Methodology for Designing Deep Boreholes for Disposal of Radioactive Waste – 22064

Tilman Fischer *, Hans-Joachim Engelhardt *, and Dirk Mallants **
* BGE TECHNOLOGY GmbH
** Commonwealth Scientific and Industrial Research Organization (CSIRO)

ABSTRACT

The concept of the deep borehole disposal (DBD) is characterized by the use of low volume, non-shielded containers that are placed with the most reliable technology into a deep disposal zone. This way, DBD maximizes the tightness of a host rock as a key barrier in the safety concept while the large distance to the biosphere further contributes to the permanent isolation of the radionuclides. The small cross-section and the spatial arrangement of the borehole offer the possibility to position one or more seals comparatively easily to provide a long-term barrier to radionuclide migration. Unlike conventional mined geological disposal facilities, for DBD all pre-closure and post-closure activities involving personnel are carried out above ground.

Due to this basic concept, the specifics of a DBD project depend in particular on the radionuclide inventory and the geological framework including different potentially suitable host rocks. Because of the large number of technical options and their modularity, a DBD project can be optimally adapted to these framework conditions. Here we present a generic workflow to identify - as efficiently as possible - a design solution for a specific DBD application. At first sight, this workflow resembles a decision tree, with the properties of the host formation and waste inventory as information sets.

This paper provides an overview of the key parameters that require consideration during the design of a deep disposal borehole. In addition, the relation between these parameters is highlighted. A limited number of framework parameters are defined to keep the methodology simple. For illustrating the methodology, the disposal depth is set to be between 2000 m and 3000 m. This depth allows the disposal and seal zone to be set up in areas with particularly advantageous properties and to maintain large distances from natural radionuclide migration pathways. Another framework boundary condition is the necessity of a vertically drilled borehole. In addition, the decision-making process is based on the requirement that the borehole must withstand the mechanical and thermal loads in-situ.

In the workflow, the first parameter to consider is the host rock. This selection influences several subsequent decisions during the design process. Among other things, the drilling method must be selected so that the host rock (i.e. borehole wall) is damaged as little as possible. In addition, there needs to be assurance that the construction of the borehole is based on predefined specifications (e.g. trajectory, minimum diameter to fit the canisters) that can be achieved with current technology or minor to moderate modifications of it.

Following the decision regarding the host formation, the next important question is the requirement of a casing in the disposal zone of the borehole and, if necessary, the selection of suitable casing material and thickness. Important characteristics of rock resistance that need consideration include rock strength, anisotropy of properties and creep capacity. For the selection of a suitable drilling fluid, an assessment of the rock porosity, its formation fluids, as well as chemical mineralogical interactions, for example in clay formations, is required.

Closely linked to the requirement of a casing is the question regarding the optimal borehole diameter. Additional to a potential casing in the disposal zone, several other factors influence the borehole diameter. One such factor is the clearance between the canister and formation or casing. This annular gap is required to secure a smooth emplacement of the canisters and maintain a laminar flow in the gap throughout the whole operation. The single most important parameter in the design of the borehole with an optimal diameter is the disposal canister. Its outer dimension sets the central reference point for the borehole

diameter at the disposal zone. To some degree, the dimensioning of the canister is determined by the formation characteristics (i.e., stress distribution with depth). The geometry of the conditioned waste packages is another important factor determining disposal canister dimensions. Each geological environment has specific characteristics, which are important for the minimum wall thickness of the canister. The pressure regime will provide a basis for mechanical calculations, which provide a first estimate for the minimum canister wall thickness. In addition, not only the rock type and the associated stress regime, but also the geochemical environment needs to be considered. The latter influences the corrosion rate and therefore the required wall thickness of the canister. Given a fixed inner diameter of the canister, the outer diameter can then be calculated. The chemical framework conditions as well as the temperature and pressure are also decisive for the selection of backfilling and sealing materials, which have to be stable over the long term.

Here we highlight the need for an iterative design process, as input parameters will change as the design process matures and/or when more site-specific parameters gradually replace generic site features. This generic framework has broad applicability across most rock types deemed suitable for geological disposal.

