Deep Borehole Disposal - a New Basic Approach for the Planning of Seals – 23372

Tilman Fischer and Hans-Joachim Engelhardt
BGE TECHNOLOGY GmbH

ABSTRACT

Deep borehole disposal (DBD) enables the disposal of radioactive waste in deep rock formations that have favourable properties for long-term isolation. The borehole is the preferred pathway for fluids that could mobilize radionuclides and for contaminated fluids. For this reason, seals have to separate the disposal zone from the areas near the earth's surface. The required seal performance depends on the waste characteristics and the isolation capacity of the host rock. In addition, the safety concept can take into account the isolation effect of the waste canisters or sealing measures that are carried out in the disposal zone. Stagnant groundwater conditions in the deep rock areas can also be relevant.

Regardless of individual concepts, it can be assumed that seals as engineered barriers are intended to restore the integrity of the host rock. Based on this fact, a methodical approach was developed for planning sealing systems. This approach takes account of the experience that BGE TECHNOLOGY GmbH has gained in the course of the planning and construction of seals in mine shafts, underground drifts and exploration boreholes (e.g. [1]). The final seal system is derived stepwise, taking into account the geological framework conditions.

Experiences show that contact zones, damaged rock zones and materials that are not corrosion-resistant impair the function of a seal. As a result, these areas, such as casing and its cementation, have to be removed; furthermore damaged rock areas are recut shortly before the emplacement of the sealing material. If necessary, special measures such as rock injections need to be performed to improve the quality of the host rock and to seal flow paths. The use of steel reinforcement within the seal is not permitted due to potential corrosion and backfill pipelines are generally pulled so that they do not remain in the seal.

Seals need to fulfil their task for a very long time, due to that there is a high probability that a range of mechanical, thermal and chemical processes could affect their function. In order to take into account uncertainties in the prognosis, a system of sealing elements should be set up. The elements have to work in different ways, so that the requirement of redundancy and diversity is met. Sealing materials that have a positive influence on the tightness of the contact zone and can contribute to the sealing of damaged rock zones are to be preferred. These include, for example, bentonites, which apply a permanent pressure to the rock surface, or bitumen (asphalt), which can penetrate cracks. Materials based on silicate solutions (water glass) such as geopolymers are also advantageous because they react with saline solutions and have a sealing effect.

In general sealing materials can be divided into materials that are self-supporting or that require additional elements to ensure their function. These can be abutments or filter elements. Abutments or support elements are load-bearing elements that ensure the positional stability of the seal and can prevent its erosion. Filter elements (filter frits) prevent erosion or suffusion of clay particles and homogenize the pressure or stresses on the face of the seals or abutments. Moreover, backfill (ballast) can be used to avoid or delay a pressure-build-up due to high porosity and the guarantee the position of seal elements. This results in a basic design of a sealing system with different functional elements, which can be simplified after the selection of the materials and the respective requirements. The choice of materials is primarily based on the structural properties, such as long-term stability and the effect of the materials on the solubility of radionuclides. Chemical reactions that have a positive influence on the properties of the elements are allowed or desired. Thus, elements can control the chemical environment, i.e. to reduce radionuclide solubility or to fix mobilized radionuclides. They can serve as chemical barriers.

After the selection of the material, the lengths of the individual elements are determined with the aim that each element can fulfil its function the long term. In this context, the effect of actions in the axial borehole direction and in the radial direction will be evaluated separately. Moreover, the influences of static and dynamic loads must be distinguished. The length and positioning of the elements must consider the hydrogeological conditions and the location of tectonic faults in particular.

Finally, technical aspects are taken into account when determining the final sealing design. For example, it can be necessary to use technical elements that remain permanently in the seal systems. Example are packers or sensors. The overall approach will be explained using an example of DBD in a crystalline rock formation.

