (2007) could, however, be adapted accordingly.

Drill pipes/drill strings

In contrast to wires, drill pipes are solid metal rods or hollow cylinders. Numerous pieces must therefore be assembled into a drill string. Drill pipes are available in different diameters and lengths. Standard diameters are e.g. 3 $^1/_2$, 4, 5, 5 $^1/_2$, 5 $^7/_8$, and 6 $^5/_8$ inch. At each end of the drill pipes, larger-diameter portions called the tool joints are located. Pulling the drill string out of or running the drill string into the hole is referred to as tripping. The assembly of the individual strings or stands requires the use of a drilling or workover rig. Modern onshore rigs are capable of handling ~90 ft pipes or stands (9.45 meters). The traditional “triples” rigs lower or pull three lengths of 9.45 meters drill pipe each time (i.e., about 28 meters) and rack the pipe stands back in the mast or derrick. Since the work requires additional space, numerous such rigs have a height of 50 to 60 meters.

Depending on the rig, the assembly work requires different degrees of manual activities. Due to the required emplacement speed and for reasons of classic occupational safety and radiation protection, only high-level automated rigs should be used (“hands-off technology”).

The use of drill strings for the disposal of radioactive waste in deep boreholes has been examined in detail and is described in numerous publications. Examples are CREATIEF (2018) and SANDIA (2015).

Reference is made to this work for detailed information. According to Cochran & Hardin (2015a) and Cochran & Hardin (2016) the 2011 reference design for waste handling and emplacement (Arnold et al. 2011) is based on a previous study of Woodward–Clyde (WCC 1983) which itself is based on the Spent Fuel Test Climax. Figure 4-31 is intended to give an impression of the dimensions of the rig required. The reference waste container design in WCC (1983) is a carbon steel container that is 10 ft (3.0 meters) in length and 12.75 inches (32 cm) outside diameter (OD). WCC (1983) contains a detailed design for the surface facilities that would be used for the transfer of waste containers from transportation casks to insertion into the borehole. The emplacement rig includes an elevated drill floor, a shielded room below the drill floor to position the transportation cask over the borehole, and a subsurface basement for insertion of the unshielded waste container into the borehole.

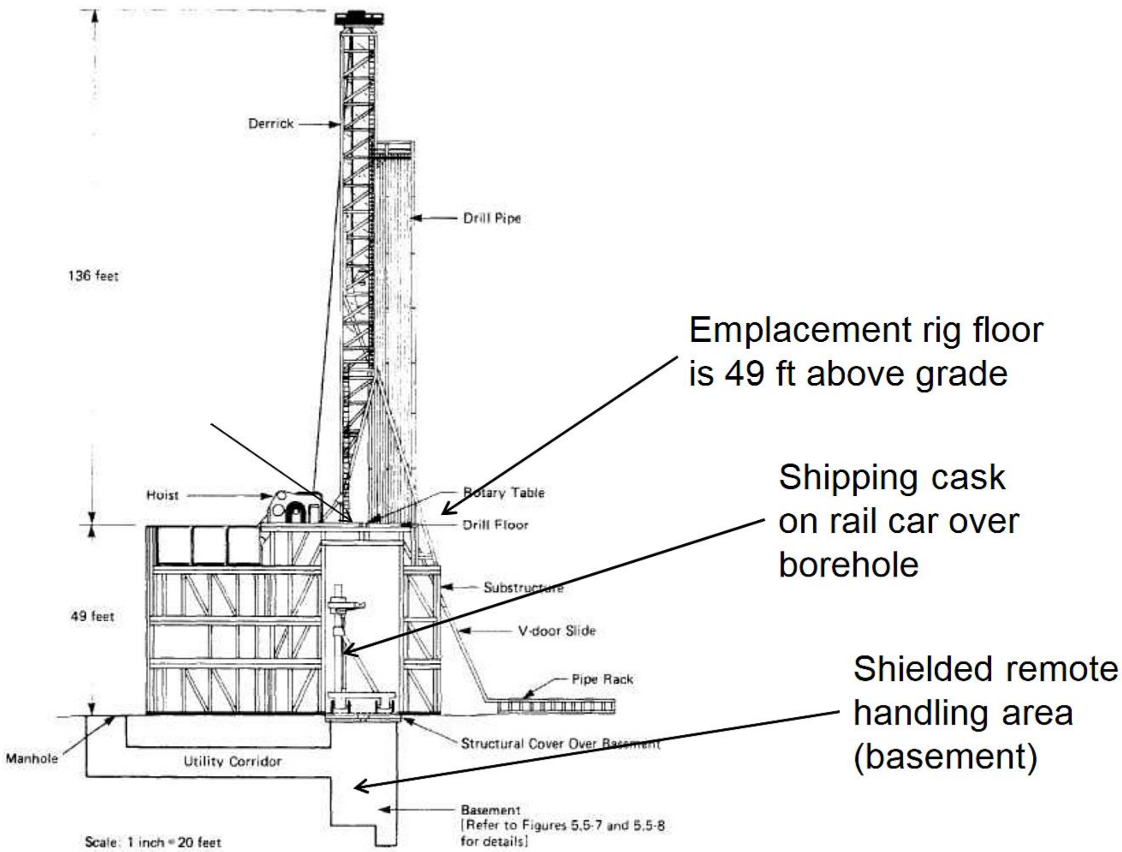


Figure 4-31 - Emplacement rig according to the study of Woodward-Clyde Consultants (Cochran & Hardin 2015a). The total height (136 ft. + 49 ft.) corresponds to 56.4 meters.

The feasibility is also given when emplacing larger containers. However, demonstration attempts have not yet been carried out. On the other hand, there are existing containers, such as the BSK container, that are currently designed for the emplacement using wireline techniques. Still, the coupling needs to be adapted for the use of drill strings.

Coiled Tubing

Coiled tubing refers to a very long metal pipe that is supplied spooled on a large reel. The small diameter pipe, normally 25 to 83 mm (1 to 3.25 in) in diameter, is hydraulically driven into the hole. Coiled tubing is made from a highly ductile steel alloy that recovers its initial strength even after being plastically deformed beyond yield. On the other hand, it is also a material that had a greatly reduced breaking stress capacity at very much reduced fatigue cycles compared to high graded steel. Therefore the number of cycles (off/on reel motion) combined with the actual stress in the material from pull and internal/external pressure needs to be carefully monitored for each coiled tubing unit in the field to avoid premature failure. But a coiled tubing intervention is also a heavy and expensive operation. It requires on a land location approximately the same footprint and access roads as for a mid-sized medium-to-heavy drilling rig. In contrast to the wireline emplacement method, which relies on gravity to lower the package coiled tubing can also work with force from the surface by pushing the tube forward. Emplacement using coiled steel tubing was briefly discussed in the Sandia National Laboratories report of Cochran & Hardin (2015). However, the current level of disposing material with coiled tubing methods comparatively small. So far, no detailed concepts for the use of this technology have been developed.

This option was evaluated in more depth in the CREATIEF project (2018). The feasibility of numerous round trips in particular is assessed as critical. The operational reliability was considered too low. Due to the high development effort, this technique is not considered further in this study. However, the development of such systems has been rapid in recent years and they are now used for drilling, well intervention, logging and well completion operations, with a wide range of equipment available. New systems incorporate electrical conductors through the continuous tube allowing data transmission and commands for release mechanisms. The equipment is widely used in different sizes and to depths well in excess of 4 km. Deployment speeds could be more than 0.6 m/s with a waste package release mechanism triggered by means of conductors in the tubing and data acquisition possible through others. The surface set-up would be relatively small so reducing environmental disruption and significantly more cost effective than maintaining a drilling rig on site, but still more costly than wireline operations for example. Due to this fact, it is assumed that this technique has great potential. Coiled tubing should therefore be considered in future assessments of the emplacement techniques.

Conveyance liner

A conveyance liner is a large-diameter casing that is sealed at the bottom and held in place at the well head. Waste packages are stacked inside the conveyance liner using a wireline. Then the entire casing is lowered into place using a drill string. To maintain a casing path for the conveyance casing, using the same size waste packages, a larger diameter borehole is needed in the disposal zone than for the other emplacement modes

(SNL 2015). Due to the low level of development, this technology is not considered further here.

Evaluation of the emplacement techniques

The first evaluations of emplacement technologies showed that wireline and drill strings could be used to dispose of the radioactive waste in Norway in deep boreholes. Modifications to the system technology are required, which also depend on the finally selected container, but these developments should be feasible within reasonable periods. This statement applies in particular to single emplacement of containers, comparable to the BSK3. However, emplacement of waste container strings or batches was also considered by previous studies (Arnold et al. 2012, Arnold et al. 2013, Gibb et al. 2008, cf. Gibb et al. 2012). This option is not pursued here due to the greater need for development. According to previous calculations, the duration of the emplacement phase of a borehole facility is relatively short compared to the total duration of the project. Thus, the time saved during emplacement would not justify the additional development effort. The number of round trips can also be reduced by choosing containers of larger capacity.

The following facts are regarded as advantages of wireline technology:

The greatest wealth of experience is available with this technology with regard to the disposal of radioactive waste. Demonstration and handling tests have been carried out.

The high emplacement rates can be achieved with this technology.

Low risk of waste package damage during emplacement. The probability that an off-normal event occurs leading to breach of a waste package is greater for the drill-string option, mainly because of the high probability of breach if a pipe string is dropped onto packages on the trip out, and the effective use of impact limiters on single packages that mitigate the consequences of drops during wireline emplacement (Hardin et al. 2015, cf. Finger et al. 2015).

The technique is less costly for normal operations.

The following aspects are classified as disadvantages in comparison to the drill string technique or are advantages of the drill string technique:

Wires are subject to wear. Checking the wire is time-consuming and so is changing the rope. Wire checks require special measures in the case of radioactive waste disposal.

Wires are flexible. Length changes occur during transport, which require special control measures and the use of shock absorbers.

- The use of drill strings has advantages if a container jams because pressure, tensile and torsional forces can be used.
- When using a drilling or workover rig, there are considerably more options for carrying out investigations and work in the borehole. A rig could be used for fishing operations.

It is currently assumed that due to the flow processes, a drill string can be used better in solution-filled boreholes.

Heavier containers can be transported with drill strings.

If necessary, the rig with which the borehole was drilled can be used for emplacement. This saves renovation work, but requires that the drill rig is rented for a longer time.

The likelihood of emplacing containers without incident (without a drop, and without getting stuck) is better for drill-string emplacement, primarily because of the greater probability of getting a container stuck using a wireline (Hardin et al. (2015).

However, it should be borne in mind that in a project in Norway, the borehole would be shorter. This can have an impact on the assessment of the emplacement techniques. With large rope diameters, considerable damage to containers can also be expected in the event of a rope break. Consequently, the validity of the individual parameters that Hardin et al. (2015) were used has to be examined in detail. This is not possible in this study. In addition, this updated evaluation should take into account the level of knowledge regarding the use of modern full-automatic drilling rigs.

It is an advantage that Norway has extensive knowledge of the construction and operation of technical facilities that are used in the field of deep drilling technology. Initial investigations and tests of emplacement techniques could be carried out for example at the Ullrigg Test Centre situated at Ullandhaug in Stavanger, Norway, where a full size triple rig is installed, at the New Devico drilling technology testing facility near Trondheim or the test rig of Herrenknecht Vertical in Rijswijk, the Netherlands.

4.2.13 Sealing and Plugging

The isolation of the radionuclides is based in particular on the long-term function of the geological barrier and engineered barriers, including seals and canisters. They form a multi-barrier system. The borehole seals should at least largely restore the integrity of the geological barrier. Due to the geomechanical properties of the crystalline rocks, a closure of the boreholes as a result of convergence can be ruled out. Rock welding is also not yet seen as an option for closing a borehole (e.g. Gibb 2015), despite the fact that Yang et al. (2019) showed that granitic materials can be purposefully engineered through chemical modifications to enhance the sealing capability. Lee et al. (2018) performed experiments in order to evaluate the granite melting technique (Lee et al. 2018). Consequently, the seals consist of foreign materials that can be placed in the position provided for the seals. These positions are characterized in particular by the fact that no cracks or general flow path exist in the host rock that could cause a notable bypassing of the seals.

With regard to the tightness of a seal, the core barrier consisting of a sealing material, its contact zone with the rock and with an adjacent zone in the host rock must be differentiated and assessed. However, in a simplified way, Darcy's law, Eq. (1) can be used as a basis for evaluating the function of a seal, where Q is the total discharge, k the permeability of the seal, A the cross-sectional area, μ the dynamic viscosity of the solution/water, L the seal length, and ΔP the total pressure drop or pressure difference at the end faces of the seal:

$$Q = (k \cdot A) / (\mu \cdot L) \cdot \Delta P$$

The pressure difference ΔP depends on the height difference of the end faces, the fluid density in this area, which is influenced by the geothermal gradient and by the residual heat output from the radioactive waste (cf. Marsic & Grundfelt 2013), as well as pressures that arise from thermal expansion of fluids and gas development.

Due to the fact that planning and construction of the seals are of prime importance, numerous working groups have dealt with these tasks. Results are summarized in the publications of Arnold et al. (2011, 2013), Bates et al. (2014), Freeze et al. (2019), Nirex (2004), Schwartz et al. (2017), and Winterle et al. (2011). With regard to the borehole disposal of disused sealed sources information is given in IAEA (2011).

In relation to the geometry, a borehole is a mine shaft with a small cross-section. According to this, the practical experience of closing shafts and the plans for the closure of mined repositories can be considered. As well as the large length of seals that can be realized in boreholes, the small cross-section is a significant advantage in relation to sealing, but it results in an inaccessibility of the rock surface. Thus, borehole quality can only be examined with measuring instruments and the investigation of drill cores. In addition, injections of cracks are difficult to perform.

The extensive experience in sealing deep boreholes, such as those drilled for raw material extraction and exploration drillings can also be highlighted as an advantage. Moreover, it is common practice to seal large-volume underground boreholes in mined repositories (Engelhardt et al. 2019). When transferring or using this knowledge, however, the special framework conditions for borehole disposal in crystalline rocks must be taken into account. In this regard, the following aspects should be emphasized:

- Due to the restricted accessibility of the borehole surface, sufficient tests must be carried out to determine the position of the seal zone already when the borehole is being drilled. If possible, drill cores should be extracted. Field measurements of crystalline rocks permeability have not previously yielded an unambiguous and universal relation between permeability and depth in the shallow crust (<2.5 km, Ranjram et al. 2014). Sites with high fracture densities must be avoided.
- The efficiency of a seal results from the tightness of the rock with the excavation damaged zone, the contact zone to the seal and the tightness of the sealing materials (cf. NAGRA 2002, Fig. 3-1). In order to reduce the seal permeability, the casing, the cementation and as far as possible the excavation damaged zone of the rock (cf. Bäckblom 2008, Tsang et al. 2005, cf. IAEA 2011) have to be removed. This is difficult due to the depth of the seals and the hardness of the rock. The mechanical stress induced by the milling head can lead to micro cracks and an unfavourable structuring of the rock surface.
- Creep of crystalline rocks and despite the great depth, borehole convergence is low. Accordingly, the pressure build-up rate in the contact zone to the sealing material will be low. This may result in minor principle stresses in relation to fluid pressures (fluid pressure criterion).
- Proofs of barrier integrity and tightness cannot take into account a self-healing of cracks. Cracks and gaps between the seal and the borehole contour formed via

chemical reaction, shrinkage, thermal expansion and contraction, etc., could therefore significantly diminish the seal properties (cf. Bates et al. 2017).
- Chemical reactions that promote the bonding of the sealing material with the rock and reduce the permeability of the contact zone can usually be neglected.
- Thermally induced reactions of the sealing materials must not lead to inadmissible increases in permeability. There are requirements for temperature stability.
- Gas could be generated in the emplacement zone. A potential pressure build-up must be taken into account when planning the seals.