INTRODUCTION

The final disposal of radioactive waste poses challenges for many countries around the world. Today's consensus is that geologic disposal deep under the earth's surface is the most practical and safe method. Different concepts have been established for different waste types, but in all cases, the general idea is the same [1]. For low level waste (LLW) near surface facilities are considered and already implemented (e.g., France, Hungary, Iran [2]). For intermediate level waste (ILW) different approaches have been presented and some countries have already constructed their disposal facilities. Two examples for ILW geological repositories are the Endlager Morsleben (ERAM) facility in Germany and the Himdalen facility in Norway. Note that many facilities are not constructed to just accommodate either LLW or ILW, but they are designed to be suitable for both waste types. Least advanced is the concept development and site selection for high-level waste (HLW). Around the globe, many concept ideas are being evaluated. In Belgium, detailed planning is under way and the former repository Gorleben in Germany was in a detailed planning phase until closure of the facility. Still, only Finland is currently constructing a repository for high-level waste in Olkiuoto. While the mentioned examples are all based on the concept of deep geological mines, the concept of deep borehole disposal (DBD) has been the subject of research for several decades [3]. While deep geological repositories (DGR) require the construction of large underground caverns, DBD concepts only consist of the boreholes. Other characteristics are that low volume, non-shielded containers are used for the disposal process. Using reliable technology, these canisters are lowered into a deep disposal zone. Especially for countries with smaller volumes of radioactive waste, this type of final disposal is a safe and cost-effective alternative to complex and expensive construction of deep underground facilities. Compared to DGRs, DBD facilities can be constructed faster and cheaper. Unlike conventional mined repositories, DBD repositories have a significantly reduced interaction of personnel with the waste packages. Generally, the waste inventory and the respective geological situation in each country require an individual solution and DBD in particular simply allows an adaptation to these framework conditions due to the multitude of options and the modular basic concept.

GENERAL CONCEPT OF DEEP BOREHOLE DISPOSAL

Characteristic for a DBD concept is the construction of the required underground openings using a drilling method. This allows disposal of the waste at great depth. In addition, the borehole has a relatively small cross-section as a connection path to the earth's surface. Instead of constructing caverns, deep boreholes are drilled into the subsurface. For this, the technical experience and expertise from the hydrocarbon and geothermal industry, as well as drilling operations in underground mines, can be used. Compared to conventional drilling operations, larger diameters might possibly be required to fit canisters including the waste into the hole. To date, some large diameter boreholes have been drilled, which show that the required diameters may be feasible [4].

The required depth and diameter of the borehole depends on different parameters, including the radionuclide inventory and the geological framework. The required total volume of the disposal zone depends on the number and dimensions of the canisters; the borehole diameter mainly depends on the outer canister diameter and the need for a casing. The stacking height of the canisters determines the length of the disposal zone, while the geological environment defines the length of the seal and backfill zone. Therefore, no generally valid statement regarding the minimum borehole depth can be made. This needs to be decided for any specific disposal site. In general, borehole depths ranging from around 2500 m to more than 5000 m have been proposed in the literature (e.g. [5], [6], [7]). Still, the depth and diameter of the borehole should be kept as low as possible.

In general, the concept of DBD provides a large variety of options and can be adapted to many different geological conditions. This means that formations generally considered as host rocks, i.e., clay, crystalline, and rock salt, can all be suitable; however, the borehole design needs to be adapted accordingly. The large number of technical options, which are already used in the hydrocarbon and geothermal drilling industry, and their modularity, are providing considerable benefits. The general structure of the borehole, however, remains essentially the same. Only the length of the different zones will differ from operation to operation. The deepest section of the hole accommodates the waste canisters, referred to as the disposal zone in Fig. 1. The length of this zone depends on the amount of waste to be disposed, noting that several boreholes can be drilled to accommodate large volumes. Above the disposal zone is the sealing zone. Here the geological profile plays a key role in determining what a suitable sealing system would look like. The shallowest section of the borehole is used for potential backfilling measures. In some cases, this part of the borehole is not compulsory. Under favorable geological conditions, a pure backfill zone may not be required. In case the host rock extends to the surface, the seal zone can be designed to extend to the surface. In other, likely cases, a mixture of backfill and seal zone is possible. These cases consider several sealing elements between which individual backfill zones are located. However, if the uppermost section of the formation is a sedimentary cover, which the borehole is drilled through, a backfill zone is indispensable. On the other hand, in strongly creeping salt formations it may even be possible that the borehole can be left open and the natural creeping behavior of the salt closes the borehole. In this case, it is difficult to divide the borehole above the disposal zone more precisely.