INTRODUCTION

When it comes to the disposal of radioactive waste, the most common approach is to dispose the waste in geological formations. Depending on the volume of the radioactive inventory and even more important, the type of waste, different disposal options are considered or already carried out currently. While for low and intermediate level waste shallow geological regions or even surface or near-surface facilities may be of interest, high-level waste types require a more complex disposal option in deeper geological formations. Here the most common approach is the disposal in deep geological mines, but also deep, large-diameter boreholes are under investigation. Especially for smaller radioactive inventories, this seems like a reasonable option. Not matter what type of disposal concept is considered, at the end, one of the most important aspect is the sealing of the repository. Not only for the disposal of radioactive waste the closure and for sealing of underground excavations is an important topic. Furthermore, in general mining or conventional drilling operations usually the excavations need to filled and closed after ending the main operation phase. In mining, sometimes only backfilling measures are required and a tight sealing is not necessary. Still, even in these cases the stability of the formation must be ensured by the backfilling measures. When it comes to the closure of underground repositories the sealing must meet certain requirements, which may vary from country to country. The most relevant part of the closure and sealing of underground mined repositories in terms of this paper is the shaft sealing. Here extensive research work and experience is available from the sealing of shafts. When it comes to the closure of deep boreholes, commonly described as plug and abandonment in the oil, gas and geothermal drilling industry, there is a lot experience available. Still compared to the requirements, especially in terms of long-term safety and durability, there are major differences. On the other hand, the techniques used for decades in drilling technology can also be used in order to seal boreholes drilled for the disposal of radioactive waste.

This paper only deals with the seal itself. Any additional aspects of a multi-barrier system are not included and taken into account. Usually, canisters are defined as part of the barrier system. Still, these are relevant and of importance for the safe enclosure of the waste, but have no direct influence on the sealing of the borehole or repository and are therefore not considered in more depth in this paper.

INFLUENCE OF THE EDZ AND DIFFERENCES BETWEEN THE FORMATION TYPES

Due to the high safety requirements and the aspect of long-term safety, the safe closure of the repository plays a decisive role here. The most common approach and general idea of sealing any type of repository is to restore the integrity of the host formation. In order to be able to fulfil this task, it is first necessary to clarify which parameters and aspects are relevant for this purpose.

As mentioned before, seals are not only required in deep boreholes, furthermore in mine shafts, underground drifts and exploration boreholes, seals need to be planned and constructed. The procedure and experience in the field of drift seals in the Asse II mine is presented by Engelhardt et al. [1] for example. In principle, the approach from the sealing of underground drifts can be adapted for the planning of seals in deep boreholes.

Regardless of the excavation type, various aspects play an important role in the approach of designing seals. The most important and central point in all cases is the geological framework condition. Usually, a general idea can be obtained by knowing the rock type in which the seal is to be constructed. For geological repositories, there are in principle three groups of rocks considered, crystalline formations, clay formations and rock salt. These formation types by themselves are considered to be impermeable and will therefore prevent the flow of contaminant fluids or a general migration of radionuclides to the environment. Each of these has some typical behaviours, which may be beneficial for the sealing operation or require special treatment. The most important favourable properties of these rock types are summarized in Table 1.

Table 1 – Favourable properties of considered host formations for the disposal of HLW.

Crystalline formations [2]	**Clay formations [3]**	**Rock salt [4]**
High strength (providing cavity stability)	Homogeneity	Good isolation properties
Low-heat sensitivity	Low groundwater flow	Low permeability of undisturbed salt
Low permeability	Chemical buffering capacity	Potential for self-sealing of fractures and openings
Dissolution properties	Propensity for plastic deformation	Dry environment
High level of technical development for the closure of fractures in the mountains	Seal-healing of fractures by swelling	Thermal conductivity
	Demonstrated capacity to chemically and physical retard the migration of radionuclides	Predictable geology

Linked to the geological framework, but not directly related to the formation type, are potential faults or fractures. Typically, these sections require special treatment during the sealing operation in order to eliminate the risk of the creation of flow paths for contaminated fluids or migration paths for radionuclides.

A more critical aspect is the excavation damage zone (EDZ) surrounding the excavation. These damages zones are typically resulting from the excavation process. Depending on several factors will this damaged and usually higher permeable area around the underground opening influence the integral permeability of the formation negatively. Through the excavation of an underground cavity stress redistributions in the remaining formation will occur. These stress redistributions usually result in changes in the permeability and formation strength. The extent of the EDZ depends strongly on the size and type of excavation, as well as well as the way the cavity was created. Another factor that needs to be considered when talking about the EDZ is the time. Generally, the longer the excavation remains open, the more the disturbed zone spreads and more distant parts of the formation also exhibit an increased permeability. The type of formation gives another factor on the dimension of the EDZ. Table 2 provides a principle overview of different formation types and the behaviour of the EDZ. Furthermore, the term excavation disturbed zone (EdZ) is introduced here. Compared to the EDZ, the EdZ describes the region, which is further away from the excavation. In principle, this area is disturbed less and not as negatively influenced as the EDZ. It must be mentioned, however, that the transition between EDZ and EdZ is usually difficult to determine. Thus, it is difficult to find a clear demarcation here and the two zones together must be seen rather as a disturbance of the formation around an excavation.