Based on these facts, the following recommendations are be made.

- In order to obtain a positive effect of gravity on the bond with the rock, the seals should be created in vertical or strongly inclined borehole sections. This applies in particular to flowable sealing materials, such as mixtures with cement. The flow of these materials requires a minimum spacing of the suspended particles. Sedimentation of the particles is therefore possible and could result in a layer of water on the surface of the suspension. This process is also known as bleeding (Figure 4-32). In addition, rising of air bubbles can impair the bond to the rock surface (Figure 4-33, Figure 4-34). Particle segregation could lead to an inhomogeneous sealing material and possibly to preferred flow paths in the seal (Figure 4-35).
- In the long-term the development of gases and rock convergence in the disposal zone can result in a pressure build-up on the end faces of the seals and consequently to shear forces at the contact of the seals with the host rock. In order to avoid high shear forces that could lead to cracking, air-filled cavities can integrated into the sealing system. They can be achieved by the use of bulk materials.
- It is advantageous to use deformable sealing materials that can penetrate into cavities and thus cracks. In this way, defects on the borehole contour can be avoided.
- In addition, it is advantageous to use sealing materials that do hardly compact in order to build up a pressure in the contour of the seal. This objective can also be achieved by means of expanding materials.
- When using suspensions, a fine grain fraction should be ensured, which can help to block flow paths.

Figure 4-32 - Formation of a water layer on the cement mixture as a result of the sedimentation of the particles.

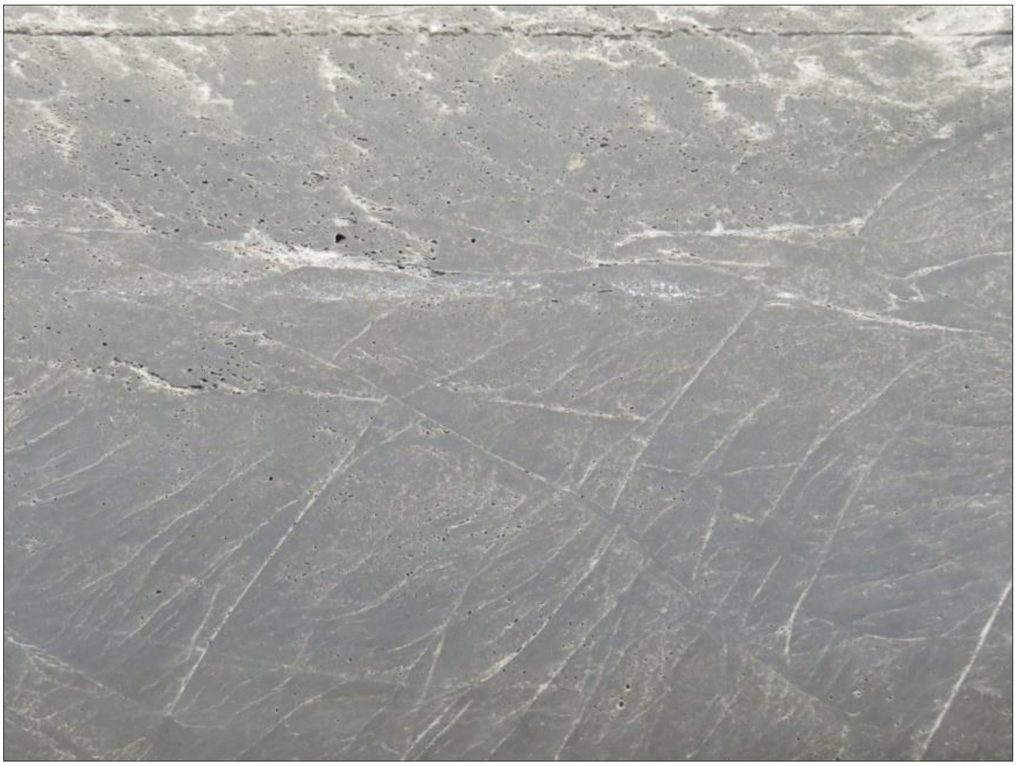


Figure 4-33 - Mock-up test by BGE TECHNOLOGY GmbH to investigate the sealing of large-volume boreholes. The black dots, especially at the top of the picture, are air pockets caused by the rising of air bubbles in the suspension (cylinder diameter 0.5 m).

Figure 4-34 - Mock-up test by BGE TECHNOLOGY GmbH to investigate the filling of large-volume boreholes. Grain (texture) on the upper area of a filled Plexiglas cylinder (diameter 0.5 m), which indicates heterogeneities in the sealing material. The arrows point to small air pockets.

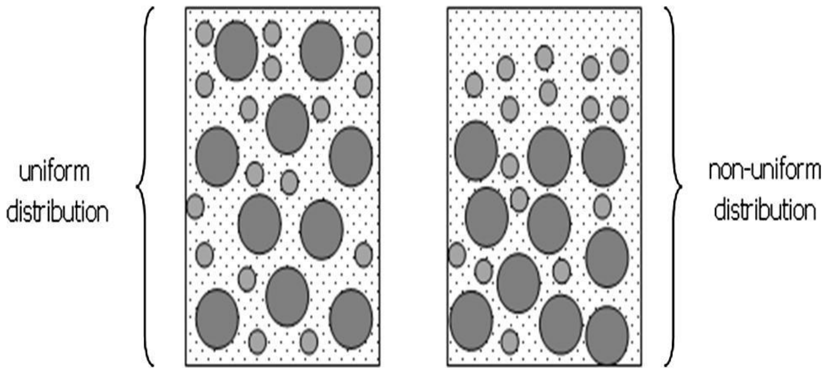


Figure 4-35 - Schematic representation of segregation by sedimentation

Seals must guarantee the tightness of the borehole over the required period. Accordingly, all actions that could influence the function of the seal must be considered and compared with the seal properties and resistance as usual in the construction technology (cf. construction standards EUROCODES). Corrosion processes must therefore be taken into account and all non-corrosion-resistant materials must be removed from the borehole in the area of the seals.

The contact zone and the host rock can be damaged by chemical reactions with the sealing material and as a result of thermal and mechanical stresses that occur directly after construction. In the case of an insufficient strength of the sealing material, these stresses can also lead to cracks in the core barrier and must therefore be considered when elaborating the structural design. This requires a low compaction of the core barrier, which, moreover, when in contact with solution, must not corrode to such an extent that the requirements are no longer met. In addition to static loads, dynamic loads such as those that can arise in the event of an earthquake must also be considered as mechanical loads (e.g. Adisoma 1996). Consequently, the use of optimized sealing materials is of great importance for the long-term isolation of the radionuclides and the seal should consist of several elements with different materials and a functional diversity and redundancy should be realised, where the sealing is based on different mechanism.

Materials that are suitable according to the available experience contain clay, (bentonites or mixtures with bentonites), bitumen/asphalt and as already mentioned cement-based materials (grouts, mortars or concretes). In principle, other materials can also be considered, such as geopolymers (Kajarathan et al. 2015, Kanesan et al. 2018, Nasvi & Gamage 2012, Nasvi et al. 2013, 20165, Salehi et al. 2017a,b) or phosphate binder systems (e.g. Patil et al. 2008, Wagh 2016), but practical experience with these materials is still too little for a recommendation.

Geopolymers are based on the reaction of amorphous aluminosilicates with alkaline activators, such as water glass (sodium or potassium silicate solutions) and sodium or potassium hydroxide. The aluminosilicates include calcined clays, such as metakaolin, slag, or pozzolans. The binder is an amorphous aluminosilicate with an alkali metal for charge balancing. Phosphate binder systems differ from calcium-based cements as setting and hardening is a result of acid–base reactions between metal cations and soluble phosphate anions. Insoluble crystalline metal phosphate hydrates are formed in the presence of water, rather than by direct hydration reactions.

Moreover, barite has been used to form seals or plugs in boreholes, for example to control gas zones in wells (Messenger 1969). The material is installed as a slurry using cementing equipment and spotted through the drill pipe. Blümling & Adams (2008) give minimum attainable hydraulic conductivities in the range of 10^{-9} to 10^{-10} m/s. Nagra developed a multi-component seal for borehole SB4a/s. In this case, a zone of barite is underlying a bentonite zone (NAGRA 2002).

During the hardening of flowable sealing materials, such as cement-based mixtures, hydration heat is released that caused thermal stresses. Changes in length of the sealing material lead to shear forces in the borehole, so that the possibility of cracks at the borehole contour must be investigated. Coarse-grained concretes contain inert aggregates and, compared to fine-grain mixtures, usually contain fewer binders (cement). For this reason, the heat of hydration and the resulting stresses are lower. Due to this fact, the use of a mortar or concrete should be given preference over sealing materials that contain only fine-grained particles, provided they can be transported through the delivery pipeline. An additional option to reduce the amount of hydration heat is the use of reactive additives, such as silica fume, calcined clays, such as metakaolin or slag. In addition, this has the positive effect of lowering the pH, so that the risk of clay mineral (bentonite) degradation is reduced.

Borehole sealing with expandable buffer clays in HLW disposal is the topic of the thesis of Yang (2015). Hadgu (2012, vgl. Arnold 2013) used such a simple clay seal to perform a sensitivity analysis of seals permeability and a performance assessment of a deep borehole disposal facility (Figure 4-36).

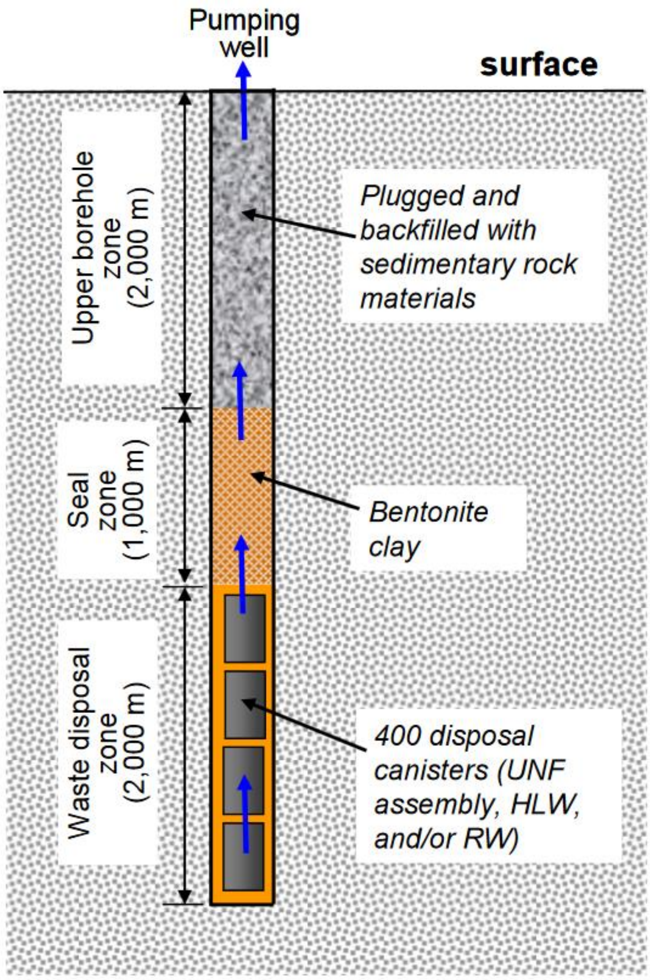


Figure 4-36 - A schematic illustration of the conceptual model for performance assessment of deep borehole disposal according to Hadgu et al. (2012, cf. Arnold, 2013)

The thesis of Mohammed (2014) deals with the composition and properties of cement-based materials, concrete and grout, for use as seals and for stabilizing fracture zones in boreholes. The proposed principle of construction is to cast the concrete on-site over clay seals to the upper end of the respective fracture zones, where the next clay seal is installed. The concrete seals will be installed where the holes intersect water-bearing fracture zones to serve as stable and low-permeable supports for adjacent clay plugs. Due to the reaction of high-pH solutions with clays the focus of the study was the use of low-pH cement-based materials.

These materials often contain additives, such as superplasticizers with organic substances, in order to improve the flowability of the suspension and / or to reduce the water content. When used in the borehole, organic substances should be avoided because organics can produce colloids with a capacity to carry radionuclides. Due to this fact, the suitability of talc as fluidizer was investigated. Figure 4-37 illustrates the procedure. Pusch et al. (2005) describes the material development in detail.

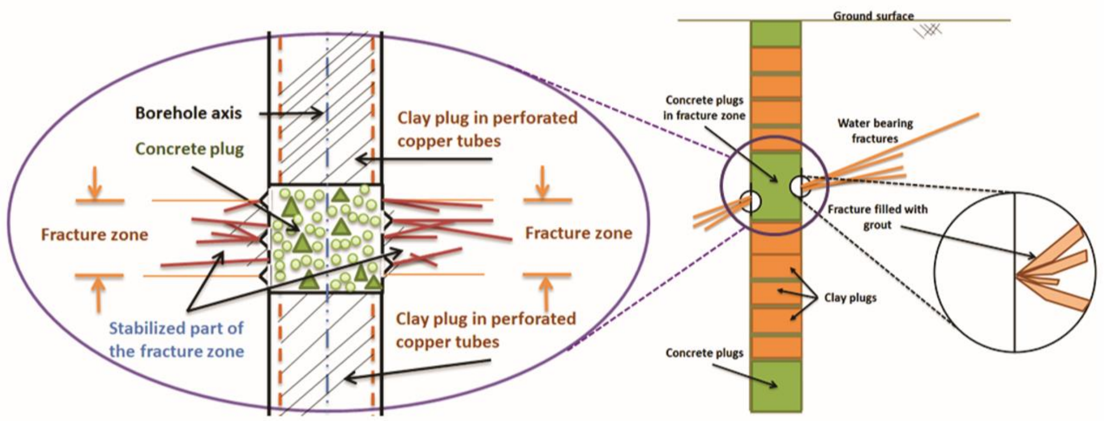


Figure 4-37 - Borehole seal design according to Mohammed (2014) (cf. Mohammed et al. 2015). Right: Principle of borehole sealing. Left: Detail of concrete cast where the borehole intersects a fracture zone.