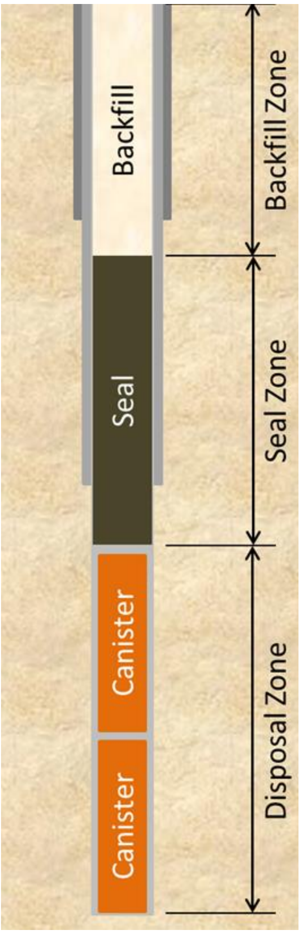

Fig. 1. Generic schematic of the different borehole sections of a borehole for the disposal of radioactive waste (note: the length of the different zones will vary depending on the geological environment at the site).

OBJECTIVES

Since many different aspects affect the design of a DBD facility, examples in this paper have been chosen to illustrate the general design approach. This paper aims to put some of these aspects in context with each other to provide a workflow to support the decisions around the design and construction phase of a borehole repository. This requires an approach similar to the decision tree principle. However, at each point of this methodology the possibility for iterations must be given and considered, as some decisions may have an impact on earlier steps. Therefore, a workflow is developed here for future operations during the initial phases of the design process.

Several specific boundary conditions are proposed in this paper to present a simple and comprehensive plan of procedures. A more generic approach, without any boundary conditions, would add complexity. In most cases, several conditions are somewhat fixed, especially where it concerns technical feasibility such as achievable depth and diameter of the borehole. Since DBD requires large diameters to fit the waste canisters, the depth-diameter correlation will set a limit. A review of drilled wells and their internal diameters versus drilled depth has shown that wells with a diameter of around 70 cm have been drilled to more than 2000 m depth [8]. Previous operations and investigation suggest that boreholes with a diameter of roughly 75 cm or more can be drilled with today’s technology to a depth of more than 2500 m.

Therefore, the first boundary condition is met, since a borehole depth between 2000 m and 3000 m is assumed. Another condition is linked to the borehole trajectory. While in conventional drilling operations, all sorts of trajectories – vertical and deviated - are drilled successfully, we consider a vertical borehole. This has the advantage of reducing the risk of stuck canisters in the hole. Furthermore, the clearance around the canister can be reduced since no curvature needs to be considered.

Two important variables that need consideration in the methodology are the host formation (crystalline, clay and salt rock) and the radionuclide inventory (influences borehole depth and canister dimensions). As a result, the methodology will have these two variables as key decision makers during the design process.

PARAMETERS CONSIDERED FOR THE WORKFLOW

In addition to the boundary conditions, many other parameters need to be considered during the design process of a DBD facility. While some parameters can be defined on an individual basis, others need to be derived and relationships to other parameters have to be accounted for. For example, during the clearance calculation defining the gap between the canister and casing or the borehole wall, the fluid flow within this gap needs to be considered. A correlated parameter that needs to be accounted for during this part of the design process is the trajectory of the borehole. The combination of the fluid flow within the borehole and trajectory play a role in ensuring a safe and continuous emplacement process.

In the following sections, the main parameters that are critical to the implementation of the methodology will be discussed briefly. In this discussion, the relationship between most parameters and the borehole diameter is paramount. It will become evident that the borehole diameter is one of the key limiting factors influencing the design.

At this point, the distinction between two different borehole designs should be noted, which results in different parameters to be considered for the borehole diameter. Firstly, the option in which no casing in the disposal section is required (Eq. 1) and secondly, the option in which a casing must be installed to ensure borehole stability (Eq. 2). This results in two general equations for the borehole diameter calculation.

In the case with no casing installed in the disposal zone of the borehole,

$$\O H_{min} = OD_{canister} + 2 * \mathit{\Delta}_{cw} + x_{cr} \qquad \text{Eq. 1}$$

And in the second case with a casing installed throughout the whole borehole:

$$\O H_{min} = OD_{canister} + 2 * \left(\mathit{\Delta}_{cc} + wt_c + \mathit{\Delta}_{cf}\right) \qquad \text{Eq. 2}$$

where $\O H_{min}$ is the minimum borehole diameter, $OD_{canister}$ is the outer diameter of the canister, Δ_{cw} is the gap between canister and borehole wall, Δ_{cc} is the gap between canister and inner casing wall, and Δ_{cf} is the gap between outer casing wall and borehole wall. The casing wall thickness is included in the formation by adding the factor wt_c. The variable x_{cr} describes a factor for potential creep of the formation, which closes the borehole. For this parameter, the duration the borehole stands open and the creeping rate of the formation are important. The two options can be found in Fig. 2.