Table 2 – Proposed definitions of the EDZ and EdZ for four different rock types [5] [6].

	Crystalline Rock	Rock Salt	Indurated Clay	Plastic Clay
EdZ	Region where only reversible (recoverable) elastic deformation has occurred. Note: It is theoretically impossible to define the outer limits of the EdZ.	Region with change of stress relative to initial state. Note: Outer boundary not clearly delineated; effects of EdZ at great depths not likely to be important over operation period, but may be significant for long-term performance.	Region where only reversible processes (elastic strain, pore pressure changes, etc.) take place; not relevant to creation of preferential pathways for radionuclide migration.	Zone with significant modification of state (pore pressures, stresses, etc.); no negative effects on safety.
EDZ	Region of irreversible deformation with fracture propagation and/or development of new fractures. Note: Strong transient behaviour; depends on construction methods, as well as stress redistribution.	Region of considerable property changed hydraulic properties. Note: Extent and quality of EDZ may change over time, depending on stress-strain conditions.	Microcracked zone with damage and failure, and with weakly connected microcracks. A zone in which permeability increases by several order of magnitude, owing to newly formed connected porosity – may become an issue in safety assessment. Note: EDZ is not the same as plastic or yielded zone.	An evolving tone with geomechanical and geochemical modifications of state and material properties, which might have a negative effect on operational and long-term safety.

A more graphical display of this the formation and around an excavation was presented by Perras & Diederichs [7] (see Figure 1). In this display, the area around the excavation is broken down into even more different zones.

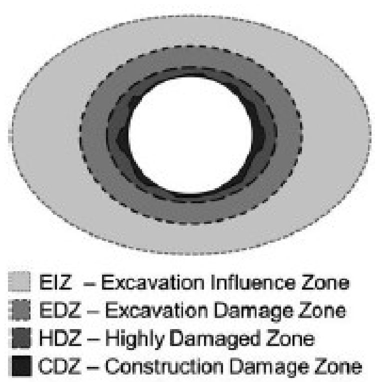

Figure 1 - Display of the excavation damage zones (HDZ, EDZ, EIZ) and the construction damage zone (CDZ). Note that the ELZ is defined as EdZ by Tsang et al. (2005) and was only re-named due to potential confusion with the lowercase "d" and the uppercase "D". [7]

These different approaches as well as numerous further publications dealing with this topic show the great interest of scientists and engineers as well as the importance for the long-term sealing of the radioactive waste. Even though it is generally expected, that the formation around a borehole is damaged to a smaller extend compared to the formation around an underground mined opening like a shaft or drift for boreholes this zone plays an important role as well. Due to the length of the borehole and the comparable small area of the opening itself the treatment of the EDZ is even more important. Furthermore, the borehole is the shortest connection to the surface environment and therefore the EDZ represents the most likely pathway for radionuclide migration. In Figure 2 the potential flow paths within the deep borehole disposal system are shown. While conducting a safety assessment for a deep borehole disposal concept for Norway, it has been made clear how great the influence of EDZ is on the long-term safety of a deep borehole repository (see [8]). In addition, the different characteristics of the formation types come to play once more. While in salt a natural healing process of the EDZ occurs, by its natural creeping behaviour, and thus also an effectively natural barrier, crystalline formations for instance show negative properties here. Crystalline formations barely absorb radionuclides and do not show and self-healing behaviour. While the damaged zone around the borehole in rock salt heals itself and thus closes potential flow paths, crystalline rock has a weak point here. Radionuclides may therefore be transported through this non-absorbing, potentially fractured zone of the crystalline formation.