Freeze et al. (2016) also favour a combination of bentonite and cement-based materials (Figure 4-38). In this case, however, the area of the seal is interrupted by sections of "ballast" and "backfill". A distinction is made between a lower and an upper seal zone.

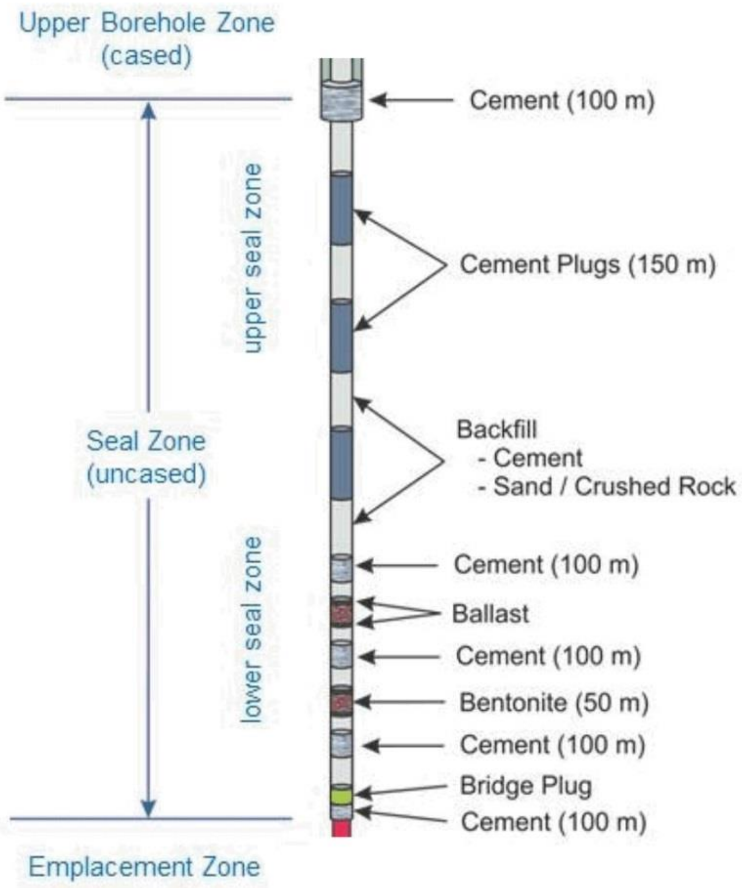


Figure 4-38 - Borehole Sealing and Plugging Schematic according to Freeze et al. (2016, Figure 4-2) (cf. Brady et al. 2012, Fig. 3).

In contrast to other reference designs, MIT (2019) describes not three but two borehole sections, i.e. in addition to the disposal (emplacement) zone, a single sealing zone up to the surface of the earth. The use of an expansive cement or concrete should be emphasized. This procedure has the advantage that the pressure of the sealing material on the borehole contour is increased at least temporarily. In addition, the use of mixtures of bentonite with crushed crystalline rock materials should be mentioned. The crystalline rock can be a product of the building materials industry or drill cuttings from the local borehole.

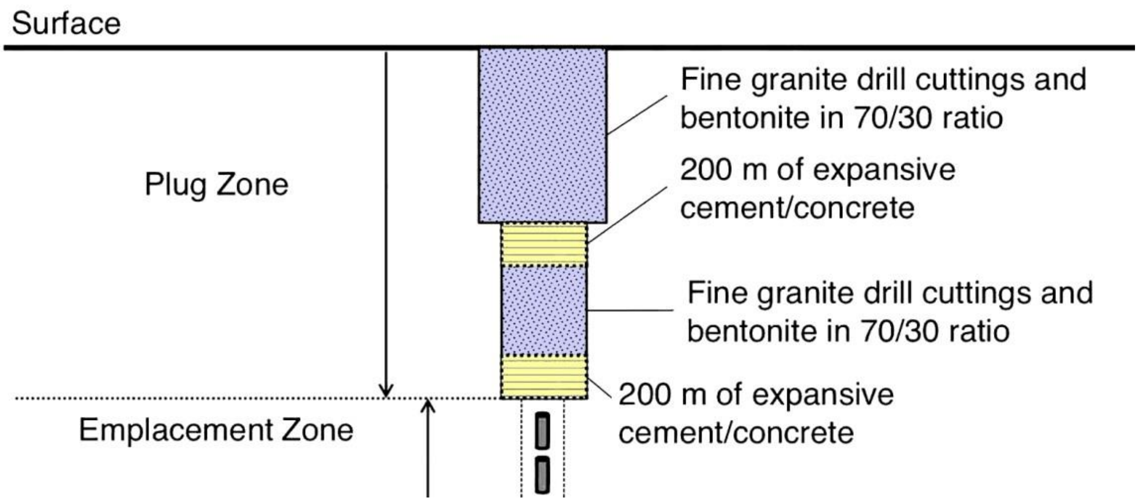


Figure 4-39 - Design of the plug zone of a deep disposal borehole according to MIT (2019).

Seal designs according to the principle of redundancy and diversity are described for example by Arnold et al. (2011), Rosenzweig et al. (2019), and SKB (2010). Figure 4-40, Figure 4-41 and Figure 4-42 show the reference designs. In this case, the elements made of bentonite and cement-based materials are separated by asphalt.

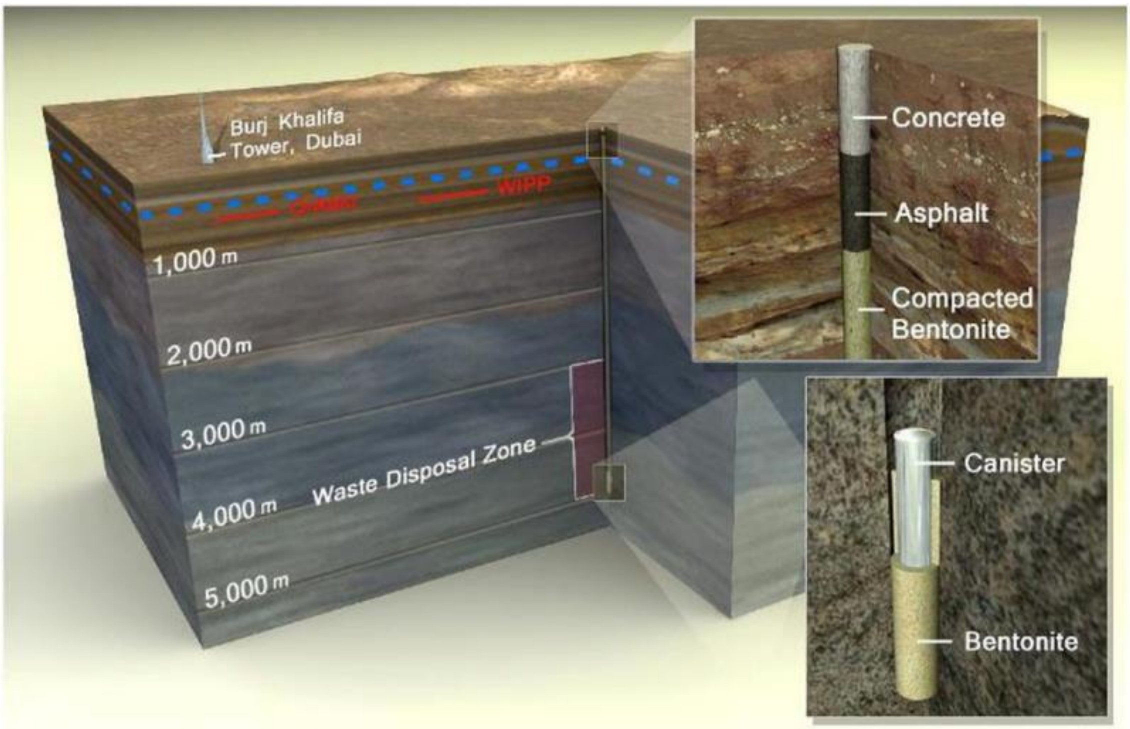


Figure 4-40 - Generalized Concept for Deep Borehole Disposal of High-Level Radioactive Waste (from Arnold et al. 2011).

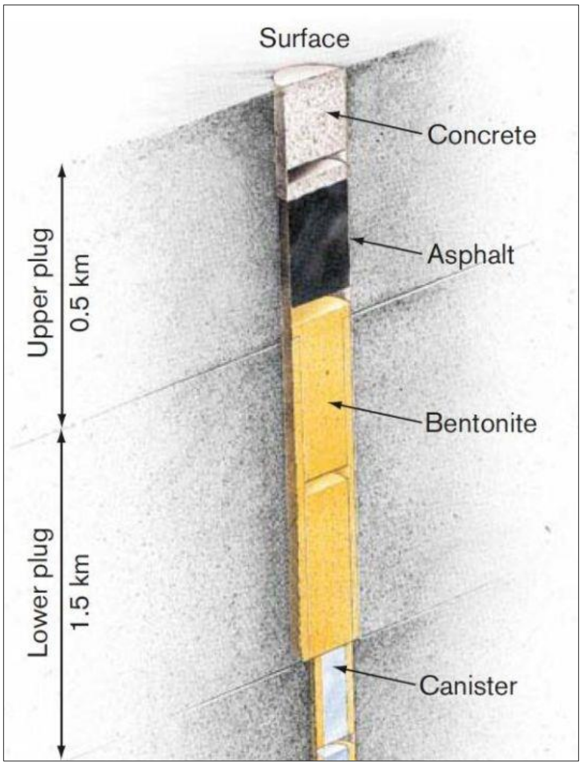


Figure 4-41 - Schematic seal design in deep disposal boreholes according to SKB (2010), from Tokunaga (2013).

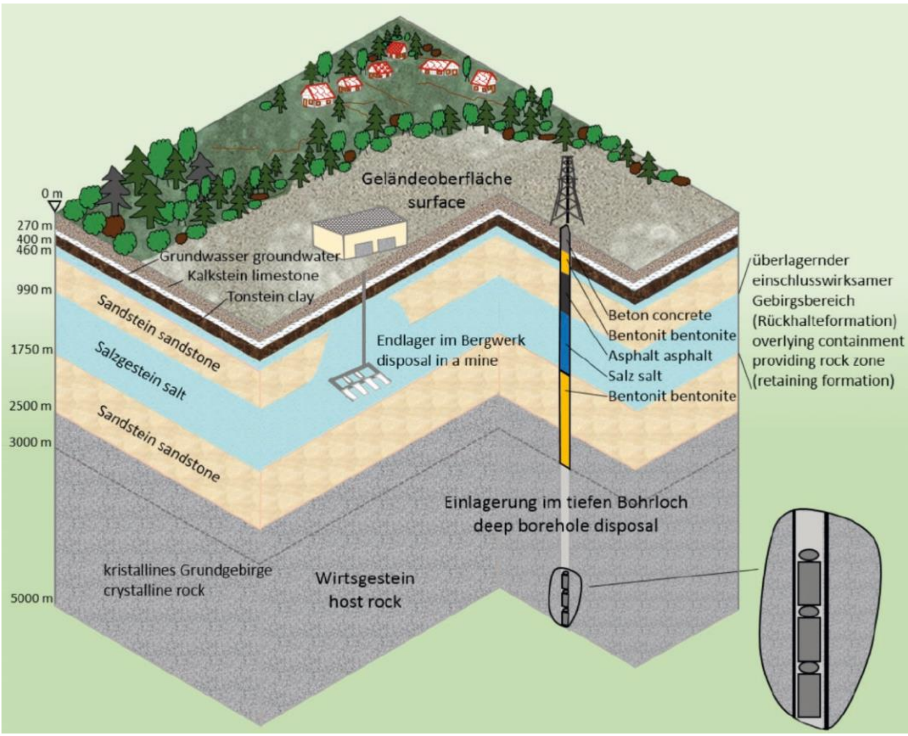


Figure 4-42 - Schematic deep borehole disposal in crystalline rock according to Rosenzweig (2019).

In addition, Brady et al. (2012) point out the importance of a seal system design that consists of multiple types of barriers emplaced in a redundant manner. Figure 4-43 identifies the primary components of the seal system, borehole casing, disturbed rock zone, bridge plugs, and keyed structural seals and backfill components. The seals will be designed typically in sets of barriers with the placement of a structural cement/concrete component keyed at the bottom to constrain the swelling pressure of clays above. This sequence is topped by another cement/concrete seal to limit clay swelling.

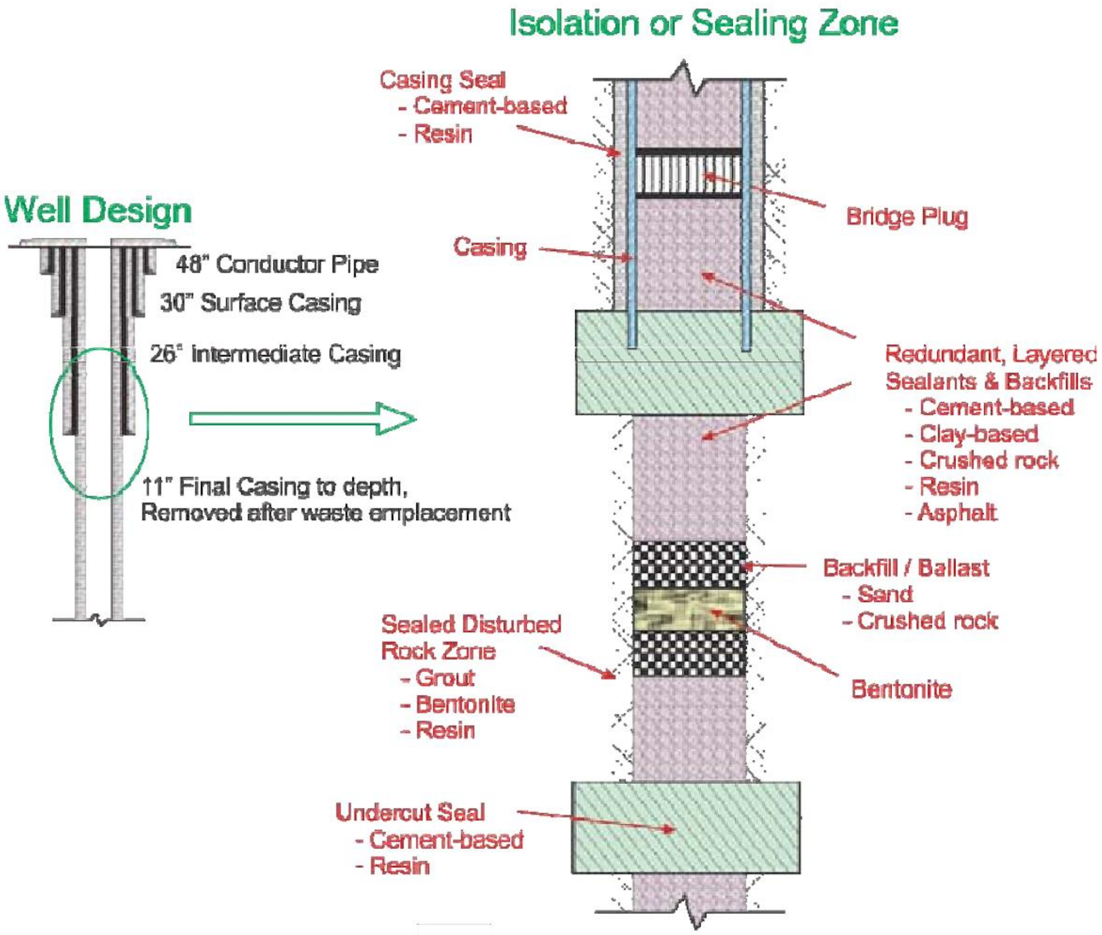


Figure 4-43 - Schematic of borehole seal components according to Brady et al. (2012).