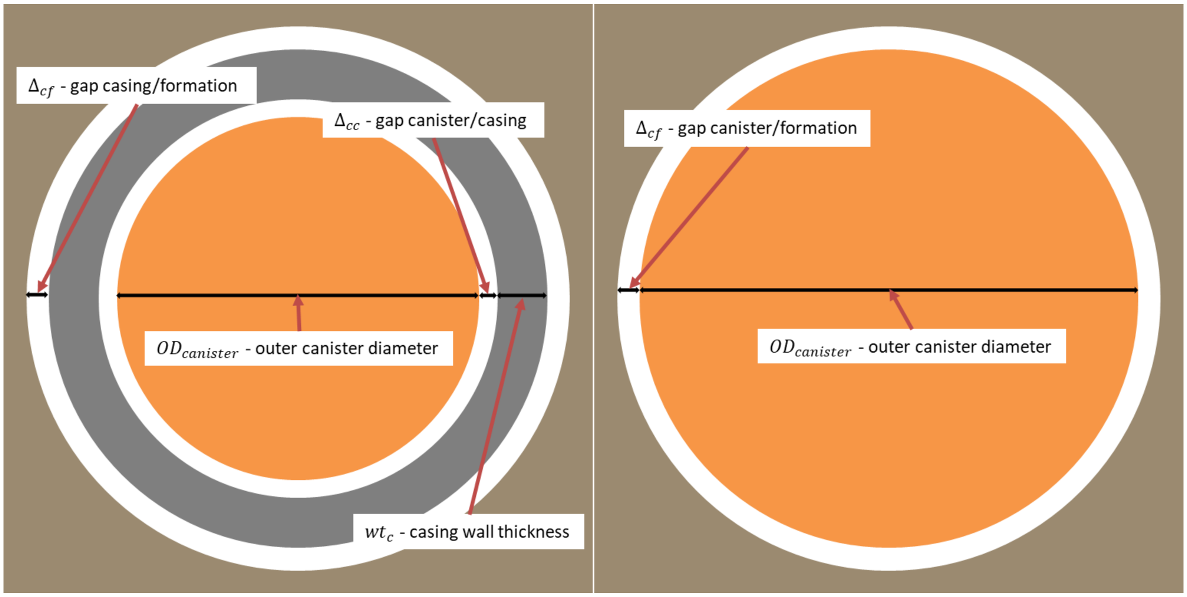

Fig. 2. Effect of including casing (left) or excluding casing (right) on annular gap.

Canister Diameter

The canister itself is a key parameter concerning the borehole and primarily influencing the borehole diameter. Especially the outer diameter is of interest for the borehole design. Several publications as well as research and development projects have proposed different waste packages and overpacks for the disposal of radioactive waste in deep boreholes. The outer diameter typically ranges from just over 40 cm to more than 70 cm. An overview of different overpacks and waste packages can be found in TABLE I.

TABLE I. Outer dimensions of different waste packages and overpacks [9].

	Outer length [mm]	**Outer diameter [mm]**
Waste packages		
BSK	4 980	430 – 440
BSK-R	5 060	520
HLW canister	1 338	430
CSD-C canister	≤ 1 345	≤ 440
BSK 3	4 980	≤ 440
Overpacks		
Modified BSK (BSK THTR/AVR)	4 980	705 – 715
DBC-R	5 600	640 – 740 [10] About 550 [11]

The borehole will be designed according to the outer diameter of the canister. Note that the waste volumes and dimensions will dictate the minimal internal diameter. As this example shows, in most cases many different parameters affect every single step of the DBD facility design.

Since the outer diameter of the canister is trailblazing for the borehole diameter, the most useful approach for the canister dimensioning is specifying and fixing the outer canister diameter. In combination with this and the site-specific properties, i.e., in this case the formation types as well as geological and geochemical environment, the canister can be dimensioned in more detail. In addition, the pressure regimes and resulting mechanical stresses on the canister are important input parameters for the canister dimensioning. Depending on the host rock, it is possible to use different materials for the canisters. Combinations of different materials can also be considered. The material is selected to provide a high corrosion resistance in the corresponding chemical milieu. For the wall thickness determination, the geochemical milieu provides important information. First, the material is selected to enable a high corrosion resistance. Based on the related corrosion rate and the mechanical calculations, the canister wall thickness can be determined. A combination of the different described aspects will lead to the final dimensioning and design of the canister.

Annular Gap

Another important parameter affecting the borehole diameter and therefore one of the central design aspects are annular gaps. Fig. 2 shows two different possibilities for the borehole design in the disposal zone, one with casing and the other one without casing. If a casing is required, two annular gaps need to be included in the borehole diameter calculation, while without a casing in the lowest section of the hole only the gap between the borehole wall and the canister needs to be considered, as shown in Fig. 2.