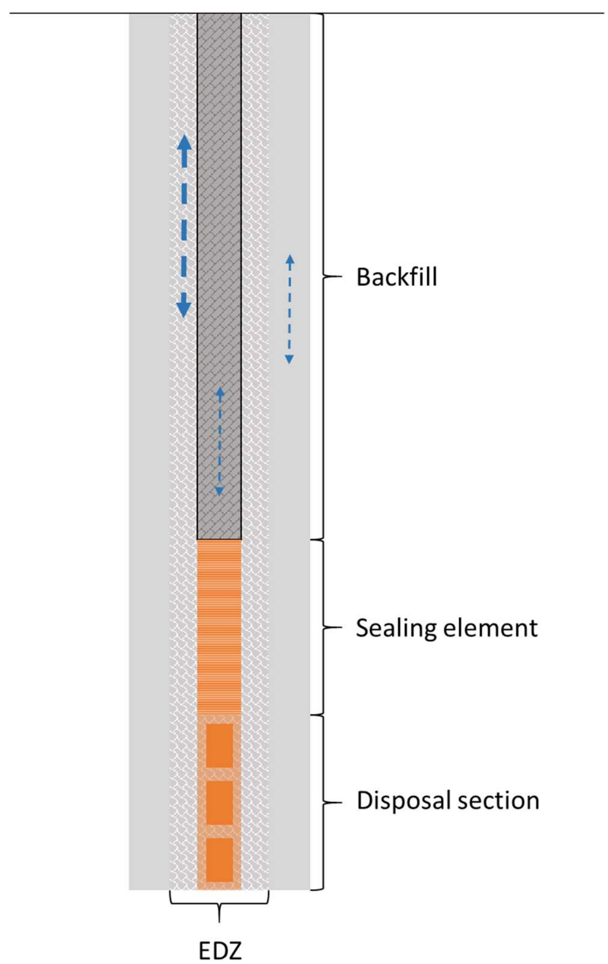

Figure 2 – potential flow paths within the sealed deep disposal borehole system. The thickness of the arrows indicate the likeliness of the individual parts. The permeability from the undisturbed rock and that of the sealing material are assumed to be the same.

This shows the importance of accurate and targeted treatment and tempering of the EDZ around the borehole. For this it is indispensable to select the right materials. Not only the general formation type, but also further information about the conditions within the excavation is of great importance to select the best material to seal the borehole. The mentioned required information include the rock stress, the pressure, the temperature, as well as the salinity and potential fluids in the excavation or borehole to be sealed. In summary, the overall properties of the surrounding rock mass are of crucial importance for the design of the seal.

When it comes to the more technical aspects, potential materials in the excavation, in boreholes these may be casing pipes and the general condition are of interest. Information about this are important in order to prepare the excavation for the emplacement of sealing elements and materials.

IMPORTANCE OF THE CONTACT ZONE

Particularly in the case of sealing boreholes, the importance of the contact area and the correct tempering of this area becomes clear when the numerical values of the dimensions are compared.

While in drift seals and shafts sealing operations, the sealing elements are significantly larger, in boreholes, the small diameter increase the impact of a poor bond between the sealing material and the formation. For this reason, three examples are presented in Table 3, a drift seal, a shaft seal and a sealed borehole. Here the potential volumes of sealing elements are put into relation to the contact area between the formation and the sealing material.

Table 3 – Relation between the sealing element volume and contact area.

Parameter	**Drift seal [1)]**	**Shaft seal [2)]**	**Borehole seal [3)]**
Length [m]	30.00	495.00	1 500
Height [m]	5.00	-	-
Width [m]	5.00	-	-
Diameter [m]	-	6.30 - 11.00	0.70
Sealing volume [m]	750.00	17 247.25	577.27
Contact area between formation and seal [m²]	600.00	10 296.11	3 298.67
Ratio (volume/contact area)	1.25	1.68	0.18

[1)] Based on drifts seals in the Asse II Mine [1]
[2)] Values are based on a shaft sealing concept for the Schacht Marie of the Radioactive Waste Repository Morsleben (ERAM) [9]
[3)] Example of a possible sealing of a borehole with a total depth of 2 500 m

The presented numbers illustrate how much larger and more important the contact area is when sealing boreholes. The actual sealing elements represent a much smaller factor in relation to the contact area. Therefore, even more care must be taken to seal off this contact area.