For comparison, the horizontal micro-tunnels (HLW disposal cells) according to the ANDRA concept for Cigéo will be presented (Armand et al. 2017). With this concept canisters will be conditioned in steel over packs, which will be stored in the micro-tunnels with a drilled diameter of approximately 0.7 meters and a length of 80 meters. The borehole will be cased. The 2009 reference design is composed of a body section for package disposal, and a head section for cell closure (Figure 4-44 (a), cf. Sellin & Leupin 2013), consisting of a metallic, clay, and concrete plug. For example, for chemical reasons linked to corrosion rates an alternative concept, in which the void between the steel casing and the rock must be filled with a concrete/bentonite mixture, emerged in 2013 and became the current reference design (Figure 4-44 (b)).

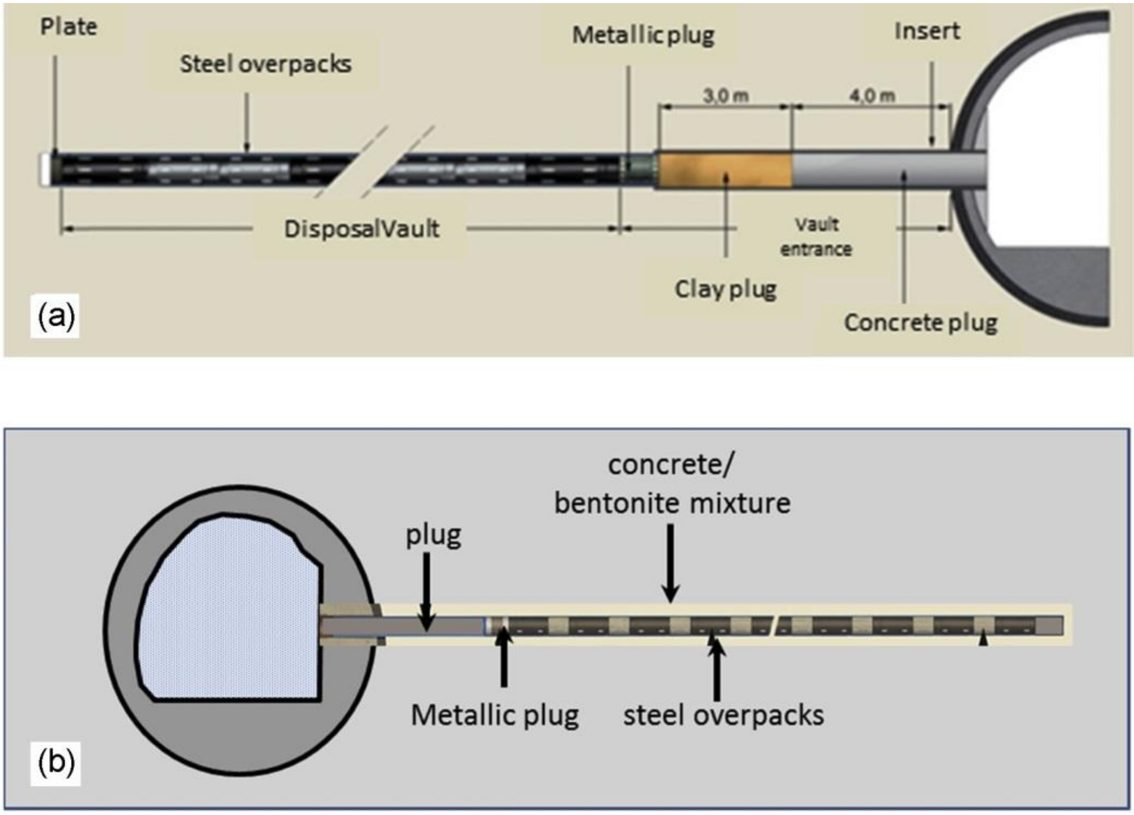


Figure 4-44 - Concept of disposal cell for HLW-LL: (a) 2009; and (b) 2013. Sellin & Leupin 2013.

The reference designs are simple because, as location-independent designs, they are not adapted to local geological and geochemical framework conditions. Thus, specific information on the positioning of the seal elements is limited to the statement that cement-based materials should be used in the area of fractures, because they form stable solids. However, the geochemical stability of the individual sealing materials is also of particular relevance.

Asphalt can be damaged by oxidation and degraded due to microbial activity, which is to be expected especially in low saline waters. Alteration of expandable clays (bentonite), which is the preferred material for the construction of borehole seals, is expected to be insignificant for natural groundwater conditions with negligible salinity at temperatures below <100 °C. However, high salinity (high potassium contents) affects the stability of montmorillonite, which is the most important component of bentonites, and illitization can occur. When montmorillonite interacts with a hyperalkaline solution, montmorillonite will be dissolved and secondary minerals are formed. Cement-based materials (the cement stone) react for example with solutions that have a low pH or high levels of magnesium, sulphate, and ammonium. The corrosion processes change the properties of the materials and can result in a loss of the seal integrity.

Further information on the construction of seals, such as their positioning in boreholes, can be found in ordinances, technical rules, and guidelines developed for conventional deep drillings, such as BVEG (2017), BVOT (2006), and OCZ (1981), which are valid in Germany or NAGRA (2002).

4.2.14 Foreign Materials remaining in the Facility

According to Posiva Oy, foreign materials are either materials that are introduced into the disposal facility on purpose (“engineering materials”) or inadvertently (“stray materials”). However, the group of foreign materials does not include the parts of the engineered barrier system (e.g. containers, shock absorbers if necessary) or the natural environment, such as rock materials or groundwater (e.g. Karvonen 2011, Sacklén 2016, Ylöstalo 2019). The presence of foreign materials has to be considered due the fact that the chemistry of waters in the vicinity of the disposal zone of the borehole could be influenced.

In the case of borehole disposal four groups of foreign engineering materials can be distinguished:

- Fluids, such as drilling and borehole fluids,
- The casing and therefore metals,
- Backfilling materials, and
- Cement-based materials, which are used for sealing fractures and for cementing the casing.

Drilling fluids are any fluids which are circulated through a borehole and can be air, a liquid or a mixture of both. Drilling engineers distinguish water, water-based mud (bentonite and/or polymers), aerated mud or water, air and foam. In crystalline rocks, where no over-pressure problems occur, rather „simple“ mud systems were preferred or air flushing. Because most of geothermal drilling is in hard rock and there are no over-pressure problems requiring heavy mud, a rather “simple” mud can be used. Foam ranges from a mist (mixture of air, foaming agent and an injection of water) to a stiff foam (consisting of a mixture of bentonite slurry and/or organic polymer, water, air and foaming agent).

Schäfer et al. (2012) describe the use of natural anoxic groundwater permanently stripped with nitrogen (to remove reactive oxygen) for drilling in the Äspö Hard Rock Laboratory (HRL). For the drilling of the KTB borehole the starting composition of the drilling fluid was a mixture of water with about 1.5 wt.-% DEHYDRIL-HT, a synthetic, hectorite-type, Li-bearing Na-Mg silicate which yielded a thixotropic, solid-free, highly lubricant mud system. Later, due to its electrolyte sensitivity, corrosive behaviour, instability at high temperatures, and other factors, adding HOSTADRILL, an organic polymer, and NaOH plus Na2CO3 to fix a pH value of 10 to 11 (Emmermann & Lauterjung 1997) continuously modified it. In the case of the COSC-1 scientific drilling the drilling fluid down to 500 meters was fresh water. From 500 to 1616 meters a bio-degradable polymer was added to reduce the friction between the drill string and the borehole walls and to improve the removal of cuttings (Lorenz et al. 2015).

Table j - Drilling Fluid System Used in the KTB Main Hole.

Borehole section	Drilling Fluid System	Properties
0 – 6760 m	0.7 % Dehydril 1 % Hostadrill NaOH, Na_2CO_3	Plastic viscosity 9–22 mPa·s Density 1.06 g/cm³ pH 10–11

If it is provided or necessary to build up in the casing a backpressure to the rock pressure, the drilling fluid is replaced by a borehole fluid specifically designed for the disposal operations. Solid-free borehole fluids should be preferred in order to allow recovery during the phase of operation. This borehole fluid should be chemically compatible with the casing and containers to minimize or inhibit corrosion, should have a sufficient density to ensure borehole stability, a suitable viscosity, and should have a low complexing ability for radionuclides. A wide range of substances are available today as corrosion inhibitors.

The composition of these fluids can largely differ. Moreover, the amount of the engineered foreign materials of the drilling fluids that remain in the borehole depends on the amount of fluid that penetrates the rock formation. Consequently, in the context of the current planning status, no detailed information can be given to the kind and quantity of foreign materials that result from the used fluids in the borehole.

If the borehole contains no fluid, voids should be backfilled with another material, for example with a bulk material. Corresponding concepts were developed for shorter boreholes in mined repositories. They use sand, which could be removed with a suction device. A slightly conical shape characterizes the adapted containers BSK-R and their heads were also sloped to allow evacuation from the backfill material. The backfill (sand) provides heat transfer through the casing into the surrounding rock mass and retains its physical properties even under the expected high temperatures (Herold et al. 2016, cf. Apted & Ahn 2017)). Thus, in case of container retrieval, a reverse extraction of backfill material out of the borehole would be possible. The amount of backfill material can be calculated based on the bulk density and the void volume. The chemical-mineralogical composition should be determined as part of a quality assurance program.

Casings are available in a variety of different materials. In deeper parts of a borehole only metal casings are currently used because of their greater stability compared to plastic casings. The metals can corrode, and depending on the chemical environment, different corrosion mechanisms can be relevant. The level of corrosion on the sides of the cementation and the borehole will differ. The selection of the casing material must take chemical and mechanical aspects into account, whereby in this study casings made of steel were provided in accordance with API standards. Steel casings are also used in mined repositories. For example, Crusset et al (2017) et al. carried out comprehensive corrosion experiments. The probable corrosion from the amount of steel can be calculated on the basis of the information on the composition of the casing and the chemical parameters of the solution that comes into contact with the casing. Influencing factors are the pH value, the Eh value, the concentrations of corrosive substances as well as the amount of substances that form a protective layer on the metals.

In terms of volume, cement-based materials that are used to seal pathways (rock fractures) and for cementing the casing are very important. The amount of these materials can possibly be reduced by using expandable casings, but not completely excluded. Cements and their mixtures are important in two ways. Degradation of cementitious materials due to radiation, thermal effects, and reactions with water generates alkaline leachates that might endanger buffer performance by enhancing erosion and mineral transformation. Potentially harmful foreign materials other than cement components in the narrow sense (portlandite, calcium silicate hydrates, etc.), admixtures and additives are hydrocarbons. They can have various sources, e.g. organic cement additives (e.g. retarder, superplasticizers), oil leaks and even the air, when using air flushing during the drilling process. Application of plasticizers in the disposal facility should be limited to certain varieties to keep the amount of organic, complexing compounds the smallest possible. Care should also be taken when choosing the type of cement. Some types may contain minor components with organic components, such as Portland shale cement (CEM II/-T) or Portland fly ash cement (CEM II/-V, CEM II/-W).

4.2.15 Safety classification

Systems, structures and components of a nuclear facility are grouped into safety classes. The safety class provides the basis for defining the quality assurance requirements for the systems, structures and components of a nuclear facility. Safety classification forms the basis for determining the scope of regulatory controls by the radiation authority. Safety classification of system is not explored in this report.

4.2.16 Fire safety

With regard to fire safety, the period of drilling and the operation of the disposal facility must be considered separately. One reason is the use of the drilling rig during the first stage and the fact that the drill bit reaches rock formations that have not yet been fully examined yet. During the operation of the disposal facility, an emplacement device is used instead of the drilling rig. In addition, the presence of radioactive waste must be taken into account.

One of the best tools for any drilling company is a job safety analysis (JSA) or job hazard assessment (JHA) program. Both are the same type of safety prevention practice. They each include as a first step conducting a basic job step determination—for example, writing down the basic steps in the process of setting up the rig, drilling, and dismantling the rig. Once you have developed the job steps, the second task is to evaluate each step for potential hazards. This includes everything from tripping and ergonomic hazards to the risk of a fire or explosion.

The third step is then to develop specific practices established as procedures to either minimize the hazard or, if possible, eliminate the hazard altogether. The importance of this task is a critical process every drilling company should conduct. One more critical piece of having a JSA or JHA is conveying the information that has been developed to the drilling crew and making sure they are fully educated on the hazards and safety processes. Training should be an ongoing process, regardless of redundancy, and should be reinforced every day on the job. The importance of being prepared for all unforeseen events that can lead to an accident should be a top priority for the drilling crew. The risk of a fire and explosion on a drilling site is always there, no matter whether the source of fuel is from the ground or from the equipment. Being ever vigilant for open sources of fuels and ignition will help to prevent the unfortunate from happening.

An important basis for the planning for the first phase is API (2019).

The layout, design and construction of the facility will be made in compliance with local building code and other relevant regulations in Norway.

4.2.17 Demonstrations of borehole disposal operation

It is assumed that deep borehole drilling and characterization methods are demonstrated at the relevant host rock prior to the construction of the facility. In addition, disposal operation (container placement), backfilling and sealing will be demonstrated in a comparative environment prior to the operation and closure phases of the facility.

4.2.18 Facility construction in phases

Due to the expected waste volume in Norway the borehole facility is planned to be implemented and constructed in a single-phase operation.

4.3 Alternative borehole design concepts

In comparison to the borehole design option mentioned and discussed earlier in this report, there are also possible alternatives. All of these alternatives have positive and negative aspects, which need to be evaluated. Even though there might be even more, the following four alternatives are presented. Additionally, some of the positive and negative aspects are shortly pointed out in Table k.