In conventional drilling operations, different annular gaps are used to safely run the casing or measuring and logging tools in the borehole. A differentiation between regular clearances and tight clearances is made. Depending on the hole size these can vary significantly. In addition, there are DBD concepts which also provide assumed clearance levels between canister and casing or casing and borehole wall. A summary of these values in combination with the borehole diameter can be seen in Fig. 3.

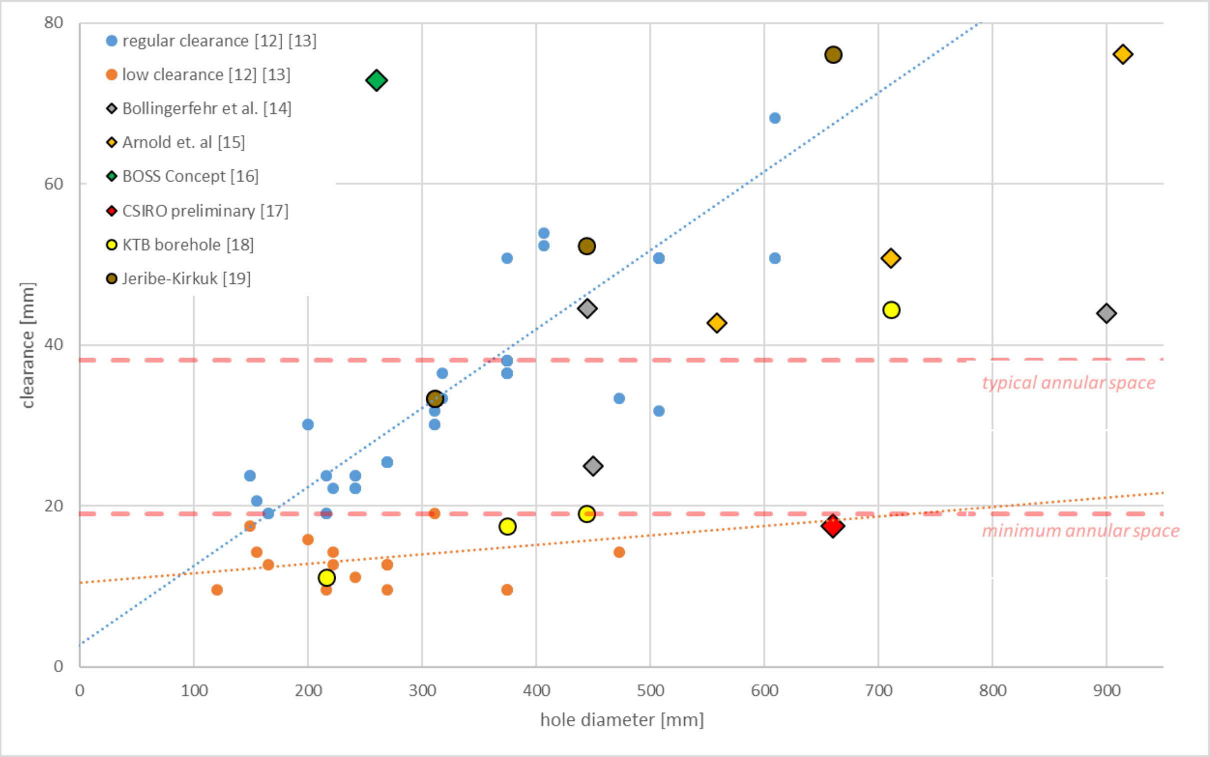

Fig. 3. Evaluation of different hole diameters and clearance values (gap between the outer casing wall and borehole wall).

Fig. 3 shows that larger borehole diameters tend to require larger clearances. The clearances provided by the drilling industry have a wide range. For regular clearances, they start at around 20 mm for 150 mm boreholes and go up to 10 cm for 70 cm boreholes. Tight clearances consider smaller clearances; just over 10 mm for 120 mm boreholes, but no specifications for boreholes of more than 500 mm are available. Most DBD concepts seem to be based on specifications from the drilling industry.

The clearance also plays a role in the calculation of the fluid flow in the borehole during the emplacement phase. Here the assurance of the laminar flow in the annular gaps is important.