IDEAL LENGTH OF A SEALING ELEMENT

It is almost impossible to make a general statement about the perfect length of a sealing element. This applies not only to borehole sealing operations, but in general. The reason for this is, that the formation and conditions will barely be perfect in any case. Fractures within the formation, small fissures or changes in the rock type will impact the requirements on the sealing elements. Compared to sealing structures of underground drifts or ramps, the geological strata can be better simulated for sealing systems of boreholes. With the knowledge of the relationship between diameter and contact area in boreholes and drift seals, as well as the ability to better mimic the geologic structures in boreholes, it can be assumed that the required length of a sealing element in a borehole is probably shorter than the required length of a drift seal.

A simple approach based on Darcy's law underlines this thesis. With the help of Darcy's law (see equation 1) it is possible to determine the permeability of a body.

$$K = \frac{Q * \eta * l}{A * \Delta p} \quad \textit{Eq. 1}$$

By rearranging this formula, other parameters can be calculated as well when input parameters are available. To get an idea of how long the sealing element should be to minimize the flow, the formula is rearranged in a way that the flow rate can be calculated (see equation 2).

$$Q = \frac{K * A * \Delta p}{\eta * l} \quad \textit{Eq. 2}$$

To get an idea of how changing the length of the closure structure affects the flow rate, the parameter l is varied while all other parameters remain the same. Furthermore, a better comparability between the sealing in the drift and in the borehole is ensured by not changing the integral permeability. The only parameter that is adjusted is the diameter of the cavity. For the borehole 0.7 m is assumed, while for the drift 8 m is set. A summary all the assumed values is shown in Table 4.

Table 4 – parameters and values used for the calculation

Parameter		**Unit**	**Value**
K	Permeability	m²	[1)]
Q	Flow rate	m³/s	-
η	Dynamic viscosity	mPas	0.001
l	Length of the sealing element	m	[2)]
A	Cross-sectional area flowed through	m²	0.436 – borehole 51.022 – drift seal
Δp	Pressure difference	MPa	1

[1)] Integral permeability varies depending on the assumed permeability of the sealing element
[2)] For the calculation different values ranging from 1 to 200 m are considered

For the permeability values several sections need to be considered in order to provide an integral permeability of the whole sealing system. The permeability of the sealing element itself is ranging between 10^{-17} m² and 10^{-23} m². Furthermore, the edge of the sealing elements need to be considered individually. Here an EDZ with a thickness of 0.01 m is defined with a value of 10^{-15} m². The near borehole formation is included in the calculation to a depth of 0.02 m and a permeability of 10^{-17} m². The results of the calculation for different potential length of the sealing elements are plotted in Figure 3.