Table k – Alternative options and their positive and negative aspects

Alternative	Positive aspects	Negative aspects
Smaller borehole diameter	- conventional drilling technologies can be used	- boreholes need to be deeper → greater temperatures and pressures in deeper regions - more boreholes are required → every new borehole represents an additional risk and a potential flowpath/connection to the surface
Drilling deeper	- more waste can be disposed of in one borehole without a totally new, additional drilling operation - greater geological barrier	- disposal might take longer (greater distance from surface to disposal zone needs to be covered) - greater temperatures and pressures → greater stresses on the containers
Drilling more boreholes	- parallel operation (drilling one hole, while the other can already be operated)	- several flowpaths/connections to surface - additional operational risk with each borehole
Using multilateral drilling operations	- only one potential flowpath to surface via botehole - greater disposal length with minimum effort/footprint on the surface - parts of the hole can be steered for independently → one part can be closed and sealed, while other parts can still be operated	- more complex operation

Some of the alternative options for the borehole design are correlated to each other. Therefore, drilling a smaller borehole has the result that more disposal length is required, which ends in deeper drilling operations or the drilling of more boreholes. On the other hand, drilling deeper wells brings the benefit that the diameters of the boreholes do not need to be that large. This correlation can be simply explained by the formula for the volume of a cylinder:

$$V_{cylinder} = \pi * r^2 * h$$

In which V is the volume, r is the radius and h describes the height, or in this case, the depth of the borehole. The value for the volume is fixed, since the amount of waste, which needs to be disposed, is set. Therefore, the borehole radius and the depth of the borehole are variables. If one of these values gets smaller, the other value needs to be increased to maintain the same total volume. To maintain the same disposal volume, either the wells can be drilled deeper or more shallow wells are required.

At this point, other aspects come in play as well. Deeper wells provide a longer geological barrier between the disposed waste and the surface. Therefore, a deeper borehole would be preferable to several shorter ones. Another plus for one deep borehole would be that one borehole means a smaller footprint on the surface. Only one surface location is needed to drill one hole, therefore the land lease is most likely to be smaller.

Another technical aspect is that small diameter boreholes are easier to drill and the required technologies are already proven and available. Conventional wells used for the production of hydrocarbons typically have a final bit size of around 8 5/8 inches. Even for the smallest option considered by Bracke et al. (2019) a final diameter of at least double this is required. Also for this hole size, conventional equipment is available, but hole cleaning and pressure changes might already be an issue during the operation. Therefore, a detailed assessment needs to be made to see what make more sense. Either drilling fewer wells with a technically more challenging hole diameter or drilling more holes, which are technically easier to achieve. Freeze et al. (2016) also went with the approach of smaller diameter holes. Here the borehole design is similar to conventional hydrocarbon wells. The deviated well has a bottom hole diameter of only 12 ¼ inch (31 cm). This diameter has enough space to fit a casing, or in this case a liner, with an inner diameter of 24.5 cm. With a wall thickness below 1 cm, the casing is designed rather small compared to the design presented in Chapter 4.2.2. This leaves the question open if the casing can withstand potential pressures from the formation at a depth of 5000 m. Another important factor, which leads to the small borehole diameter is the fact, that small containers are considered. An outside diameter of 21.9 cm for the canister, leaves a clearance of just over 2.5 cm and. This has an impact on the whole borehole design, which is also considered in the report. These small and minimal design assumptions do not leave much space for mistakes. (Freeze et al., 2016)

The possibility of using a horizontal borehole is proposed and investigated by Deep Isolation (Muller et al., 2019).

Other than the first three options, drilling smaller diameters, drilling deeper and drilling more boreholes, the fourth option is not that closely related. Directional drilling is a well-developed technology, which is widely applied in the field of hydrocarbon drilling. The huge benefit of this technology is the reduced total borehole length, since the upmost part of the hole only needs to be drilled once and the several wells deviate laterally from this stem to reach their respective targets. . Each of these laterals can be steered independently. An option in the disposal of radioactive waste is to dispose of containers in one of the laterals, sealing this lateral off and moving to the next lateral. This brings the possibility to have existing waste disposed of safely already, which leaves the option to dispose of future waste without drilling a totally new well. Still, there are also negative aspects. First, and once again, multilateral drilling is most likely to limit the borehole diameter. Also, by leaving the hole open for a long time will provide a potential flow path from the waste to the surface. An open hole will also mean a longer operational time, which will impact the costs.

As discussed, each of these options have negative and positive aspects. These alternative borehole design options were not assessed further in this document. When developing the Norwegian concept further, some of these alternative options could be later revisited and looked at in more detail. It is noted that financial aspects, in addition to the technical feasibility, play also in role assessing the various options.

4.4 Adaptation for different waste volumes

The deep borehole facility is designed for the currently expected waste volumes in Norway. The facility consists of only one deep borehole for the disposal of HLW. The disposal capacity of the facility can be adjusted to different waste volumes by adjusting the deep borehole length and/or drilling additional boreholes from the same surface footprint.

There are basically three ways to expand the capacity of the facility.

- Deepening the borehole.
- Drilling of a second disposal zone by means of sidetracking.
- Drilling of a second borehole.

The possibility of realizing the first option depends on the depth of the crystalline rocks. With the usual lengths of the borehole sections that are usually provided for sealing and backfilling measures, the feasibility is classified as low. Sidetracking the original is a common drilling technique, which reduces the total drilled depth. Drilling a sidetrack is often more challenging than drilling a new hole from surface. Piloting the right hole, either the original hole or the sidetrack, during the disposal phase can be rather complicated. Using a whipstock to kick off the sidetrack after the original hole is completed and the disposal operation of this part is done, would overcome this challenge. Having both holes open at the same time would lead to an unnecessarily complicated operation. Therefore, the second option can only be a serious option if first the original hole is drilled, the disposal zone is closed up and then the sidetracking operation is started. Compared to the second option, the third option has the disadvantage that a second potential connection path is created from the area of the biosphere to the host rock of the disposal zone.

5 OPERATION

5.1 Operational duration of borehole disposal facility

The life cycle of a waste disposal facility is divided into several phases and sub-phases that can overlap in time. Figure 5-1 provides an overview.

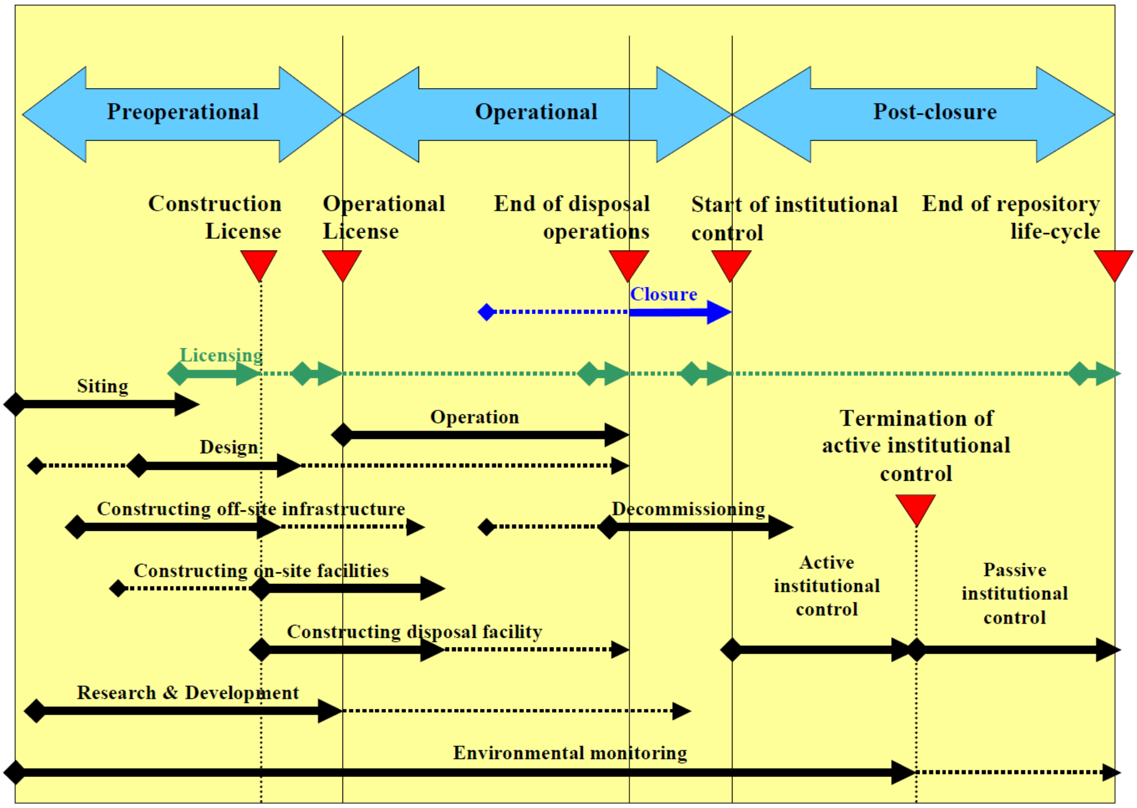


Figure 5-1 - Life cycle of a disposal facility divided into phases according to IAEA (2007, IAEA-TECDOC-1552).

Currently, on the duration of the individual project periods or phases no assured level of knowledge is available that is based on practical experiences in the field of deep borehole disposal. However, information on the schedule can be obtained on the basis of planning data.

5.1.1 Pre-operational period

In particular for the phase of construction (pre-operational period), information on classic drilling technology and existing planning data from repositories can also be used. Information on the duration was described, for example, by Arnold et al. (2012) and SANDIA (2014), which relate to a demonstration project. Major activities include: site selection and characterization, the design and drilling of boreholes (for example a characterization borehole and a field test borehole), the design of the field test (containers, container handling, and container emplacement and retrieval), an engineering demonstration of container emplacement, and related scientific R&D activities to validate the merits of the deep borehole disposal concept. Key milestones related to these major activities are shown in Table l.

Table l - Deep Borehole Field Test Key Milestones (FY= Fiscal Year, US based term).

	FY15	FY16	FY17	FY18	FY19
Field Test – Award Engineering Services Contract	◆				
Site Selection – Decision	◆				
Documentation – Borehole and Field Test Design	◆				
Characterization Borehole – Award Drilling Integration Services Contract		◆			
Characterization Borehole – Start Drilling		◆			
Characterization Borehole – Complete Construction			◆		
Field Test Borehole – Award Drilling Integration Services Contract			◆		
Field Test Borehole – Start Drilling			◆		
Field Test Borehole – Complete Construction				◆	
Field Test – Start Emplacement Demonstration				◆	
Field Test – Complete Emplacement Demonstration					◆
Documentation – Field Test Analyses and Evaluation					◆

More detailed information on the duration of the drilling process can be obtained by evaluating data of the deep drilling industry, of which geothermal wells in particular can be used as a basis (e.g. Brady et al. 2009, Pálsson 2017). According to Brady et al. (2009), a 3 kilometres deep well will take about 53 days to construct (Figure 5-2).

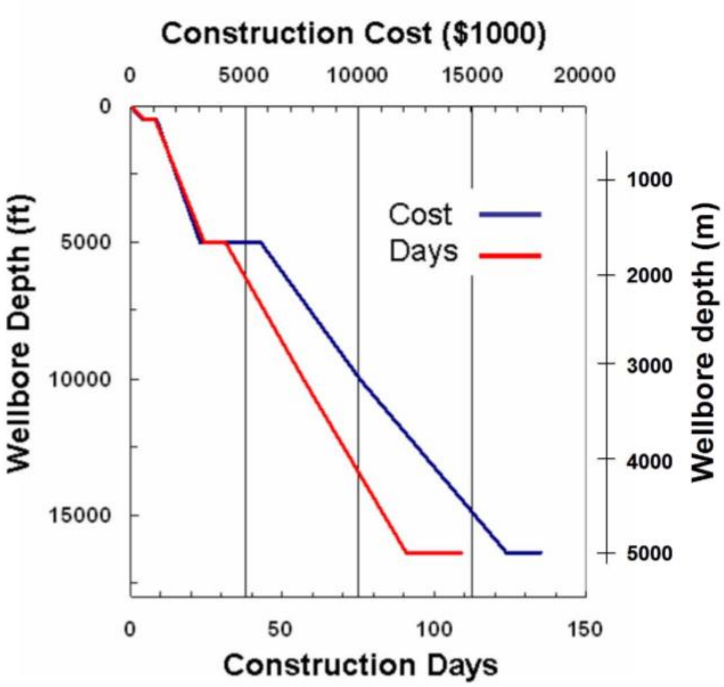


Figure 5-2 - Deep Borehole Drilling Design Schedule and Cost. (Stein et al., 2014)

According to Pálsson (2017), drilling of a typical 2500 meters deep directionally drilled well with an 8- $^1/_2$" production zone can take from 30 to 170 days depending on the complexity of geology, delay in delivery of items and services, and other factors that can cause the work to take longer. Pálsson (2017) also states that the availability of drilling rigs and special items and equipment is highly dependent on the situation in the drilling market. Moreover, it is the experience of the author that the time required for the civil works, such as making suitable access roads, drill pads, drilling water and waste water treatment are commonly underestimated. These items are often depending on seasons. Figure 5-3 presents the drilling progress of well HG-1, drilled in central Iceland. In this case, the well had been predrilled to 100 metres before the main drilling rig arrived on site.

Figure 5-4 illustrates how further work affects the drilling time taken of the borehole. In the case of a deep disposal borehole, it can be assumed that extensive investigations of the borehole quality must be carried out and cores will be taken from greater depths.