Casing Requirement

A challenging aspect in almost every drilling operation is borehole stability. There are several options to maintain borehole stability throughout the entire drilling operation, including the use of optimized drilling fluid and the installation of a casing string in the borehole. In addition to the casing for the borehole stabilization, other casings can and will be installed in the borehole and removed prior to sealing. Here the guiding casing, important for a smooth disposal of the canister(s), needs to be mentioned. For the disposal of radioactive waste in deep boreholes, the introduction of any foreign material from outside the borehole needs to be evaluated carefully. The borehole itself has the highest potential to become a pathway for radionuclide migration to the biosphere; therefore, the sealing of the borehole is of major interest and utmost importance. Installing a casing string would enable two such pathways, one on the inside of the casing, the other one on the outside. In the likely event that the casing is removed, at least in the upper section of the borehole, there will still be a pathway left. Additional aspects to be considered are corrosion and gas development. Therefore, it is widely accepted and recommended by many experts that the casing must be removed from the borehole before it is sealed. An alternative is to waive the casing completely or at least partially in the disposal zone. To be able to evaluate this option more precisely, the different rock types and the associated borehole stability must be examined more closely.

General knowledge and experience leads to the recommendation that the casing could be dispensed in both salt rock and crystalline rock. In the drilling industry, salt is considered a grateful formation to be drilled. High rates of penetration (ROP) and limited bit wear make the job comparably easy and cost effective. In both cases, in salt and crystalline formations, however, the possibility of dispensing the casing still needs to be analyzed in more detail based on site-specific information. One of the greatest risks related to salt drilling is over-pressured anhydrite (anhydrous calcium sulfate) layers that need to be penetrated, although solutions exist [19]. In rock salt, a beneficial aspect during the closure phase is the creeping behavior of the formation. During the operational phase this may have a negative impact since the disposal zone might close too early and the canisters might potentially get stuck or might not fit in the open hole section anymore. However, thorough planning can help to overcome this problem. Once again, excellent knowledge of the formation is required to estimate the creeping rate of the formation to be consider during the planning phase.

Crystalline formations, on the other hand, are known to be a hard and stable formation. The major challenge in crystalline rock is potential fracturing caused by the drilling process. These fractures might result in breakouts throughout the borehole, which are regarded as borehole stability problems [17]. Borehole breakouts can influence waste emplacement and can once again lead to stuck canisters. Simple calculations (see below) have shown that borehole stability should be ensured down to more than 2000 m with only air in the borehole. With fluids, for example water, the stable depth can be extended to more than 3500 m. For the calculations an unconfined compressive strength of 120 MPa was assumed.

Air in the borehole:

$$d_a = \frac{UCS}{\left(2 * g * \rho_{formation}\right)} \qquad \text{Eq. 3}$$

Drilling fluid in the borehole:

$$d_w = \frac{UCS}{\left(2 * g * \rho_{formation}\right) - \left(2 * g * \rho_w\right)} \qquad \text{Eq. 4}$$

where d_a and d_w are the maximum depth at which borehole stability is guaranteed when filled with air or drilling fluid (in this case water), respectively, UCS is the unconsolidated compressive strength (here 120 MPa), and g is gravitational acceleration (9.81 m/s^2). Furthermore, $\rho_{formation}$ is the density of the formation (here 2700 g/cm^3), and ρ_w is the density of the drilling fluid (1000 g/cm^3). Several studies have dealt with the topic of open hole operations in crystalline formations (e.g. [20]) and shown that a scenario similar to the one assumed in this paper can be possible. Nonetheless, calculations that are more detailed and complex are required, in the best case with real figures from the disposal site. Based on these a final decision on whether to use a casing or not can be made.

Clay formations are generally regarded most complex and unstable. This formation type combines negative aspects of salt and crystalline rock. First, clay tends to swell when in contact with drilling fluids or fluids in general. This can cause the borehole to close slowly, however it will not result in positive effects like in salt. Sealing elements or sealing features will still be required. The swelling process is more complex than salt creep and therefore harder to predict. Second, in many cases, instability of the borehole walls will cause rocks to break off and fall into the borehole. It is therefore advisable to use casing in the disposal zone of clay formations.

If the casing can be dispensed, the required borehole diameter would be reduced. The possibility of installing a casing or not will have further ramifications on the final workflow: in salt and crystalline rock casing may not be required, while in clay a casing in the disposal zone is required.

Technical feasibility of the borehole depth and diameter

Based on the canister dimensioning and the number of canisters the length of the disposal zone can be derived. In addition, an assumption for the length of the seal and backfill zone can be made. For both estimates, additional information, like the waste inventory and detailed formation information, is mandatory. The combination of these parameters will lead to a required depth and diameter of the borehole. In Fig. 4 previously drilled boreholes, whether in the hydrocarbon or geothermal industry or for research purposes, are summarized and mapped. This gives an idea of what is feasible with the current technology and equipment. The black circle in the graph below indicates the depth, with associated diameter, that can be reached with currently available technology, according to experienced drilling engineers. However, the example assumed in this paper seems also realizable, although it would require adjustments and reassemblies of already available and used drilling rigs. One example of this is that the pumps used to pump the drilling fluid and thus to transport the cuttings out of the hole must be dimensioned larger.