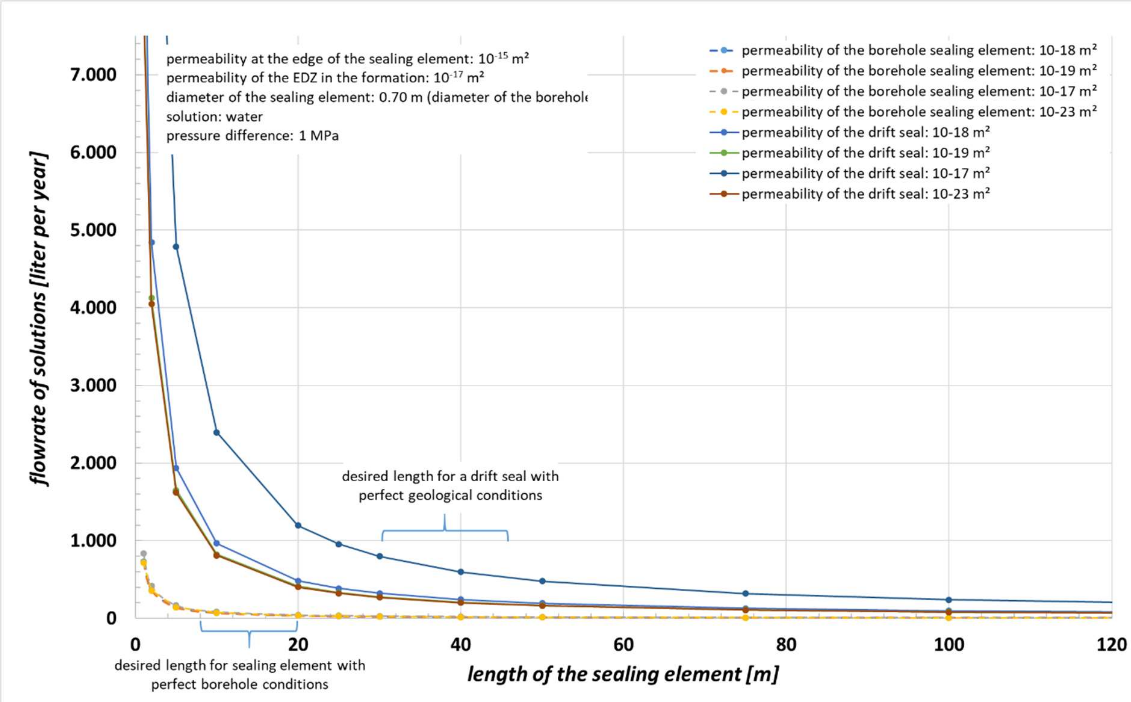

Figure 3 – graphical illustration of flow rates through borehole sealing elements and drift seals with different permeability values.

These results show, that a starting at a length of roughly 30 m the yearly flow rate through a drift seal will not be reduced significantly by an extension of the sealing element. For a borehole sealing element, this required length will around 10 to 20 m. Maybe even more reduced length might be sufficient.

Former publications have discussed the topic of sealing systems for deep disposal boreholes already. Here different approaches have been presented. In most cases, several elements of different materials have been considered.

Due to the great depth of the boreholes and the resulting great length for sealing and backfilling measures, the individual elements are significantly greater than described above. Bentonite plugs of 50 m length and cement plugs of length ranging from 100 to 150 m are the main sealing system of one of these examples. In addition cements and sand or crushed rocks are planned as backfill material, over a length of 100 m each, between the sealing elements in this example [10]. Other publications propose the to cut or grind away several meters of the casing in order to provide direct access to the formation in order to install the sealing elements. Here no detailed values for the length of these sealing elements are presented [11].

With regard to the minimum required length of the sealing elements, initial statements can therefore be made based on the presented calculation. Important is the fact, that ideal conditions are considered and any disturbance or change in the formation has an effect on the sealing effect. However, with targeted and accurate placement of the single element a great sealing effect of the borehole can already be achieved. Basis for this is, once again an accurate and detailed knowledge about the formation and the condition of the borehole.

CORROSION OF THE SEALING MATERIAL

The behaviour of sealing structures and sealing elements can be represented schematically with the help of computational models. With the help of programs like PetraSim the flow behaviour through different materials can be simulated and graphically displayed. It is possible to define different areas with different parameters. This allows to create a model with different permeability values for the formation, the sealing element material and the EDZ. This model can then be flowed through with a solution. The result is the saturation of the considered area with solution at different times. An example is provided in Figure 4.