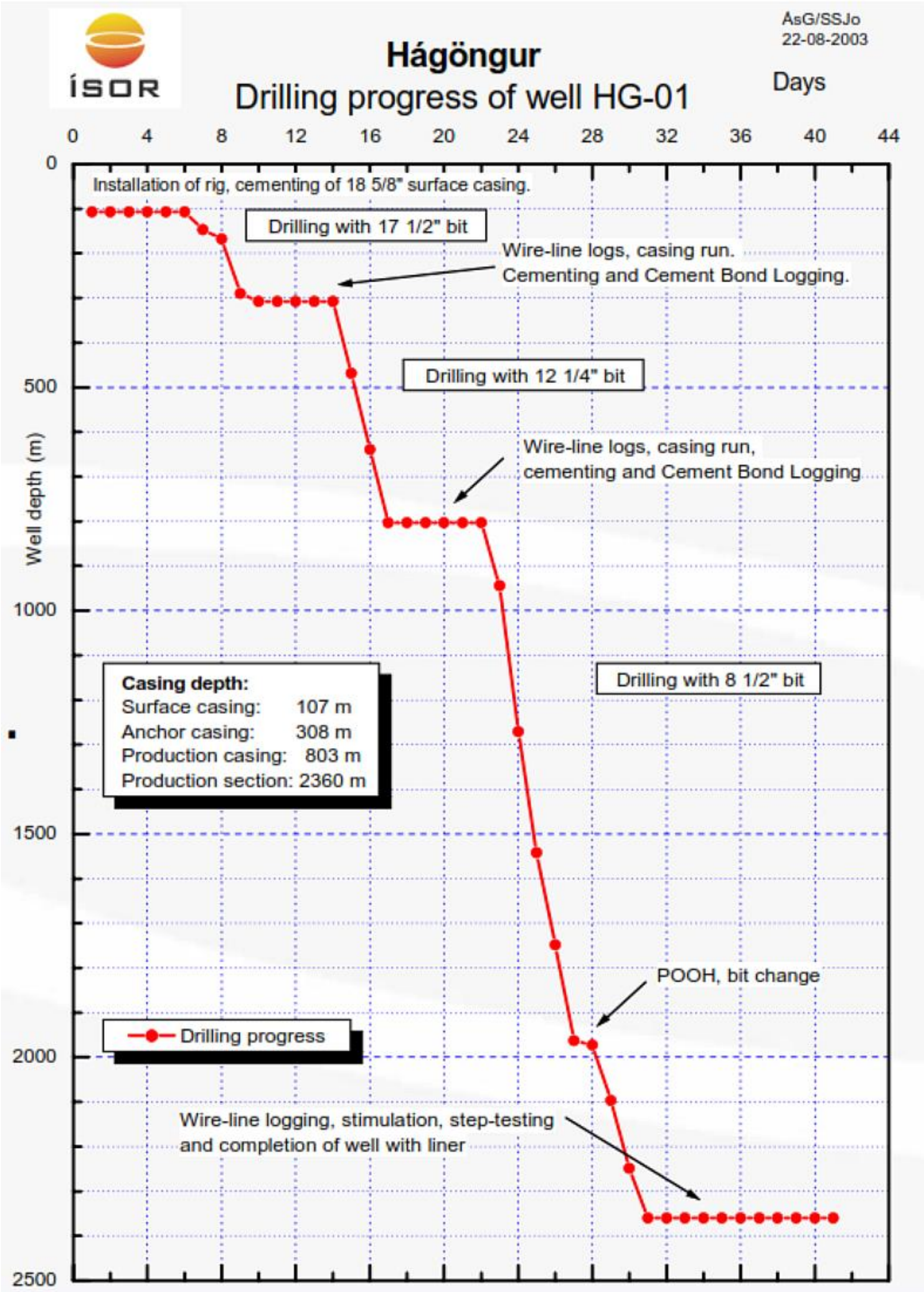


Figure 5-3 - Drilling progress for well HG-1 in Iceland according to Pálsson (2017).

Figure 5-4 - A typical time versus depth diagram for an evolving and maturing drilling project according to Harms (2015).

The information on the Continental Deep Drilling Program (KTB) gives an idea of the speed of the casing installation. In April 1993, 469 pipes with diameters of 13 $^3/_8$ and 13 $^5/_8$ inches (34 and 34.6 cm) were lowered and screwed into the 14 $^3/_4$ inches (37.5 centimetres) wide borehole. The entire pipe string weighed 706 tons in air and 614 tons in the flushing liquid. The installation speed was reduced from 20 to 5 cm/s in order to avoid pressure surges on the rock surface due to the annular space of 15 mm. In the vertical borehole, the depth of 6013.5 meters was reached after five and a half days.

Numerous tasks that are required for the commissioning of the facility are carried out simultaneously with the borehole drilling. These include the erection of buildings, measuring devices of the monitoring and surveillance program, etc. Work that can only be carried out after completion of the borehole and therefore is decisive for the time of the pre-operational activities is the removal of the drilling rig, the construction of the unloading hall, the installation of the emplacement device and its housing. A year is estimated as the time for the work until the first waste package is delivered.

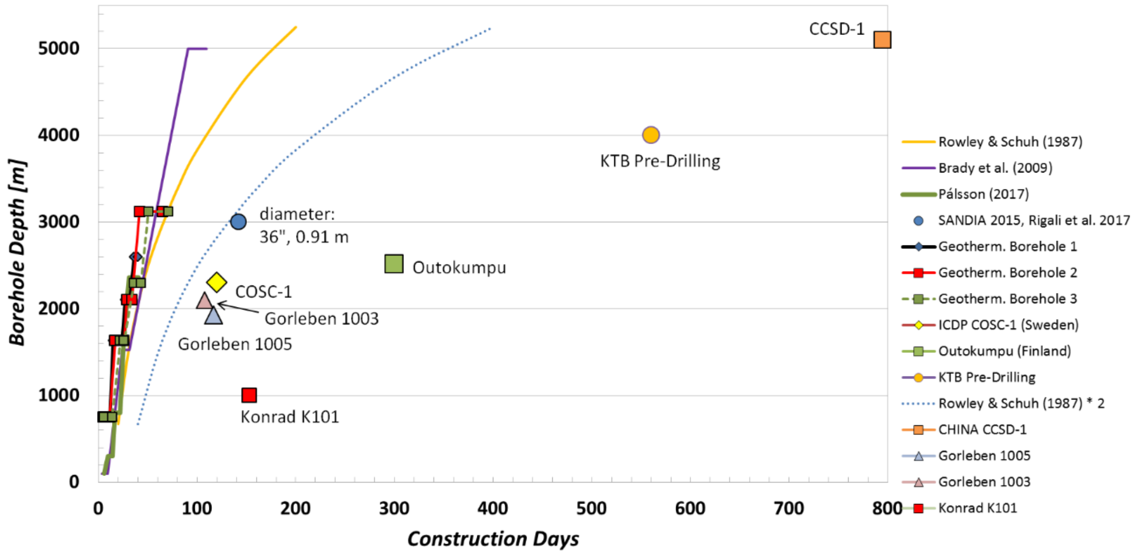


Figure 5-5 – Correlation of the borehole depth and construction days,

5.1.2 Operational period

The duration of the operational period depends on the number of containers and the duration of the emplacement, whereby this time span depends primarily on the speed of transport. In addition, tests of the emplacement technology, such as with dummy containers must be taken into account. The backfilling of residual cavities requires additional working hours as well as the performance of borehole measurements. Finally, repair and maintenance work on emplacement-relevant devices must be taken into account. Other work such as the duration of the acceptance control or the unloading and unpacking of the container, however, are of secondary importance because they can be carried out at the same time as the emplacement device is in operation.

Estimates (see chapter 3.4) showed that between 69 containers are to be placed into the borehole. With the wireline technique, the first rough estimate of the speed is based on cable conveyor systems. Their speed varies between 1.5 m/s and 12 m/s, whereby the high speeds are achieved for a short time in deep shafts. Mobile hoist winches that are used as auxiliary drive system for inspecting shafts and as an emergency drive system for rescuing people reach a depth of around 1300 meters. The rope load is up to 50 kN corresponding to a weight of 5.1 tons and their maximum speed is about 22 m/s. However, the average speed of the auxiliary drive system currently used in the Konrad 2 shaft is only about 1 m/s. The maximum weight transported is 3.0 tons and the maximum conveying distance is around 1250 meters. Freeze et al. (2016) give waste package descent rates of about 0.5 ft/s (0.305 m/s) for the first kilometre (slower to control load transients that could break the wireline), then 2 ft/s (0.610 m/s) thereafter (SNL 2016b, Section 2.9.3). The string would then be hoisted out of the borehole with an ascent rate of 4 ft/s (1.2 m/s).

According to descriptions by Arnold et al. (2011) and Hardin et al. (2015), the rate of lowering of containers by wireline would be comparable to lowering bridge plugs (6,000 ft/hr; 0.51 m/s). The wireline would be respooled at twice this rate thus the round-trip time would be approximately 3 hours. The tripping speed for the first and last few hundred metres would be limited to 0.15 m/s to control load transients. Additionally to the tripping times, a total loading and unloading time of 60 minutes per container is considered. Taking all these values into account, a total time to dispose one container of almost 6 hours is the result. Including the total number of containers this result in a total working time of 17 days and 6 hours. The detailed calculation can be seen below.

Table m – calculation of the disposal time via wireline

Unit number		Value	Unit	Calculation
[1]	Number of containers	69		
[2]	Lowering speed	0.51	m/s	
[3]	Respooling speed	1.00	m/s	
[4]	Reduced tripping speed (first and last 300 m)	0.15	m/s	
[5]	Borehole depth	3 500	m	
[6]	Length of the reduced tripping speed	300	m	
[7]	Effective „normal“ tripping length	2 900	m	$= [5] - 2 * [6]$
[8]	Duration per round trip (only tripping)	4.6	h	$= {}^{[7]}\!/_{[2]} + {}^{[7]}\!/_{[3]} + 4 * {}^{[6]}\!/_{[4]}$
[9]	Total time per container	5.6	h	$= [8] + 1.00$
[10]	Total time (all containers9	414 17.25	h d	$= [9] * [1]$ $= \frac{[9] * [1]}{24}$

Arnold et al. (2011) and Hardin et al. (2015) also provide information on the speed of emplacement when using drill strings. They consider that the drill pipe would be used to lower a string of waste packages to a depth of approximately 4760 meters (15,600 ft plus the length of a package string). Assuming the crew can assemble or dismantle one 90-ft stand (27.4 m) of drill pipe every 5 minutes, the rate of progress is about 0.085 m/s (1,000 ft/hr). Additionally, a time of 30 minutes for loading and 60 minutes for unloading is considered per container. Based on these numbers, a total time to dispose all the containers is almost 70 days.

Table n – calculation of the disposal time via drillstring

Unit number		**Value**	**Unit**	**Calculation**
[1]	Number of containers	69		
[2]	Tripping speed	0.085	m/s	
[3]	Borehole depth	3 500	m	
[4]	Duration per round trip (only tripping)	22.5	h	$= 2 * \left({}^{[3]}\!/_{[2]}\right)$
[5]	Total time per container	24	h	$= [4] + 1.50$
[6]	Total time (all containers9	1656 69	h d	$= [5] * [1]$ $= \frac{[5] * [1]}{24}$

Compared to the wireline technique, using the drillstring method takes almost four times as long. However, this difference can be reduced due to the need to change and check the rope. The repair and maintenance effort must also be taken into account (e.g. Bin 2015, DIN 15020-1, EN 12385-3). An additional time saving can result from the fact that one drilling rig can be used during the pre-operational and the operational phase. In this case it is advisable to house the drilling rig as soon as possible.

The disposal phase ends with backfilling or the setting of plugs as well as final control measurements. It is estimated that this work will require two months including casing removal. The uninterrupted execution of the work always requires timely planning of the work in preliminary work phases. In any case, the work in context with waste disposal should be completed in one year.

The subsequent work can be assigned to the site closure. Special works are

- Cutting and milling of the casing in seal sections.
- Assessment of the borehole, implementation of borehole measurements.
- Work to process the borehole surface, cleaning work, sealing of fracture zones (e.g. Pusch & Ramqvist 2008), etc.
- Construction of the seals.
- Implementation of additional backfilling and sealing measures.
- Demolition / dismantling of the surface facilities (buildings, roadways, etc.).
- Greening the area.

Due to the diversity of the work and its location, it must be carefully checked which work tasks can be carried out simultaneously or in sequence. Basically, the work in the borehole and the work on the company site can be differentiated. It should also be taken into account that there will be an increased frequency of truck traffic because materials have to be removed and delivered. Since the need for all of the work is not known and the work in the borehole depends on the geological conditions, the time required can currently only be roughly estimated at around six months. This would result in a period of 1.5 years for the entire operational period of the facility.

5.1.3 Post-operational or post-closure period

The post-closure period includes measures of institutional control. These measures can be divided into active and passive controls (e.g. IAEA 2009, IAEA 2011, chapter 5.6). Active controls are for example restrictions on access, post-closure environmental monitoring, surveillance and remedial work, e.g. maintenance of vegetative covers. Passive controls are restrictions on land use and record keeping.

The type and duration of the measures depend in particular on the possibility of a human intrusion, which decreases with increasing depth of the effective containment zone (barrier system) and its decreasing footprint. In the case of deep borehole disposal, the risk of human intrusion is low, so that active institutional control may not absolutely necessary. Other deep holes must be prevented. Due to this fact the area of the facility should continue to be in some kind of an institutional controlled state. Moreover, due to the long half-life of the disposed radionuclides, information should be retained for as long as possible to provide a basis for any future decisions concerning the site. On this basis, regulatory agencies can refuse to permit deep drillings near the facility.

5.2 Accidents and incidents

The route of a waste package can be divided into several sections. In the case of a deep geological repository after delivery and transport on the surface premises, a shaft transport or a transport via a ramp follows. The waste packages are then to be moved through the underground openings, in particular drifts. A further distinction must be made between drift and borehole disposal. In the case of borehole disposal, the transport container must be separated from the disposal container, which is emplaced into the borehole. Extensive analyses have already been carried out for this transport path (see for example BfS 2009, chapter 9.3; Filbert et al. 2008; Peiffer & McStocker 2012). The following differences are emphasized in contrast to DGR.

The transport and the disposal containers are separated above ground near the borehole opening and not in underground structures.

The vertical transport path is longer in the borehole compared to a repository shaft. There is the possibility of wedging and falling over greater heights. The container is lowered in the borehole without the protective transport container.

Borehole disposal does not require transport activities through excavated tunnels, drifts or underground caverns that would be carried out by operating transfer equipment and personnel.

While the points can be considered as differences of deep borehole disposal, the transport in the borehole should be assessed in terms of the occurrence of accidents in detail. Figure 5-1 provides an overview of the work during the operational phase of the facility. Figure 5-6 shows an event tree for the case of disposal using a wireline technique.

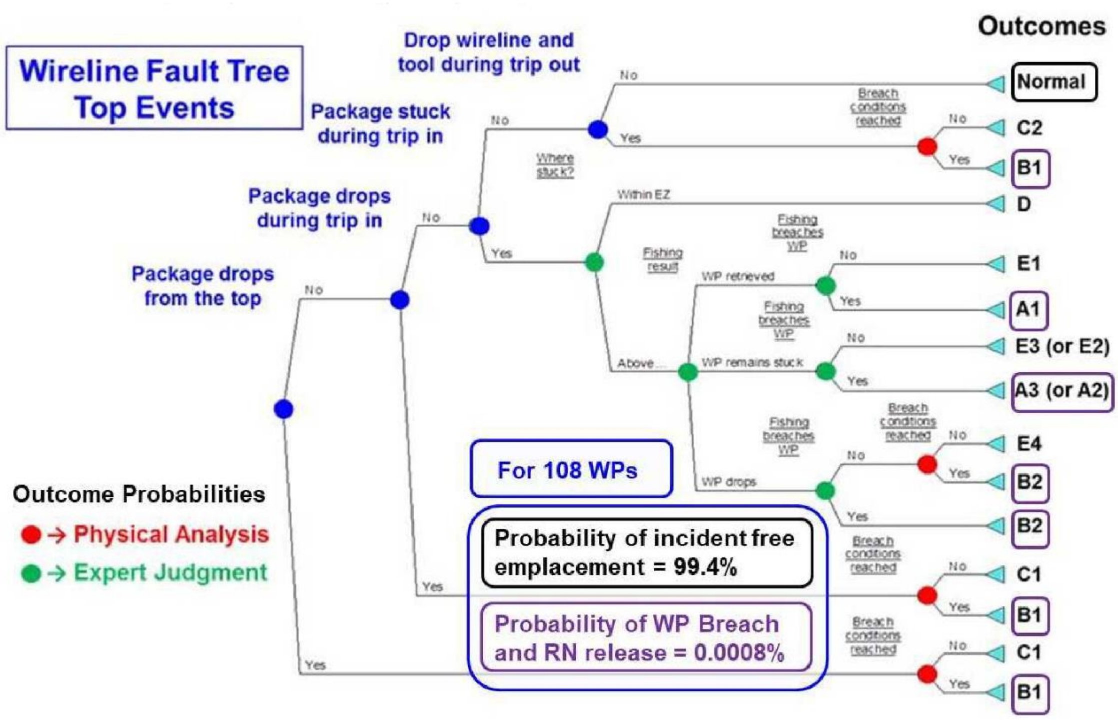


Figure 5-6 - DBD PCSA – Wireline Emplacement Event Tree according to Freeze et al. (2016, Section 5.1), SNL (2016), Freeze (2018).