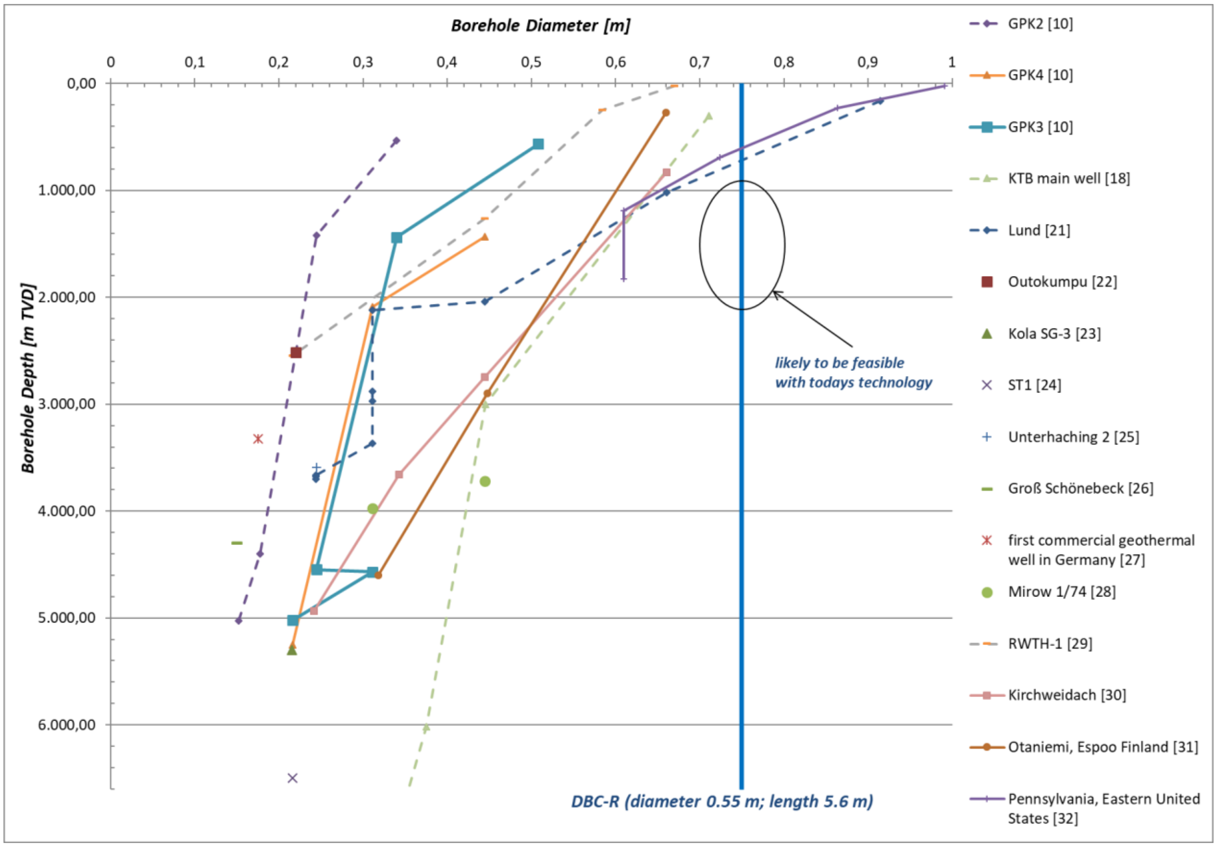

Fig. 4. Collation of large diameter boreholes. Blue line indicates the diameter required to accommodate the DBC-R container [5].

PROPOSED WORKFLOW

Taking all discussed aspects and parameters in consideration, many links within the design of a deep borehole for the disposal of radioactive waste need consideration. The host formation, the pressure regimes and geochemical environment at the repository site define the first design choices (Fig. 5). Framework conditions such as depth and trajectory of the borehole are still left out at this point. Depending on the formation, one can make a general, but not always accurate, statement about the casing. While in crystalline rock and rock salt the installation of a casing can often be dispensed, it can be assumed that a casing is required in clay formations due to its specific characteristics. Thus, two major design pathways emerge in the workflow.