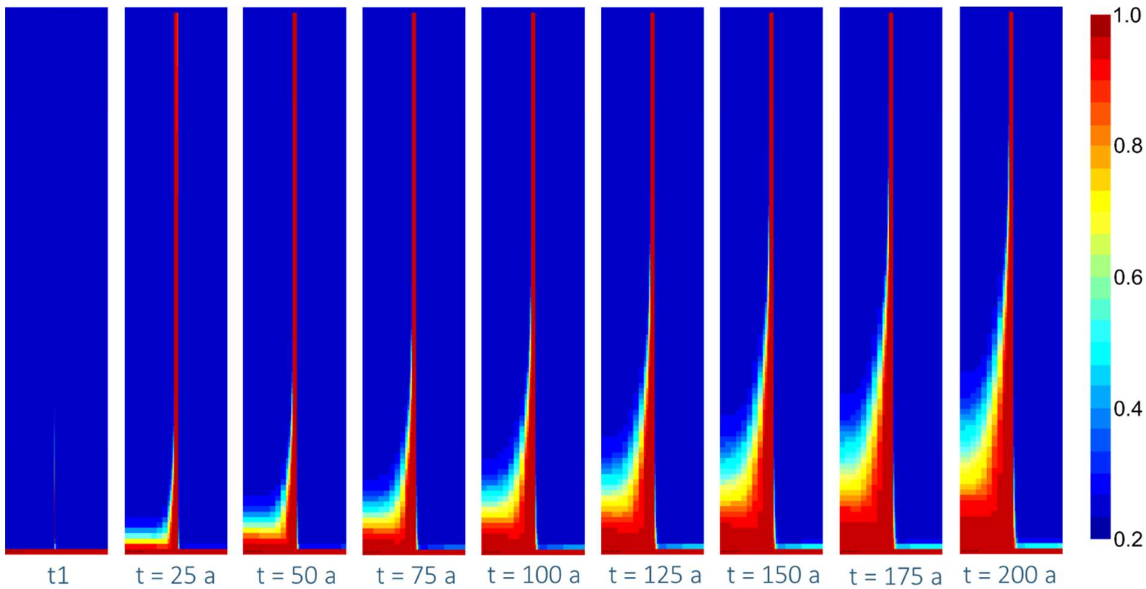

Figure 4 – example of the saturation with fluid of a predefined contact zone between a sealing material and the formation. The left side of each section is the sealing material, the right side is the formation and the EDZ in between. Here the sealing material is fixed at $k = 10^{-19}$ m², the formation at $k = 10^{-21}$ m² and the EDZ ranges at around 10^{-17} m².

This illustration shows that, as expected, the solution follows the path of least resistance. In this case, this is the EDZ. As a result, the sealing material is flowed through, while the mountain is not affected until the end.

The graphic shows, that the front of the solution is located directly at the edge of the building material. Another aspect is the fact that a gradual flow through the sealing material can be noticed. At this point the corrosion problem needs to be mentioned. Since the solution, which may flow through the EDZ, has direct contact with the building material here the risk of corrosion is urgent. It is therefore all the more important to ensure the corrosion resistance of the sealing material. Otherwise, a significantly faster flow and thus reduced sealing effect of the sealing element can be the result.

POTENTIAL MATERIALS FOR SEALING OF BOREHOLES

As mentioned before, the material considered for the sealing of the borehole plays an important role. Not only does this have to meet certain requirements in terms of permeability, but also there are requirements regarding the compatibility with the geochemical environment to be fulfilled. The examples presented in Figure 3 and Figure 4 considers a perfect environment, without any fractures and the same formation throughout the whole length of the sealing element. Since this is not necessarily realistic, different materials must be considered which fit to different conditions. Here special attention needs to be put on fractures or fissures penetrating deeper into the formation than the EDZ. In order to close and seal these disturbances, special injection materials are required. Furthermore, for borehole sealing measures not only sealing elements will be part of the sealing system, but filter elements or just backfill materials need to be taken into account as well.

For the main sealing elements, potential materials can be subdivided into three groups:

1. Materials for the main sealing elements.
2. Injection materials, which may be required so close off fractures and fissures outgoing from the borehole.
3. Physical plugs, in order to position sealing materials at desired location or isolate materials or sections from each other.

Depending on the geological framework conditions, a preselection of the materials for the main sealing elements will be made. Based on the selected materials, decision regarding the further procedure can be made. Due to the different behaviours and properties of the materials, the placement options will vary significantly between the materials.

Overall, almost any material can be used for the sealing of boreholes. When it comes to the final disposal of radioactive waste in deep boreholes certain requirements need to be fulfilled when it comes to the material. The permeability of the material is the most important factor. The material must therefore be as impermeable as possible to gas and fluids. Another important parameter is the corrosion resistance of the materials. Due to the required long-term stability, many materials can already be excluded for which this property could not be proven. This also includes, for example, all organic materials. A list of potential materials for the sealing of disposal boreholes in crystalline formations classified into different groups can be found in Table 5 below. In addition, there are emplacement methods, which may be used during the sealing process.

Table 5 – overview of different material groups, example materials and corresponding emplacement methods.

Material group	Example materials	Emplacement method(s)
Flowable materials	Barite suspensions Bitumen/asphalt Cement-based Geopolymer Phosphate binder	Balance method/balanced-plug method Dump bailer method Two-plug method
Bulk materials	Crushed rocks Clay pellets, briquettes etc.	Coiled tubing pumping Gravity placement High-velocity and high-pressure pumping
Pieces	Bitumen/asphalt Clay tubes, e.g. copper tubes Packers	Wireline Coiled tubing Rods

A more in depth description of potential materials as well as the different emplacement methods can be found in report prepared for the Norwegian Nuclear Decommissioning programme [12].