As shown in the event tree, some of these top events (e.g., container/WP drops) could directly cause a breach of a waste package (Outcome B1), or not (Outcomes C1 and C2). Other top events (e.g., WP stuck) could indirectly result in a breach of a waste package if the primary mitigation technique (fishing) is not successful (Outcomes A1, A2, A3, and B2). The publications cited above also contain information on event probabilities. However, this information is not given here, since transport using a drill string is seen as an alternative to the wireline technique. So far there are no reliable numerical values for the use of a drill string, although event probabilities could be derived.

Bracke et al. (2017, chapter 6.4 Hazards) point out that a wall crack or break of a single container during disposal results in a contact of the waste with the borehole fluid and its contamination. The amount of released radionuclide would depend on the contact time of fluid and waste and on the composition of the waste package. Measures for retrieval and repair should be provided and comply with radiation protection regulations. A worst case, which should be unlikely, would be the loss of container that cannot be retrieved for some reason. A release of radionuclides would take place in the long- or short-term and would have to be assessed taking account of the geochemical and hydrological conditions.

It should be emphasized, however, that with a similar design of the emplacement technique, a level of security comparable to that of a generic shaft transport is achieved. That means, for example, if the ropes of a wireline emplacement technique are dimensioned according to the technical requirements for shaft and inclined conveyor systems. A high security level can also be achieved when using a drill string for the emplacement. Moreover, this technology offers advantages when a container is wedged or has to be retrieved.

In the case of a solution-filled borehole, the speed of a falling container is reduced with increasing density and viscosity of the flow medium. An option for slowing down the speed is the design of a container surface with unfavourable flow characteristics. In this regard, the work on developing drop-in concepts might be relevant (e.g. Bates et al. 2012, Chu et al. 2005). In addition, materials could be placed to protect containers that have already been disposed of, for example in air-filled boreholes bitumen, which can also act as a long-term seal. Plugs and pellets are available especially for use in boreholes. Of course, it is possible to set plugs.

With the aim of being able to react adequately when a container is wedged, borehole designs have already been developed which allow the streaming of solution around this container (Freeze et al. 2016).

Special features of the catalogue of measures for accidents and incidents will result from the fact that the borehole and thus the connection to the biosphere and the earth surface has a small cross-sectional area. This simplifies efficient and targeted implementation of site monitoring measurements and radiation protection measures. For example, by means of wellbore caps radioactive leakage from the borehole can be prevented. The small cross-section also favours the use of seals to isolate damaged containers or contaminated borehole areas. With regard to the limitation of the effects of accidents, it should also be noted that flammable aggregates, such as diesel or electricity motors, can be spatially separated from the containers.

Further information on the safety analyses of borehole disposal can be found in Freeze et al. (2016). Grundfelt (2013) discusses the radiological consequences of accidents during disposal of spent nuclear fuel in deep boreholes. Important recommendations are also contained in IAEA (2009).

The objective is to design the borehole disposal facility so that incorrect operation will not result in an accident. This report does not cover any further analysis for incidents and accidents.

5.3 Controlled and uncontrolled areas

The objective for radiation protection during the operational period of a borehole disposal facility and the related safety criteria are the same as for any licensed nuclear facility. Basic information on this topic can be found, for example, in IAEA publications such as IAEA (2009, chapter 3). Regarding the definition of radiation protection areas, the IAEA (2018) must be considered as well as national laws, ordinances, and regulations. According to the level of radiation exposure, a distinction is made between supervised areas, controlled areas and restricted areas:

Supervised areas are operational areas that do not belong to the control area, in which people can receive an effective dose of more than 1 mSv in the calendar year.

Controlled areas are areas in which people can receive an effective dose of more than 6 mSv [...] in the calendar year.

Restricted areas are areas of the controlled area in which the local dose rate can be higher than 3 mSv/h. Controlled areas and restricted areas must be clearly visible and permanently marked. Restricted areas must be secured in such a way that people cannot access them uncontrolled even with individual parts of the body.

- All areas surrounding the controlled area are supervised areas.

All areas in which the waste packages (containers with shield) are handled or stored belong to the controlled area. This includes the unloading hall and the hall with the emplacement device including the transfer areas, rooms for special treatment (e.g. for decontamination activities) as well as rooms which are used for repair work of technical equipment used in the control areas. In addition, the controlled area includes rooms for the collection of solid and liquid radioactive operational waste and for their preparation, a laundry, the radiation protection laboratory, the laboratory for chemical and radiochemical analyses, the rooms for personal decontamination and the ventilation system for the exhaust air from the surface control area.

The restricted area includes the borehole if it already contains radioactive waste.

5.4 Safeguards

Nuclear safety, security, and safeguards share the same fundamental objective: to protect people, society, the environment and future generations from the harmful effects of ionizing radiation. For the nuclear safeguards, the proliferation of nuclear weapons is of particular importance. The worldwide basis for safeguards is the Non-Proliferation Treaty (NPT). Norway's commitment to non-proliferation has been a key foreign policy for decades. The practical implementation of safeguards is based on the Safeguards Agreement between the State and the IAEA.

Detailed information about deep borehole disposal facility safeguards is described in Finch & Haddal (2016) and in particular in Finch et al. (2016). According to Finch et al. (2016) deep borehole disposal presents some unique safeguards challenges compared to a conventional mined repository. These challenges include:

1) verifying borehole design below the surface,
2) strong reliance on continuity of knowledge up to and including disposal,
3) limitations on the ability to observe or verify successfully emplaced containers, and
4) Successfully monitoring a closed and the sealed disposal facility over the long term.

In some cases, such challenges may prove easier for a borehole disposal facility than for a conventional mined geological repository, others more difficult, and still others may require new methodologies (or existing methodologies newly applied to safeguards). Long-term monitoring in particular might be somewhat less onerous.

5.5 Monitoring

To ensure that facilities are operated and activities conducted so as to achieve the highest standards of safety that can reasonably be achieved, measures have to be taken to control the radiation exposure of people and the release of radioactive material to the environment (IAEA 2017, see also IAEA 2010).

According to IAEA (2003, chapter 5.3.9) monitoring and surveillance are important for public and technical reassurance. Monitoring programmes need to be designed and implemented so as not to reduce the overall level of long-term safety. A programme of surveillance and monitoring should form part of the safety case.

In general, monitoring will be required during each phase of disposal facility development:

i. To provide reassurance to stakeholders including members of the public that the facility is performing as planned;
ii. To record or confirm the system description, to provide information for safety assessment and to provide baselines against which any changes can be assessed;
iii. To assure satisfactory conditions for the safe continuation of the current stage, including that doses to workers and members of public remain within design constraints and safety limits;
iv. To provide information to confirm the understanding which underlies a previous step or enhance the technical confidence to take the next step in the phased development of a borehole facility, or to identify reasons to delay or amend plans;
v. To give an appropriate level of confirmation of the results of assessment calculations.

In general, the procedures cover

- radiological monitoring with respect to the safety of the staff and environment and
- monitoring of the effects of the operation of the disposal facility on the environment.

During the design or construction phase of a borehole facility, background data should be collected as a pre-disposal benchmark, and used as reference levels (cf. Posiva Oy 2012). The results of pre-disposal monitoring will assist in building confidence in the safety and long-term performance of the facility and assist decisions for its future development. According to IAEA (2003) the data might include gamma radiation fields, radionuclide content of the dust, radon–thoron concentrations and radionuclide content of the soils, water and air on site. Facilities containing deep boreholes could be monitored for potential releases through the nearby water bearing horizons, although releases of activity are not anticipated to occur (IAEA 2003).

According to the German atomic law, radiation protection law and other regulations, disposal of radioactive waste in deep boreholes requires the same monitoring efforts as in the case of disposal in a deep geological repository. The disposal and monitoring in the operation phase must be done according to the requirements of the KTA (Nuclear Safety Standards Commission) and radiation protection standards. These standards include hot cell conditions and remote handling techniques, as during the disposal procedure the containers are unshielded. All disposal operations at the site of the borehole have to comply with the general requirements:

- Every container must have a unique identification number (ID).
- The tightness of the container has to be ensured.
- The stress levelling of container has to be given.
- Any deadlock must be manageable for retrieval.
- The contamination of tools must be checked.
- The conditions in the borehole must be monitored until closure.

Parameters to be monitored are amongst others the humidity, the temperature, the radiation field, gas generation and composition.

In the Euratom 7th Framework Programme, the project MoDeRn addressed monitoring of a mined repository with the aim to provide a reference framework for development and possible implementation of monitoring activities during disposal processes. In this project the following parameters were identified to be monitored:

- Temperature.
- Mechanical pressure.
- Water content and humidity.
- Hydraulic pressure.
- Radiation.
- Displacement.
- Gas concentration (O_2, CO_2, H_2, CH_4).
- Gas pressure.
- pH value and redox potential (Eh)
- Concentration of colloidal particles.
- Alkalinity.

If the use of a tight casing or liner is foreseen to provide a dry borehole, then the tightness of the casing or liner has to be monitored regularly during the disposal operation. Any fluid has to be detected in order to prevent corrosion of the containers. Any contamination in the gas phase (e.g. fission gas Xenon) has to be monitored. If the casing is perforated in the disposal zone, then the borehole could be wet and metal corrosion could occur with resultant hydrogen generation. Depending on pressure evolution, the stability and corrosion resistance of the containers and a contamination of fluids is monitored.

Due to the special framework of borehole disposal, for example the depth of the disposal zone and the small cross-section of the borehole, it must be checked precisely to determine which measurements can be carried out, make sense, and at which locations the investigations should be carried out. IAEA (2003) describes that the regulatory body should provide guidance in order to establish the monitoring programme, including monitoring of releases and external exposure, and to assess the environmental impact of construction, operation, closure and post-closure activities. The regulatory body should ensure by inspection on the site that the operations are carried out in accordance with established procedures as specified or referred to in the relevant licence or authorization and in existing regulations. The operator ensures by means of monitoring measures that the requirements established by the national authorities are met. In addition, the regulators or another independent body may carry out an independent monitoring programme as a measure of public reassurance.

The retrieval of containers is a particular challenge because the containers are not self-shielding. The waste must be repacked from the retrieved containers, taking into account radiation protection. For this purpose, a conditioning system is required and must be kept available, which allows the waste to be repacked into transport and storage containers. Transport and storage containers must therefore also be kept available. Pulling the containers out of the casing should not damage the containers. All these works also results in special demands on the monitoring program.

6 CLOSURE

6.1 Dismantling work

Decommissioning include removing any surface structures and systems that are not needed after the closure in the facility.

6.2 Closure

After successful disposal of the waste packages and the proof that no radionuclides are released from the borehole, the facility's closure phase can begin. Information about this phase can be found in IAEA (2003, 2009, 2011). It can be roughly divided into the sub-phases of decommissioning, backfilling and sealing of the borehole, and site rehabilitation.

The objective of decommissioning is the *release* of the site from nuclear regulatory control and the removal of plant parts that are no longer required. The phase can be divided into two fields of work. Initially, contaminated materials or tools are removed, and technical facilities are decontaminated so that the working area is cleared. The cleaned area should then be monitored again to see if the level of radioactivity has sufficiently decreased, thus, a radiation-controlled area is no longer required. The improved accessibility of the site simplifies the following work steps, such as the removal of unnecessary plant parts in order to improve the spatial framework for the backfilling and sealing activities. This will affect in particular the remaining parts of the emplacement device. However, depending on the technology, it could be possible that parts of the system can be used for the backfilling and sealing activities. In this case, the modification of the system takes place. Due to the extensive experience in dismantling nuclear facilities, this work should be feasible without significant problems.

If sufficient favourable framework conditions have been created, technical equipment for sealing and backfilling can be installed. These activities end the possibility of simply retrieving the waste packages.

Often an end state as greenfield is aimed at, that is, all facilities and buildings are completely removed and the site is restored to its natural condition. However, other objectives are feasible, for example, the industrial use of the site or reuse of remaining buildings. Particular attention should be paid to institutional control (Chapter 6.3). Consequently, the extent and type of rehabilitation measures (cf. IAEA 2011, chapter 5.5.2) depend on the planning for the use of the site. Rehabilitation will usually include the removal of

- buildings, such as also garages and roofed places, parking lots, roadways, walkways,
- water and electricity supply and infrastructure for communication,
- fences and lighting devices,
- and the removal of waste/surplus materials and debris.

Additional work comprises the re-levelling of the site to natural grade and restoration of natural vegetation. All these demolition and rehabilitation work are common practice in the construction industry and can be done routinely.

6.3 Institutional Control Period

Institutional control comprises a wide range of measures that can be assigned to three main objectives:

- Preventing a damage of the barrier integrity (technical and geological barriers),
- Checking the function and thus effectiveness of the barrier system, and
- Passing of information, knowledge and skills from one generation to the next.

In principle, the measures begin with the facility construction, whereby different priorities are set during the phases of the facility life cycle. However, the term "institutional control" is usually used for the measures after the closure of the facility (post-closure period). For a part of the preliminary measures the terms "monitoring", "surveillance" or “documentation” are used. The quality of this work is an extremely important requirement for the success of the institutional control measures.

Institutional control measures are also used in conventional construction projects and as part of projects for the disposal of toxic substances (e.g. ELW 1995). Information regarding the disposal of radioactive waste can be found, for example, in IAEA (2003, 2009). Accordingly, a distinction is also made between active and passive measures according to the type of work. Active institutional controls include:

- Maintaining signs, fences and guards at sites to prevent unauthorized access (Land Use Control, LUC),
- Maintaining access, maintaining the grounds, weed control, etc.
- Monitoring and surveillance.
- Performing of remedial work.

Passive institutional controls include:

- Long term markers;
- Restrictions on land use and ownership;
- Preservation of records;
- Financial assurances.

The measures can also be assigned to time phases. As a rule, it is necessary that a phase of active and passive institutional control is followed by a time phase of passive measures. The basic goal is to reduce the scope of the work, but changes in the framework conditions may require an optimization of the measures.