The casing not only plays a central role for the borehole stability but also influences other steps in the design of the DBD facility. As discussed earlier, the borehole diameter is strongly influenced by the choice whether or not to install a casing. When no casing is installed, the borehole diameter calculation takes account of:

- Outer canister diameter,
- Annular gap/clearance between canister and formation,
- Potential creeping or swelling rates of the formation.

The last one of these three parameters is an important factor for the diameter calculation. The faster the borehole closes, the larger the diameter needs to be. In combination with the time the borehole will be open, this closure rate will provide a value to be included in the calculation of the borehole diameter. Factors like the drilling time, the installation of the emplacement facility or the conversion of the drilling rig, in case this is used for the emplacement, as well as the actual emplacement time need to be considered.

For the second option, the installation of a casing in the borehole, diameter calculations consist of more parameters:

- Outer canister diameter,
- Annular gap/clearance between canister and casing,
- Wall thickness of the casing,
- Thickness of the cementation, which might be installed between the outer casing wall and the formation or the gap between the casing and formation.

The parameter that needs to be considered in both options is the outer canister diameter. One option is to set this value at the beginning of the design process, the other one is to start with the waste type and volume and to construct and dimension the canister around this. Either way, the borehole can only be designed once the outer canister diameter is fixed. From this point, well planning and drilling engineers will use bottom up and inside out principles, which is commonly used in the industry. For the canister dimensioning, the workflow needs input from the host formation and its geochemical environment. In addition, mechanical stresses exerted by the formation are part of the canister dimensioning process. In the past, numerous research projects have dealt with corrosion of different material in different geochemical environments (e.g. [33], [34], [35], and [36]).

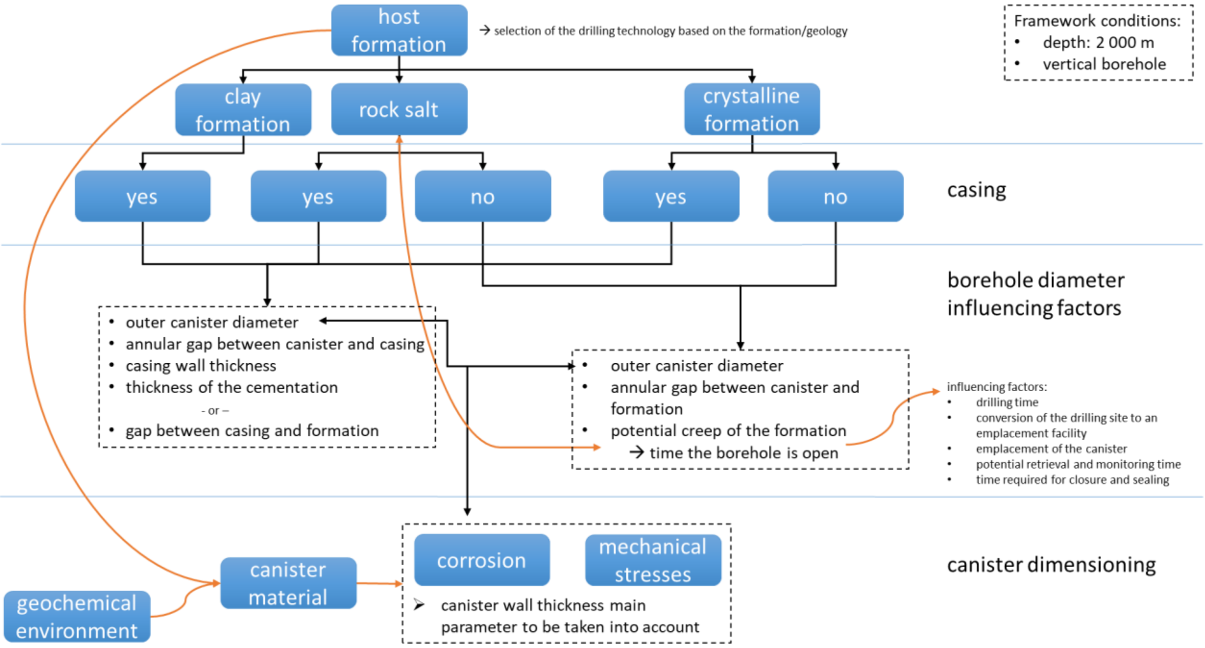

Fig. 5. Workflow for designing deep boreholes for the disposal of radioactive waste.

CONCLUSION

A simple workflow was developed that can be used to help plan and design a deep borehole intended for disposal of radioactive waste. The current workflow is preliminary and needs further development to include other factors that have been considered as fixed here. The workflow will help understand the complexity of developing a DBD facility.

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