FURTHER ASPECTS THAT ARE IMPORTANT FOR THE SEALING

This paper aims to provide an overview of what needs to be considered in the safe and tight closure of deep boreholes designed for the final disposal of radioactive waste. Experience from the construction of sealing structures in underground repositories, for example from the Asse II mine, shows that the EDZ in particular plays a central aspect in the closure process.

During the planning process of the sealing system of a disposal borehole, however, the preparation of the borehole must also be taken into account as well. The preparation is of great importance for the tightness. Two examples to be mentioned are the removal of foreign materials, such as casing strings, as well as a possible recut of the borehole contour. Both will have a great influence on the previously discussed EDZ.

In all the topics discussed, however, one thing is central, and that is the formation itself. Not only the selection of the sealing materials, but also the recutting, the exact placement of the individual sealing elements as well as their lengths, require a detailed knowledge of as many details of the borehole and formation as possible.

REFERENCES

[1] Engelhardt, H.-J.; Teichmann, L. & Adelt, J. (2021) Drift Seals at the Asse II Salt Mine – A Summary of more than a Decade of Experience. WM2021 Conference, March 7-11, 2021, Phoenix, Arizona, USA, paper 21107.

[2] OECD-NEA (2022) Expert Group on Geological Repositories in Crystalline Rocke Formations (Crystalline Club). https://www.oecd-nea.org/jcms/pl_31092/expert-group-on-geological-repositories-in-crystalline-rock-formations-crystalline-club Website accessed on: 04.11.2022.

[3] OECD-NEA (2022) Working Group on the Characterisation, the Understanding and the Performance of Argillaceous Rocks as Repository Host Formations (Clay Club). https://www.oecd-nea.org/jcms/pl_29314/working-group-on-the-characterisation-the-understanding-and-the-performance-of-argillaceous-rocks-as-repository-host-formations-clay-club Website accessed on: 04.11.2022.

[4] OECD-NEA (2022) Expert Group on Repositories in Rock Salt Formations (Salt Club). https://www.oecd-nea.org/jcms/pl_31091/expert-group-on-repositories-in-rock-salt-formations-salt-club Website accessed on: 04.11.2022.

[5] Davies, C. & Bernier, F. (2005) Impact of the excavation disturbed or damaged zone (EDZ) on the performance of radioactive waste geological repositories. European Commission - Nuclear science and technology. Luxembourg. European Commission Cluster conference and workshop.

[6] Tsang, C.-F.; Bernier, F.; Davies, C. (2004) Geohydromechanical processes in the Excavation Damaged Zone in crystalline rock, rock salt and indurated and plastic clays - in the context of radioactive waste disposal. International Journal of Rock Mechanics and Mining Sciences. 02. August 2004, S. 109-125.

[7] Perras, M.A. & Diederichs, M.S. (2016) Predicting excavation damage zone depths in brittle rocks. Journal of Rock Mechanics and Geotechnical Engineering, 8 (1): 60–74.

[8] Marcos, N.; Haverkamp, B.; Bertrams, N.; Nordman, H.; Hellä, P.; Wanne, T. (2022) Generic Safety Assessment for the Norwegian National Facility. Draft for NND review, September 23rd, 2022. To be published.

[9] ERCOSPLAN Ingenieurgesellschaft Geotechnik und Bergbau mbH (2017) EW-Bau IX/7 – Verschlussbauwerk Schacht Marie – Bauphase 1. Erfurt, 15.12.2017.

[10] Arnold, B.W.; Brady, P.V.; Bauer, S.J.; Herrick, C.; Pye, S.; Finger, J. (2011) Reference Design and Operations for Deep Borehole Disposal of High-Level Radioactive Waste. Sandia National Laboratories. SAND2011-6749.

[11] Beswick, A.J.; Gibb, F.G.F.; Travis, K.P. (2014) Deep borehole disposal of nuclear waste: engineering challenges. Proceeding of the Institution of Civil Engineers. Paper 1200016. http://dx.doi.org/10.1680/ener.13.00016.

[12] Engelhardt, H.-J.; Fischer, T.; Wanne, T. (2021) Sealing of Deep Boreholes in Crystalline Rock – Norwegian National Facility. Technical Report. Germany, September, 2021.