If it is ensured that the surface area of the repository has been completely decontaminated, only the characteristics of the deep borehole disposal concept must be taken into account when planning the institutional control measures. This includes the large distance between the disposal zone and the earth surface and the small ‘footprint’ of a borehole disposal facility, which extremely reduces the probability of human intrusion (cf. IAEA 2009). Due to these facts, the safety of the facility will not depend on active measures. Moreover, long term markers are not necessary and quite short periods may be justifiable, so land could soon be returned to local community use with, possibly, restrictions on ownership and use within a period of a few years. Measures that have to be taken into account include remedial measures in the near-surface section of the borehole that cannot be completely ruled out and the production of a concrete slab above the casing (cf. BVEG 2017, Figure 6-1).

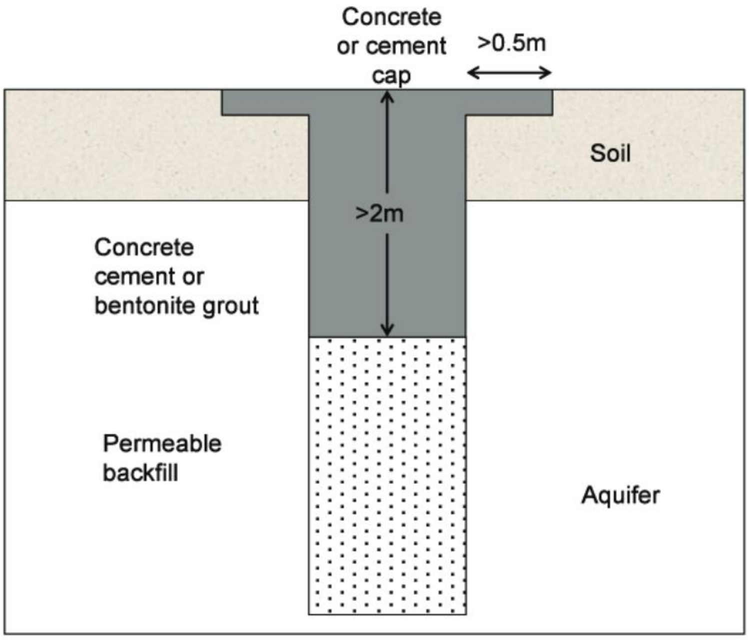


Figure 6-1 - Schematic diagram for a borehole cap according to SEPA (2010).

In the deep drilling industry, it is customary to protect casings and liners cathodically from corrosion. Such a measure could also be continued during the institutional control period. However, it can be assumed that deep drillings and general mining activities will have to be approved in the future as well. For this reason, passive measures and the availability of information are of extremely important for borehole disposal projects. Information that should be preserved with respect to a borehole disposal facility is primarily (IAEA 2009):

- Its location (borehole path with the location of the disposal and closure/sealing zones);
- Its geology, geochemistry and hydrology derived from site characterization data;
- Design details of the facility, including descriptions of, for example, the backfill, casing and seals;
- Detailed descriptions of the waste packages, including waste origin, radionuclide content, encapsulation matrix and containers;
- Descriptions of the construction and operation, including dates and details such as measured water inflows to boreholes and, especially, any non-conformances and actions taken to rectify them;

- The facility safety case and supporting information (e.g. from site characterization);
- A description of the post-closure arrangements;
- Outputs from the surveillance and monitoring programme, including baseline surveys.

Such information should be retained for as long as possible to provide a basis for any future decisions concerning the site. This may be most easily done by making use of national archives. In comparison to other options for radioactive waste disposal, the institutional control of deep borehole disposal is less extensive.

7 DISCUSSION AND RECOMMENDATIONS

Among the options discussed for disposing of high level radioactive waste, an international consensus has emerged that deep geological disposal on land is the most appropriate means for isolating such waste permanently from the human environment. The basic requirement for any geological formation is its ability to contain and isolate the radioactive wastes from the environment until the radiotoxicity of the waste has decayed to non-hazardous levels.

Two important reasons why deep geological disposal on land has evolved into the disposal method of choice for virtually every country with a nuclear power programme are:

- It is an entirely passive disposal system with no requirement for continued human involvement to ensure its safety.
- Radioactive wastes present no hazard while they remain in a deep underground repository. Because of their depth of burial (several hundreds of metres or more), the possibility of intentional human intrusion is virtually eliminated, and, with a suitable choice of location, the likelihood of inadvertent human intrusion can be made minimal.

Using deep boreholes as a disposal option is demonstrably practical and feasible with currently existing technology used in other mining and civil engineering practices.

Compared to countries with commercial nuclear power, the Norwegian inventory is extremely small. For small amounts of waste, borehole disposal may prove to be significantly more cost effective than a mined repository. In comparison to mined repositories, borehole disposal has some positive aspects, which examples are listed in the following. The full analysis and comparison of positive and negative aspects between borehole disposal and mined repositories are out of scope of this report.

- In a mined repository there are cavities with large cross-sections, such as shafts and drifts. Fractures can cross such cavities and thereby increase the risk of radioactivity dispersion.
- There are very different seals to be made in the mined repository compared to the borehole sealing. Borehole seals are easier to make than seals in mined repositories.
- In mined geological repository, larger masses of rock need to be moved and handled.
- A mined repository requires more personnel, for example for the inspection and maintenance work.
- Borehole disposal does not require a hoisting system for the transport of the staff which is important in terms of occupational safety.
- Borehole disposal does not involve the occupational risks associated with underground work

During the concept development several aspects arose which need to be investigated in more detail. For the disposal concept in Norway, the geology seems to be beneficial for deep borehole disposal. Unlike the geology in the US for example, the Norwegian geology has the benefit that no or only a small zone of sedimentary formation can be found. The crystalline formations, which are well-suited for the disposal of radioactive waste, start at a shallow depth. This limits the required total depth of the borehole.

For the construction of the deep borehole repository, the experience and knowledge from conventional oil, gas and geothermal drilling can be used. Still, the technologies need to be adapted for the larger diameter required to fit the containers. A detailed planning of the construction of the borehole can only be carried out once the location is selected and more information regarding the geology is available. Additionally, the container design impacts the borehole design. Here the available containers can set the basis and can be adapted individually to the waste existing in Norway.

For the operation and closure of the facility the general concept is described in Chapters 5 and 6. Here only a few points are left open. For the waste emplacement technology two options are considered here: wireline and drill strings.

Several decisions are required during the development of a borehole disposal concept. Since most variables are related and dependent on each other, at some point decisions or assumptions need to be made in order to develop a concept. Some central decision points are the container design, which then strongly affects the borehole design. The borehole design on the other hand influences the container design as well. This is one of the mutual dependencies during the concept development of deep borehole disposal. In addition, the geology affects the borehole and container design significantly. As Figure 7-1 shows there are three major aspects which influence all the other aspects discussed throughout this report:

- Borehole design
- Container design
- Geology

While the borehole and container design are variables and can be changed and adapted relatively easily, the geology is set. This factor can only be influenced by the selection of the location.

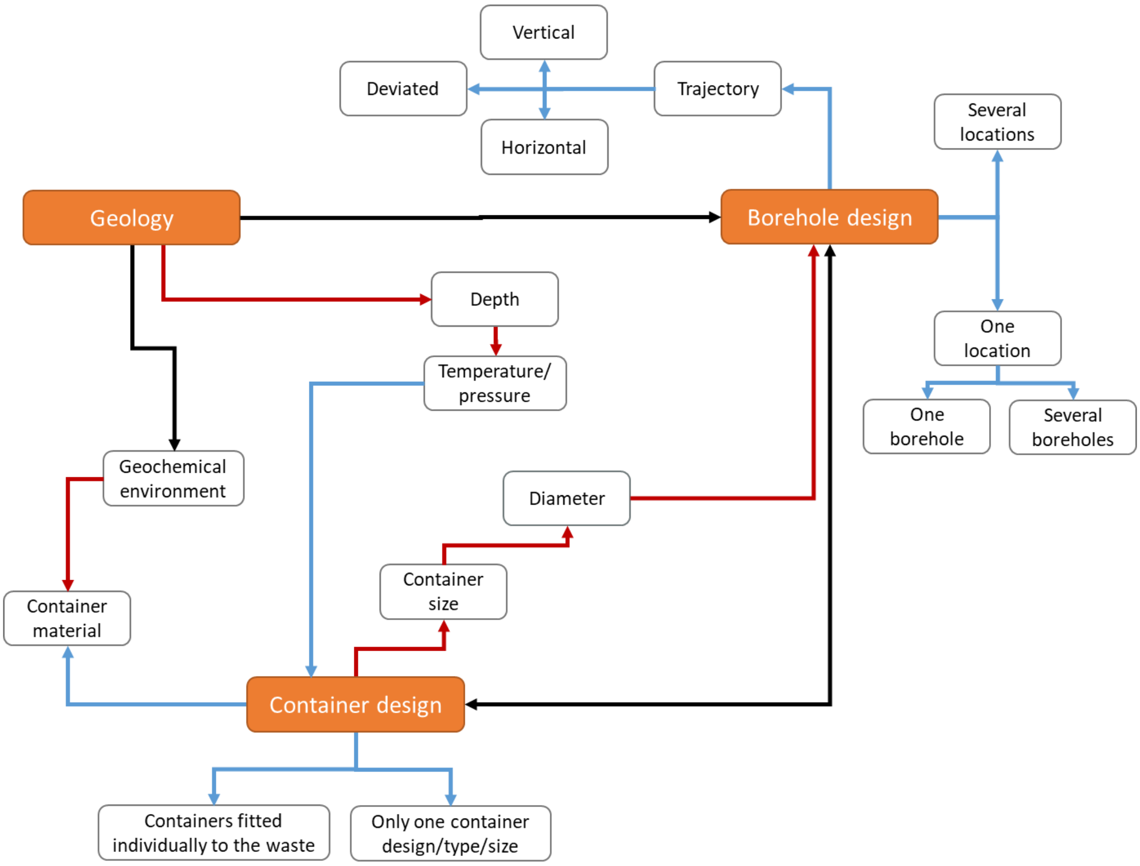


Figure 7-1 - Decision tree for a detailed borehole disposal concept and variables, which are impacted by these decisions.

Each of the three main decision points are require additional decisions. Some of these are also dependent on other factors. For example, the container material is basically a decision linked to the container design, but also strongly impacted by the geology. Here the chemical environment plays an important role. An example in which it becomes clear how the three different major aspects interact with each other is the borehole depth. At first thought, the borehole depth is related to the borehole design only. The main driver of the depth is however the geology. The borehole needs to be as deep as the suitable geological environment is located. In addition, the technical feasibility plays a role, which influences the maximum possible depth as well. The borehole depth affects to the temperature and pressure, deeper holes lead to greater temperatures and pressures. Figure 7-1 has the intention to show the complexity which is faced during the development of a deep borehole repository. Without some decisions, a more detailed concept cannot be established.

Still the figure does not include all open questions, but already provides an overview of the complexity of the concept development.

The main part of the deep borehole disposal concept is based on American guidelines and reports. Most available research and reports are based on the geological situation as it is found in the USA. This geology required a long backfilling zone since the sedimentary upmost layers of the subsurface are not suitable for a sufficient inclusion of the radioactive waste. In Norway the geology is different. No or only small layers of sediments are found and the crystalline formations, which are suitable for the disposal and sealing zone, can be found at a significantly shallower depth. Therefore, a step back needs to be made to include these facts into the decision and concept development. Other aspects like the salt concentration, which plays a role for the container design, require more research, because there is almost no information available.

A potential design layout of the borehole can be seen in Figure 7-2. Here the borehole is adapted to the geological circumstances in Norway. The borehole diameter and the depths of the different parts of the borehole are not set yet.

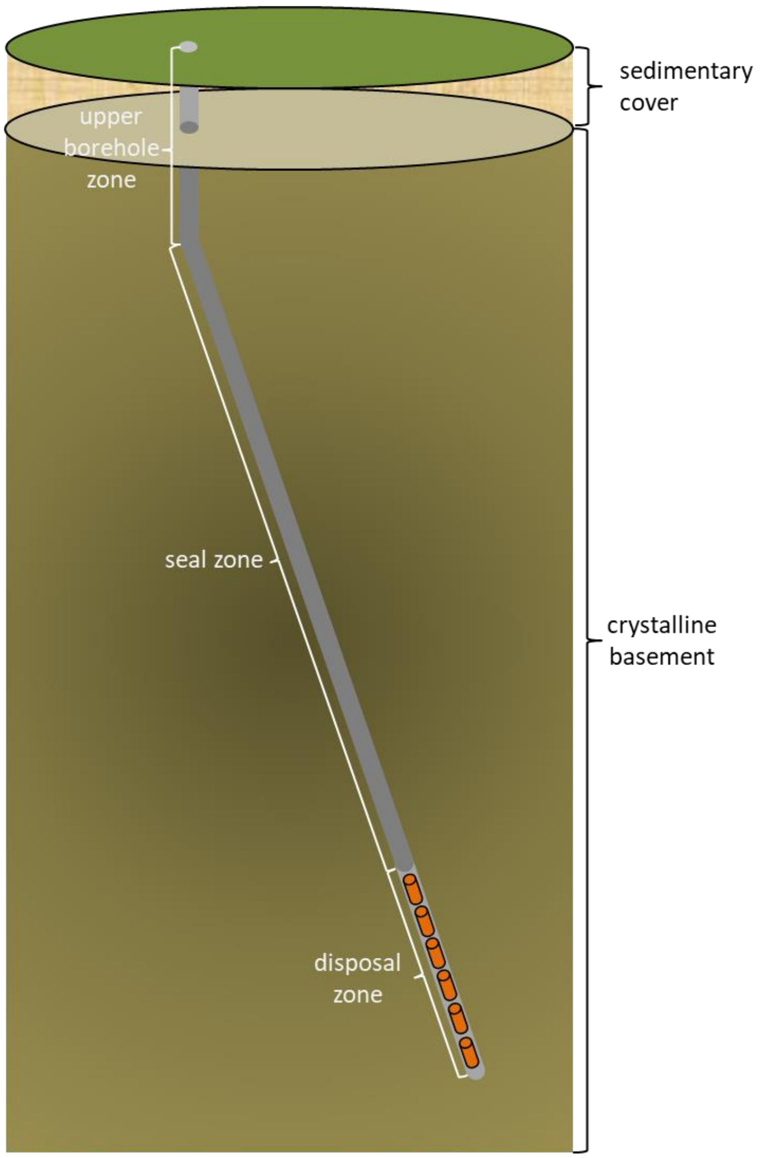


Figure 7-2 - Potential borehole design for Norway.

The most rational approach for a more detailed concept description would be to start from the geological aspect, as this is influencing most of the following steps. From this point onwards, the technical feasibility of the borehole construction in combination with the container design can be included. With this report as a guideline and basis for the next steps, the borehole disposal concept can be adjusted to the prevailing geological formations found in Chapter 2. From this point onwards, the design of the borehole can be continued step by step. Important points are the diameter of the borehole and the borehole trajectory.

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